-FINAL REPORT- Townsend

EVALUATION OF FILTER CRITERIA AND THICKNESS FOR MITIGATING PIPING IN SANDS

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FOR:

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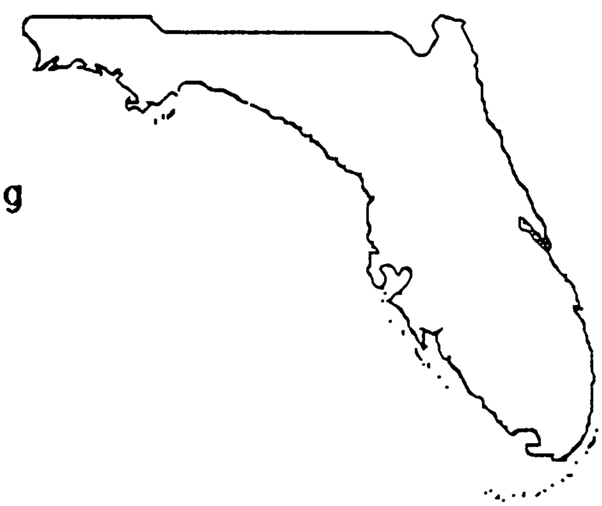

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ANALYTICAL AND EXPERIMENTAL EVALUATION OF PIPING AND FILTER DESIGN FOR SANDS

by

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Preface

This report was prepared by the Department of Civil Engineering, University of Florida, Gainesville, Florida 32611 under U. S. Bureau of Reclamation (USBR) contract 4-CR-81-04100, "Experimental Evaluation of Piping Theory and Filter Design for Sand and Dispersive Clays," Phase I and USBR contract 7-PG-81-22160, Phase II. The investigation was supervised by Dr. DeWayne Campbell of the USBR Engineering and Research Center. This report describes work completed during October 1984 to December 1985 (Phase I) and May 1987 to October 1987 (Phase II). The report was submitted in January 1988.

This report is the Master of Engineering thesis of Mr. Shiau (Phase I) and High Honors project of Miss Heidi Rubin (Phase II). The work was performed under the supervision and guidance of Professors F. C. Townsend and D. Bloomquist. Messers J. Shiau, B. Doan, R. Martinez, M. Oliver and Miss H. Rubin performed the experimental portion of the research.

Dr. J. H. Schmertmann, Schmertmann & Crapps, Gainesville, Florida, was instrumental in the design of the flume and initial portions of the research on Reid Bedford sand. Florida Power and Light contributed to design and fabrication of the flume.

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Abstract

A laboratory testing program was undertaken in order to understand better the phenomena of hydraulic piping in sand and to evaluate current filter design criteria. To simulate field conditions a hydraulic flume was used in which a saturated sand layer could be placed and subjected to variable pressure heads of water. With small initial pipes formed in the sand, the critical heads required to initiate piping were determined. Six sand gradations were tested, three of the gradations are uniform but with different effective grain diameters, one gradation was well graded and lastly, two gradations were gap gradings which also have different effective grain diameters. The most piping susceptible uniform sand among those tested was subsequently used as a base soil in filter design evaluation experiments. Based upon the ratio of soil to filter grain diameters, several different filter gradations and thicknesses were tested to evaluate filter design criteria.

Based on the results obtained, it was concluded that:

1. It is harder to initiate piping in a cohesionless soil with a higher C_u value than in one with a lower C_u value; i.e., uniform sands pipe more easily.
2. It is harder to initiate piping in a uniform cohesionless soil with a larger grain size than in one with a smaller grain size; i.e., fine sands pipe more easily.
3. A filter design criterion for cohesionless soil is established, $D_{15f}/d_{85b} \leq 4$, with a safety factor of two. This criterion substantiates that proposed by Sherard and Dunnigan, and the filter design criteria of the U. S. Army Corps of Engineers (COE), $D_{15f}/d_{85b} < 5$ (consider piping only). However, this criteria only addresses filtering.
4. The criteria used by the USBR, the SCS and the COE do not address the problem of erosion of the filter by piping. Filters which met the specified criteria were breached by this type of erosion. Filters of uniform gradation with a factor of safety of approximately one, violating the filter design criteria by a factor of two, performed successfully. These filters have larger particles than those filters with a factor of safety of two and require a higher velocity to erode and move the filter material.
5. Graded filters perform satisfactorily in resisting

erosion yet filtering the base soil.

6. The thickness of a filter is not a main factor for success of the filter.

CHAPTER I
INTRODUCTION

1.1 Definition of Piping

"Piping" is the phenomenon of internal soil erosion within an embankment dam or its foundation. The pipe or erosion channel appears to originate with cracks, joints, animal tunnels, or other features which serve to concentrate flow to that region. If the hydraulic gradients become sufficiently large at the pipe tip, then piping or internal erosion begins. The pipe will continue to migrate upstream provided there exists sufficient flow to transport and deposit the eroded material at the downstream point. The pipe may become larger in diameter as it progresses upstream. The average hydraulic gradient to the pipe usually increases due to the upstream migration shortening the length of action. Hence the action should accelerate due to this increased gradient and the piping process will continues until it emerges at the upstream face breaching the structure which may result in a catastrophic condition to the surrounding environment.

1.2 Description of Problem

Based on a survey (United States Committee on Large Dams, 1975) of existing U.S. dams, over 42 percent of dam incidents reported were related to leakage and piping. The problems at Balderhead Dam (Vaughan, 1970), Baldwin Hills (Jansen,1967), Florida Power&Light Martin Co. Dike (Schmertmann, 1980), and Teton Dam (Seed, 1981), were all related to piping. Despite the general advance of soil mechanics and embankment dam engineering, the problem of piping (erosion) of fine sands continues to plague the geotechnical engineering profession.

Current methods for analyzing piping are based upon creep ratios and lines of creep (Lane, 1935). That is, increasing the line of creep will result in an increased factor of safety against piping. This method was developed from case history reviews of small weir-dam failures in India and is strictly an empirical tool. The use of empirical methods often leads to designs with unknown factors of safety. In part,as a result of this limitation, modern dam designs rely heavily on the use of filters. But, current filter design methods that are based upon the ratios of soil to filter grain diameters are also semi-empirical methods.

Until the initial theoretical research performed by Schmertmann (1980), no quantitative design theory existed for the prevention of piping. Furthermore, piping had not been observed in the laboratory until the University of Florida experiments in 1981 (Townsend et al., 1981).

Empirical methods and engineering judgement are currently the only available techniques to evaluate factors of safety against piping and to design filters. Only Schmertmann's method is available for quantifying piping safety and it requires additional laboratory verification. In addition, more investigation is needed for the effectiveness of soil filters to prevent piping.

1.3 Scope of the Project

A specially designed hydraulic flume with a transparent plastic top to permit visual observation of the pipe was used to simulate field conditions for the experimental part of the project. Chronologically, the project consisted of two phases: Phase I evaluated sand gradation characteristics conducive to piping and filter design criteria; and Phase II evaluated filter thickness and erodability.

In Phase I six sand gradations were tested to determine the threshold piping gradients. Three of the gradations were uniform, Reid Bedford sand, 20/30 sand,and 8/30 sand, but with different effective grain diameters. One gradation was well graded and two gradations were gap graded, both having different effective grain diameters. A single overburden pressure of 5 psi supplied by the bladder in the base of the flume, and three initial pipe penetration lengths, 15%, 30%, and 45%,were tested. Subsequently, the most piping susceptible uniform sand, the Reid Bedford sand, was subsequently used as a base soil in filter design experiments. Based upon the ratios of soil to filter grain diameters, three different filter gradations and thicknesses were tested to evaluate filter design criteria.

In Phase II two base soils (Reid Bedford sand and 30/65 sand) with different effective grain diameters were used in the filter design experiments. Filter thicknesses of 3-, 6- or 12-inches were tested using various filter materials including one graded filter.

CHAPTER 2

HISTORICAL REVIEW

OF PIPING PROCESS AND FILTER DESIGN

2.1 Causes of Piping

"Piping" is the phenomenon of internal soil erosion within a water retaining structure or its foundation. Decaying vegetation, burrowing animals, site stratigraphy, previously mined areas, cracks and excavations may all form initial pipe channels. The piping process originates largely due to the presence of a high exit gradient. Once the pipe is initiated, the pipe progresses upstream if there exists enough flow to carry the eroded soil to an exit point. As a result, the piping process continues in an upstream direction and the average hydraulic gradient to the pipe may be increased as the pipe grows. Some of the common causes of piping failures are shown in Table 2-1.

2.2 An Empirical Design for Prevention of Piping-Lane's Creep Ratio

The line of creep theory was developed based on the assumption that piping resistance is reduced along horizontal contacts between a rigid structure and its foundation, compared with vertical or inclined contacts. Lane(1935), in his study of 280 dams, including 150 failures, established an empirical weighted creep ratio as a design concept to avoid piping.

In this method, the length of the creep is computed as the sum of the vertical component V plus one third the horizontal component H of the shortest seepage path beneath a structure i.e.

TABLE 2-1

CAUSES OF PIPING FAILURES

a. Lack of filter protection
b. Poor compaction along conduits in foundation trenches, etc.
c. Gopher holes, rotted roots, rotted wood, etc.
d. Filters or drains with pores so large soil can wash through
e. Open seams or joints in rocks in dam foundations or abutments
f. Open-work gravel and other coarse strata in foundations or abutments
g. Cracks in rigid drains, reservoir linings, dam cores, etc. caused by earth movements or other causes
h. Miscellaneous man-made or natural imperfections

Source: Cedergren, 1977

$$Rc = \frac{1/3\ H + V}{h} \qquad \text{(Eq. 1)}$$

where H = horizontal contacts (< 45)

V = vertical contacts ($\geq$ 45)

h = head loss throughout the system

Lane recommended that Rc should not be less than those values shown in Table 2-2 to avoid piping. Incidentally, Eq.1 is merely a modification of the inverse of the average hydraulic gradient. From Table 2-2, recommended minimum values for Rc range from 1.6 for very hard clay or hardpan, to 8.5 for a very fine sand.

It should be mentioned that Harr (1962) has pointed out theoretical errors and cautioned against blind application of this piping criteria without cognizance of subsurface soil conditions. Therefore, the importance of a theroetically sound and quantitative piping theory is self evident.

2.3 Development of a Quantitative Piping Theory

Piping is the erosive action of seepage velocities. Figure 2-1 shows the seepage velocities required for erosion for various particle diameters as a function of pipe diameter. These relationships are for horizontal stream beds in the absence of seepage forces, and were derived by equating the average wall shear stress, τ_o, to the Shields equation for critical shear stress to cause erosion, τ_c, as shown below. (Graf, 1971)

$$\tau_c = 0.06(\gamma_s - \gamma_w)De \qquad \text{and}$$

$$\tau_o = \frac{\gamma_w R (Vm)^2}{M^2 (R)^{4/3}}$$

where γ_s, γ_w = unit weight of solids and water, respectively

De = effective grain size d_{35}

R = hydraulic radius (R = d/4 for circular pipe)

Vm = seepage velocity

= discharge velocity / porosity

M = $(8.25 \sqrt{g})/ (De)^{1/6}$

d = diameter of pipe

From Figure 2-1, the velocity required to initiate erosion far exceeds that which would occur in a pipe in a soil, by a factor of 10 to 100. Schmertmann thus concluded that upward seepage forces must be a significant variable in reducing the erosion velocity required to initiate and maintain the piping process. Using flow nets, he found the vertical gradient at the pipe entrance by dividing the change in total head between the last 2 equipotential drops by the vertical distance over which the drops occurs. Likewise, a similar procedure was used to determine the

TABLE 2-2

RECOMMENDED WEIGHTED CREEP RATIOS (Lane,1935)

Material	Safe weighted creep-head ratios, Rc
Very fine sand	8.5
Fine sand	7.0
Medium sand	6.0
Course sand	5.0
Fine gravel	4.0
Medium gravel	3.5
Coarse gravel, including cobbles	3.0
Boulders with some cobbles and gravels	2.5
Soft clay	3.0
Medium clay	2.0
Hard clay	1.8
Very hard caly or hardpan	1.6

Source: Lane, 1935

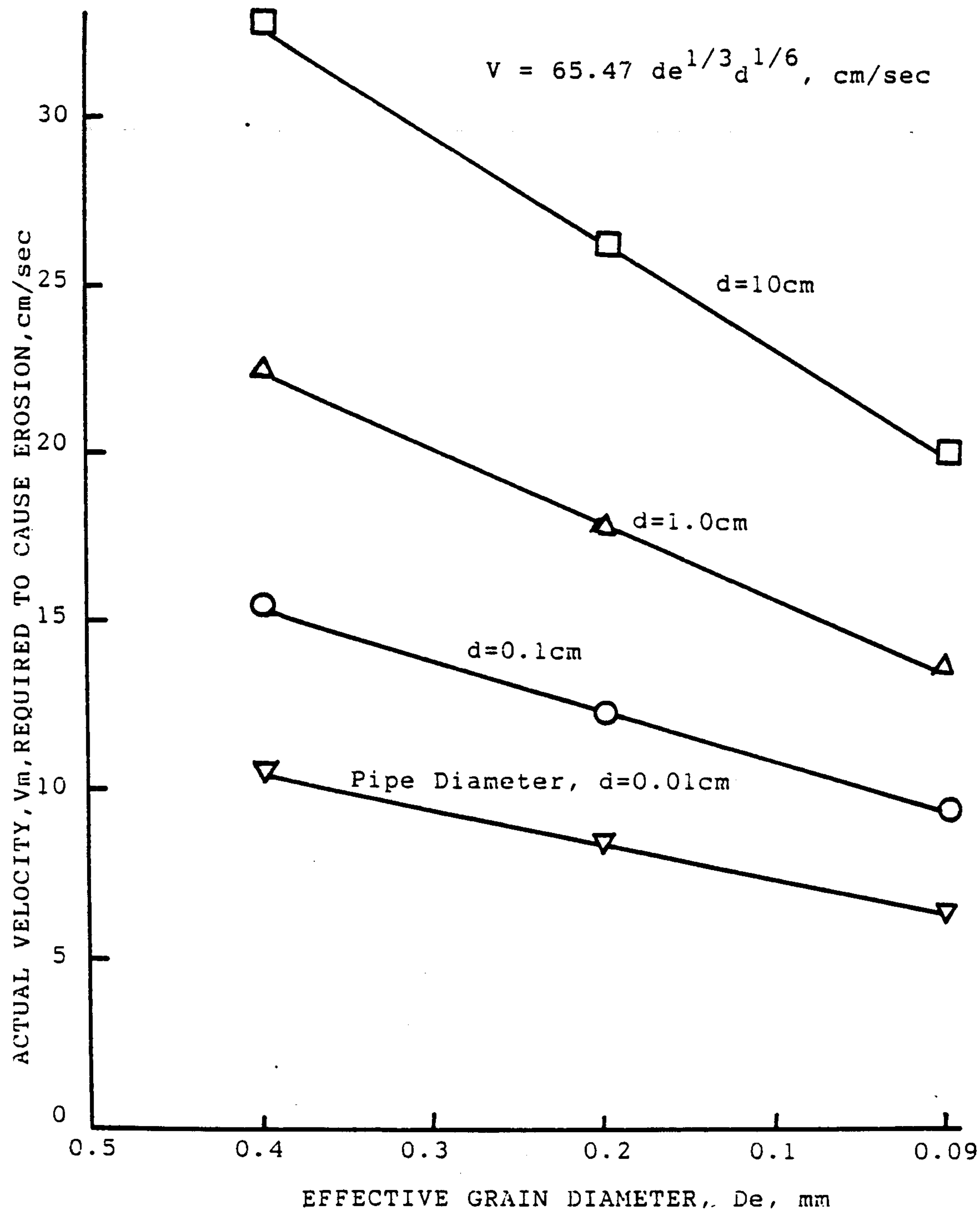


Figure 2-1. Critical velocities required for initiation of erosion of sand particles

horizontal gradient at the head of the original pipe. The concentration of these gradients was then expressed as a product of the average hydraulic gradient that exists parallel to the pipe.

To avoid the laborious process of constructing flow nets, seepage computer programs, Logan (1980) and Wong (1981), were developed to provide more accurate solutions than the hand-sketching methods used by Schmertmann.

In order to better understand the phenomena of hydraulic piping in sand, a unique experimentation flume testing program was performed at UF in 1981 (Townsend et al.). Figure 2-2 presents the results of flume tests using two semi-circular pipes of different relative radii (B/r =10 and B/r = 50, where B= 6"=1/2 width of flume i.e., actual radii of 0.6" and 1/8") for various percent pipe penetrations. From Figure 2-2, it can be seen that the smaller the pipes and the greater pipe the penetration, the lower the average gradients required to initiate piping. Both observations are in accord with Schmertmann's concepts.

From this UF investigation, Schmertmann's theory was basically subtantiated; and a laboratory flume and test methodology developed. Further studies with a variety of materials are needed to verify the theory since only one sand, Reid Bedford sand, was used in this UF investigation.

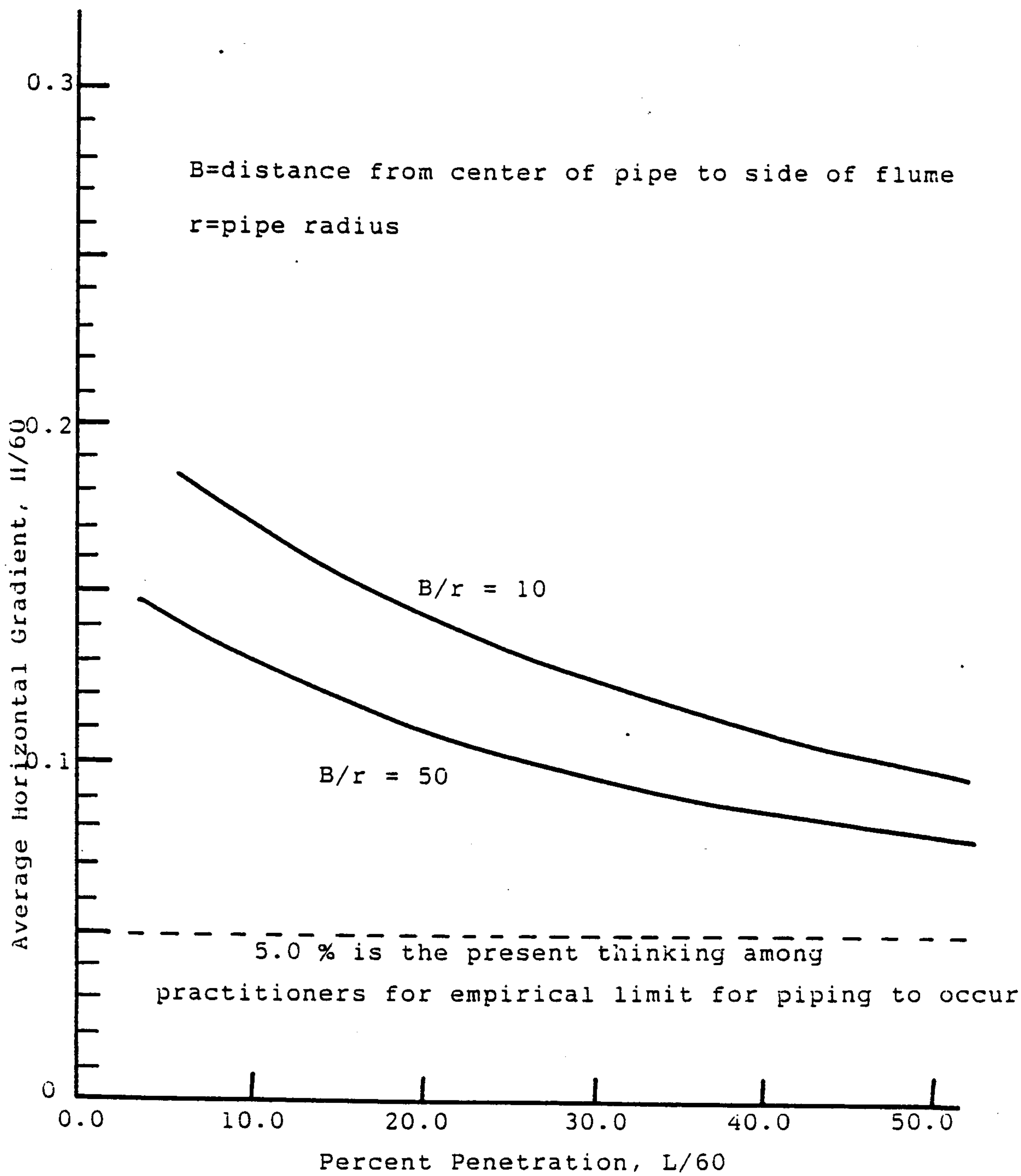


Figure 2-2. Percent penetration vs. average horizontal gradient (parallel flow case)

2.4 Kenney and Lau's Research

In more recent research (Kenney and Lau, 1985), a method was proposed for evaluating the potential for grading instability based on the shape of a material's grain size curve. The method is illustrated in Figure 2-3. In the left-hand diagram, at any point on the gradation curve corresponding to a value of "mass fraction smaller than", denoted by F, and a particle diameter D, the mass fraction H is measured between particle size D and 4D and plotted in the right-hand diagram against F. This procedure is repeated for different points on the grading curve until sufficient points are obtained to establish an H:F shape curve. The point representing the coarse end of the grading curve falls on the line $F + H = 1$. Large values of H correspond to steep grading curves, and vice versa. Constant values of H correspond to straight line portions of grading curves and increasing values of H indicate a steepening of the grading curve.

The reason for choosing the size interval equal to 4 times is that the size of the predominant constrictions in a void network of a granular soil is approximately equal to one-quarter the size of the small particles making up the soil (Kenney et al. 1985). This means that particles of size D can pass through constrictions in a granular soil formed by particles of size 4D and larger. The range of F= 0 to 0.3 for materials having narrowly-graded "primary fabrics" and F= 0

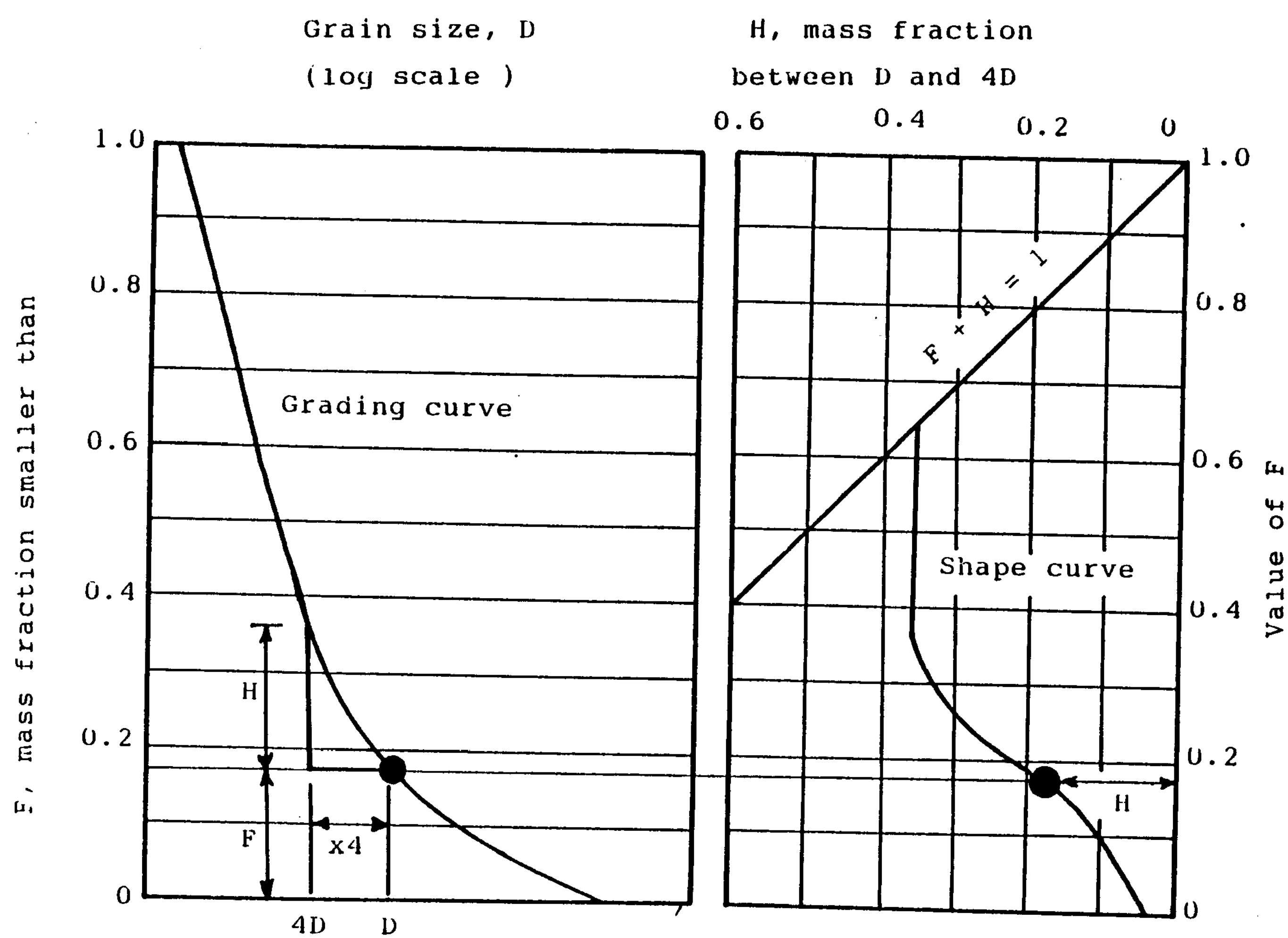
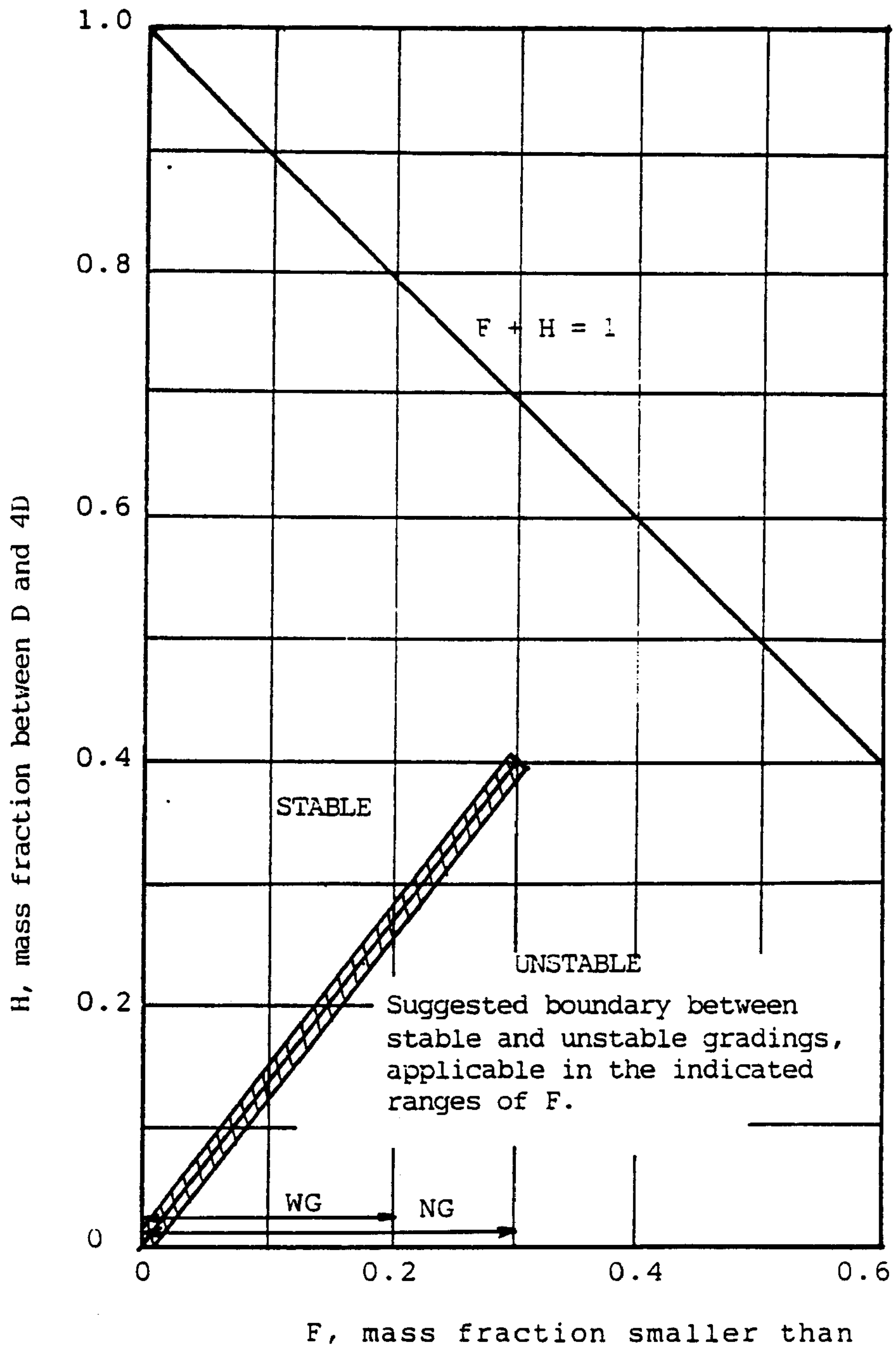


Figure 2-3. Method of describing the shape of a grading curve

to 0.2 for materials with widely-graded "primary fabrics" are the estimated maximum contents of loose particles which can be removed within the pores of granular materials.

A boundary shape curve which separates stable and unstable grading curves was proposed as shown in Figure 2-4. Stable gradings are not deficient in any particle size, their H values being larger than those of the boundary curve, and therefore their shape curves are located above the boundary. On the contrary, unstable gradings are deficient in certain particle sizes and the corresponding parts of their shape curves lie below the boundary.

An approximate method is shown in Figure 2-5 illustrating how the boundary relationship in Figure 2-4 can be used to assess whether or not materials are potentially unstable. The two grain size curves are the envelope of gradings of filter materials used in a rockfill dam. The method consists of drawing, at several values of F along the grading curve, the minimum required values of H for stable gradings given by the boundary line in Figure 2-4. Both materials in Figure 2-5 are widely-graded in the particle range of the primary fabric and therefore H-values were obtained within the range F=0 to 0.2. It can be seen that the upper grading curve lies below these points and it can be concluded that this material is potentially unstable. By applying this method to the lower curve the same conclusion would be reached.



LEGEND

WG: soils widely graded in range F=0.2 to 1.0

NG: soils narrowly graded in range F=0.3 to 1.0

Figure 2-4. Boundary Shape Curve

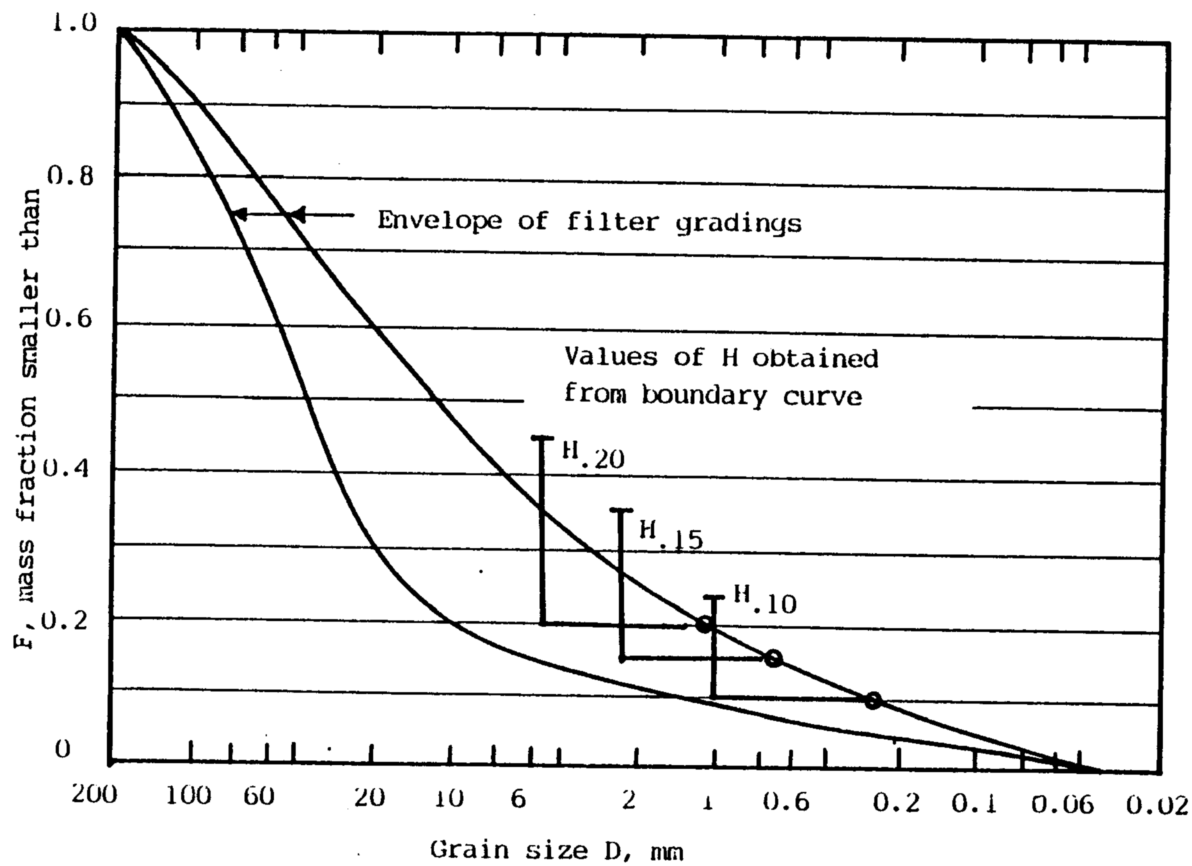


Figure 2-5. Method to evaluate the potential for grading instability

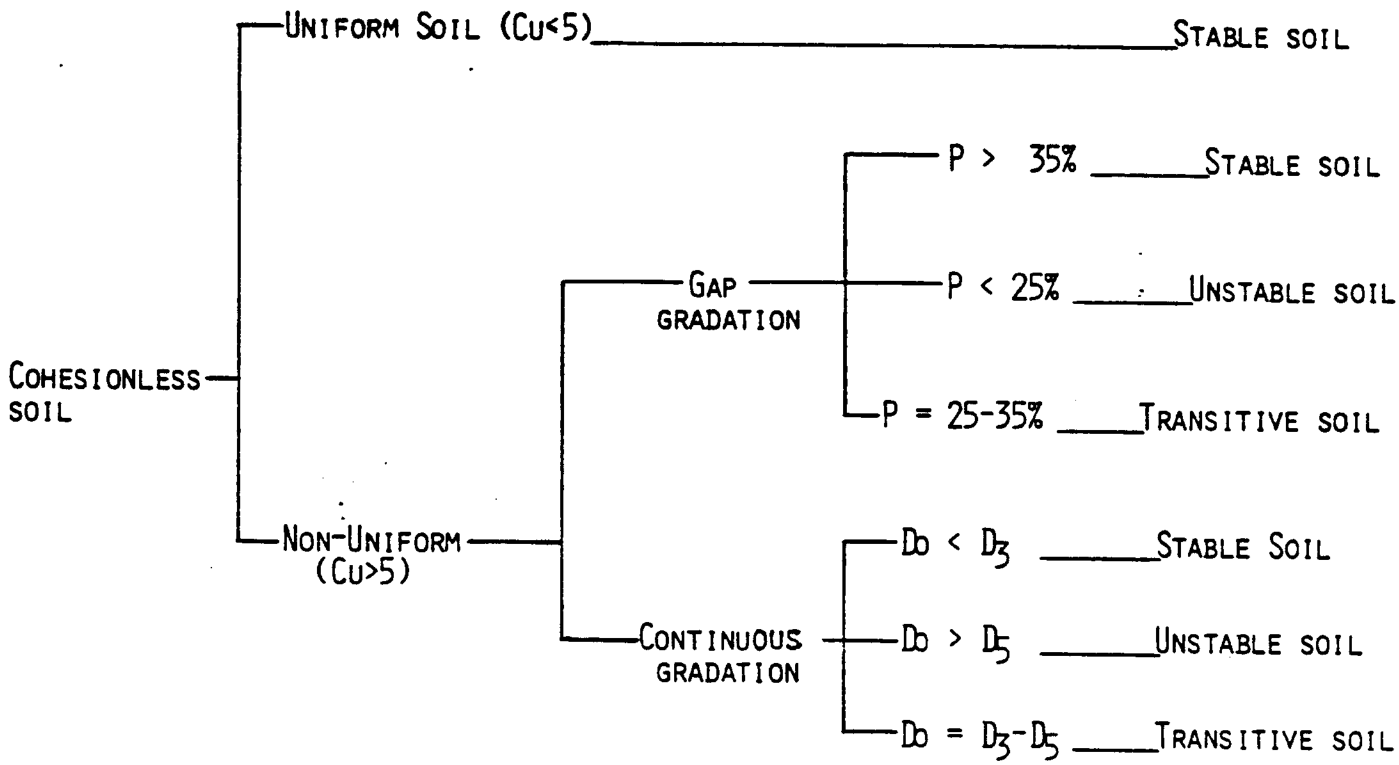
2.5 Liu's Research

In a research project at the Hydrotechnical Science Research Institute, China (Liu, 1984), cohesionless soils were classified into piping soil, transitive soil and non-piping soil. Considering a soil under the influence of a certain hydraulic gradient, if particles of the soil are eroded and carried out through pores of the soil, then this soil is a piping soil; if the soil is not carried out particle by particle but is removed all together, i.e. sheet flow, then this soil is a non-piping soil. A soil which has both characteristics of piping and non-piping soils is classified as a transitive soil.

To classify a soil's property of piping, several factors are considered, such as the coefficient of uniformity, the gradation curve, portions of fine material, and the average diameter of pores in soil. Firstly, cohesionless soils are distinguished by the coefficient of uniformity, Cu. A soil with a Cu equal to or less than 5, classifies as a uniform soil and is a non-piping soil. For soil with a Cu greater than 5, i.e. a non-uniform soil, the gradation curve is used to classify the soil into a discontinuous or continuous gradation. For discontinuous gradation soils, a soil is classified as a non-piping soil if the portion of fine material, P, is greater than 35 percent. A soil is classified as a piping soil if P is less than 25 percent and as a transitive soil if P lies between 25 and 35 percent. For continuous gradation soils, a soil is classified as a non-piping soil if its average diameter of pores, Do, is less than D_3, where D_3 is the soil diameter at which 3 percent of the soil weight is finer. A soil is classified as a piping soil if Do is greater than D_5 and as a transitive soil if Do lies between D_3 and D_5. The classification of cohesionless soils can be seen in Table 2-3.

In Liu's research, critical gradients for cohesionless soils were also established, as shown in Table 2-4. For non-piping soils, the allowance gradients are calculated using a safety factor of 2. For piping soils, a safety factor of 1.5 is used since the soil still has some potential to sustain piping under the gradient of initiation piping. However considering the factor of practical experience, 0.1 is thought as the minimum allowance gradient.

TABLE 2-3
NHSRI CLASSIFICATION OF COHESIONLESS SOILS FOR INTERNAL STABILITY



P = THE PORTION OF FINER MATERIAL IN GAP GRADATION

D_o = THE AVERAGE DIAMETER OF PORES, $D_0 = 0.63nD_{20}$ (N = POROSITY)

(FROM LIU, 1984)

TABLE 2-4

CRITICAL AND ALLOWANCE GRADIENTS IN COHESIONLESS SOILS

Gradient	Non-piping soil		Transitive soil	Piping soil	
	$Cu \leq 5$	$Cu > 5$		Continuous gradation	Discontinuous gradation
i_{cr}	0.8-1.0	1.0-1.5	0.4-0.8	0.2-0.4	0.1-0.3
i_{allow}	0.4-0.5	0.5-0.8	0.25-0.4	0.15-0.25	0.1-0.2

TABLE 2-5

FILTER DESIGN CRITERIA OF THE U.S. ARMY CORPS ENGINEER

$D_{15f}/d_{85b} < 5$	piping ratio
$5 < D_{15f}/d_{15b} < 20$	permeability ratio
$D_{50f}/d_{50b} < 25$	parallel gradation

2.6 Filter Design Criteria

From the recent research of Sherard and Dunnigan (1985), some changes in the practice of earth dam engineering have been proposed. The changes consist of less emphasis on the necessity for keeping the dam core watertight by avoiding cracks and more emphasis on the importance and details of downstream filter. Sherard and Dunnigan state,

> "In the past pactice the designer held as an axiom that:
> The impervious core is the most important element in the dam. As long as the impervious core remains intact, with no cracks or other concentrated leaks, the dam will be safe. Therefore, the primary and most important objective of the design is to provide measures which will minimize the likelihood of a concentrated leak to the greatest extent possible.
> Based on the current available experience the designer is now inclined to see the situation differently:
> We have been deluded in the past thinking that the impervious sections of our dams remain intact. Evidence now shows that concentrated leaks commonly develop in well designed and constructed dams. It is now clear that the most important element in the dam is the filter (or transition zone) downstream of the core. By providing a conservative downstream filter, we can quit worrying about possible concentrated leaks through the core."

A number of the filter design criteria have been proposed during the past century. The current criteria used commonly in the United States is the U.S. Army Corps of Engineers's, as shown in Table 2-5. After a 4-year research program in the Soil Conservation Service, Sherard and Dunnigan (1985) recommended the design criteria shown in Table 2-6-A. This criteria was augmented by additional criteria shown as footnotes and Table 2-6-B, and subsequently adopted by the Soil Conversation Service (SCS) and U. S. Bureau of Reclamation (USBR).

Based on research at the Hydrotechnical Science Research Institute, China, Liu (1984) also proposed filter design criteria for cohesionless soils. His criteria are based on the uniformity of protected soil, the piping property of protected soil, and the ratio of D_{20f}/d_k, where D_{20f} is the filter grain diameter at which 20 percent of the filter weight is finer, and d_k is the control grain diameter of the protected soil. These criteria are shown in Table 2-7, and the control grain diameter of the protected soil, dk, can be found according to Table 2-8 and Figure 2-6.

TABLE 2-6-A
FILTER DESIGN CRITERIA PROPOSED BY SHERARD AND DUNNIGAN
ADOPTED BY SOIL CONSERVATION SERVICE (SCS) AND
U. S. BUREAU OF RECLAMATION (USBR)

soil group	% Fines (<No.200 sieve)	description	Filter criteria (safety factor included)
1	85 to 100 %	fine silts and clays	$D_{15f}/d_{85b} \leq 9$
2	40 to 85 %	sands, silts, clays and silty & clayey sands	$D_{15f} \leq 0.7mm$
3	15 to 40 %	silty and clayey sands and gravels	$D_{15f} < [(40-A)/(40-15)]*(4d_{85b}-0.7)+0.7mm$
4	0 to 15 %	sands and gravels	$D_{15f}/d_{85b} \leq 4$

a) Determine the minimum D_{15f} size for the filter, $D_{15f}>4d_{15b}$, but no smaller than 0.1 mm.

b) Set maximum particle size at 3.0 inches and the maximum passing the No. 200 sieve at 5%.

c) For coarse, gap-graded filters the limitations of Table 2-6-B should be applied to minimize segregation.

* A = percent passing the No. 200 sieve

TABLE 2-6-B
SCS/USBR CRITERIA FOR PREVENTING SEGREGATION

minimum D_{10} (mm)	maximum D_{10} (mm)
< 0.5	20
0.5 - 1.0	25
1.0 - 2.0	30
2.0 - 5.0	40
5.0 - 10	50
10 - 50	60

TABLE 2-7
FILTER DESIGN CRITERIA
FOR COHESIONLESS SOILS PROPOSED BY LIU

		Design criteria
$Cu \leq 5$		$D_{20}/d_{70} \leq 7$
$Cu > 5$	non-piping soil	$D_{20}/d_{k} \leq 7$
	piping soil	$D_{20}/d_{15} \leq 5$

d_k = the control grain diameter of protected soil

TABLE 2-8
CONTROL GRAIN DIAMETER, d_k

	Control grain diameter, d_k		
	non-piping soil		piping soil
	$Cu \leq 5$	$Cu > 5$	
Continous gradation	d_{70}	d_k (Figure 2-5)	d_{15}
Discontinous gradation		d_{70} P	d_{15}

P = the portion of fines in discontinuous gradation

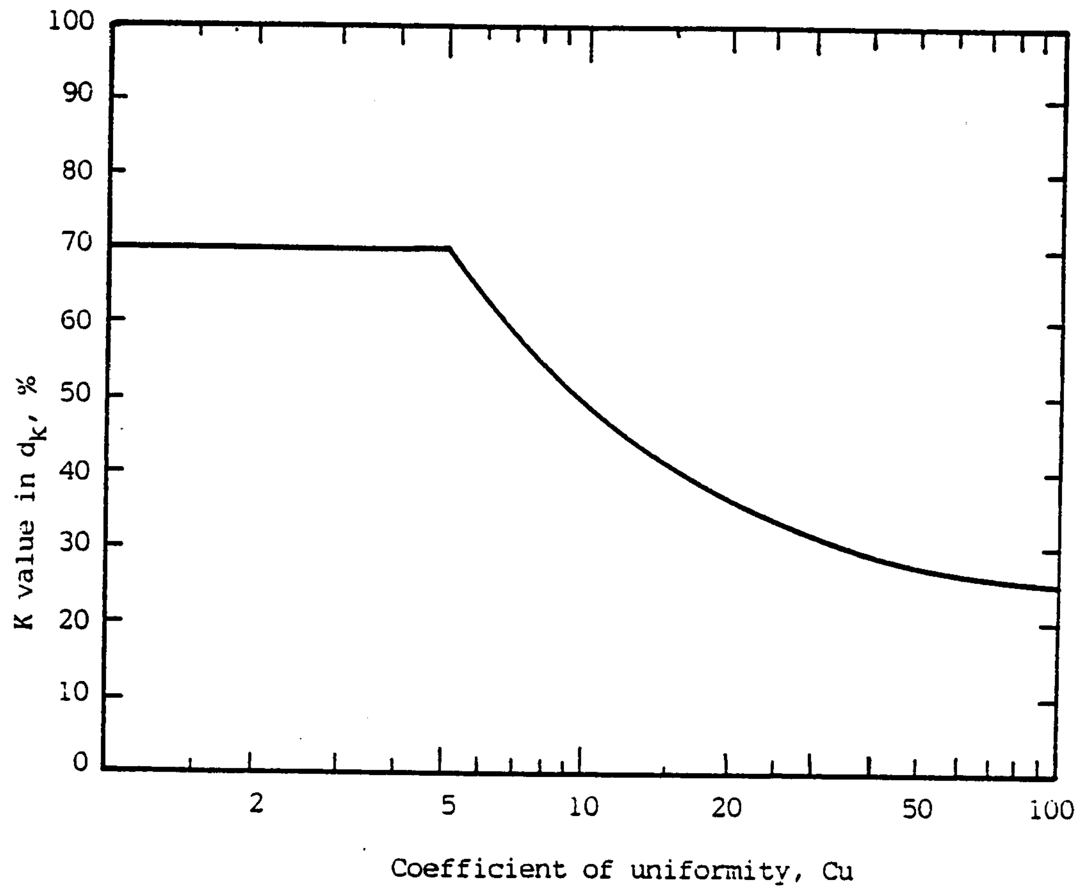


Figure 2-6. K value in Control Grain Diameter, d_k, for continuous gradation

CHAPTER 3

LABORATORY EQUIPMENT, MATERIAL, AND PROCEDURES

3.1 General

The analytical and experimental evaluation of a piping theory and filter design for sands is a unique study which required special equipment and supplies. Most of the laboratory equipment for this study was modified from the equipment that was used in a piping study performed at University of Florida in 1981.

A number of modifications were still made as the testing progressed in order to improve the testing conditions and data. For example, a vertical pulley system and a regulator were used to adjust the upstream head, cookie sheets were used to place the filter material, sugar was used to create the original pipe at upstream side of filter. A brief description of the equipment is as follows.

3.2 Details of the Hydraulic Flume

A drawing of the hydraulic flume which was used for all the laboratory tests is shown in Figure 3-1. The flume is constructed of aluminum with dimensions of 1 foot by 1 foot by 7.5 feet. It consists of 3/8 inch thick aluminum bottom and sides which were welded at the joints. Internal weirs provide for a sample length of 5 feet with upstream and downstream reservoirs. A plexiglass top acts as an impermeable roof along which piping can be visually observed. A rubber bladder at the bottom of the flume can provide an upward pressure that keeps the sample in contact with the plexiglass top. A constant head is applied at upstream through an adjustable water reservoir. A series of manometers located at 1/4 points were inserted in order to measure the heads acting along the sample.

The flume contains three internal weirs, as shown in Figure 3-1, which are porous and covered with filter fabric material, that extended across the entire one foot width. The test specimen, with a total length of five feet, lies between the upstream and downstream weirs. The upstream weir extends the full one foot depth of the flume in order to prevent any sloughing of sand into the upstream reservoir. The downstream weir was thought originally unnecessary since the test specimen sloped downstream from this point. However, the sample was pushed onto the downstream slope when the rubber pressure bladder located at the bottom of the flume was expanded. Therefore, the downstream weir was inserted in order to prevent any sample disturbance due to the expansion of the rubber bladder. The height of this weir is ten inches which allows two inches of clearance for the creation of the original horizontal pipe into the sample.

The slope weir was provided for the construction of a downstream slope with an angle of fifteen degree.

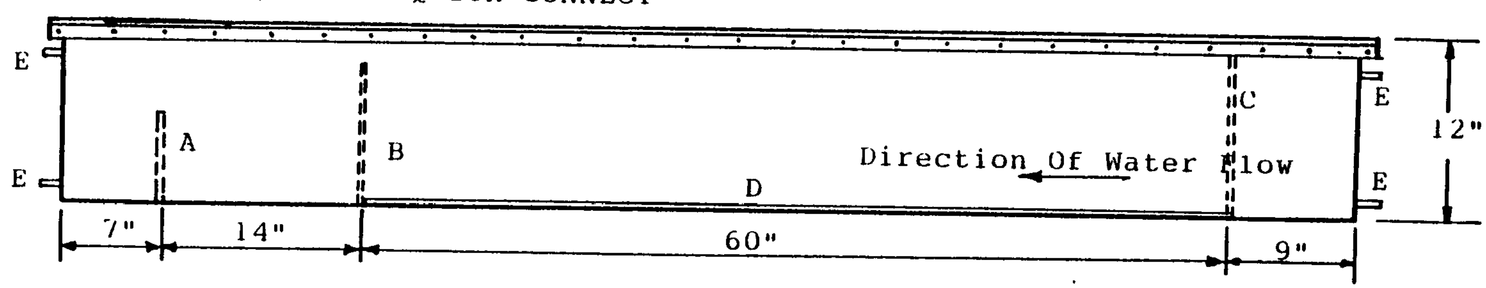
The rubber bladder, 1/4 inch thick, extends along the bottom of the entire length of the sample. It is fixed by a 1/4 inch wide aluminum frame bolted to the bottom of the flume. In order to provide a seal against leaks during vacuum and saturation, rubber O-rings were attached to the bolts. A 1/4 inch quick connect was inserted at the bottom of the flume to provide for expansion of the bladder by means of water pressure. This upward exerted pressure maintains the sample in contact with the plexiglass top of the flume and prevents sheet flow of water between the plexiglass top and sand. The plexiglass top acts as an impervious roof beneath which the piping action takes place.

The Hydraulic Flume Lid was made of one inch thick plexiglass. Figure 3-2 shows the lid.

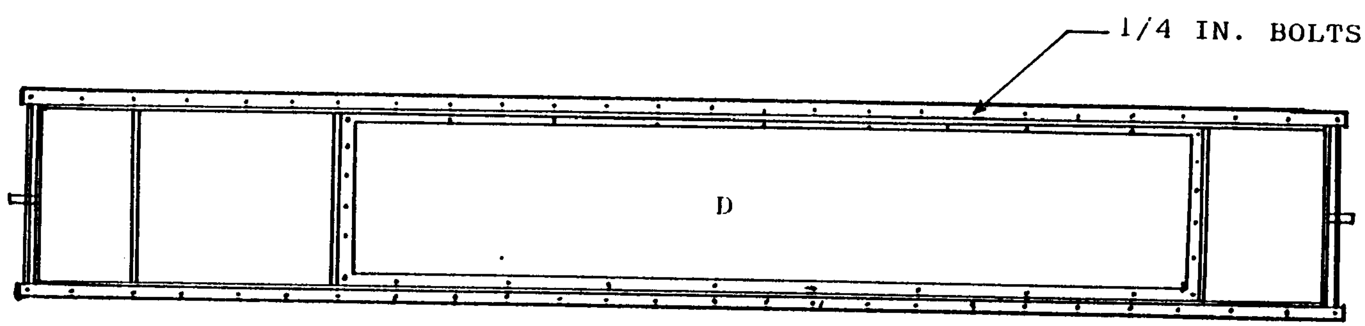
In order to provide a seal between the flume and the lid, a continuous rubber O-ring was inserted in a 1/16 inch deep groove which was cut into the top of the aluminum walls. One inch square reinforcing bars are bolted to the flume to provide a downward force sealing the plexiglass lid against the O-ring.

A series of manometers were inserted in order to measure the heads acting along the sample. One of the manometers was inserted at the upstream reservoir to determine the applied head. The others were placed at 15, 30 and 45 inches from the downstream end of the sample and 1.5 inches from the side of the flume. The layout of the manometers is shown in Figure 3.3.

INDEX: A - SLOPE WEIR
B - DOWNSTREAM WEIR
C - UPSTREAM WEIR
D - RUBBER PRESSURE BLADDER
E - 1/4 INCH QUICK CONNECT



ELEVATION



PLAN

Figure 3-1. Hydraulic Flume

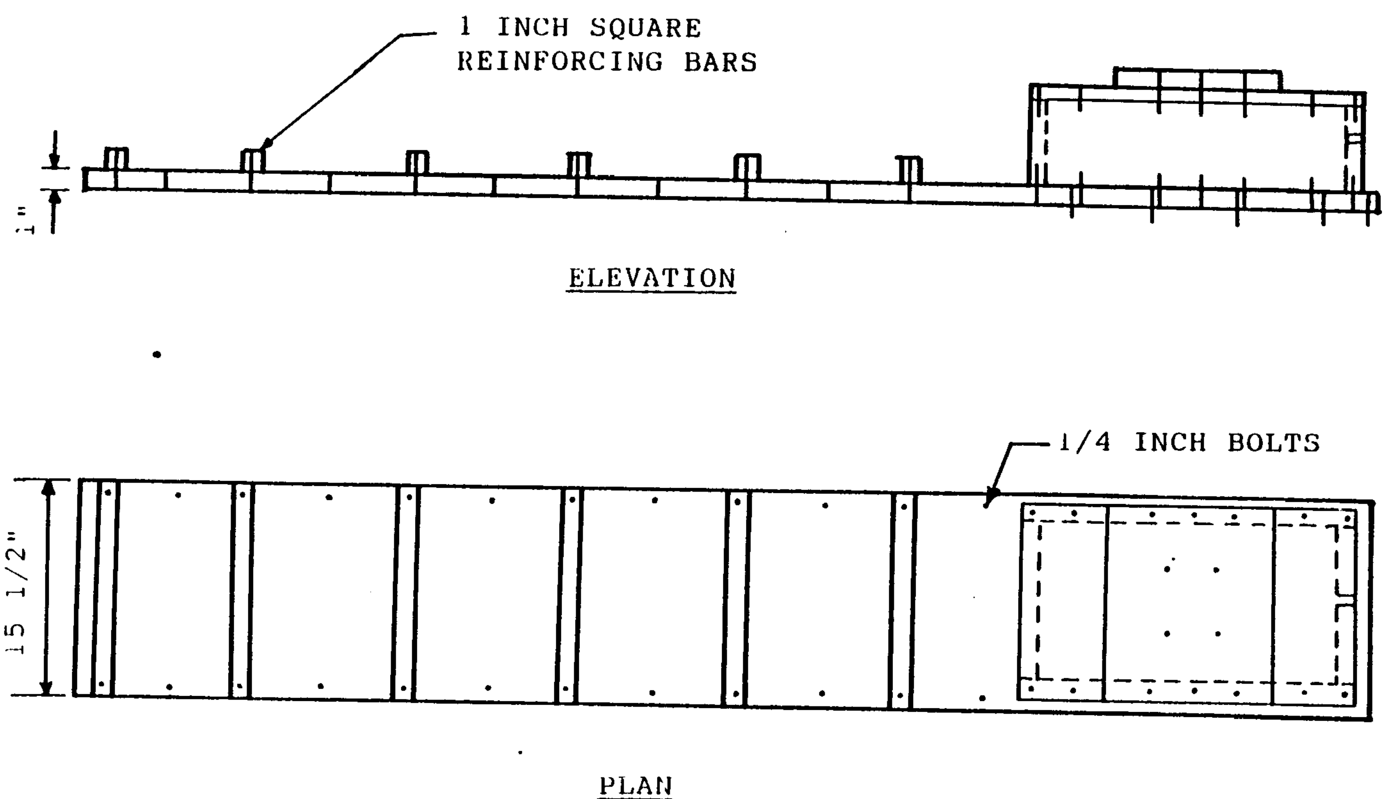


Figure 3-2. Hydraulic Flume Lid

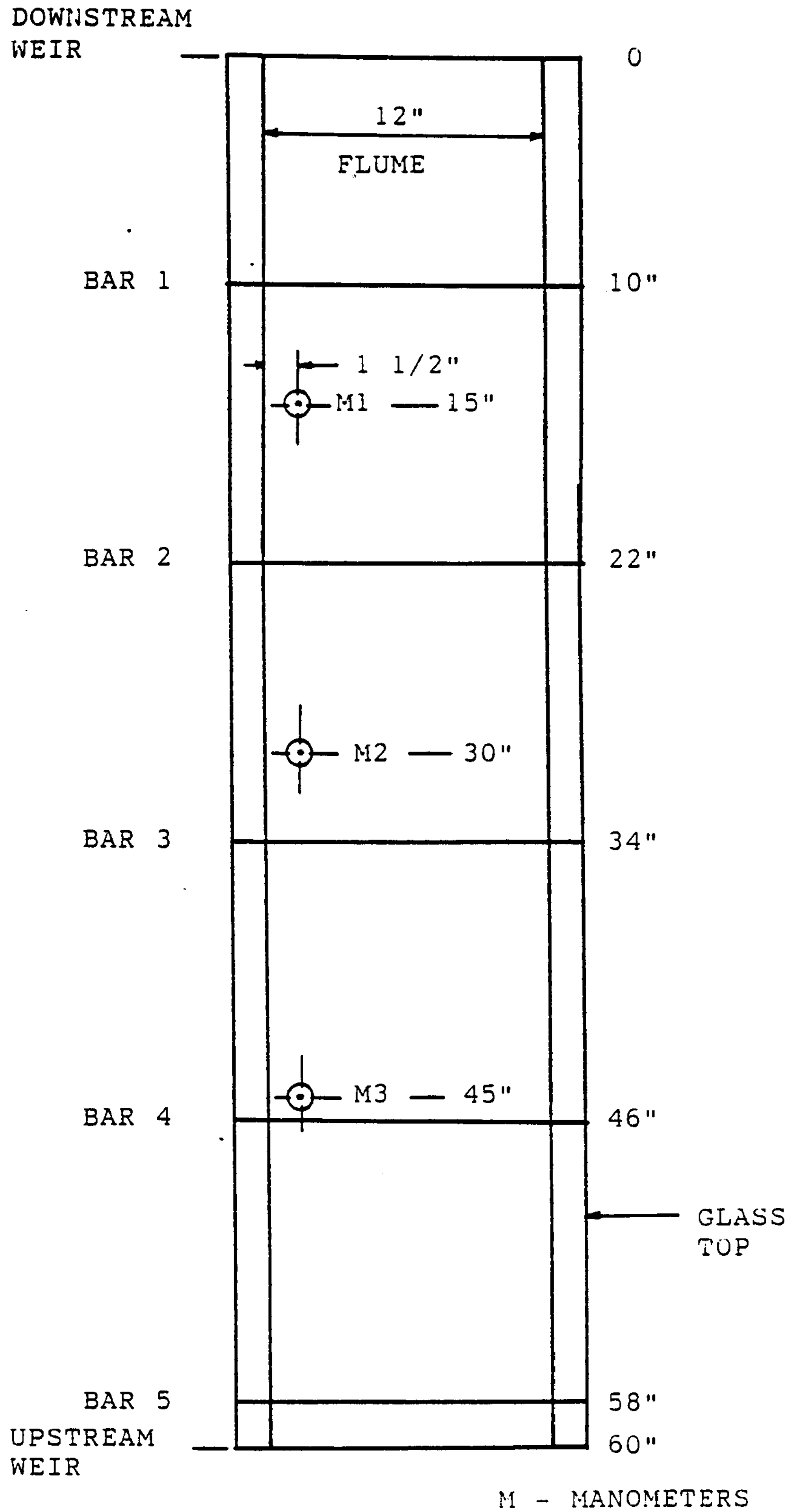


Figure 3-3. Location of manometers and reinforcing bars

Water enters the flume through a 1/4 inch tube with a quick connect inserted at the upstream end of the flume. A 1 inch water hose has been used later instead of the 1/4 inch tube since more quantity of flow is needed to maintain the applied head for sands with higher permeability.

Drainage from the flume takes place through a 1/4 inch opening at the downstream reservoir. But for sands with higher permeability, additional drainage tubes are needed. Note that the water level in the downstream reservoir is higher than the sample so that the sample remains fully saturated throughout the test.

3.3 Bladder Pressure Tank

The pressure to inflate the rubber pressure bladder described in Section 2 is provided by a supply tank which is shown in Figure 3-4.

The tank was filled with water. Air pressure was applied through the top inlet onto the water, which forced the water through the bottom outlet into a 1/4 inch tube which connected to the rubber bladder at the bottom of the flume. The bladder was expanded until the pressure was neutralized. A air pressure of 5 psi was used for all the tests performed.

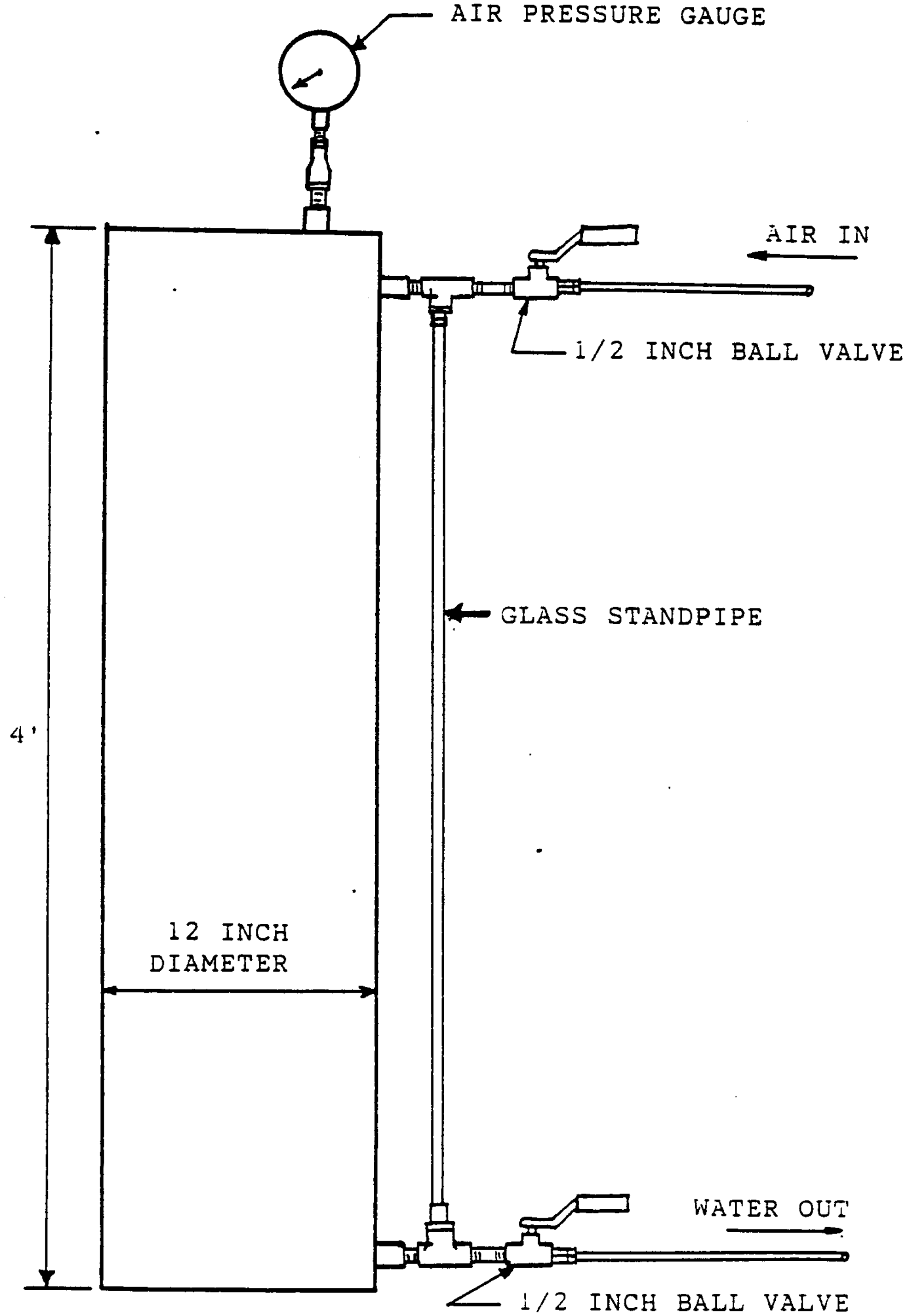


Figure 3-4. Bladder Pressure Tank

3.4 Water Supply Reservoir

The water supply reservoir shown in Figure 3-5 provides the constant upstream head which initiates piping. Two systems were used to adjust this upstream head. One, a vertical pulley system which increases the elevation head, or secondly, a water regulator which adjusts the pressure head.

Water enters the reservoir at the top through a 1 inch water hose connected to a faucet. Water exits through the bottom outlet and is controlled by a regulator in the hose to the upstream water reservoir of the hydraulic flume. The overflow outlet serves as a means of monitoring a constant head of water.

A vertical pulley system was used to raise the reservoir, and a regulator connected to upstream reservoir of the flume was used to adjust the elevation head. The applied head was determined from the upstream reservoir manometer readings.

3.5 Sand Rainer

A sample of uniform density is prepared using a sand raining device to deposit the sand into the hydraulic flume from a fixed height.

The sand raining device, is shown in Figure 3-6. Tracks were mounted on the floor to guide the rainer over the hydraulic flume. The rainer was filled with sand while the

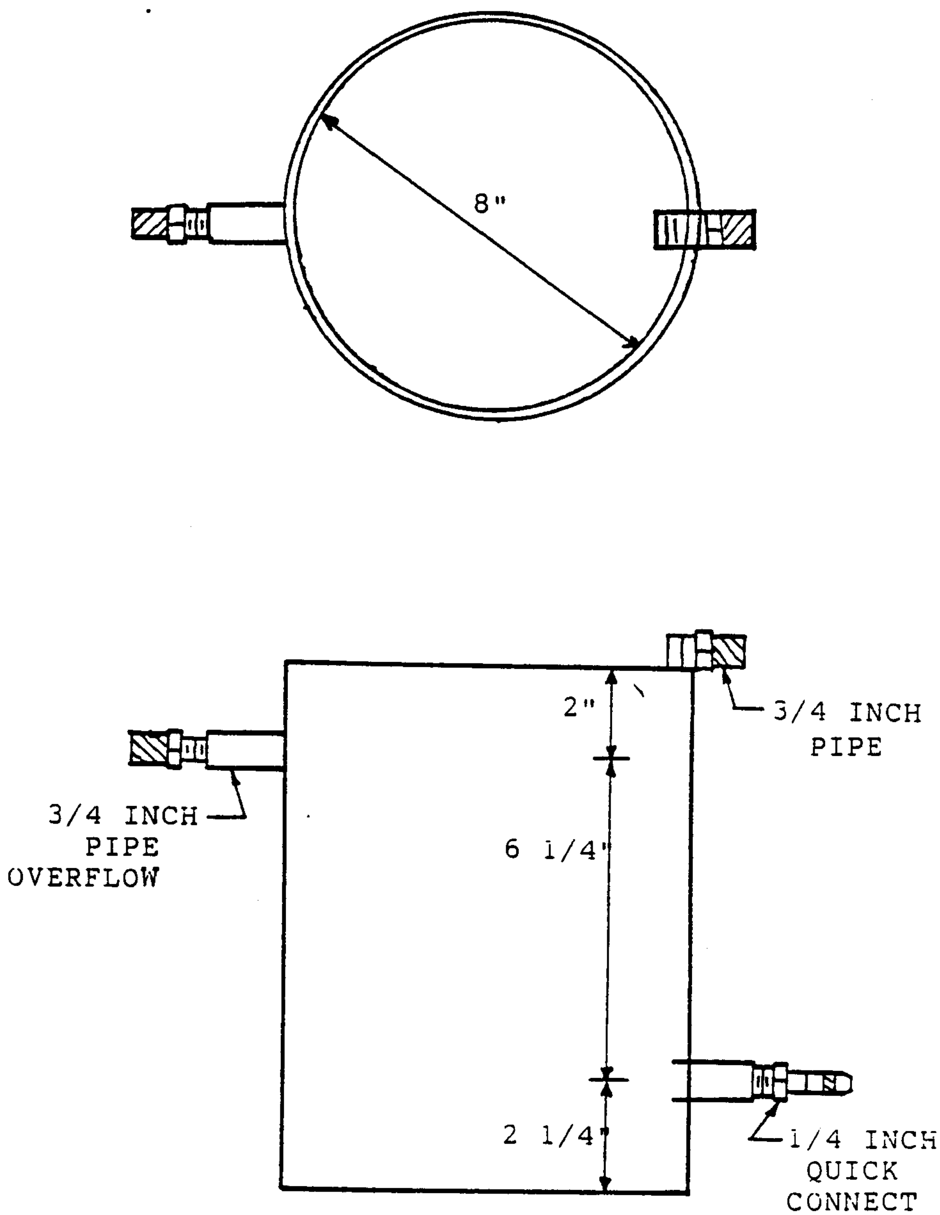


Figure 3-5. Water Supply Reservoir

shutter plate remained in a closed position. The sand was allowed to fall freely into the flume by pulling out the shutter plate. Subsequently the rainer was continuously moved back and forth at a constant rate to assure a uniform density.

3.6 Materials and Density Determination

Six sand gradations were used in this project to evaluate the piping theory and filter design as shown in Figure 3-7. Three of the gradations are uniform; Reid Bedford sand, 20/30 sand, and 8/30 sand, but with different effective grain diameters, D_{10}= 0.14mm, 0.63mm, and 0.8mm, respectively. One gradation is well graded and lastly, two gradations are gap gradings which also have different effective grain diameters. The effective grain diameters, D_{10}, the mean grain diameter, D_{50}, and uniformity and curvature coefficients are summarized below:

SAND	D_{10}(mm)	D_{50}(mm)	Cu	Cc
Reid Bedford	0.14	0.20	1.5	1.23
20/30	0.63	0.93	1.6	0.97
8/30	0.8	1.6	2.1	1.48
W.G	0.24	1.42	6.7	2.20
gap I	0.16	0.50	5.6	0.31
gap II	0.28	0.60	6.1	0.26

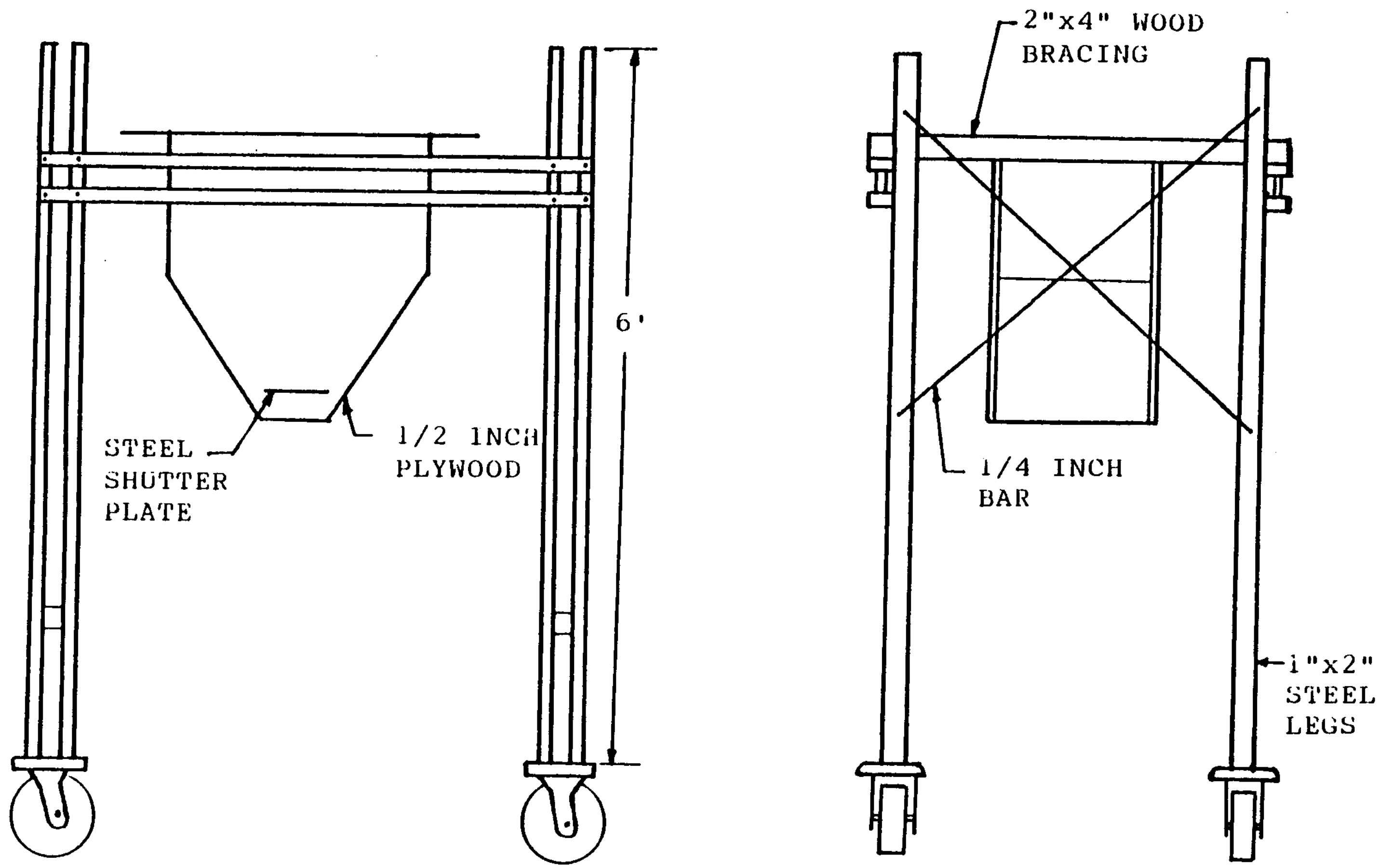


Figure 3-6. Sand Rainer

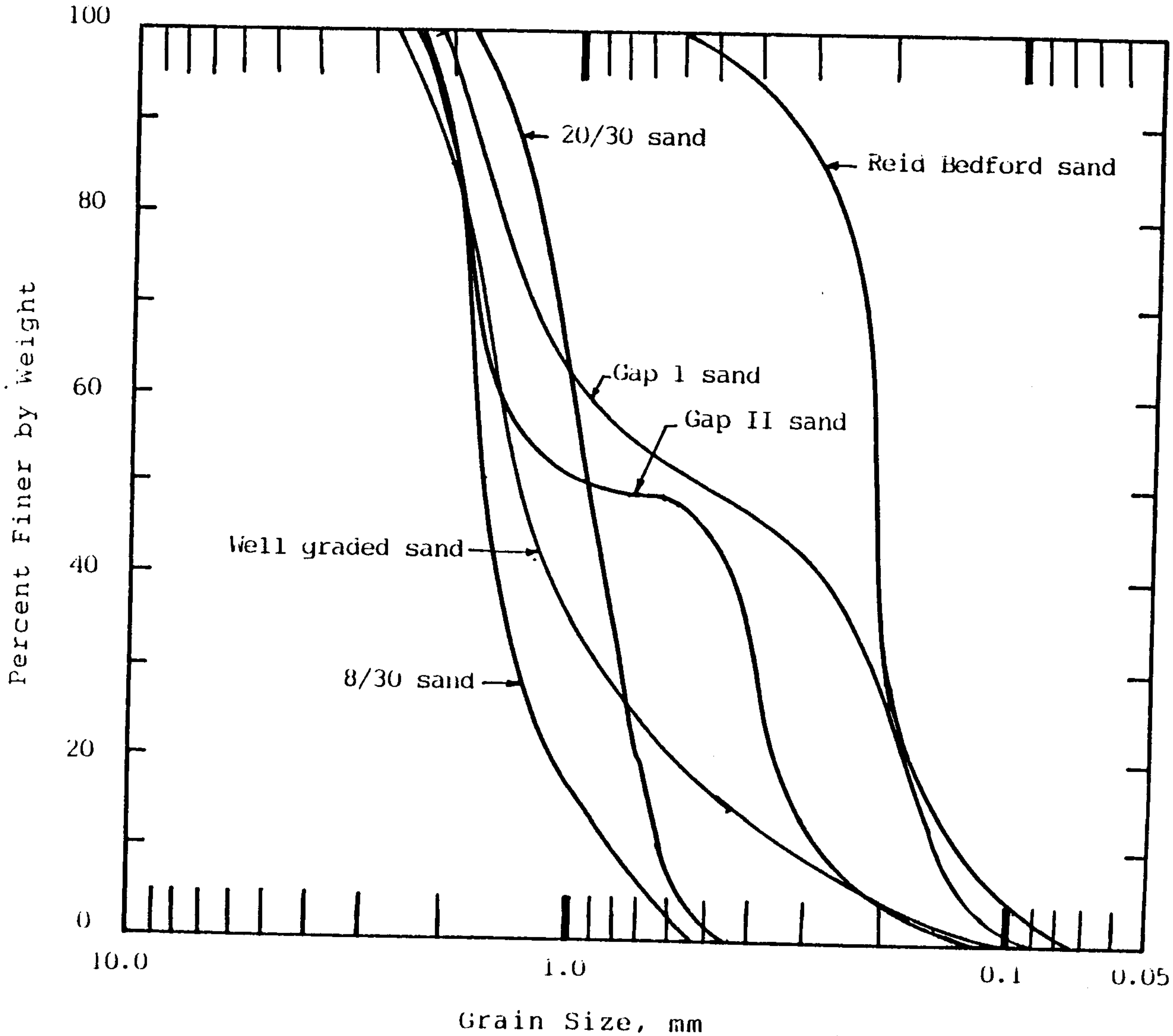


Figure 3-7. Grain Size Distribution of the sands tested

The gradation used for filter design experiment was Reid Bedford sand since this sand is the most piping susceptible gradation among those tested.

The method used to determine the in-place density is decribed as following. Three tare cans were placed into the flume during the sand raining process. When the cans were full, the surfaces of the cans were screeded and then weighed. Since the weight and volume of the cans were known, the density of the material could be calculated.

The same procedures were performed in the bottom and upper layers of the sample. The density of the sample was the average of the density of bottom and upper layers.

3.7 Sample Preparation

In order to prepare a specimen with uniform density and to insure consistency between specimens, several steps must be followed. Figure 3-8 shows schematically the procedures for preparation of test sample.

With the pressure bladder deflated and the flume top removed, the rainer is placed within its tracks to start the filling procedure. Since the rainer's volume is smaller than that of specimen, the rainer must be filled 2 to 3 times to achieve a full flume. During this filling procedure, the density is determined by the method described in Section 6. The sand is deposited only between the upstream weir and

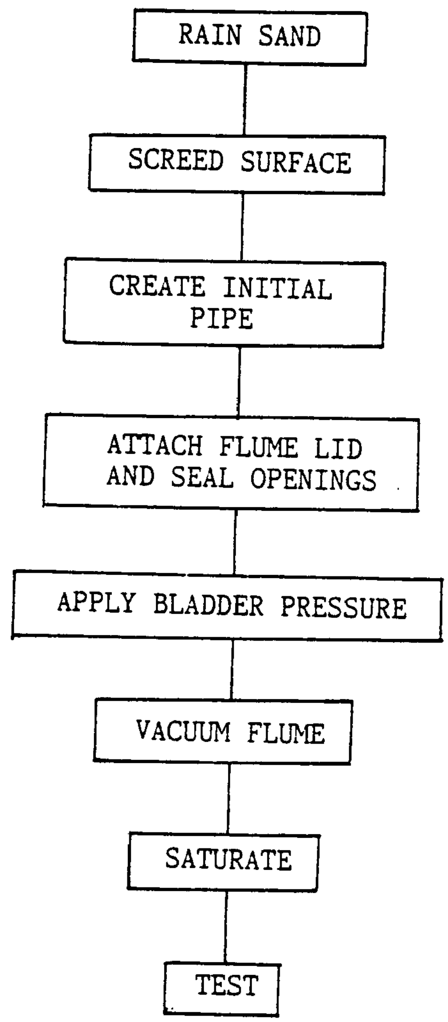


Figure 3-8. Procedures for preparation of test sample

slope weir, so that the upstream and downstream reservoir are formed.

After the flume is filled, the surface is screeded with a straightedge to obtain a smooth and uniform surface, sometimes it is necessary to drop sand by hand from the same height of the rainer to fill in irregularities left by screeding.

The original pipe is constructed by placing a semi-circular wooden dowel on the middle of the sand surface at the downstream end. The circular portion of the dowel rests in the sand and the flat surface will be in contact with the flume top. The dowel is placed at a depth to insure the flat portion is level with the sand surface. The dowel was not withdrawn until saturation was complete.

For filter tests, the filling procedure is different. With the pressure bladder deflated and the flume top removed, the filter material is first placed in desired positions between two vertical cookie sheets separated at the prescribed filter thickness. The cookie sheets are suported by numerous dowels. To prevent mixing with sand, the filters are covered by plastic during the raining procedure. Once the flume is filled, the surface is screeded and the cookie sheets are slowly pulled out to obtain a level surface.

The original pipe at the downstream end is formed by the semi-circular wooden dowel. A dissolvable material, sugar, was used to create the original pipe at the upstream side of filter. The original pipe was formed when the sugar was dissolved during the saturation processing.

After the original pipe is formed, the plexiglass lid is then placed and bolted on the flume in order to have a fully sealed condition. The bladder pressure is applied temporarily by connecting with water supply reservoir which is raised to 9 feet height. The applied pressure results in expansion of the rubber bladder, which pushes upward on the sample to contact it against the plexiglass lid.

In order to obtain a saturated sample, a vacuum procedure was used before the saturation procedure. However, leak problems happened in almost every test, hence it was decided to perform the tests by using samples with identical conditions except the vacuum procedure was ommitted. It was found that the difference between results was insignificant; therefore, the vacuum procedure was abandoned for the later tests in this project.

With the glass lid bolted on the flume and the bladder pressure applied by the Water Supply Reservoir, the saturation procedure was started. A water tank supplied water at room temperature into the downstream reservoir of the flume. Initially, saturation was tried by supplying water into the flume from the upstream reservoir, but the downstream slope failed due to seepage forces. Obviously, the time needed to saturate the sample depends upon the permeability of the sand used, with 24 hours usually required for this procedure.

It is not easy to obtain a fully saturated sample. Some air bubbles are still visible in the sample after the saturation procedure. However, the sample is ready for testing.

3.8 Test Procedures

When the sample is ready for testing, the glass covering over the downstream reservoir can be removed. The bladder pressure is now applied by connecting with bladder pressure tank in which air pressure, 5 psi, is applied. The bladder pressure is applied throughout the whole test to insure the contact between the sample and the glass lid.

The water supply reservoir is set initially at low elevation and tap water is applied to the reservoir through a hose. The overflow outlet on the reservoir provides for a constant head. The dowel is then slowly withdrawn from the sample. Some disturbance is unavoidable, but the diameter of the created pipe is considered to be the diameter of the dowel used to form it.

A head of water is applied to the sample by connecting a 3/4 inch hose between the water reservoir and the upstream reservoir of the flume. A regulator, which is connected between the hose and upstream reservoir, is used as a fine adjustment of the head. The heads are read from the manometers which are inserted along the sample. Time increments of 5 to 10 minutes were used before the head was increased when piping could not be initiated. The head was gradually increased stepwise until piping began. Subsequently the upstream and downstream heads and the manometer's heads were recorded and monitored.

A study of the rate of piping was attempted but the piping would stop in most tests. In these cases, the head would be increased until piping was re-initiated, therefore, the timing procedures were useless. Figure 3-9 presents a typical data sheet used for recording the test data. The test data sheets are presented in the Appendix. Details for each of the tests are presented in the test results described in Chapter 4.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	__________
Date:	__________
Bladder Pressure:	__________
Length of Pipe Penetration:	__________
Percent Pipe Penetration:	__________
Initial Pipe Diameter:	__________
Time at Start of Test:	__________
Head at Upstream End:	__________
Head at Downstream End:	__________
Total Head:	__________

Location of Pipe	Time	Time Increment
Bar #1		
Bar #2		
Bar #3		
Bar #4		
Bar #5		
Upstream Weir		

Comments:

Figure 3-9. Test Data Sheet

CHAPTER 4

TEST RESULTS

4.1 General

A brief summary of each test is given below. Reasons and details for modifications are explained and described.

Six sand gradations were tested to determine the threshold piping gradients. Three of the gradations are uniform; the Reid Bedford sand, the 20/30 sand, and the 8/30 sand. One gradation is well graded and the other two gradations are gap gradings. A single overburden pressure of 5 psi, and three penetration lengths, 15%, 30%, and 45% were tested. A single pipe diameter, 1/4 inch, was used. The grain size distribution of the six gradations are shown in Chapter 3.

For the filter design test, the Reid Bedford sand was used as the base soil. Three filter gradations and three filter widths were tested.

4.2 Piping Tests

Test #1.

Since this is the first test of this project, the Reid Bedford sand was chosen in order to compare with the UF's piping investigation of 1981. The sample was prepared according to the procedures outlined in Chapter 3. The sand was rained in, and the density of the sand was determined using the method described in section 3.6. After the surface of the sand was screeded, a 12 inch long or 20 percent penetration 1/2 inch diameter semicircular dowel was placed into the sample. The plexiglass lid was placed and bolted on the flume in order to have a fully sealed condition. The vacuum procedure was performed in this test. Some leak problems were encountered during this test. In addition, we initially tried to supply water into the flume from the upstream reservoir during the saturation procedure, but the downstream slope slid due to seepage force. Therefore, water was supplied into the flume from the downstream reservoir.

After saturation was completed, the dowel was slowly removed and the upstream head was gradually raised. Piping was intiated when the head reached a value of 8.0 inches. The sand being piped was deposited into the initial 12 inch pipe, with only a little bit of sand being carried to the downstream slope. After few minutes, the piping stopped. It was decided to raise the upstream head in order to maintain progression of the piping and piping was re-initiated. When the piping reached bar#3, it stopped again. The head was raised, and the piping moved again. Whenever the piping stopped, the upstream head was raised to maintain the piping. The upstream heads and the downstream heads were recorded during the entire test. Meandering of the piping occurred along the entire sample since the piping extended itself along the path of least resistance.

The results of this test were consistent with those of the UF's piping investigation in 1981.

Test #2.

Since the result from test #1 was consistent with the results of UF's piping investigation in 1981, confidence in our procedures was obtained. Therefore, the 20/30 sand gradation was used for this test. The sample was prepared according to the procedures outlined in Chapter 3.

A 1/4 inch diameter semicircular dowel was used to form a 9 inch long or 15 percent penetration trough. After saturation was completed, the dowel was slowly removed and the upstream head was applied. It was found that the head loss between the water supply reservoir and the upstream reservoir was very large, and therefore the upstream head was not sufficient to initiate piping even though water supply reservoir was raised to its maximum height (about 9 feet). The problem was that the 1/4 inch tubing, which connects the water supply reservoir with the upstream reservoir of the flume, was too small to provide a large quantity of water. This water supply problem did not manifest itself in test #1 because the permeability of the Reid Bedford sand is smaller than that of the 20/30 sand. Accordingly a one inch diameter water hose was used to replace the 1/4 inch tube, which worked satisfactorily.

The piping began at a head of 11.38 inches. Whenever the piping stopped, the upstream head was raised to maintain progression of the pipe. Meandering of the piping also happened in this test. The hydraulic head to maintain the piping process fluctuated in a small range during the entire test; the average head being about 11.4 inches. The leak problem also was encountered during the vacuum procedure in this test, and some air bubbles could be seen in the surface of the sample.

Test #3.

The soil used in this test was also the 20/30 sand. Once again a 1/4 inch diameter pipe was originally constructed for a length of 9 inches or 15 percent penetration. The piping initiated at a head of 14.5 inches. When the piping reached bar #3, #4, and #5, the heads were 12.75, 14.88, and 17.88 inches respectively.

Test #4.

The 20/30 sand was used in this test. A 1/4 inch diameter semicircular dowel was used to form a 18 inch long or 30 percent penetration trough. After the sample was ready for testing, the upstream head was gradually raised. The piping was initiated at a head of 8.25 inches. Whenever the piping procession stopped, the upstream head was raised a little to maintain piping. When the piping reached bar #2, #3, #4, and #5, the heads were 12.75, 11.75, 16.50, and 23.0 inches respectively. It can be seen that the head required to maintain the piping procession was higher at the latter part of the sample. This head increase to maintain piping is contrary to expectations as the gradient (h/l) is increasing due to progression of the pipe (l decreasing) and a head increase is not anticipated.

Test #5.

The 20/30 sand was used in this test. A 1/4 inch diameter semicircular dowel was used to form a 27 inch long or 45 percent penetration trough. After the sample was ready for testing, the upstream head was gradually raised. The piping initiated at the head of 9.25 inches. The heads along the sample at the distance of 15 inches, 30 inches, and 45 inches from the upstream end were also recorded as 5.63, 2.81, and 0.75 inches respectively. Figure 4-1 shows a plot of the heads obtained. When the piping reached bar #3, #4, and #5, the heads were 9.5, 10.13, and 9.94 inches respectively.

Test #6.

Since the leak problem was encountered in every test, the effect of the vacuum process was in doubt. It was decided to repeat this test at same condition with test #4 except that the vacuum procedure was not performed in this test. That is, the 20/30 sand was used and 1/4 inch diameter semicircular dowel was used to form a 18 inch long or 30 percent penetration trough. After this test started, the piping was

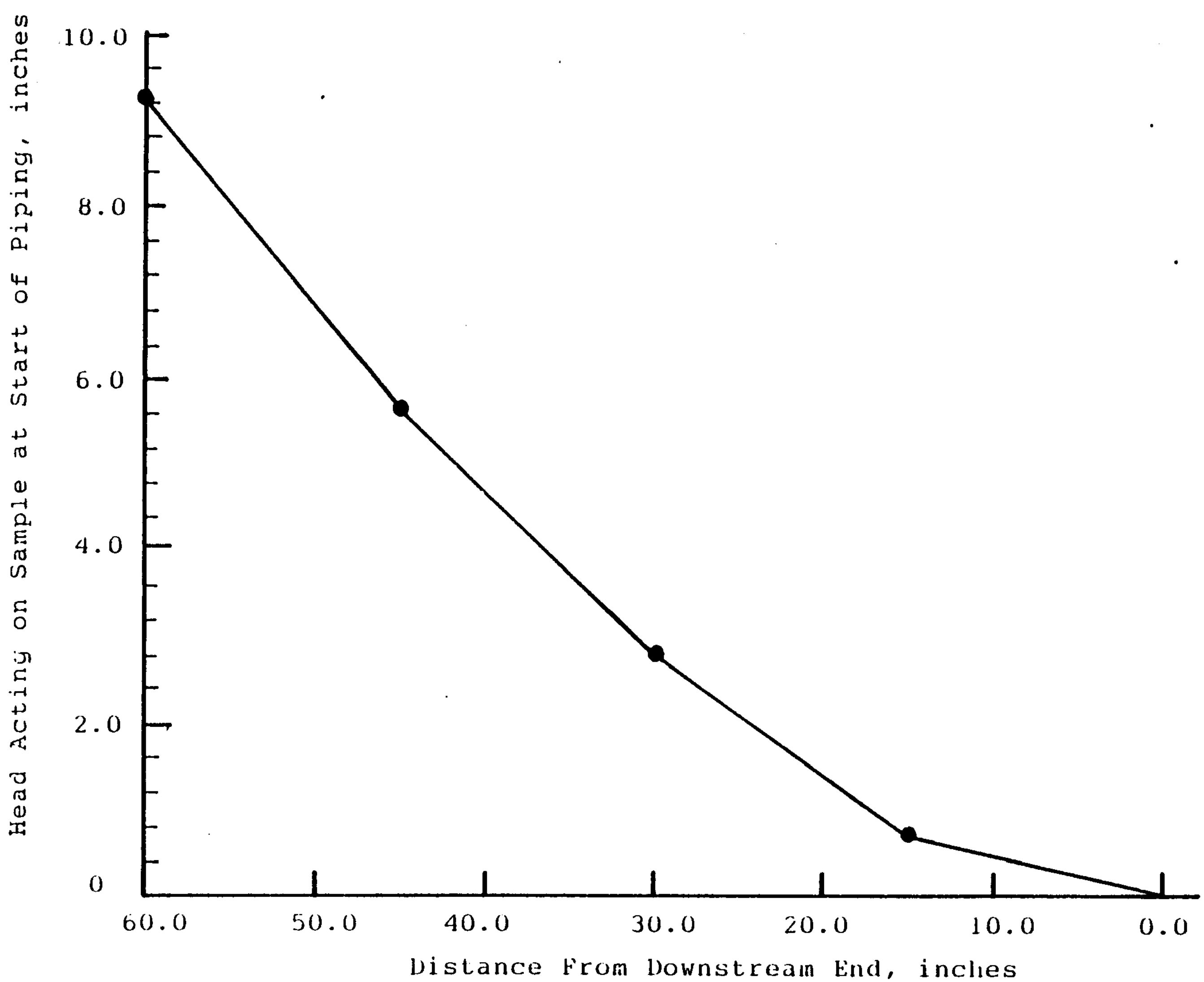


Figure 4-1. Head distribution for test #5

initiated at a head of 9.25 inches. When the piping reached bar #2, #3, #4, and #5, the heads were 10.38, 10.0, 12.13, and 12.75 inches respectively. When the piping reached bar #2, #3, #4, and #5, the heads along the sample at the distance of 15, 30, and 45 inches from the upstream end were also recorded. Figure 4-2 shows a plot of the heads obtained when the piping reached bar #2.

Test #7.

After the 20/30 sand was tested at three penetration lengths, 15%, 30%, and 45%, a well graded sand was used in this test. The grain size distribution curve of the well graded sand is shown in Chapter 3. The length of pipe penetration was 18 inches or 30 percent penetration, and the diameter of the pipe was 1/4 inch. It seemed that the effect of the vacuum procedure was doubt since the results obtained from test #4 and #6 were similar. Therefore, it was decided that the vacuum process would not be used for this test. After the sample was ready for test, the dowel was removed slowly and the upstream head was gradually applied. It was found that the piping was not easy to intiate. At a head of 32.5 inches, only a little fine sand was removed in the original pipe, and then stopped a few minutes later. The head was raised several times but the piping did not occur except a little fine sand was removed occasionally in the original pipe. After raising the head to 58 inches with no

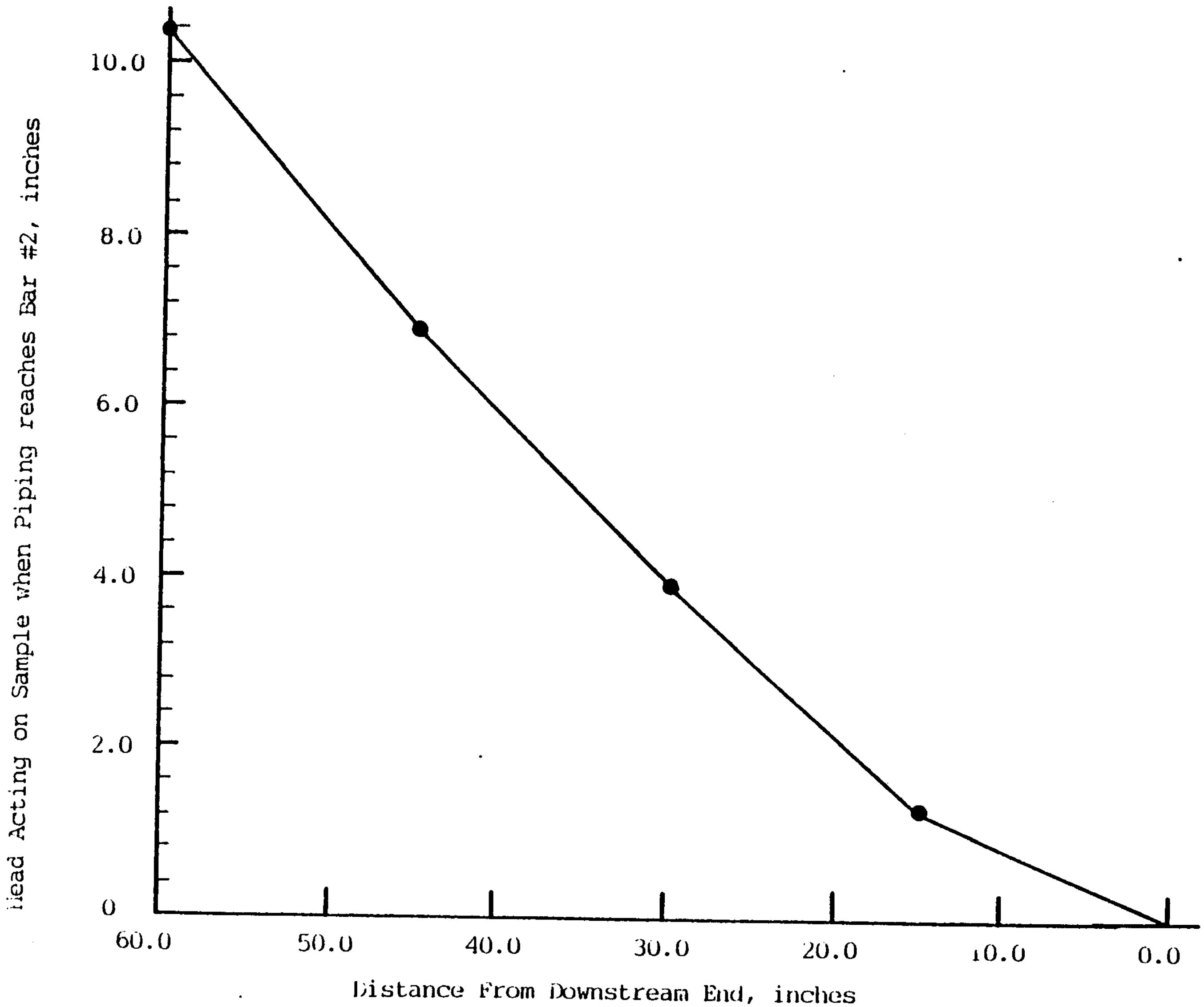


Figure 4-2. Head distribution for test #6

effect, the test was terminated. Please remember that the specimen length in the flume is 60 inches, hence a head of 58 inches is approaching the critical gradient.

Test #8.

Because no piping was initiated in test #7, the length of original pipe was increased to 30 inches or 50 percent penetration and the vacuum process was performed during preparing the sample of the well graded sand. The results obtained from this test were similar to those of test #7. The head was raised several times but the piping was not achieved. After raising the head to 52.5 inches with no effect, the test was terminated as the critical gradient was being approached.

Test #9.

Since the piping could not be initiated at 50 percent penetration in Test #8, the test at 15 percent penetration in the well graded sand was abandoned. A uniform sand, the 8/30 sand, was used for this test. The grain size distribution curve of the 8/30 sand is shown in Chapter 3. A 1/4 inch diameter semicircular dowel was used to form a 27 inch long or 45 percent penetration condition. The vacuum process was performed in this test.

After the test started, the piping was initiated at a head of 11 inches. It was necessary to raise the head often in order to maintain progression of the pipe. It was found that a maximum head of only 16 inches could be achieved when the water supply reservoir was raised to the top of the pulley system (about 9 feet height). The reason being that the permeability of the 8/30 sand is very large and insufficient water was supplied to increase the head. Therefore, it was decided to supply the upstream head directly from a faucet. The upstream head was not easy to maintain constant since the water was supplied directly from the faucet. However, the head was raised by increasing the flow from the faucet when the piping progressing stopped. The heads were recorded when the piping reached bar #3, #4, and #5 (19.0, 33.25 and 38.5 inches respectively).

Test #10.

The sand used for this test was the same as in test #9 -the 8/30 sand. The diameter and length of the initial pipe were 1/4 inch and 18 inches (or 30 percent penetration) respectively. The vacuum process had been performed before the saturation procedure started. After the sample was prepared for testing, the dowel was removed slowly, and the head was then gradually applied. The water supply reservoir was raised to a height of about 8 feet when the piping started, and the head was recorded, 12.25 inches. In order to maintain the piping progressing, the head was raised several times. However, as in test #9, the water supply system was changed from the water supply reservoir to a faucet because the head supplied from the water supply reservoir, even when the reservoir was raised to the top of the pulley system, was insufficient to maintain pipe progression. After the head was supplied directly from the faucet, the head was raised by increasing the flow from the faucet to continue pipe progressing whenever the piping stopped. When the piping reached bar #2, #3, #4, and #5, the heads were recorded; 14.88, 15.0, 20.5, and 22.75 inches, respectively. The heads along the sample at the distances of 15, 30, and 45 inches from the upstream end were also recorded when the piping reached the bar #2, #4, and #5. Figure 4-3 shows a plot of the heads obtained along the sample when the piping reached bar #2.

Test #11.

The gapI sand was used for this test. This gap gradation was formed by mixing 50 percent of the 8/30 sand and 50 percent of the EGS sand. The grain size distribution curve of the gapI sand is shown in Chapter 3. The diameter of intial pipe for this test was also 1/4 inch, and the length of the initial pipe was 9 inches or 15 percent penetration. The vacuum process was performed in this test. After the sample was ready for testing, the dowel which formed the initial pipe was removed slowly and the head gradually increased. For this gap graded sand, only the fine sand moved in the initial pipe after the head was gradually applied, but no piping occurred. The head was raised several times, but piping did not occur except that the fine sand in the initial

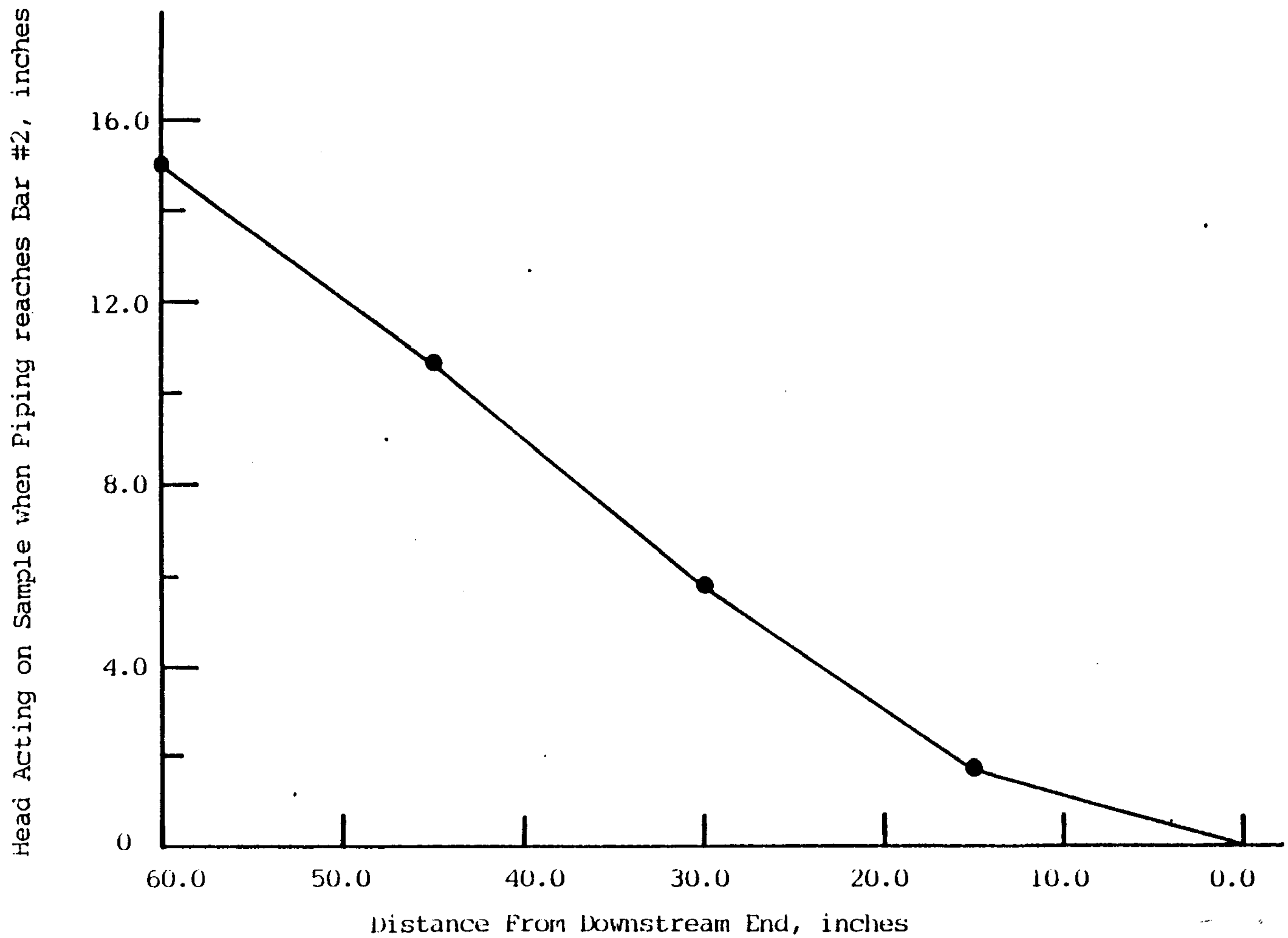


Figure 4-3. Head distribution for test #10

pipe moved occasionally. Although the head was continually raised in an attempt to initiate piping, when the head was raised to more than 6 feet, sheet flow happened; accordingly the test was terminated.

Test #12.

The same sand as Test #11, the gapI sand, was used in this test. The diameter of the initial pipe was 1/4 inch and the length of it was 18 inches or 30 percent penetration. After the sample was ready for testing, the dowel was removed slowly, and the head was then applied gradually. Only the very fine sand moved in the initial pipe. The head was continually increased in order to initiate piping. However, the piping did not occur except the fine sand in the initial pipe moved occasionally, just like test #11. Again as previously obtained in Test #11, the sheet flow happened when the head was raised to more than 6 feet and the test was terminated at this point.

Test #13.

Since the piping could not be initiated in the gapI sand at 15 percent and 30 percent penetration, the 45 percent penetration test was abandoned. The gapII sand was used for this test. The grain size distribution curve of the gapII sand is shown in Chapter 3. The initial pipe for this test was 1/4 inch diameter and 9 inches long or 15 percent penetration. The vacuum process was not performed during preparing the sample. After the test began, piping occurred when the head was raised to 21.5 inches. Only the very fine sand moved, and a self-healing phenomenon happened a few minutes later. Eventually, the piping stopped. The head was continually raised to maintain the pipe progressing. At a head of 29.75 inches, very little piping occurred. But when the head was raised to 32.75 inches, the piping moved rapidly. The piping progressing stopped when it reached the bar #2. The head was raised again to keep the pipe moving, but it was difficult to maintain the pipe progressing. By tapping the plexiglass top, the piping moved very slowly. After the piping reached the bar #3, it was found that the piping stopped even when tapping the plexiglass top and raising the head. When the head was raised to about 62 inches, the test terminated.

Test #14.

The gapII sand was used in this test. A 1/4 inch diameter dowel was used to form the initial pipe with a length of 18 inches or 30 percent penetration. The vacuum process was not performed in this test. After the sample was ready for testing, the dowel was removed slowly. When the head was gradually applied, some air bubbles moved but no piping happened. The head was raised to 15.5 inches, still nothing happened. By increasing the size of the initial pipe, piping occurred. But the sand appeared to be self-healing, and the piping eventually stopped. The head was continually raised in order to initiate piping. At a head of 57.5 inches, piping would occur by tapping the plexiglass top, but self-healing would result downstream causing the pipe to stop. The test was terminated at this time.

Test #15.

Since it was difficult to intiate piping in tests #13 and #14, a larger diameter of semicircular dowel, 7/16 inch, was used to form a 27 inches or 45 percent penetration pipe for this test. The vacuum process was not performed during preparing the sample. After the sample was ready for testing, it was discovered that the dowel could not be removed, hence, the bladder pressure was decreased in order to remove the dowel. The bladder pressure was then increased to 5 psi. After the head was gradually applied, only the fine sand moved in the initial pipe when vibrations were induced by tapping on the plexiglass top. But movement soon stopped because of self-healing of the sand. The head was continually raised, but because the initial pipe was soon plugged, piping would then develop its own path branching from the original pipe. But this piping also soon stopped because of the self-healing of the sand. After the piping reached bar #3, it could not move upstream even though the head was raised to 57.5 inches. This test terminated at this time as the critical gradient was being approached.

4.3 Filter Tests

Test #16.

The filter evaluation tests were started with this test. The base gradation used for these filter design experiments was Reid Bedford Sand since this sand was the most piping susceptible gradation used. The filter I material used in this test was designed to meet both the criteria of the U.S. Army Corps of Engineers and the ones proposed by Sherard and Dunnigan. The grain size distribution curve of the filter I is shown in Figure 4-4, and Table 4-1 shows the filter I meets both of these filter design criteria.

TABLE 4-1

COMPARISON BETWEEN FILTER MATERIALS AND FILTER DESIGN CRITERIA

	FILTER I	FILTER II	FILTER III	CRITERIA OF C.O.E.	CRITERIA OF SCS
D_{15f}/d_{85}	2.8	8.0	12.0	< 5	≤ 4
D_{15f}/d_{15}	5.2	14.7	22.1	$> 5, < 20$	-
D_{50f}/d_{50}	7.6	16.8	21.2	< 25	-

For efficiency, two filter thickness were tested in each filter test. The initial pipes at the upstream side of filter were formed with sugar. The initial pipe at the downstream end was constructed with a dowel to assure piping would happen and to observe the effect of piping when it reached the filter. The sand placement procedure was different for the filter evaluation tests. The filter material was first placed in their desired positions formed vertically by cookie sheets which were suported by numerous dowels. The positions and thickness of the filter in this test can be seen in Figure 4-5. The sample was prepared according to the procedures described in section 3.7. It was difficult to construct the filters with uniform thicknesses since it was inevitable to disturb the filters when the cookie sheets were removed. The thickness of the filters also can be seen in Figure 4-5. Because the existence of the dowels which supported the cookie sheets, the density of the base sand was determined only at the upper part of the sample using the method described in section 3.6. The diameter of the initial pipe was 1/4 inch, and the pipe penetration was 15 percent (4.5 inches long for the pipe at the downstream end and 2.25 inches long for both of the pipes at the upstream side of the filters). The vacuum process was not performed in this test.

After the sample was prepared for testing, the initial pipes at the upstream side of filters were created since the sugar which used to form the pipe was dissolved during the saturation procedure, and the dowel which was used to create the downstream end initial pipe was removed slowly. With no

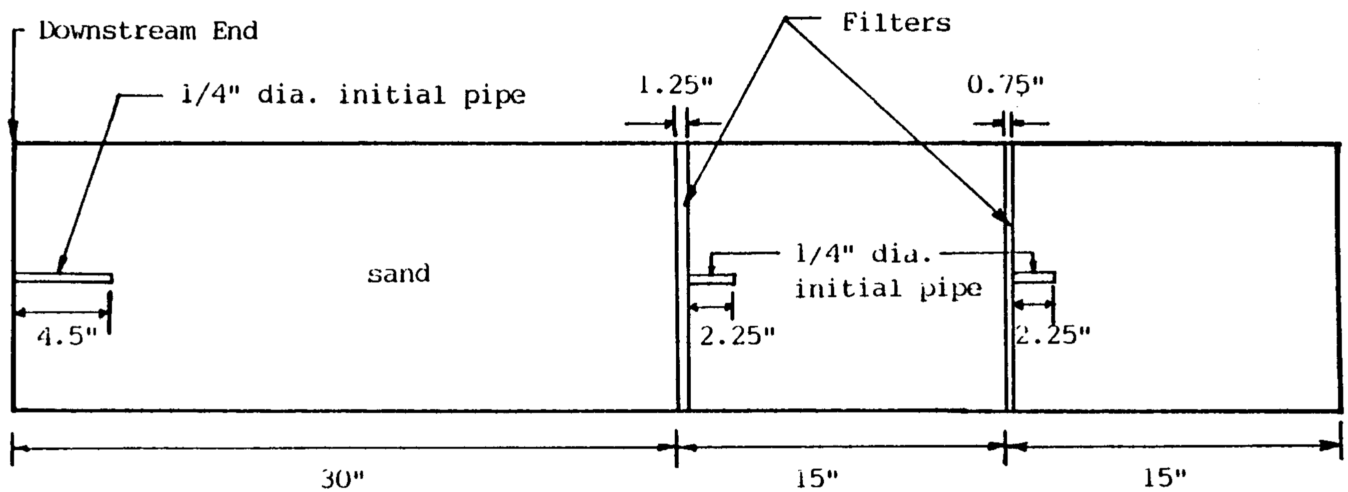


Figure 4-5. Arrangement of filters for test #16

experience in creating the initial pipe at the upstream side of filter, the initial pipe was formed with variable diameter,and some air bubbles could be seen at the surface of the sand. Nevertheless, the test was initiated, and piping at the downstream end happened when the head was gradually raised to 7.63 inches. The heads along the sample at the distance of 15, 30, and 45 inches from the upstream end were recorded as; 5.75, 4.0, and 2.0 inches respectively. Nothing happened at the upstream side of the filters. When the downstream end piping reached the first filter (at the position of 30 inches from the upstream end), it stopped. Subsequently, another pipe initiated from the downstream end, and it also stopped when it reached the first filter. The piping behind the first filter started at a head of 22.0 inches, the heads along the sample at the distance of 15, 30, and 45 inches from the upstream end were 17.38, 11.75, and 6.5 inches, respectively. The piping behind the first filter did not last long because the sand carried out by the piping was held by the filter.

When the head was raised to 30 inches, sheet flow happened from the downstream side of the first filter, and the initial pipes at the upstream side of both filters were filled with sand. After a while, entire sheet flow happened. The sand at the downstream end moved very fast, but the sand upstream of the filter moved slightly and was then held in place by the filter. The sand at the downstream side of the first filter was removed because of the sheet flow. After a long time, the first filter lost the support at the downstream side since the sand was moved out by the sheet flow. By tapping the plexiglass top, the first filter was breached after losing the downstream side support completely. The piping moved through the first filter and reached the second filter (at the position of 15 inches from the upstream end). The piping stopped when it reached the second filter, and then the sheet flow happened at the downstream side of the second filter. The sand which supported the second filter was then gradually removed by the sheet flow. After the support lost completely, the second filter was then broken and the piping moved through the sand untill it reached the upstream end. It seemed that both the filters worked very well. The failure was because the sand which supported the filter was removed by the sheet flow.

Test #17.

It was decided to repeat test #16 using the filter I material, since the sample used in test #16 was not well prepared. Two filter layers with different thickness were placed in this test. The two filters, 1.25 inches thick, and 1 inch thick were placed at the position of 15 inches and 30 inches from the upstream end respectively. The length of the initial pipes were 15 inches (50 percent penetration) at downstream end and 7.5 inches (50 percent penetration also) at the upstream side of both the filters. The diameter of all the initial pipes was 1/4 inch. The arrangement of the filters and the initial pipe are shown in Figure 4-6. The 15 inch long initial pipe at downstream end was formed by using a 1/4 inch diameter semicircular dowel, and both the 7.5 inch long initial pipes at the upstream side of the filters were created with sugar.

The sample was prepared according to the procedures decribed in section 3.7. The vacuum process was not performed during the sample preparation. The filter layers were more uniform in thickness than that in test #16, and the pipes created by sugar were also better (more symmetrical) than those for test #16. After the sample was ready for testing, the dowel at the downstream end was removed slowly, and the head was gradually applied. When the head was gradually raised to 8.38 inches, piping was initiated at the downstream end. The heads along the sample at the distances of 15, 30, and 45 inches from the upstream end were also recorded; 6.5, 4.38, and 2.25 inches, respectively. There was no piping at the upstream side of the filters. The head was raised occasionally to maintain the downstream end pipe progressing. When the piping reached bar #2, the head was 12.63 inches. The heads along the sample were also recorded, 9.63, 6.25, and 3.25 inches at the distances of 15, 30, and 45 inches from the upstream end, respectively. Nothing happened at the upstream side of the filters.

When the piping reached the thin filter (at the position of 30 inches from the upstream end), it stopped. The head was continually raised. A second pipe developed at the

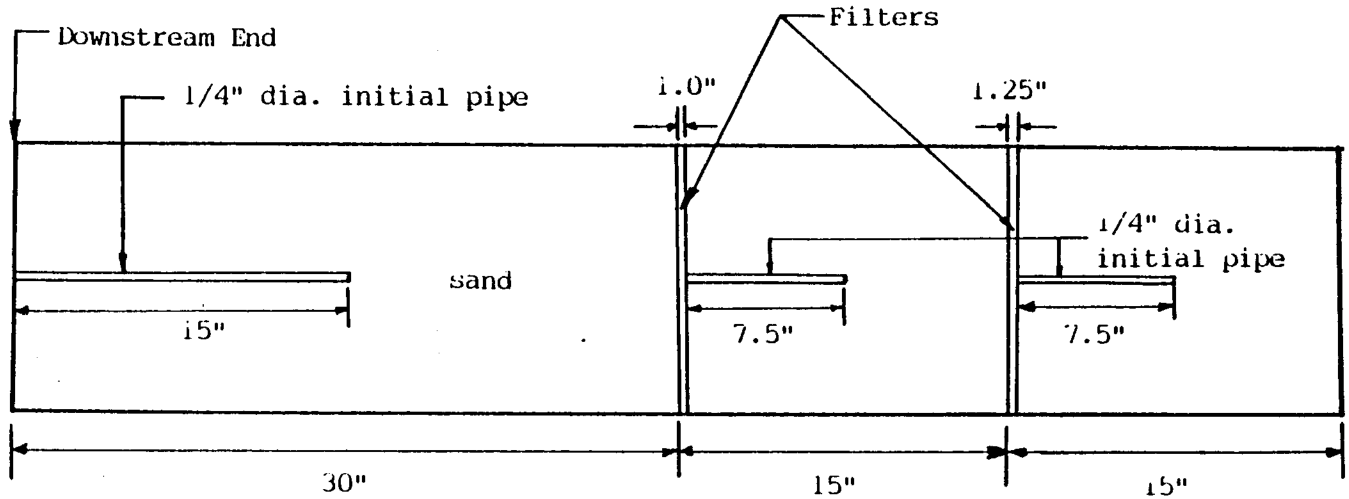


Figure 4-6. Arrangement of filters for test #17

downstream end, and it also stopped when it reached the thin filter. Still no piping occurred at the upstream side of the filters. The head at this time was 22.88 inches, and the heads along the sample at the distance of 15, 30, and 45 inches from the upstream end were 17.88, 12.25, and 7.75 inches respectively. After a while, the pipe upstream of the thin filter started to move, and a new pipe was forming and moving toward the thin filter at the downstream end. The piping behind the thin filter soon stopped, and the thin filter held the sand carried to it by the piping. The sand at the opposite dowmstream end of the filter moved very fast, but the sand upstream of the thin filter was held by the filter. The thin filter was losing support at the downstream side since the sand was eroded very quickly.

The head was continually raised. The sand at the surface of the downstream end continued to erode very fast, and the thin filter was deteriorating and deforming but the sand behind the thin filter still was held in place. The head was 32.5 inches, and the heads along the sample at the distances of 15, 30, and 45 inches from the upstream end were 21.0, 5.25, and 4.25 inches, respectively. Vibrations induced by tapping on the plexiglass top, caused the thin filter to fail. The piping moved rapidly upstream to the thick filter (at the position of 15 inches from the upstream end), and then stopped. The situation was repeating as before. The sand which supported the thick filter at the downstream side was eroded. But the sand at the upstream side was held by the downstream end, and it also stopped when it reached the thin filter. Still no piping occurred at the upstream side of the filters. The head at this time was 22.88 inches, and the heads along the sample at the distance of 15, 30, and 45 inches from the upstream end were 17.88, 12.25, and 7.75 inches respectively. After a while, the pipe upstream of the thin filter started to move, and a new pipe was forming and moving toward the thin filter at the downstream end. The piping behind the thin filter soon stopped, and the thin filter held the sand carried to it by the piping. The sand at the opposite dowmstream end of the filter moved very fast, but the sand upstream of the thin filter was held by the filter. The thin filter was loosing support at the downstream side since the sand was eroded very quickly.

The head was continually raised. The sand at the surface of the downstream end continued to erode very fast, and the thin filter was deteriorating and deforming but the sand behind the thin filter still was held in place. The head was 32.5 inches, and the heads along the sample at the distances of 15, 30, and 45 inches from the upstream end were 21.0, 5.25, and 4.25 inches, respectively. Vibrations induced by tapping on the plexiglass top, caused the thin filter to fail. The piping moved rapidly upstream to the thick filter (at the position of 15 inches from the upstream end), and then stopped. The situation was repeating as before. The sand which supported the thick filter at the downstream side was eroded. But the sand at the upstream side was held by the thick filter. The test stopped before the thick filter completely lost its support and failed because the bladder, which pushed the sample up to contact with the plexiglass top, burst. The bursting might have been caused by the bladder rubber expanding too much at the downstream side of the sample since the sand at that position.

Test #18.

Based upon tests #16 and #17, it was concluded that filter I worked very well. It was decided to conduct a test using a filter which did not meet the current filter design criteria. Filter II was used in this test. The grain size distribution curve of the filter II is shown in Figure 4-4, and Table 4-1 shows the comparison between the filter II and the filter design criteria.

The sample was prepared according to the procedures described in section 3.7. Two filter layers with different thicknesses, 1 inch and 3/4 inch, were placed at the position of 15 inches and 30 inches from the upstream end respectively. The length of the initial pipe was 15 inches (50 percent penetration) at downstream end and 7.5 inches (50 percent penetration also) at the upstream side of the both filters. The diameter of all the initial pipes was 1/4 inch. The arrangement of the filters and the initial pipes are shown in Figure 4-7. The method used to create the initial pipes was the same as that used in test #17. With the experience of constructing the filter layers and the initial

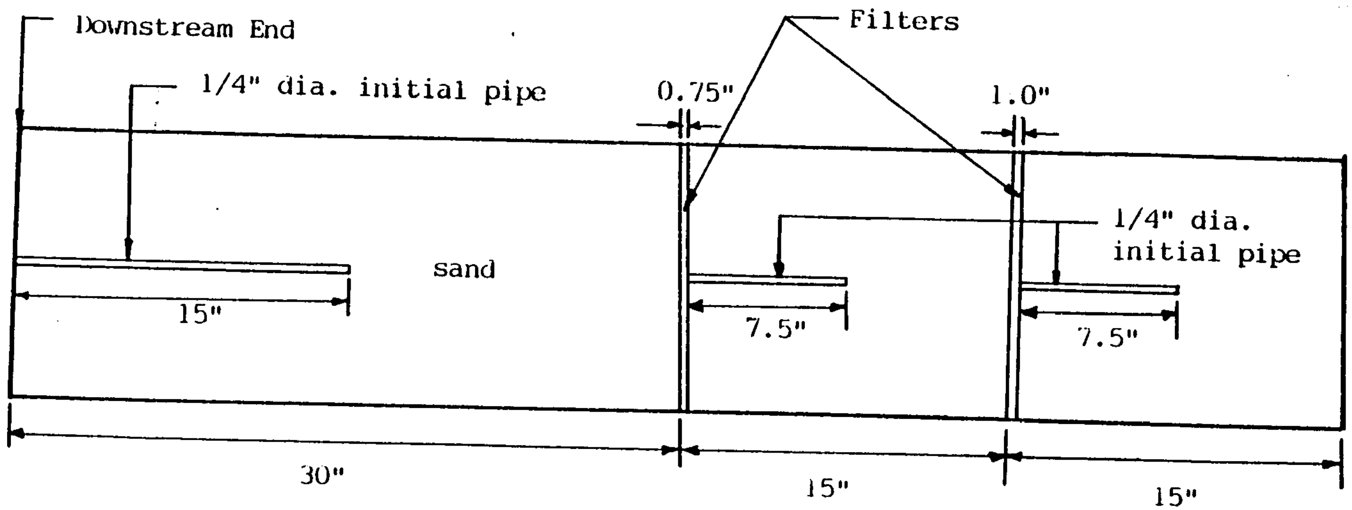


Figure 4-7. Arrangement of filters for test #18

The head was continually raised trying to make the filter fail, however even with excessive tapping on the plexiglass top, the filter did not fail. When the head was raised to 45.38 inches with no effect, the test was terminated. At this time, the heads along the sample at the distances of 15, 30, and 45 inches from the upstream end were 24.38, 1.38, and 0.88 inches, respectively.

Test #19.

The filter II worked very well in test #18 even though it did not meet the filter design criteria. Therefore, a coarser material, filter III, was used as filter in this test. The grain size distribution curve of the filter III is shown in Figure 4-4, and Table 4-1 shows the comparison between the filter III and the filter design criteria.

The sample was prepared according to the procedures decribed in section 3.7. The arrangement of the filters and initial pipes was the same as that in test #18 (see Figure 4-7). The vacuum process was also not performed in this test. After the sample was ready for testing, the dowel which formed the initial pipe at the downstream end was removed slowly, and the head was gradually applied. Piping was initiated at the downstream end when the head was raised to 11.0 inches. The heads along the sample at the distances of 15, 30, and 45 inches from the upstream end were 8.5, 6.13, and 3.0 inches respectively. No piping occurred behind the filters. When the piping reached bar #2, the head was

11.63 inches, and the heads along the sample from the upstream end were 9.0, 6.25, and 3.0 inches. Still no piping happened upstream of the filters.

When the piping reached the first filter (at the position of 30 inches from the upstream end), the head was 13.25 inches. Piping behind the first filter began, the sand was carried through the first filter. It was obvious that the first filter failed to hold the sand. The head was 13.25 inches, and the heads along the sample from the upstream end were 10.75, 6.63, and 3.63 inches.

The piping moved throughth the first filter and continued to move to the second filter. The head was 12.63 inches when the piping reached the second filter (at the position of 15 inches from the upstream end). Piping happened upstream of the filter after the piping reached the second filter. The second filter also failed to hold the sand which was carried out by the piping. This test was stopped when sheet flow happened at the downstream end.

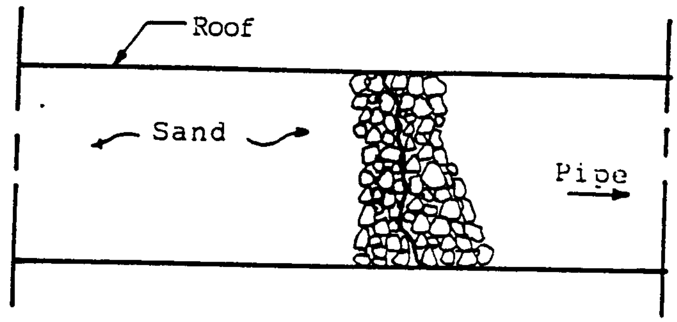
CHAPTER 5

DISCUSSION OF RESULTS

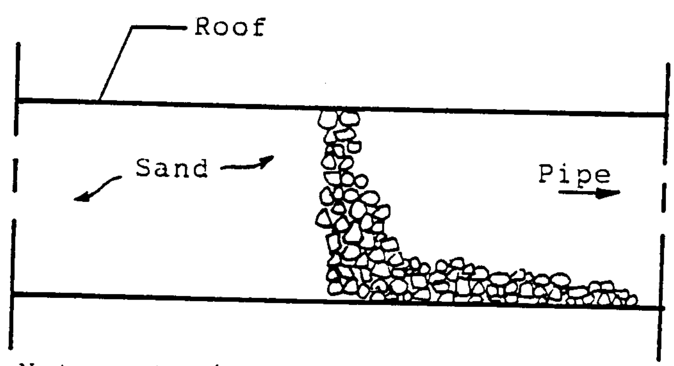
5.1 The Piping Process

From the laboratory testing results, a better understanding of piping action was established. Piping begins to form with the displacement of several sand particles at the tip of the initial pipe. The particles slide into the newly created channel, and when finally washed away, several more new particles become displaced as a retrogressive slide. A continuous landslide and erosion process exists which propagates the pipe. Figure 5-1 shows a diagram of the piping action. However for sand with large grain sizes or large coefficients of uniformity, Cu, insufficient water velocities exist to erode the soil particles after they slide into the initial pipe and deposition may occur downstream in the pipe. Because of this deposition, the piping may be retarded or even ceased by self-healing. These situations occurred in many tests of this project.

As a pipe develops, it extends itself along the path of least resistance. Meandering of the pipe takes place, which leads to scouring of material at some points and deposition at others (see Figure 5.2). As the piping progresses upstream, most of the head loss occurs at the upstream portion from the



Section of material as pipe developes.



Note material after sliding into the pipe and carried downstream.

Figure 5-1. Development of piping action pipe tip because the head needed to initiate the piping is more than the head needed to carry away the sand particles which slide into the pipe. But when self-healing occurs, the head loss is almost constant along the sample.

The rubber bladder, which pushes the soil sample into contact with the plexiglass top, is fixed by a frame bolted to the bottom of the flume. When the bladder pressure is applied, the rubber bladder expands non-uniformly. The amount of expansion at the center of the flume is larger than that at the edge of the flume. Therefore, the upward pressure against the soil is not uniform. For this reason a second piping often develops at side of the flume or the head must be increased as the pipe approaches the middle of the flume where the upward pressure is greatest.

5.2 Discussion of the Piping Tests

Once the critical heads necessary to initiate piping are obtained, the average horizontal hydraulic gradient is easily found by dividing the critical head by the length of the sample. Table 5-1 presents the piping test results with the critical heads (if any) obtained and the gradients calculated. Some characteristic grain diameters and coefficients of uniformity and curvature of each soil used in the piping tests are shown in Table 5-2.

Three uniform sands were tested; (1) Reid Bedford sand, (2) 20/30 sand, and (3) 8/30 sand. The Reid Bedford sand was

TABLE 5-1

SUMMARY OF PIPING TEST RESULTS

Test No. (1)	Sand [(a)] (2)	Pipe Diam (cm) (3)	Penetration % (4)	Ave. Graident [(b)] (5)	Final Gradient (6)	Density [(a)] (pcf)
1	R.B.	1.27	20	0.133	0.135	92.6
2	20/30	0.635	15	0.19	-	-
3	20/30	0.635	15	0.242	0.298	100.5
4	20/30	0.635	30	0.138	0.383	101.8
5	20/30	0.635	45	0.154	0.166	102.6
6	20/30	0.635	30	0.154	0.212	-
7	WG	0.635	30	N/P	-	110.9
8	WG	0.635	50	N/P	-	112.3
9	8/30	0.635	45	.183	.642	106.1
10	8/30	0.635	30	.204	.379	106.1
11	Gap I	0.635	15	S/H	-	110.1
12	Gap I	0.635	30	S/H	-	110.4
13	Gap II	0.635	15	.358 (S/H)	1.03	112.0
14	Gap II	0.635	30	.958 (S/H)	0.957	113.0
15	Gap II	0.635	45	.958 (S/H)	0.958	114.0
16	R.B.	0.635	10	0.130	0.200	106.0
17	R.B.	0.635	10	0.131	0.156	104.8
18	R.B.	0.635	14	0.133	0.138	-
19	R.B.	0.635	20	0.111	0.177	106.2
20	R.B.	3.05	20	0.150	0.112	-
21	R.B.	3.05	50	0.098	0.100	107.4
22	R.B.	3.05	20	0.146	0.158	108.1
23	R.B.	3.05	20	0.142	0.142	-
24	R.B.	0.635	50	0.081	0.127	107.5

(a) R.B. = Reid Bedford, WG = well graded
(b) N/P = No Piping, S/H = Self Healing
(c) 1 pcf = .16kN/m^3

Table 5-2
CHARACTERISTIC GRAIN DIAMETERS
OF EACH SOIL USED IN PIPING TESTS

	Pipeable			Non Pipeable		
Grain Diam (1)	Reid Bedford (2)	20/30 (3)	8/30 (4)	W.G. (5)	gap I (6)	gap II (7)
D_{10} (mm)	0.14	0.63	0.8	0.24	0.16	0.28
D_{15}	0.17	0.66	0.9	0.35	0.17	0.31
D_{30}	0.19	0.78	1.4	0.92	0.21	0.35
D_{50}	0.20	0.93	1.6	1.42	0.50	0.60
D_{60}	0.21	1.00	1.65	1.60	0.90	1.70
Cu	1.5	1.6	2.1	6.7	5.6	6.1
Cc	1.23	0.97	1.48	2.20	0.31	0.26

$Cu = D_{60}/D_{10}$

$Cc = (D_{30})^2/(D_{10})(D_{60})$

tested only at 20 percent penetration since this sand was tested in UF's earlier research. A 1/2 inch diameter semicircular dowel was used only in this test to form the initial pipe, a 1/4 inch diameter semicircular dowel was used in all the other tests. The gradient obtained to initiate piping at 20 percent penetration was 13.33 percent (see Table 1.). which agreed well with the results of UF's earlier research. For completeness, the 1981 UF test results for Reid Bedford sand are included in Table 5-1 as tests #16 to 24.

The effects of initial pipe penetration and diameter for the Reid Bedford sand tests are presented in Figure 5.3. There results show that, as anticipated, smaller diameter pipes require lower gradients to initiate piping. This observation is consistent in that small diameter pipes concentrate flows more than large diameter pipes, thereby creating higher gradients and velocities to initiate erosion. The results also show that as the percent penetration increases, the average gradient, i_{ave}, to initiate piping decreases. This observation is consistent that for greater penetration the actual gradient is greater due to the reduced distance from the head waters.

For the 20/30 sand, five tests were performed at 15, 30, and 45 percent penetration. The 8/30 sand was tested at 30 and 45 percent penetration. The gradients required to initiate piping are presented in Table 5-1. From the tests

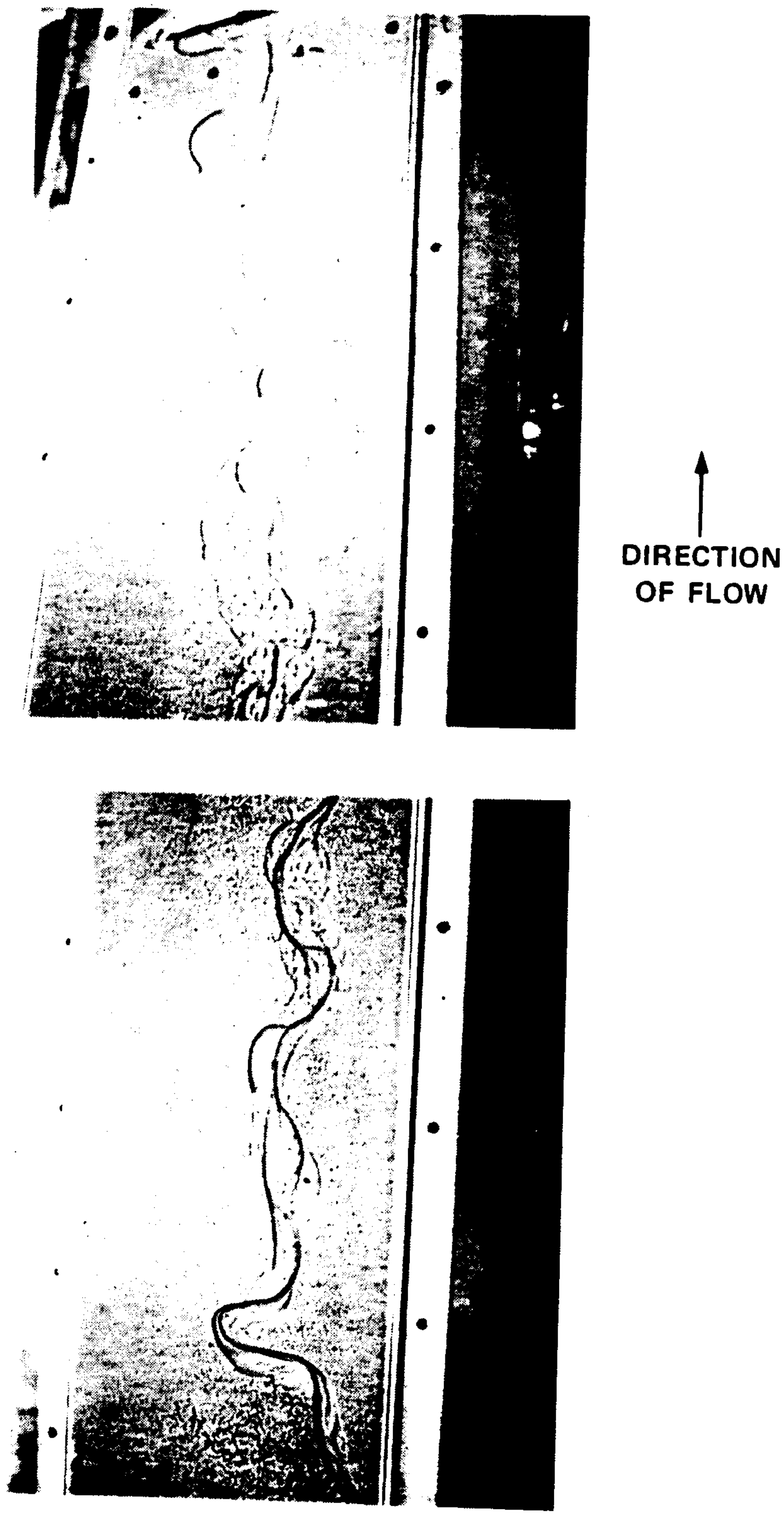


Figure 5-2: Close Up View of Pipe at Downstream (Top) And Upstream (Bottom) Ends

on the 20/30 sand and the 8/30 sand, it was found that the hydraulic head required to maintain the piping progression was higher at the latter part of the sample. This head increase to maintain piping is contrary to expectation as the gradient is increasing due to progression of the pipe (l decreasing) and a head increase is not anticipated.

Figure 5-4 presents the hydraulic gradients required to initiate piping versus the corresponding percent penetration of the initial pipe for the three uniform sands tested in this project. For uniform sands, the test results indicate that, as anticipated, the smaller grain diameters are more susceptible to piping. Obviously, lower velocities are required to erode smaller particles.

The well graded sand was tested at 30 and 50 percent penetration of initial pipe. No piping occurred in these tests. The gap I sand was tested at 15 and 30 percent penetration, and self-healing occurred in both tests. The gap II sand was tested at 15, 30, and 45 percent penetration. The gradient required to initiate piping in the gap II sand at 15 percent penetration was 35.83 percent; the gradient was raised several times to maintain the piping, but even at a gradient of 103 percent the piping stopped before bar #4. The test using the gap II sand at 30 percent penetration (test #14), no piping occurred even at a gradient of 95.83 percent. In test #15, the piping initiated and moved, but stopped after reaching bar #3; even a gradient of 95.83 percent could not maintain piping.

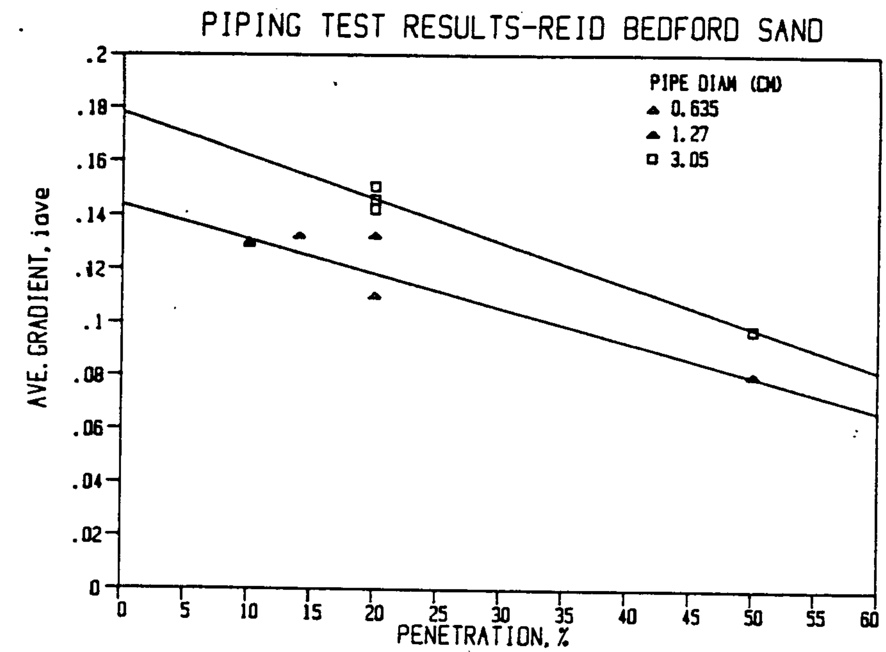


Figure 5-3: Effects of Pipe Penetration and Diameter

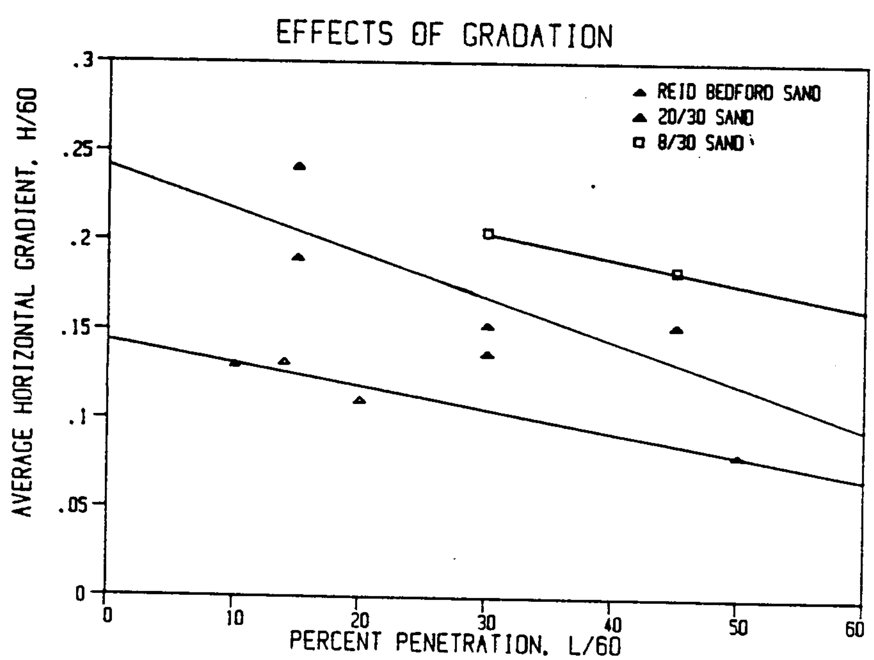


Figure 5-4: Effects of Gradation on Piping Susceptibility

The effects of gradation are summarized in Table 5.2 and show that the well-graded and gap-graded soils did not sustain piping, while the uniform sands all piped. Other than Cu and/or Cc, no single granulation characteristic distinguishes piping susceptibility. Although some instability of the finer sizes was observed as movement in the gap-graded sands, self-healing occurred causing erosion.

5.3 Comparison with Earlier Research

Based upon the research of Kenney and Lau in 1985, a method was proposed for evaluating the potential of grading instability based on the shape of a material's grain size curve. This method was described in section 2.4 and was used to evaluate the various sands used in this research project. The Reid Bedford sand, the 20/30 sand, and the 8/30 sand are narrowly-graded in the particle range of the primary fabric and therefore H-values were obtained within the range F= 0 to 0.3 (see Figure 5-5). From Figure 5.5, it can be seen that all of the grading curves lie above those points obtained from the boundary shape curve, and thus it can be concluded that the Reid Bedford sand, the 20/30 sand, and the 8/30 sand are all stable. The well graded sand, the gap I sand, and the gap II sand are widely-graded in the particle range of the primary fabric and therefore H-values were obtained within the range of F= 0 to 0.2 (see Figure 5-6). From Figure

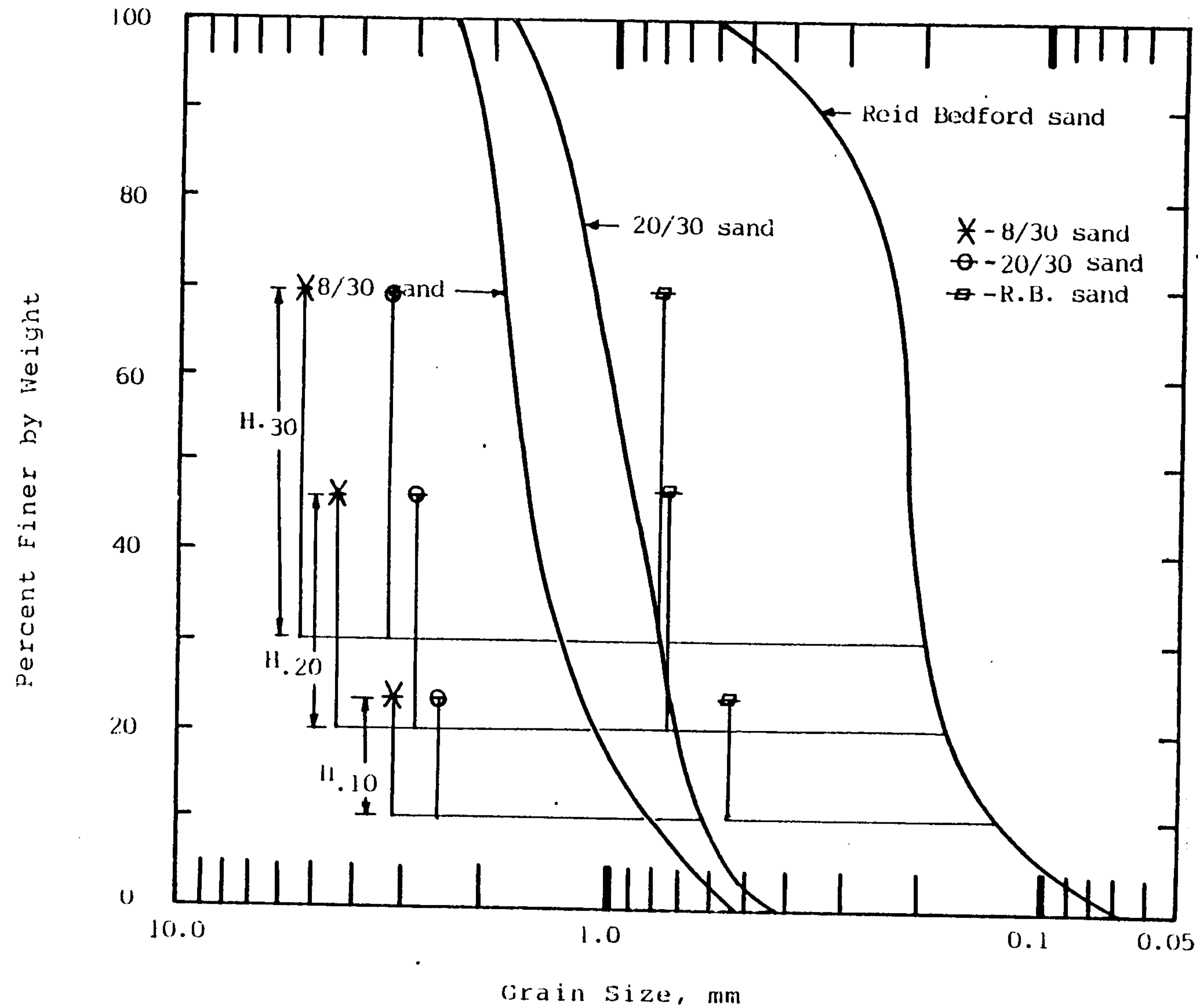


Figure 5-5. Potential of grading instability for the uniform sands tested

5.6, it also can be concluded that all of the well graded sands, the gap I sand, and the gap II sand are stable.

According to Liu's classification of cohesionless soils described in section 2.5, the Reid Bedford sand, the 20/30 sand, and the 8/30 sand are non-piping soils since their Cu values are less than 5. The well graded sand also is a non-piping soil since it exhibits a non-uniform and continueous gradation with the average diameter of pores, Do, less than D_3; where Do = $0.63nD_{20}$[Do = 0.63(0.33)(0.55)] and D_3 = 0.15. The gap I sand and the gap II sand are also non-piping soils since they are non-uniform and discontinueous gradations with the portion of fine material, P, greater than 35 percent, i.e, Gap I, P = 47%. It is obvious that all kinds of soils used in this project are stable or non-piping soils according to Kenney and Lau's or Liu's research. However, piping occurred in the uniform sands in this project. The reason being that they observed piping action by applying a hydraulic head through soil specimens which were placed in a cylinder, with no initial pipes being formed. Initial pipes were formed in this project, and piping occurred as decribed in section 5.1. However, when the self-healing occurs, the situation is more like the test without an initial pipe, which is similar to the tests on the well graded sand, the gap I sand, and the gap II sand. Accordingly, Kenney and Lau's criteria is to evaluate the internal stability of a filter; that is to say, whether small particles will move, and not to evaluate piping susceptibility. Although some

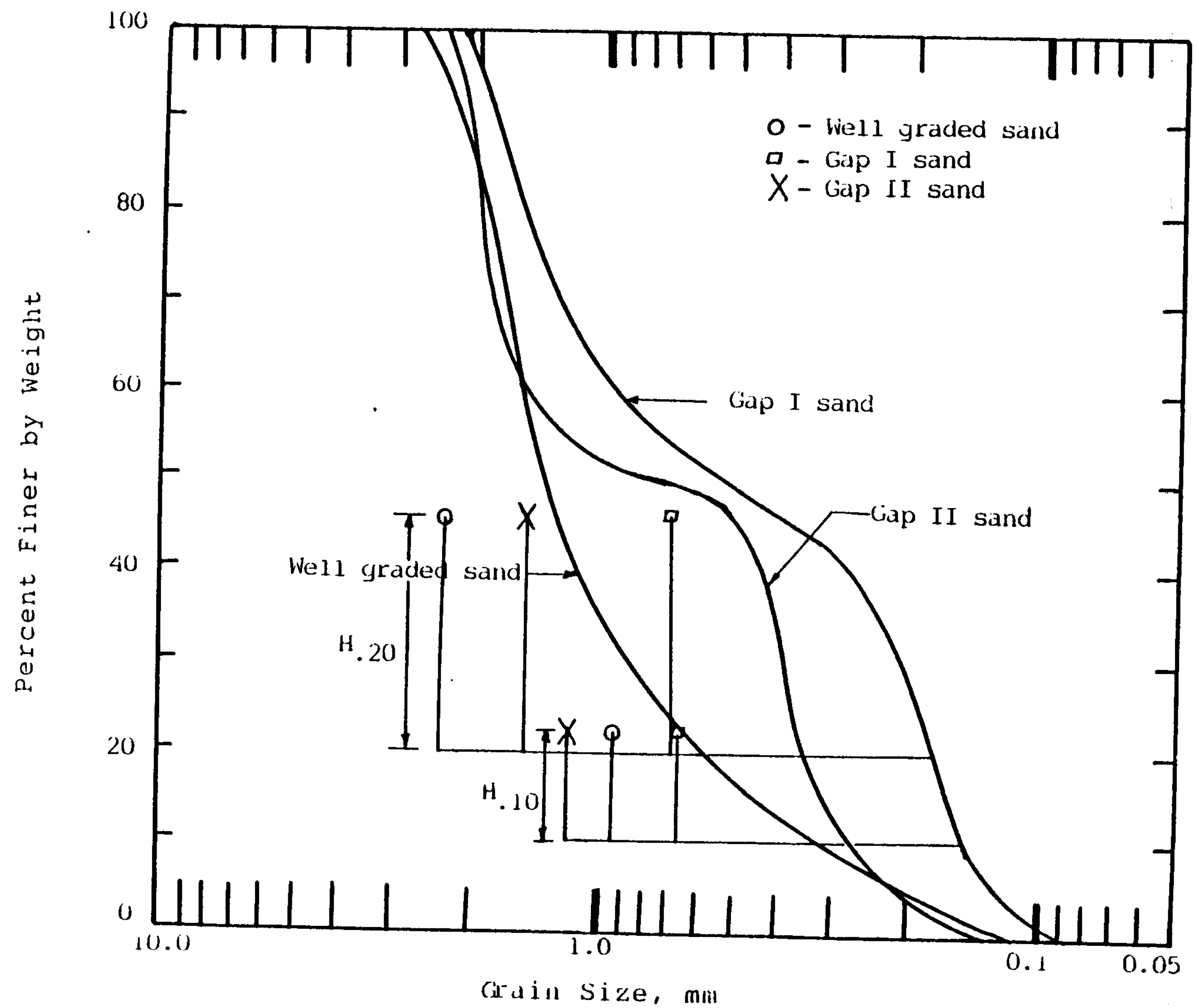


Figure 5-6. Potential of grading instability for the well graded and gap graded sands

movement of the fines was observed for tests on the gap I and II soils, these sand essentially were stable as predicted by Kenney and Lau's criteria. Thus our results coincide and validate with Kenney's and Liu's research for the internal stability of filters.

5.4 The Filter Tests

The Reid Bedford sand was used as base soil for the Phase I filter tests. Three filter gradations were tested. The grain size distribution curves of these three filter materials and the Reid Bedford sand are shown in Figure 4-4. Some characteristic grain diameters of these filters are shown in Table 5-3. A summary of the filter tests is given in Table 5-4.

From the test results, it was found that a filter with $D_{15}/d_{85} \leq 8$ would protect the cohesionless base soil properly, where D_{15} is the 15% size of the filter and d_{85} is the 85% size of the base soil. Therefore, a filter design criterion for cohesionless soil can be established, $D_{15}/d_{85} \leq 4$, with a safety factor of two. This conclusion coincides with the criteria proposed by Sherard and Dunnigan and adopted by the SCS and USBR (see Tables 2-6-A and 2-6-B, soil group 4). Also, the filter design criteria of the U.S. Army Corps of Engineers shown in Table 2-5, $D_{15}/d_{85} < 5$

(consider piping only), is deemed reasonable and practical.

A comparison also was made between the filter test results and the filter design criteria proposed by Liu (see Table 2-7). If a filter with $D_{20}/d_{70} \leq 10.9$, the filter would protect the base soil properly (see Table 5-4). Therefore, the criterion for uniform cohesionless soil, $D_{20}/d_{70} \leq 7$, has a safety factor about 1.5 to 2.0. Recalling the D_{15}/d_{15} criterion for the COE is $5<D_{15}/d_{15}<20$, while that for the SCS/USBR is $D_{15}/d_{15}>4$ and observing the results in Table 5-4, suggests that the COE criterion is appropriate. All agencies, COE, SCS and USBR agree on the lower bound (5 or 4), but it appears an upper limit similar to the COE (20) is needed.

Filter thickness ranging from 1-1/4 to 3/4 inches (31.8 to 19.0 mm) performed satisfactorily, which are far thinner than any conceivable field filter. However, in the case of filters I and III, as the pipe approached from the downstream side and the filter should have functioned as a "crackstopper"; the filters were breached. We did not observe the filter ravelling into the pipe. Instead as the pipe arrived at the downstream side of the filter, its progress was halted and a scouring hole would develop. This hole, provided the head was high, would continue to enlarge until support of the filter was removed and via a miniature landslide the filter collapsed into the scour hole causing breaching of the filter. This failure of the filter is investigated further in Phase II (Chapter 6).

TABLE 5-3

CHARACTERISTIC GRAIN DIAMETERS OF FILTERS AND BASE SOIL

	Filter I	Filter II	Filter III	Reid Bedford sand
D_{15}	0.85	2.4	3.6	0.17
D_{20}	1.0	2.5	3.8	-
D_{50}	1.55	3.4	4.3	0.20
D_{70}	-	-	-	0.23
D_{85}	-	-	-	0.30

unit: mm

TABLE 5-4

SUMMARY OF THE FILTER TESTS

No.	Filter material	D_{15}/d_{85}	D_{20}/d_{70}	D_{15}/d_{15}	Result
16	Filter I	2.83	4.3	5.0	Work
17	Filter I	2.83	4.3	5.0	Work
18	Filter II	8.0	10.9	14.1	Work
19	Filter III	12.0	16.5	21.2	Fail

D_{15}, D_{20}: the 15% and the 20% size of the filter

d_{15}, d_{70}, d_{85}: the 15%, the 70% and the 85% size of the base soil

Base soil: Reid Bedford sand

CHAPTER 6

FILTER DESIGN INVESTIGATION

INTRODUCTION

Following the initial piping and filter studies, it was decided that the effects of filter width and the possibility of filter material erosion should be investigated. The present criteria of the United States Bureau of Reclamation (USBR) and the Corps of Engineers (COE) were used to design the filters to determine if these sets of criteria were sufficient to encompass the problem of the piping of a filter material.

6.1 Scope of Phase II

Reid Bedford sand and 30/65 sand were the base soils used in phase II of this investigation. Of the three filter materials one fit the criteria, the 8/30 sand, one violated the criteria by a factor of two, the 8/20 sand, and one violated the criteria by a factor of three, gravel. Filter widths of 3, 6 and 12 inches depending on the filter material and the situation were tested with Reid Bedford sand as the base soil. Additionally, one graded filter was tested with this base sand. Two supplemental tests were performed with the 30/65 base sand to augment and verify the results from the tests using the Reid Bedford sand.

6.2 Materials

The materials used are listed in Table 6-1 and the corresponding sieve analysis in Figure 6-1. The base soils were Reid Bedford sand and the 30/65 sand. The 8/30 sand filter meets the COE and the USBR filter criteria which has a factor of safety of two as determined in Phase I. The limiting values computed for the filter criteria were multiplied by two and three to reduce the factor of safety by one-half and one-third, respectively, resulting in factors of safety of one and, approximately, two-thirds, respectively. The 8/20 sand and gravel met the criteria for the factors of safety of one and two-thirds, respectively. The 8/20 sand was scalped below the No. 16 sieve for use in this experiment.

6.3 Equipment

The equipment used in phase II of this experiment is identical to that used in phase I.

TABLE 6-1

MATERIALS

Material	D_{85} (mm)	D_{50} (mm)	D_{15} (mm)	Factor of Safety
8/30	1.96	1.18	0.74	2
8/20	1.77	1.51	1.29	1^{+}
Gravel	8.22	4.99	3.36	< 1
Reid Bedford	0.30	0.20	0.17	
30/65	0.98	0.56	0.39	

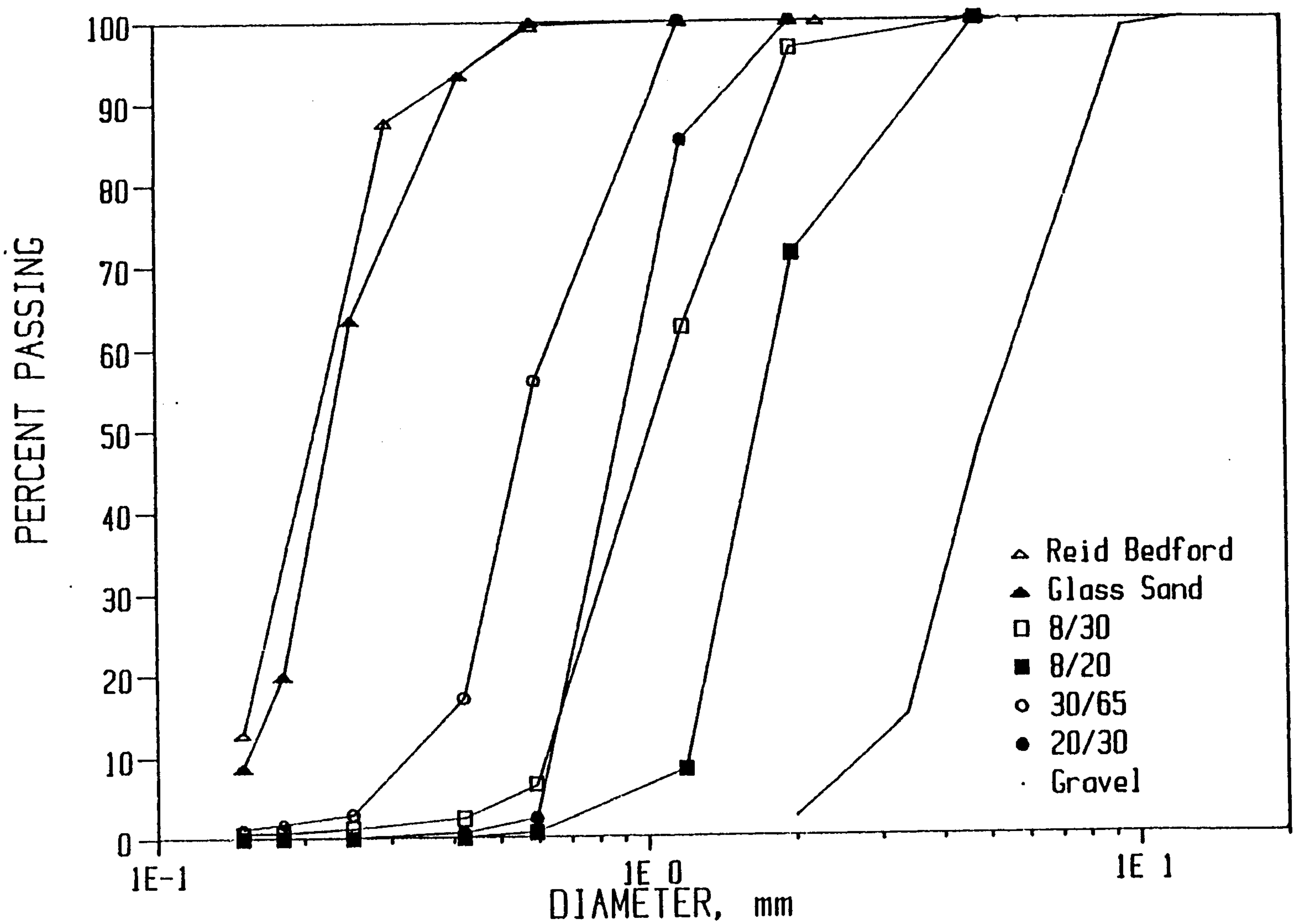


FIGURE 6-1: Grain-size distribution of the materials used

6.4 Sample Preparation

The sample preparation procedure is shown in Figure 6-2. The only changes from phase I made in this preparation were the following:

1) The base soil was packed to within two inches of the top of the flume instead of raining the entire depth; this was to attempt to avoid settling of the sample during saturation.
2) Only the last two inches of the soil were rained.
3) A dissolvable sugar pipe was inserted upstream of the filter to initiate upstream piping.

6.5 Filter Design Calculations

The calculations for the USBR filter design are shown in Figure 6-3 and the COE filter design in Figure 6-4. The factors of safety were incorporated by multiplying the desired reduction factor by the limiting values computed. For example, to reduce the factor of safety by one-half the limiting values are multiplied by two.

6.6 Discussion of Test Results

The results of this investigation are shown in Table

SAMPLE PREPARATION

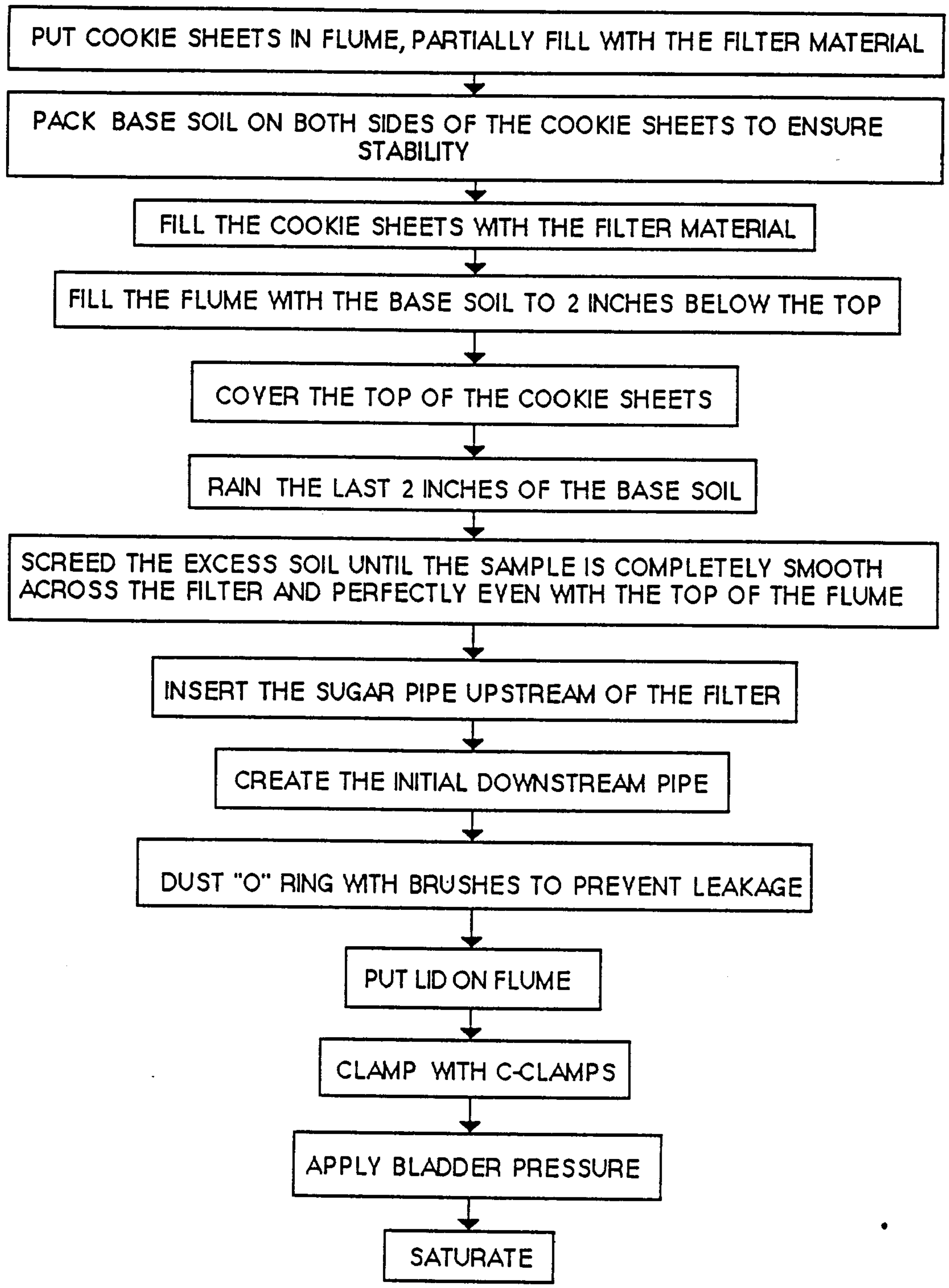


FIGURE 6-2

FILTER DESIGN CALCULATIONS

USBR CRITERIA

STEP 1: 100% of the Reid Bedford sand passes the No. 4 sieve and the fines compose less than 15% of the sand. Therefore, according to Table 2-6-A (pg. 24), the soil is category 4.

STEP 2: Refer to Table 2-6-A to calculate the maximum D_{15} of the filter.

max. $D_{15} < 4 \times d_{85b}$

max. $D_{15} < 4 \times 0.30 \text{ mm} = 0.12 \text{ mm}$

STEP 3: Compute the minimum D_{15} of the filter.

min. $D_{15} > 4 \times d_{15b}$

min. $D_{15} > 4 \times 0.17 \text{ mm} = 0.68 \text{ mm}$

The minimum D_{15} cannot be less than 0.1 mm

STEP 4: Set the maximum particle size at 3 inches and the maximum passing the No. 200 sieve at 5%.

STEP 5: The filters in this experiment are uniformly graded and do not contain particles that are coarse enough to require limitations on filter broadness to prevent segregation. Those filters that are composed of coarse material and a range of finer materials or are gap-graded should have limitations on D_{10} and D_{90} in accordance with Table 2-6-B (pg. 24)

FIGURE 6-3: Example filter design calculations for USBR criteria

FILTER DESIGN CALCULATIONS

CORPS OF ENGINEERS CRITERIA

(Base - Reid Bedford, Filter - 8/30)

$D_{15f}/d_{85b} < 5$	$0.74/0.30 = 2.47 < 5$
$5 < D_{15f}/d_{15b} < 20$	$0.74/0.17 = 4.35^{*}$
$D_{50f}/d_{50b} < 25$	$1.18/0.20 = 5.90 < 25$

* This value is close to the range of values to be acceptable.

FIGURE 6-4: Example filter design calculations for COE criteria

6-2. The failure mode designated as "piped" indicates a failure by pipe erosion progressing through and breaching the filter to allow the upstream material to flow to the downstream slope. This mode was observed in Tests 1 and 3.

The failure mode "did not filter" indicates a filter that allows the upstream material to flow into the filter throughout the depth of the flume and to migrate to the downstream side of the filter as observed in Tests 4 and 5.

The filter constructed of 8/20 material was successful in providing a filter of the upstream material, Test 2, and was also sufficiently coarse to resist pipe erosion and the progression of the downstream pipes across the filter. The success of this material contradicts expectations dictated by the filter design criteria. This material was expected to perform poorly since the factor of safety against filtering is approximately one. Conversely, the filter constructed of the 8/30 material (Tests 1 and 3) had a factor of safety of 2 and was expected to be successful; yet it was breached. The graded filter (Test 6)provides the best alternative for preventing pipe erosion from damaging a structure as seen in Test 6.

The 30/65 base material was used to verify the controversial results observed using the Reid Bedford as a base soil with the 8/20 filter material. The 8/20 filter material was successful even though the factor of safety only approached unity. Unfortunately, the 30/65 sand used in

TABLE 6-2

SUMMARY OF FILTER TEST RESULTS

Test No.	Filter Material	Base Material	Filter Width (in)	Result
1	8/30	RB[1]	3	piped
2	8/20	RB	3	successful
3	8/30	RB	12	piped
4	gravel	RB	6	did not filter
5	gravel	RB	3	did not filter
6	8/30[2] gravel	RB	3 3	successful
7	8/20	30/65	3	filter did not fail due to piping; support was lost due to erosion of the base soil

1 abbreviation for Reid Bedford

2 graded filter of 8/20 upstream and gravel downstream

Tests 7A and 7B failed to verify these results. The piping of the downstream material proceeded quickly and widened to the extent of sheet flow over the entire width of the flume before the initial pipe even reached the filter. Due to this excessive erosion, the support for the filter was lost. The filter was not legitimately tested due to the inadequate base soil.

From these results it is apparent that existing USBR or COE filter criteria merely address migration of the base soil particles, but neglect the erosion of the filter itself. When the fluid velocities are sufficiently high, these results demonstrate that the coarser filter particles themselves are subject to erosion. Accordingly, the coarser the filter particles, the more resistant the filter to erosion as demonstrated by the 8/20 filter outperforming the finer 8/30 filter. Obviously, a trade-off exists; coarse filters resist erosion yet may unsuccessfully filter the base soil. To overcome this dilemma, graded filters are viable.

A quandary exists concerning the performance of existing filters, in that to date numerous filters have performed satisfactorily in the field; yet, these test results show filter erosion can occur. Apparently, the field boundary conditions are different than those imposed by the laboratory flume. For filter erosion to occur an open channel with high velocities is required as provided by the plastic flume top and downstream pipe. Obviously, similar filter erosion would be anticipated for similar field conditions. It is conceivable that a crack in the impervious core of a dam or arching within the filter could produce these unfavorable conditions.

6.7 Summary of Phase II Tests

Table 6-3 summarizes the test conditions of the test performed in Phase II of the investigation.

NOTES: 1) d = density

2) k = permeability

3) The location of the filter is measured to the center of the filter.

Test 1

The base soil used in this test was Reid Bedford sand with d = 1.66 g/cm^3 (103.58 lb/ft^3); k = 0.05317 cm/s (0.00174 ft/s); initial downstream pipe penetration = 12 inches (33%), diameter = 1/2 inch; 3 inch filter of 8/30 sand located 36 inches upstream from the downstream slope; upstream pipe length = 14.5 inches, diameter = 3/8 inch; bladder pressure = 5 psi. The head was increased at a constant rate from the beginning of the test. The downstream piping began at the length of the initial pipe (12 inches) with a head of 12.8 inches. Upstream piping began at the same time. The upstream pipe clogged at the filter and stopped. When the downstream pipe reached 19.68 inches in length, the head was held constant until the pipes reached the filter at a head of 20.55 inches and a gradient of 0.54

TABLE 6-3

SUMMARY OF TEST RESULTS

TEST No.	BASE sand	BASE density (g/cm^3)	FILTER type	FILTER width (in)	PERMEABILITY (cm/s)	PENETRATION in(%)	UPSTREAM HEAD AT START OF PIPING (in)
1	RB	1.66	8/30	3	0.05317	12.0(33)	12.80
2	RB	1.61	8/20	3	0.02920	12.5(35)	9.37
3	RB	1.58	8/30	12	0.06680	12.0(33)	14.96
4	RB	1.58	gravel	6	0.04340	12.0(33)	8.54
5	RB	1.57	gravel	3	0.05010	13.0(26)	14.25
6	RB	-	8/30 -gravel	3-3	0.04850	12.0(33)	10.08
7A	30/65	1.55	8/20	3	0.11530	12.0(33)	13.62
7B	30/65	1.56	8/20	3	0.12490	8.0(38)	14.17

across the filter. The downstream material piped and eroded by sheet flow. The filter was damaged by pipes pulling material from the filter. The filter was breached by pipes progressing in a meandering path across the filter. See Fig. 6-5. The gradient across the filter at failure was 0.944. The 8/30 sand functioned as a filter but not as a crackstopper at high gradients. At gradients < 0.5 the filter will stop cracks, but as the fine particles in this sand wash away by constant erosion, the skeleton of larger particles is weakened and collapses even at low gradients.

<u>Test 2</u>

The base soil used in this test was Reid Bedford sand with d = 1.61 g/cm^3 (100.3 lb/ft^3); k = 0.0292 cm/s (0.000958 ft/s); initial downstream pipe penetration = 12.5 inches (35%), diameter = 1/2 inch; 3 inch filter of 8/20 sand located 36 inches upstream from the downstream slope; upstream pipe length = 14 inches, diameter = 3/8 inch; bladder pressure = 7 psi. A higher bladder pressure than Test 1 was used to ensure full contact between the flume lid and the sand. Failure due to settling and bladder relaxation was encountered in a preliminary test. The head was increased at a constant rate, and piping began at the length of the initial pipe, 12.5 in, at a head of 9.37 inches. Upstream piping began at a head of 12.83 in, but the transported material clogged the pipe at the filter. Air

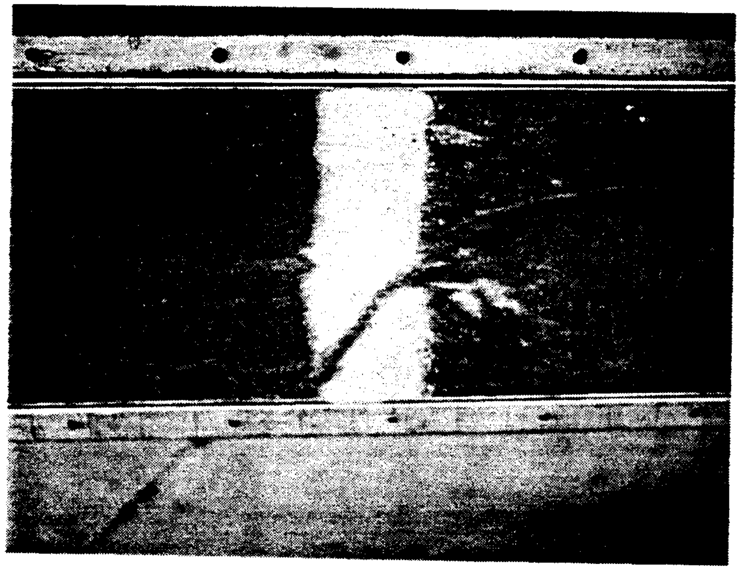


Fig. 6-5: Photo of Test 1 illustrating filter failure by piping

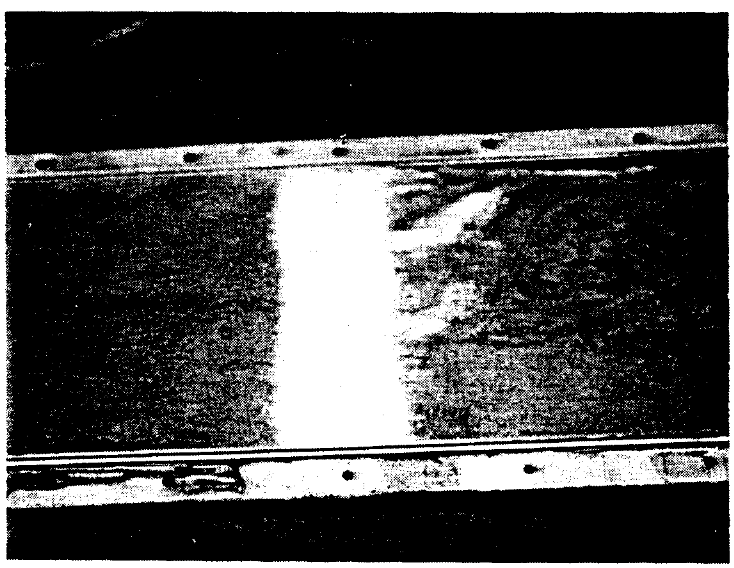


Fig. 6-6: An illustration of slight damage to a successful filter in Test 2

bubbles slowed and almost stopped the progression of the downstream pipes. As the air flowed out of the pipes, the pipes progressed to the filter and stopped. At this point the gradient was 0.40. The eroded sand was deposited at the downstream slope. The higher gradient caused by the increasing head cut deep channels in the deposited material. The high velocities in these channels caused the heads to drop. The 8/20 material functioned as a filter and did not fail at gradients as high as 1.45; the head was raised to its highest value. The coarse material of this filter was damaged, but the filter did not pipe and did not fail even when the bladder pressure was reduced to 2 psi. See Fig. 6-6. The pipes and channels became too wide to allow the filter to function as a crackstopper. However, the material was sufficiently coarse and permeable to prevent heads from producing the pressure needed to breach the filter. The filter was successful. Thus, tests on the 6 inch and 12 inch filters of this material were not necessary.

Test 3

The Reid Bedford sand was the base soil in this test with d = 1.58 g/cm^3 (98.48 lb/ft^3); k = 0.0668 cm/s (0.00219 ft/s); initial downstream pipe penetration = 12 inches (33%), diameter = 1/2 inch; 12 inch filter of 8/30 sand located 36 inches from downstream slope; upstream pipe length = 6 1/2 inches, diameter = 1/2 inch; bladder pressure = 5 psi. With the head increasing at a constant rate, the loose material from the removal of the dowel used to form the initial downstream pipe was carried away at a head of 9.06 inches. The actual piping began at a head of 14.96 inches at the length of the initial pipe. The pipes progressed and widened quickly. Upstream piping was observed at a head of 17.44 inches. The upstream pipe clogged at the filter. When the downstream pipes reached 28 inches in length, the head was held constant at a head of 21.06 inches. As the pipes reached the filter, the fines of the filter material were eroded and carried downstream. The high velocities began cutting large, meandering channels in the deposited material 6 inches from the downstream slope. The gradient across the filter reached 0.265 as the filter material piped to cause a breach of the filter. The upstream material flowed through the filter pipes. See Fig. 6-7. Before the filter was breached, the 8/30 material functioned as a filter for the upstream material, but the filter material completely failed by piping as did the 3 inch filter of the same material.

Test 4

The base soil was Reid Bedford sand with d = 1.58 g/cm^3 (98.94 lb/ft^3); k = 0.0434 cm/s (0.00142 ft/s); initial downstream pipe penetration = 12 inches (33%), diameter = 1/2 inch; 6 inch filter of gravel located 36 inches upstream from downstream slope; upstream pipe length = 11 inches, diameter

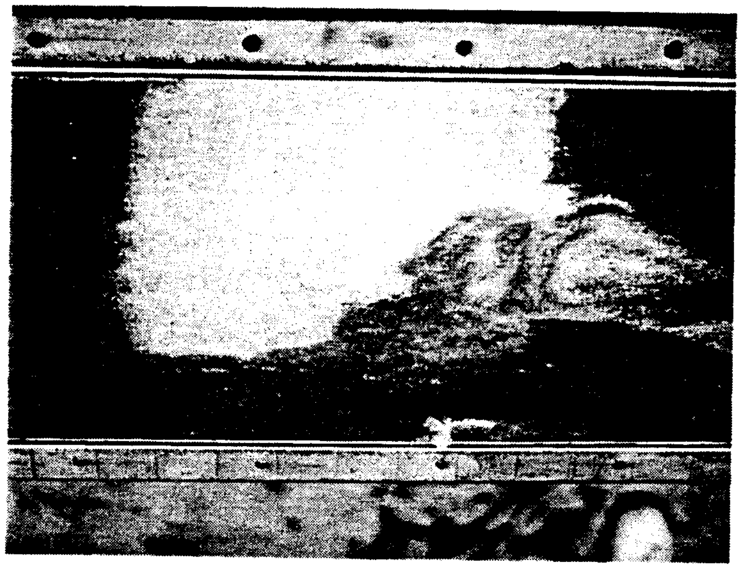


Fig. 6-7: A photo from Test 3 illustrating a breach begun by piping and resulting in a mass flow of upstream material carrying away the filter material

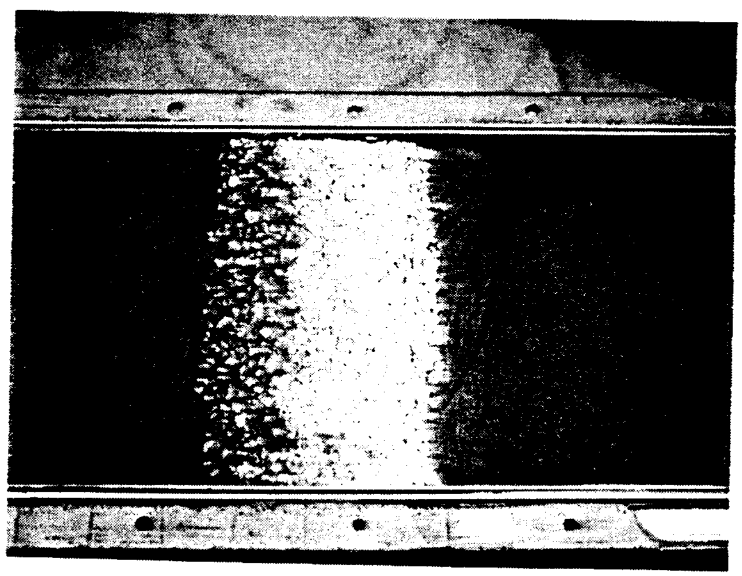


Fig. 6-8: Test 4 photo illustrating a filter failing to function as a filter allowing migration of the upstream material into the filter

= 3/8 inch; bladder pressure = 7 psi. The piping began at the tip of the initial pipe at a head of 8.54 inches. The upstream piping began at a head of 11.02 inches. The piping was stopped by air bubbles in the filter. With the head increasing steadily the pipes progressed to 19.5 inches in length, widening at the downstream slope to the width of a channel, where the head was stopped at 21.3 inches. After a 12 minute lapse, the bladder was relaxed to 6 psi due to slow pipe progression. The initial pipe was clogging with transported material because of the excessive bladder pressure. Side pipes formed as these middle pipes were clogged, since the outside pipes feel less pressure than the inside pipes feel. The shape of the bladder causes an uneven pressure distribution. The pipes were forced to progress by resuming the constant head increase. As the downstream pipes reached the filter at a gradient of 0.80 across the filter, air was released from the large interstitial spaces of the filter. This release caused a migration of 2 1/2 inches of the upstream material into the filter. Thus, this material failed to function as a filter. The filter did not fail by piping and was not completely breached, even when the bucket applying the head was at its highest point. However, the filter was sufficiently clogged by the upstream material to render the filter material unsuitable for this base material. See Fig. 6-8. The velocity of the water through the base soil was not high enough to carry the sand through the voids of the filter, causing deposition of the sand within the gravel. As the sample was excavated, infiltration of the base soil throughout the filter depth was discovered.

Test 5

The base soil was Reid Bedford sand with d = 1.57 g/cm^3 (97.88 lb/ft^3); k = 0.0501 cm/s (0.00164 ft/s); initial downstream pipe penetration = 13 inches (26%), diameter = 1/2 inch; filter of 3 inch gravel located 49 inches upstream from the downstream slope; no upstream pipe; bladder pressure = 5 psi. The filter was placed farther upstream to subject the filter to a higher velocity than in Test 4. The filter was too close to the upstream reservoir to install an upstream pipe. The head was increased at a constant rate, and piping began at the length of the initial pipe at a head of 14.25 inches. The pipe progressed to 19.69 inches under a head of 18.90 inches, when the head was temporarily held constant. After a lapse of 16 minutes and the pipes had progressed to a length of 31.5 inches, the increase of the head was resumed. At a head of 25.6 inches the upstream material began migrating through the filter material. At a gradient of 0.19 the migration of the upstream soil was completely through the filter. The head fell to 3.1 inches and remained there as the water flowed freely through the filter and the sample. This filter also failed by migration of the upstream material completely through the gravel filter. The 12 inch filter of this material was not tested. The same migration will occur regardless of the size of the filter. The extent of the migration is the only variable.

Test 6

The base soil was Reid Bedford sand with k = 0.0485 cm/s (0.00159 ft/s); initial downstream pipe penetration = 12 inches (33%), diameter = 1/2 inch; graded filter of 3 inches of 8/30 sand (upstream) and 3 inches of gravel (downstream) located 36 inches from the downstream slope; upstream pipe length = 14 inches, diameter = 3/8 inch; bladder pressure = 5 psi. The piping began at the tip of the initial pipe at a head of 10.08 inches. The upstream piping initiated at a head of 13.82 inches. This upstream pipe clogged itself at the 8/30 filter, indicating the 8/30 sand acted to filter the upstream material. The constantly increasing head caused excessive flows of the base sand and widening of the downstream pipes. Thus, the bladder pressure was increased to 7 psi. When the initial pipes reached 19.68 inches in length, the head was temporarily stopped at 20.94 inches. The pipes progressed, widened and began clogging downstream with deposited material. When the head was increased again as the pipes reached the filter, the increase in flow caused channels to cut through the deposited sand. Some minor migration of the 8/30 sand into the gravel was observed. The fines of the 8/30 sand flowed through the gravel at a gradient of 0.81 across the filter. The upstream reservoir manometer overflowed without any failure observed. At a gradient of 0.99 across the filter the channels downstream of the gravel at the interface between the base and the filter widened to the entire width of the flume. The head was raised to its highest point to reach a gradient of 1.42 across the filter, and the bladder pressure was reduced to 2 psi. The filter remained intact and was marginally damaged. See Fig. 6-9.

NOTE: Tests 7a and 7b were performed to test the 8/20 filter material with a different base soil with approximately the same grain-size distribution curve as the Reid Bedford sand. This was to verify the controversial results that the material with a marginal factor of safety and uniform gradation is successful, while a well-graded material with a factor of safety of 2 fails.

<u>Test 7A</u>

The base soil was 30/65 sand with d = 1.55 g/cm^3 (96.68 lb/ft^3); k = 0.1153 cm/s (0.00378 ft/s); initial downstream pipe penetration = 12 inches (33%), diameter = 3/8 inch; 3 inch filter of 8/20 sand located 36 inches from the downstream slope; upstream pipe length = 14.5 inches, diameter = 3/8 inch; bladder pressure = 7 psi. The head was being increased at a constant rate as the piping began at the

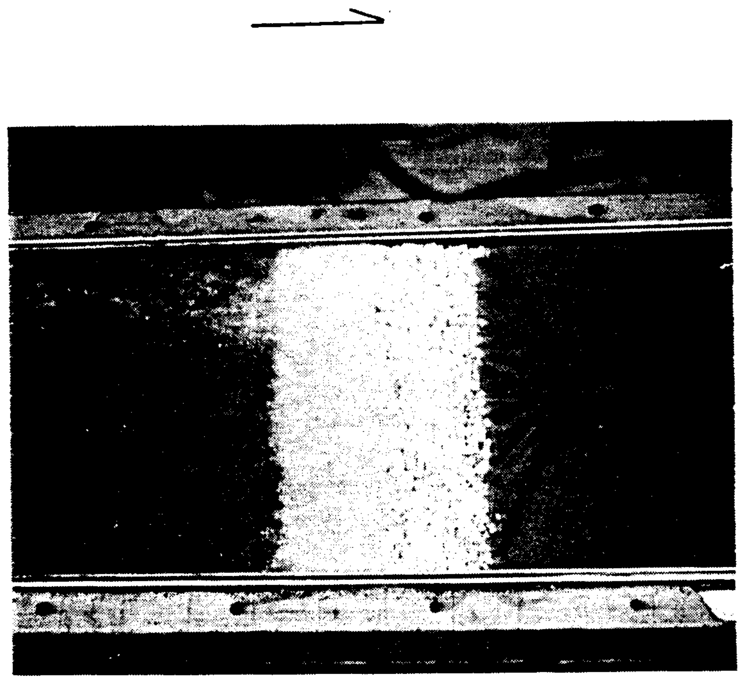


Fig. 6-9: Photo from Test 6 of a successful graded filter

initial pipe tip at a head of 13.62 inches. The pipe was uniform and widened quickly. This 30/65 sand did not allow meandering pipes to form; the pipes were very straight. The sand transportation in the pipes was considerably faster than with the Reid Bedford sand due to the higher permeability of the 30/65 sand. The pipe or channel progressed to 19.68 inches in length where the head was held constant at 24.84 inches. The pipe progressed to within 2 inches of the filter and stopped. The head was increased again and, the bladder pressure was lowered to 6 psi to induce pipe progression. The pipes began flowing and widening to cause sheet flow across the width of the flume. The base material completely eroded downstream of the filter without damaging the filter until the filter collapsed solely due to the loss of support of the base soil.

Test 7B

The identical test was repeated except the filter was placed 21 inches from the downstream slope with an 8 inch (38%) initial downstream pipe penetration of 3/8 inch diameter and a 17 inch upstream pipe of 3/8 inch diameter. The purpose of the test was to attempt to force the pipes to the filter before sheet flow started. This test yielded the identical results to Test 7a. This suggests an inappropriate base soil for this kind of test. The piping did not progress to the extent that the filter design was tested.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Based upon the results obtained from the laboratory testing program, the cohesionless soils which were used, and the specific testing equipment designed for this project, the conclusions are summarized as follows:

1. It is harder to initiate piping in a well graded (high coefficient of uniformity, Cu) cohesionless soil than a uniformly graded (lower Cu) soil. For the uniformly graded soils which are susceptible to piping, those with a larger grain size are more difficult to initiate piping than those with a smaller grain size. In other words, fine uniform sands are more susceptible to piping than coarse well graded sands.

2. The internal stability criteria of Kenney and Lau, and Liu, were verified for well-graded sands. However, a difference was observed for uniform sands. It is believed that this divergence was due to this research using an initial pipe to concentrate flow and using a horizontal valve.

3. A filter design criterion for cohesionless soil is established, $D_{15f}/d_{85b} \leq 4$. This criteria has a safety factor of two, and coincides with that proposed by Sherard and

Dunnigan and used by the USBR and SCS. Also the filter design criterion of the U.S. Army Corps of Engineers, $D_{15f}/d_{85b} < 5$ (considering piping only), is deemed reasonable and practical for filters only.

5. The criteria used by the USBR, the SCS and the COE do not address the problem of erosion of the filter itself by piping. Filters which met the specified filtering criteria were breached by this type of erosion. Filters of uniform gradation with a factor of safety of approximately one, violating the filter design criteria by a factor of two, performed successfully. These filters have larger particles than those filters with a factor of safety of two, and thus require a higher velocity to erode and move the filter material.

6. Graded filters perform satisfactorily in resisting erosion yet filter the base soil, and are recommended to mitigate breaching.

7. The thickness of a filter has little effect on the performance of the filter.

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APPENDIX
TEST DATA SHEETS

HYDRAULIC PIPING TEST DATA SHEET

Test # :	1 (Reid Bedford sand)
Date:	3-11-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	12"
Percent Pipe Penetration:	20.0
Initial Pipe Diameter:	1/2"
Time at Start of Test:	11:09 AM
Head at Upstream End:	12.5"
Head at Downstream End:	4.5"
Total Head:	8.0"

Location of Pipe	Time	Time Increment
Bar #1	-	-
Bar #2	12:07	58
Bar #3	1:35	88
Bar #4	3:57	142
Bar #5	5:08	71
Upstream Weir	5:18	10

Comments:

1. Piping started at 11:09, stopped a minute later. The head had to be raised.
2. Heads at upstream end and heads at downstream end were recorded at different time:

Time	12:40	1:42	1:57	2:04	2:25	3:11
Head at US end	13.38	12.88	11.63	11.9	12.25	12.0 inches
Head at DS end	5.25	5.13	4.25	4.25	4.25	4.25inches

3. Density of sand: 92.64 pcf

HYDRAULIC PIPING TEST DATA SHEET

Test # :	2 (20/30 sand)
Date:	4-10-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	9"
Percent Pipe Penetration:	15
Initial Pipe Diameter:	1/4"
Time at Start of Test:	10:55 AM
Head at Upstream End:	16.5"
Head at Downstream End:	5.12"
Total Head:	11.38"

Location of Pipe	Time	Time Increment
Bar #1	10:56	1
Bar #2	10:59	3
Bar #3	11:09	10
Bar #4	11:14	5
Bar #5	11:25	11
Upstream Weir	11:26	1

Comments:

1. Air voids could be seen in sand.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	3 (20/30 sand)
Date:	4-18-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	9"
Percent Pipe Penetration:	15
Initial Pipe Diameter:	1/4"
Time at Start of Test:	9:57 AM
Head at Upstream End:	20.0"
Head at Downstream End:	5.5"
Total Head:	14.5"

Location of Pipe	Time	Time Increment
Bar #1	9:59	2
Bar #2	10:21	22
Bar #3	10:24	3
Bar #4	10:51	27
Bar #5	11:15	24
Upstream Weir	11:15.5	0.5

Comments:

1. Heads at upatream end and heads at downstream end were recorded when piping reached Bar #3, #4, and #5:

Bar #	3	4	5	
Head at US end	17.25	20.38	22.38	inches
Head at DS end	4.5	4.5	4.5	inches

2. Density of sand: 100.5pcf

HYDRAULIC PIPING TEST DATA SHEET

Test # :	4 (20/30 sand)
Date:	4-25-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	18"
Percent Pipe Penetration:	30
Initial Pipe Diameter:	1/4 "
Time at Start of Test:	9:08 AM
Head at Upstream End:	12.75"
Head at Downstream End:	4.5"
Total Head:	8.25"

Location of Pipe	Time	Time Increment
Bar #1	-	-
Bar #2	9:39	31
Bar #3	10:00	21
Bar #4	10:17	17
Bar #5	10:28	11
Upstream Weir	10:29	1

Comments:

1. Heads at upstream end and heads at downstream end were recorded when piping reached Bar #2, #3, #4, and #5:

Bar #	2	3	4	5	
Head at US end	12.75	11.75	16.5	23.0	inches
Head at DS end	4.5	4.5	4.5	4.5	inches

2. Density of sand: 101.8 pcf

HYDRAULIC PIPING TEST DATA SHEET

Test # :	5 (20/30 sand)
Date:	4-30-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	27"
Percent Pipe Penetration:	45
Initial Pipe Diameter:	1/4"
Time at Start of Test:	10:24 AM
Head at Upstream End:	13.75"
Head at Downstream End:	4.5"
Total Head:	9.25"

Location of Pipe	Time	Time Increment
Bar #1	-	-
Bar #2	-	-
Bar #3	10:42	18
Bar #4	10:58	16
Bar #5	11:13	15
Upstream Weir	11:18	5

Comments:

1. Density of sand: 102.6 pcf
2. Heads along the sample were recorded when piping started and reached Bar #3, #4, #5, and upatream weir:

	Start	Bar#3	Bar#4	Bar#5	US weir	
US end head	13.75	14.25	14.88	14.69	15.06	inches
M-3	10.13	12.38	11.25	12.69	13.06	inches
M-2	7.31	8.75	9.88	9.56	9.63	inches
M-1	5.25	7.31	7.63	7.0	6.88	inches
DW end head	4.5	4.75	4.75	4.75	4.75	inches

HYDRAULIC PIPING TEST DATA SHEET

Test # :	6 (20/30 sand)
Date:	5-16-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	18"
Percent Pipe Penetration:	30
Initial Pipe Diameter:	1/4"
Time at Start of Test:	8:50 AM
Head at Upstream End:	13.38"
Head at Downstream End:	4.13"
Total Head:	9.25"

Location of Pipe	Time	Time Increment
Bar #1	-	-
Bar #2	9:17	-
Bar #3	9:21	4
Bar #4	9:27	6
Bar #5	10:07	40
Upstream Weir	10:09	2

Comments:

1. The sample was prepared without vacuum procedure.
2. Heads along the sample were recorded when piping reached Bar#2, #3, #4, #5, and upatream weir:

	Bar#2	Bar#3	Bar#4	Bar#5	US weir	
US end head	14.88	14.63	16.63	17.5	17.5	inches
M-3	11.38	11.13	12.13	17.0	17.0	
M-2	8.38	8.5	10.25	12.38	12.38	
M-1	5.75	7.38	7.5	8.13	8.13	
DW end head	4.5	4.63	4.5	4.75	4.75	

HYDRAULIC PIPING TEST DATA SHEET

Test # :	7 (well graded)
Date:	5-29-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	18"
Percent Pipe Penetration:	30
Initial Pipe Diameter:	1/4"
Time at Start of Test:	11:18 AM
Head at Upstream End:	37"
Head at Downstream End:	4.5"
Total Head:	32.5"

Location of Pipe	Time	Time Increment
Bar #1	-	
Bar #2	-	
Bar #3	-	
Bar #4	-	
Bar #5	-	
Upstream Weir	-	

Comments:

1. Sample was prepared without vacuum process.
2. Density of sample: 110.9 pcf
3. Only a little fine sand was removed in the original pipe at a head of 32.5".
4. The head was raised several times but the piping did not occur. After raising the head to 58" with no eddect, the test was terminated.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	8 (well graded)
Date:	6-5-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	30"
Percent Pipe Penetration:	50
Initial Pipe Diameter:	1/4"
Time at Start of Test:	-
Head at Upstream End:	-
Head at Downstream End:	-
Total Head:	-

Location of Pipe	Time	Time Increment
Bar #1	-	
Bar #2	-	
Bar #3	-	
Bar #4	-	
Bar #5	-	
Upstream Weir	-	

Comments:

1. Sample was prepared without vacuum process.
2. Density of sample: 112.3 pcf
3. The head was raised several times but piping was not intiated. After raising the head to 52.5" with no effect, the test was terminated.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	9 (8/30 sand)
Date:	6-21-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	27"
Percent Pipe Penetration:	45
Initial Pipe Diameter:	1/4"
Time at Start of Test:	9:33 AM
Head at Upstream End:	16"
Head at Downstream End:	5"
Total Head:	11"

Location of Pipe	Time	Time Increment
Bar #1	-	-
Bar #2	-	-
Bar #3	10:05	-
Bar #4	10:12	7
Bar #5	10:22	10
Upstream Weir	10:22	0

Comments:

1. The vacuum process was performed.
2. Density of sample: 106.1 pcf
3. The water supply system was changed to a faucet since only a maximum head of only 16" could be achieved when the water supply reservoir was raised to the top of the pulley system.
4. The heads were recorded when the piping reached bar #3, #4, and #5; 19.0", 33.25", and 38.5", respectively.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	10 (8/30 sand)
Date:	6-27-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	18"
Percent Pipe Penetration:	30
Initial Pipe Diameter:	1/4"
Time at Start of Test:	9:05 AM
Head at Upstream End:	17.0"
Head at Downstream End:	4.75"
Total Head:	12.25"

Location of Pipe	Time	Time Increment
Bar #1	-	-
Bar #2	9:23	-
Bar #3	9:28	5
Bar #4	9:50	22
Bar #5	9:57	7
Upstream Weir	9:57	0

Comments:

1. The vacuum process was performed.
2. Density of sample: 106.1 pcf
3. The water supply system was changed to a faucet after the water supply reservoir was raised to the top of the pulley system.
4. When the piping reached bar #2, #3, #4, and #5, the head were recorded; 14.88", 15.0", 20.5", and 22.75", respectively.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	11 (gap I sand)
Date:	7-23-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	9"
Percent Pipe Penetration:	15
Initial Pipe Diameter:	1/4"
Time at Start of Test:	9:15 AM
Head at Upstream End:	-
Head at Downstream End:	-
Total Head:	-

Location of Pipe	Time	Time Increment
Bar #1	-	
Bar #2	-	
Bar #3	-	
Bar #4	-	
Bar #5	-	
Upstream Weir	-	

Comments:

1. The vacuum process was performed.
2. Density of sample: 110.1 pcf
3. The head was raised several times, but piping did not occur except that the fine sand in the initial pipe moved occasionally.
4. When the head was raised to more than 6 feet sheet flow happened.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	12 (gap I sand)
Date:	8-5-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	18"
Percent Pipe Penetration:	30
Initial Pipe Diameter:	1/4"
Time at Start of Test:	10:30 AM
Head at Upstream End:	-
Head at Downstream End:	-
Total Head:	-

Location of Pipe	Time	Time Increment
Bar #1	-	
Bar #2	-	
Bar #3	-	
Bar #4	-	
Bar #5	-	
Upstream Weir	-	

Comments:

1. The vacuum process was performed.
2. Density of sample: 110.4 pcf
3. The head was continually increased in order to initiate piping. But piping did not occur except the fine sand in the initial pipe moved occasionally.
4. Sheet flow happened when the head was raised to more than 6 feet.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	13 (gap II sand)
Date:	9-9-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	9"
Percent Pipe Penetration:	15
Initial Pipe Diameter:	1/4"
Time at Start of Test:	10:00 AM
Head at Upstream End:	26"
Head at Downstream End:	4.5"
Total Head:	21.5"

Location of Pipe	Time	Time Increment
Bar #1	10:26	-
Bar #2	10:57	31
Bar #3	11:35	38
Bar #4	-	-
Bar #5	-	-
Upstream Weir	-	-

Comments:

1. The vacuum process was not performed.
2. Density of sample: 112.0 pcf
3. Piping occurred when the head was raised to 21.5", and a self-healing phenomenon happened a few minutes later.
4. After the piping reached bar #3, the piping stopped even when tapping the plexiglass top and raising the head.
5. The test terminated when the head was raised to about 62".

HYDRAULIC PIPING TEST DATA SHEET

Test # :	14 (gap II sand)
Date:	9-16-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	18"
Percent Pipe Penetration:	30
Initial Pipe Diameter:	1/4"
Time at Start of Test:	9:30 AM
Head at Upstream End:	-
Head at Downstream End:	-
Total Head:	-

Location of Pipe	Time	Time Increment
Bar #1	-	
Bar #2	-	
Bar #3	-	
Bar #4	-	
Bar #5	-	
Upstream Weir	-	

Comments:

1. The vacuum process was not performed.
2. Density of sample: 113.0 pcf
3. When the head was gradually applied, some air bubbles moved but no piping happened.
4. When the head was raised to 15.5", still nothing happened. By increasing the size of the initial pipe, piping occurred. But the sand appeared to be self-healing, and the piping eventually stopped.
5. At a head of 57.5", piping woild occur by tapping the plexiglass top, but self-healing woild result downstream causing the pipe to stop. The test was terminated at this time.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	15 (gap II sand)
Date:	9-25-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	27"
Percent Pipe Penetration:	45
Initial Pipe Diameter:	7/16"
Time at Start of Test:	9:20 AM
Head at Upstream End:	-
Head at Downstream End:	-
Total Head:	-

Location of Pipe	Time	Time Increment
Bar #1	-	
Bar #2	-	
Bar #3	10:09	
Bar #4	-	
Bar #5	-	
Upstream Weir	-	

Comments:

1. The vacuum process was not performed.
2. Density of sample: 114.0 pcf
3. At beginning of teat, it was discovered that the dowel could not be removed, hence, the bladder pressure was decreased in order to remove the dowel. The bladder pressure was then increased to 5 psi.
4. After the head was gradually applied, only the fine sand moved in the initial pipe by tapping the plexiglass top. But movement soon stopped because of self-healing of the sand.
5. After the piping reached bar #3, it could not move upstream even though the head was raised to 57.5". The test terminated at this time.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	16 (Filter I)
Date:	10-7-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	4.5", 2.25", 2.25"
Percent Pipe Penetration:	15
Initial Pipe Diameter:	1/4"
Time at Start of Test:	9:40 AM
Head at Upstream End:	-
Head at Downstream End:	-
Total Head:	-

Location of Pipe	Time	Time Increment
Bar #1	-	
Bar #2	-	
Bar #3	-	
Bar #4	-	
Bar #5	-	
Upstream Weir	-	

Comments:

1. The base soil was Reid Bedford sand.
2. Density of base soil: 94.85 pcf
3. Two thickness, o.75" and 1.25",were tested in this test.
4. Piping occurred at downstream end.
5. Nothing happened at the upstream side of the filters.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	17 (Filter I)
Date:	10-16-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	15", 7.5", 7.5"
Percent Pipe Penetration:	50
Initial Pipe Diameter:	1/4"
Time at Start of Test:	9:15 AM
Head at Upstream End:	-
Head at Downstream End:	-
Total Head:	-

Location of Pipe	Time	Time Increment
Bar #1	-	
Bar #2	-	
Bar #3	-	
Bar #4	-	
Bar #5	-	
Upstream Weir	-	

Comments:

1. Base soil: Reid Bedford sand
2. Density of base soil: 91.73 pcf
3. Two thickness, 1.25" and 1.0", were tested.
4. Piping occurred at downstream end.
5. The filters worked well until the sand which supported the filters at the downstream side was eroded.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	18 (Filter II)
Date:	10-28-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	15", 7.5", 7.5"
Percent Pipe Penetration:	50
Initial Pipe Diameter:	1/4"
Time at Start of Test:	9:00 AM
Head at Upstream End:	-
Head at Downstream End:	-
Total Head:	-

Location of Pipe	Time	Time Increment
Bar #1	-	
Bar #2	-	
Bar #3	-	
Bar #4	-	
Bar #5	-	
Upstream Weir	-	

Comments:

1. Base soil: Reid Bedford sand
2. Density of base soil: 94.8 pcf
3. Two thickness, 0.75" and 1.0", were tested.
4. Piping occurred at downstream end.
5. The filters worked well.

HYDRAULIC PIPING TEST DATA SHEET

Test # :	19 (Filter III)
Date:	11-6-85
Bladder Pressure:	5 psi
Length of Pipe Penetration:	15", 7.5", 7.5"
Percent Pipe Penetration:	50
Initial Pipe Diameter:	1/4"
Time at Start of Test:	9:30 AM
Head at Upstream End:	-
Head at Downstream End:	-
Total Head:	-

Location of Pipe	Time	Time Increment
Bar #1	-	
Bar #2	-	
Bar #3	-	
Bar #4	-	
Bar #5	-	
Upstream Weir	-	

Comments:

1. Base soil: Reid Bedford sand
2. Density of base soil: 95.7 pcf
3. Two thickness, 0.75" and 1.0", were tested.
4. Piping occurred at downstream end.
5. When the piping reached the first filter, piping behind the first filter began. The sand was carried through the first filter.
6. Piping happened upstream of the filter after the piping reached the second filter. The second filter also failed to hold the sand behind the filter.

TEST 1

DATE: 7 - 13 - 87

FILTER MATERIAL: 8/30

FILTER THICKNESS: 3 inches

BLADDER PRESSURE: 5 psi

FILTER LOCATION: 36 inches from downstream reservoir

LENGTH OF PIPE PENETRATION: 12 inches

PERCENT PIPE PENETRATION: 33%

INITIAL PIPE DIAMETER: ½ inch

LENGTH OF UPSTREAM PIPE: 14.5 inches

INITIAL PIPE DIAMETER: 3/8 inch

PERMEABILITY:

H_1 18.5 cm
H_2 13.4 cm] 114.3 cm apart
t 8:01.43 minutes
V 1061.2 cm^3
A 929.03 cm^2
k 0.05317 cm/s

DENSITY:

mass of tare: 23.68 g
mass of tare + soil: 242.55 g
mass of soil: 218.87 g
volume: 131.87 cm^3
density: 1.660 g/cm^3

TIME AT START OF TEST: 10:03 am

LOCATION OF PIPE	H_1 —21"—	H_2 —15"—	H_3 —15"—	H_4
initial - 30 cm	32.5 cm	25.9 cm	21.3 cm	15.9 cm
50 cm	43.2 cm	33.5 cm	27.1 cm	18.4 cm
head increase stopped				
70 cm	48.2 cm	37.3 cm	29.3 cm	19.7 cm
pipe reached filter	52.2 cm	39.7 cm	31.2 cm	20.8 cm
head increase resumed				
channel erosion	81.1 cm	59.4 cm	46.3 cm	27.5 cm

NOTES:

1) Upstream piping began at the same time as the downstream piping. The pipe clogged itself as the transported material was stopped by the filter.
2) At a gradient of 0.70 across the filter channels cut through the deposited material downstream.
3) The downstream pipes breach the filter at a gradient of 0.940.
4) This filter material functioned as a filter but was erodable and, therefore, unsuccessful in stopping pipe progression.

TEST 2

DATE: 7-16-87

FILTER MATERIAL: 8/20

FILTER THICKNESS: 3 inches

BLADDER PRESSURE: 7 psi

FILTER LOCATION: 36 inches from the downstream reservoir

LENGTH OF PIPE PENETRATION: 12.5 inches

PERCENT PIPE PENETRATION: 34%

INITIAL PIPE DIAMETER: ½ inch

LENGTH OF UPSTREAM PIPE: 14 inches

INITIAL PIPE DIAMETER: 3/8 inch

PERMEABILITY:

H_1 19.7 cm] 114.3 cm apart
H_2 13.3 cm
t 13:47.06 min
V 1257.3 cm^3
A 929.03 cm^2
k 0.02922 cm/s

DENSITY:

mass of tare: 20.80 g
mass of tare + soil: 190.85 g
mass of soil: 170.05 g
volume: 105.77 cm^3
density: 1.608 g/cm^3

TIME AT START OF TEST: 10:08 am

LOCATION OF PIPE	H_1 —21"—	H_2 —15"—	H_3 —15"—	H_4
initial 30 cm	23.8 cm	20.5 cm	17.5 cm	13.8 cm
upstream piping	32.6 cm	26 cm	22.3 cm	15.8 cm
50 cm	54 cm	40.2 cm	31.9 cm	20.3 cm
pipe reached filter	54 cm	39.7 cm	31.0 cm	20.4 cm

NOTES:

1) A higher bladder pressure was used to ensure full contact between the lid and the sand.
2) Air bubbles slowed the progression of the downstream pipes.
3) The 8/20 material functioned as a filter and did not fail at gradients as high as 1.45.
4) The filter was successful. Therefore, no need to test the 6 and 12 inch thicknesses of this material.

TEST 3

DATE: 7-21-87

FILTER MATERIAL: 8/30

FILTER THICKNESS: 12 inches

BLADDER PRESSURE: 5 psi

FILTER LOCATION: 36 inches from the downstream slope

LENGTH OF PIPE PENETRATION: 12 inches

PERCENT PIPE PENETRATION: 33%

INITIAL PIPE DIAMETER: ½ inch

LENGTH OF UPSTREAM PIPE: 6.5 inches

INITIAL PIPE DIAMETER: ½ inch

PERMEABILITY:

H_1 22.9 cm] 114.3 cm apart
H_2 15.3 cm
t 5:01.65 min
V 1244.7 cm^3
A 929.03 cm^2
k 0.0668 cm/s

DENSITY:

mass of tare: 20.79 g
mass of tare + soil: 187.71 g
mass of soil: 166.92 g
volume: 105.77 cm^3
density: 1.578 g/cm^3

TIME AT START OF TEST: 10:01 am

LOCATION OF PIPE	H_1 --21"--	H_2 --15"--	H_3 --15"--	H_4
initial - 34 cm	38 cm	27.6 cm	26.5 cm	18.9 cm
upstream piping	44.3 cm	31.5 cm	29.9 cm	20.0 cm
70 cm	53.5 cm	37.0 cm	33.6 cm	22.4 cm
head increase stopped				
pipe reached filter	53.6 cm	37 cm	33.5 cm	23.4 cm
head increase resumed				
sheet flow	63.4 cm	41.2 cm	19.4 cm	15.4 cm

NOTES:

1) Bladder pressure was increased to 7 psi as sheet flow began to slow filter erosion.
2) The fines of the filter were easily washed away by the downstream pipes. The filter piped similarly to the 3 inch filter of this material.
3) The gradient across the filter at failure of the filter was 0.265.
4) The filter functioned as a filter of the upstream material, but was erodable.

TEST 4

DATE: 7-24-87

FILTER MATERIAL: gravel

FILTER THICKNESS: 6 inches

BLADDER PRESSURE: 7 psi

FILTER LOCATION: 36 inches from the downstream reservoir

LENGTH OF PIPE PENETRATION: 12 inches

PERCENT PIPE PENETRATION: 33%

INITIAL PIPE DIAMETER: ½ inch

LENGTH OF UPSTREAM PIPE: 11 inches

INITIAL PIPE DIAMETER: 3/8 inch

PERMEABILITY:
H_1 24.0 cm] 114.3 cm apart
H_2 14.9 cm
t 6:03.77 min
V 1168.9 cm^3
A 929.03 cm^2
k 0.0434 cm/s

DENSITY:
mass of tare: 20.8 g
mass of tare + soil: 188.5 g
mass of soil: 167.7 g
volume: 105.77 cm^3
density: 1.585 g/cm^3

TIME AT START OF TEST: 9:32 am

LOCATION OF PIPE	H_1 —21"—	H_2 —15"—	H_3 —15"—	H_4
initial - 30 cm	21.7 cm	18 cm	14.7 cm	13.3 cm
upstream piping	28.0 cm	22.2 cm	17.6 cm	15.1 cm
50 cm	54.1 cm	40.3 cm	32.6 cm	22.9 cm
head increase stopped				
bladder relaxed to 6 psi				
pipe reached filter	54 cm	38.2 cm	32.1 cm	21.9 cm
head increase resumed to failure				

NOTES:

1) This material would function better as a drain than a filter.
2) High bladder pressure caused pipe clogging.
3) Upstream material migrates through half of the filter throughout the depth.
4) No filter piping. The filter clogs with sand because the velocity through the filter was not high enough to carry the upstream material through the width of the filter. Thus, the material was deposited into the filter.

TEST 5

DATE: 7-28-87

FILTER MATERIAL: gravel

FILTER THICKNESS: 3 inches

BLADDER PRESSURE: 5 psi

FILTER LOCATION: 49 inches from the downstream reservoir

LENGTH OF PIPE PENETRATION: 13 inches

PERCENT PIPE PENETRATION: 26%

INITIAL PIPE DIAMETER: ½ inch

LENGTH OF UPSTREAM PIPE: None

INITIAL PIPE DIAMETER: N/A

PERMEABILITY:

H_1 25.2 cm] 114.3 cm apart
H_2 15.5 cm
t 8:43.15 min
V 2065.6 cm^3
A 929.03 cm^2
k 0.0501 cm/s

DENSITY:

mass of tare: 23.6 g
mass of tare + soil: 230.45 g
mass of soil: 206.45 g
volume: 131.87 cm^3
density: 1.568 g/cm^3

TIME AT START OF TEST: 9:30 am

LOCATION OF PIPE	H_1 --21"--	H_2 --15"--	H_3 --15"--	H_4
initial - 30 cm	36.2 cm	32.2 cm	25.5 cm	18.6 cm
50 cm	48 cm	42.2 cm	31.5 cm	20.4 cm
head increase stopped				
80 cm	52 cm	46.9 cm	34.7 cm	22.6 cm
head increase resumed				
pipe reached filter	65 cm	23.8 cm	16.7 cm	

NOTES:

1) The head falls as the pipes reach the filter because the water and upstream material is flowing freely through the filter.
2) The upstream material flows into the filter, and the filter fails by complete migration of the upstream material through the filter.

TEST 6

DATE: 7-31-87

FILTER MATERIAL: gravel - 8/30

FILTER THICKNESS: 3 inches - 3 inches

BLADDER PRESSURE: 5 psi

FILTER LOCATION: 36 inches from the downstream reservoir

LENGTH OF PIPE PENETRATION: 12 inches

PERCENT PIPE PENETRATION: 33%

INITIAL PIPE DIAMETER: ½ inch

LENGTH OF UPSTREAM PIPE: 14 inches

INITIAL PIPE DIAMETER: 3/8 inch

PERMEABILITY:
H_1 26.4 cm] 114.3 cm apart
H_2 15.8 cm
t 6:05.53 min
V 1527.7 cm^3
A 929.03 cm^2
k 0.0485 cm/s

DENSITY:
mass of tare:
mass of tare + soil:
mass of soil:
volume:
density:

TIME AT START OF TEST: 1:30 pm

LOCATION OF PIPE	H_1	--21"-- H_2	--15"-- H_3	--15"-- H_4
initial - 30 cm	25.6 cm	21.1 cm	18.9 cm	14.6 cm
upstream piping	35.1 cm	28.0 cm	24.1 cm	17.6 cm
50 cm	53.2 cm	40.5 cm	33.8 cm	22.6 cm
head increase stopped				
pipe reached filter	53.6 cm	40.5 cm	34.3 cm	24.2 cm
head increase resumed				
channel cutting	72.1 cm	33.7 cm	18.0 cm	15.0 cm

NOTES:

1) The 8/30 material stops the migration of the upstream material to the downstream slope.
2) Slight migration of the 8/30 material into the gravel filter.
3) Even with decreased with decreased bladder pressure and the applied head at its highest point, no failure occurs.
4) The gradient across the filter at failure is 1.42.

TEST 7A

DATE: 8-28-87

FILTER MATERIAL: 8/20 (30/65 base soil)

FILTER THICKNESS: 3 inches

BLADDER PRESSURE: 7 psi

FILTER LOCATION: 36 inches from the downstream reservoir

LENGTH OF PIPE PENETRATION: 12 inches

PERCENT PIPE PENETRATION: 33%

INITIAL PIPE DIAMETER: 3/8 inch

LENGTH OF UPSTREAM PIPE: 14.5 inches

INITIAL PIPE DIAMETER: 3/8 inch

PERMEABILITY:

H_1 29.6 cm] 114.3 cm apart
H_2 17.1 cm
t 1:55.71 min
V 1355.2 cm^3
A 929.03 cm^2
k 0.1153 cm/s

DENSITY:

mass of tare: 20.80 g
mass of tare + soil: 184.67 g
mass of soil: 163.87 g
volume: 105.77 cm^3
density: 1.549 g/cm^3

TIME AT START OF TEST: 10:00 am

LOCATION OF PIPE	H_1 --21"--	H_2 --15"--	H_3 --15"--	H_4
initial - 30 cm	34.6 cm	27.9 cm	23.0 cm	17.0 cm
upstream piping	53.9 cm	41.7 cm	33.0 cm	21.4 cm
50 cm	63.1 cm	47.6 cm	36.6 cm	21.6 cm

head increase stopped
5 cm before filter - bladder pressure lowered to 6 psi and head increased

NOTES:

1) The 30/65 base soil piped uniformly and very straight, progressing quickly. The soil flows very easily and becomes sheet flow before the initial pipe reaches the filter.
2) The bladder pressure was lowered because the pipes were filling before reaching the filter.
3) The filter collapsed due to excessive erosion of the base soil and lack of support.

TEST 7B

DATE: 9-1-87

FILTER MATERIAL: 8/20 (30/65 base soil)

FILTER THICKNESS: 3 inches

BLADDER PRESSURE: 7 psi

FILTER LOCATION: 21 inches from the downstream reservoir

LENGTH OF PIPE PENETRATION: 8 inches

PERCENT PIPE PENETRATION: 38%

INITIAL PIPE DIAMETER: 3/8 inch

LENGTH OF UPSTREAM PIPE: 17 inches

INITIAL PIPE DIAMETER: 3/8 inch

PERMEABILITY:
H_1 19.5 cm] 114.3 cm apart
H_2 13.3 cm
t 2:17.98 min
V 868.7 cm^3
A 929.03 cm^2
k 0.1249 cm/s

DENSITY:
mass of tare: 23.7 g
mass of tare + soil: 229.5 g
mass of soil: 205.8 g
volume: 131.87 cm^3
density: 1.5606 g/cm^3

TIME AT START OF TEST: 9:45 am

LOCATION OF PIPE	H_1 --21"--	H_2 --15"--	H_3 --15"--	H_4
initial - 8 inches	36 cm	29 cm	27.8 cm	17.9 cm
35 cm	59.1 cm	46.2 cm	34.1 cm	24.9 cm
45 cm	63.7 cm	50 cm	36.8 cm	27.2 cm
head increase stopped				
48 cm	63.7 cm	51 cm	36.8 cm	27.1 cm
head increase resumed				

NOTES:

1) Filter failed again as a result of loss of support.
2) The results were identical to that of Test 7a.