SUPPLEMENTAL LABORATORY TESTING TO DEFINE THE CRITICAL EXIT GRADIENT, EXIT GRADIENT, EXIT VELOCITY, AND INCURRED VOLUME CHANGES IN FOUNDATION SANDS - CALAMUS PICK - SLOAN MISSIOURI BASIN PROGRAM - NORTH LOUP DIVISION NEBRASKA

WRITTEN BY:

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Memorandum

Chief, Dams Branch RWK 7/30

Denver, Colorado
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Chief Design Engineer
Chief, Division of Research HJC 7/29/81

Chief, Hydraulics Branch

Supplemental Laboratory Testing to Define the Critical Exit Gradient, Exit Velocity, and Incurred Volume Changes in Foundation Sands - Calamus Dam - Pick-Sloan Missouri Basin Program - North Loup Division, Nebraska (Your Memorandum Dated April 16, 1980)

Written by: Eugene Zeigler and Traver Metcalf

INTRODUCTION

The foundation of Calamus Dam is a complex arrangement of fluvial and aeolian deposited sands. For design purposes, an exit gradient is needed to ensure safety of the foundation from piping and blowout. Current practice is to compute the critical exit gradient from the Harza relationship which was supported by limited laboratory tests (Mockmore and Dougherty, ASCE Transactions, 1935). However, Calamus Dam foundation sands are finer than sands Mockmore and Dougherty tested. Because of the size and importance of Calamus Dam, the Hydraulics Branch was requested to test sand samples received from the field.

Development and performance of the testing program was a cooperative effort by Elbert Esmiol (Dams Branch), Traver Metcalf (Geotechnical Branch), and Eugene Zeigler (Hydraulics Branch). Tests were conducted in a large plastic box located in the hydraulic laboratory (figs. 1 and 2). Water flowed upward through the sand test specimen to produce sand movement (figs. 3 and 4). Purpose of the tests was to define the following items:

1. The point in the test at which the test specimen starts to dilate, i.e., the volume expansion of the test specimen

2. Critical exit gradient, i.e., the point at which the sand begins to pipe

3. The gradient and velocity at which "boiling" ("fluidizing") starts

4. The exit gradient at which boiling or fluidizing is occurring throughout the test specimen

CONCLUSIONS

1. Five tests were performed on two samples of dune sand and pertinent test data are given in table 1. For some portions of the test program, much depended upon judgment of the observer. The test results are correlations of measurable quantitative data with visual qualitative data and varied somewhat from test to test.

2. Volume expansion (or dilation) occurred between hydraulic gradients ranging from 0.48 to 0.82.

3. The critical exit gradient (the point where sands begin to pipe) ranged from 0.59 to 0.88. The criterion of incipient piping was the first detection of small boils on the sand surface where piping purged sand from the specimen (small mounds shown in fig. 3a).

4. The gradient at which fluidization began was not clearly definable.

5. Almost complete fluidization of the sand specimen occurred in tests 1 and 2 at 0.88 and 0.85 hydraulic gradients. Complete fluidization was believed an excessive mode of failure, and was not performed for tests 3 through 5.

6. After performing five tests, the crux of the problem was defining failure of the sand specimen. Volume expansion, cracking, boiling, and piping of the sand sample can be considered failures and occurred at hydraulic gradients less than the Harza relationship or theoretical "flotation gradient."

7. These tests are considered preliminary research. Sand failure phenomena were detected at lower hydraulic gradients than anticipated. Much remains to be learned from and about performing tests of this nature, and the Bureau should consider this type of testing for future research.

8. Because of the preliminary nature of these tests, judgment should be used in applying the test results.

SAND SAMPLES

Three sand samples were received from the field for testing. Each sample was to be placed and tested at relative dry densities of approximately 30, 50, and 70 percent. However, because two of the samples were similar, one was discarded from the program. Also, as the testing progressed, it appeared that testing a sample at approximately 30 and 70 percent RD (relative density) would provide sufficient test data.

The two sand samples that were tested had the following properties:

Sample No.	Classification	Specific gravity	Minimum RD	Maximum RD
57U-279	SP-SM	2.65	89.4	114.8
57U-281	SM	2.63	87.5	121.4

These results are shown on figures 5 and 6.

TEST APPARATUS

The test apparatus (plastic box and water system) was available from a previous filter study. Sand was placed on a gravel filter in the box, figure 1a. The plastic box was 0.30 by 0.61 by 1.83 m (1 by 2 by 6 ft); the sand test specimen was 0.3 m deep with a 0.19 m^2 (2 ft^2) flow area; and filter dimensions are given on figure 2. Uniform flow distribution was provided to and from the sand test specimen by the bottom plate which has a grid of thirty-six 6.4-mm (1/4-in) diameter holes. Piezometer ports, which were connected to water manometers (scale = 0.01 ft), were located on the face of the test box as shown on figures 1b and 2. A 25-mm (1-in) diameter piece of No. 200 standard sieve size screen covered the inside of the piezometer ports to prevent excessive movement of fine sand into the piezometers.

The water system was self contained whereby water was pumped to the plastic box and returned to the storage box. Waterflow was controlled by valves and the water could be directed either upward or downward through the sand specimen. Difficulty was encountered during testing in making minute adjustments to flow discharges passing through the sand specimen. In the previous study, the test apparatus operated with discharges of 0.25 to 5.68 L/s (4 to 90 gal/min), but these tests had much lower discharges from 0.0025 to 0.014 L/s (0.04 to 0.22 gal/min). Different valves were tried during the tests for better control of the small flow discharges.

TEST PROCEDURE

The tests were not standard, but were for a relatively unmeasured phenomena. Some details of the phenomena were identified as the test program proceeded and some development of test procedure occurred during the study. Tests 4 and 5 had the benefit of the experience gained from tests 1, 2, and 3. The general test procedure was (1) placement of the sand sample, (2) filling with water, (3) downward flow testing, and (4) upward flow testing.

Placement of the sand sample. - The sand was passed through a No. 18 screen to break any lumps and placed in layers in a plastic box. Four layers were placed for test 1 and eight layers for tests 2 through 5. A given layer was tamped if required to obtain the desired dry density. Some stratification of the sand was evident at the sides of the plastic box;

figure 1b. Metric scales were placed at three points on the box so volume expansion or contraction of the sand specimen could be measured. Also small tape strips were used to help record volume changes of the sand specimen, figures 3b and 4a.

Filling with water. - Water was introduced into the bottom of the box so that the wetted front moved upward very slowly (fig. 1b). The objective was to drive air from the sand and saturate the sand specimen. However, water also moved upward by capillary action and minute air bubbles were entrapped in the sand grain interstices. The sand specimen was not completely saturated. For test 1 the rate of inflow was evidently too fast as some small (hairline) horizontal cracks were observed, indicating fracturing of the sand specimen by the upward flowing water. The inflow valve was turned off, the cracks gradually sealed, and inflow was resumed at a slower rate. A better filling technique was developed. When the water level reached piezometer tap No. 1 (fig. 2), inflow was stopped and the manometer purged of air. Inflow was resumed and observations made of the elevation difference between the water level in manometer No. 1 as compared to elevation of the wetting front in the test specimen. If the difference exceeded from 0.15 to 0.23 m (0.5 to 0.75 ft), inflow was reduced to lower pressure acting on the bottom of the test specimen.

Downward flow testing. - The sand specimens were first subjected to seepage (with the exception of test 3) or water flowing downward through the specimen. Initially the objective was to obtain some measure of the sand specimen permeability. As the test program progressed, downward flow proved beneficial in removing minute air bubbles from the sand specimen. The air bubbles were removed by a leaching process whereby air was dissolved into the flowing water. Downward flow testing was the most extensive for tests 4 and 5.

Upward flow testing. - The sand specimens were subjected to water flowing upward through the specimen. For a given test a low discharge was initially established, and discharges increased until failure of the sand specimen occurred.

TEST DATA

Data collected during the tests were:

1. Manometer readings for the different flow discharges of the downward and upward flow tests.

2. Discharge measurements of flow passing through the sand specimen. Discharge was computed from the volume of water collected in a graduated cylinder during a timed interval.

3. Notes of visual observations were recorded for the tests (Appendix 1 - Test Notes). The notes include volume changes of the sand specimens, and events of fractures, boils, pipes, and fluidizing that occurred.

4. Numerous 35-mm color slides were taken by Elbert Esmiol (figs. 1, 3, and 4 were selected from his slides).

5. Video tape documentation of tests 3, 4, and 5 was done by James Nasi of the Public Affairs Service Center.

THE TESTS

Summary of Test Results

Pertinent results of the five tests are given in table 1. These results are from the first sequence of upward flow tests made for the sand specimens. More extensive data are presented in head loss versus velocity graphs (figs. 7, 8, 9, 10, and 12). Following is a description for each of the five tests performed.

Test 1

Sand was placed in the box with an initial 0.3-m (1-ft) depth and 1505-kg/m^3 (94-lb/ft^3) density. During filling, the test specimen settled slightly; this was probably caused by the surface tension of the water in the capillary fringe zone. Additional settlement occurred after the water level was above the sand specimen when the specimen was allowed to stabilize 1 day before testing. Total settlement of the sand specimen was approximately 15 mm (0.05 ft), thus the dry density of the sand specimen had changed to approximately 1585 kg/m^3 (99 lb/ft^3).

Initially downward flow tests were made to measure sand specimen permeability before proceeding to the upward flow testing and failure of the sand specimen. Discharge measurements were made and manometer readings taken. These data are shown on figure 7. Velocity is discharge divided by 0.19-m^2 (2-ft^2) flow area, and head loss is that for flow across the 0.30-m (1-ft) deep sand specimen and was the difference between the Nos. 3 and 7 manometer readings.

Data points for the July 30 upward flow (fig. 7) are numbered consecutively in order of the individual discharges passed through the sand test specimen. The first activity for the sand specimen was noticed at data point 4. Wisps of slightly turbid water exited from the sand and later developed into small boils of less than 10-mm (1/2-in) diameter. These sand boils were smaller than shown on figure 3, and had very infrequent sand grain movement. Depth of the sand sample increased about 1 mm (0.04 in) in one corner of the box. The discharge was reduced (data points 5 and 6), and sand movement on the boils stopped; with an increased discharge (data point 7), the sand boils became active again. More consistent sand grain movement occurred for data point 8 and a 1-mm (0.04-in) bulking occurred over the entire sand specimen.

Table 1. - Summary of test results

Test No.	Sample No.	Depth mm (ft)	Dry density kg/cm³	(lb/ft³)	Relative density percent	Porosity	Permeability 1/ k x 10^{-4} m/s (ft/s)	Start of dilation h mm (ft)	i 2/	Start of piping h mm (ft)	i 2/	Theoretical flotation HFc mm (ft)	i
1	-279 (SP-SM)	290 (0.95)	1586	(99)	44	40	2.10 (6.89)	238 (0.78)	0.82	238 (0.78)	0.82	287 (0.94)	0.99
2	-279 (SP-SM)	305 (1.00)	1698	(106)	70	36	1.25 (4.10)	210 (0.69)	0.69	244 (0.80)	0.80	323 (1.06)	1.06
3	-279 (SP-SM)	298 (0.98)	1538	(96)	30	42	1.36 (4.46)	143 (0.47)	0.48	-	-	287 (0.94)	0.96
4	-281 (SM)	315 (1.03)	1682	(105)	60	36	0.35 (1.16)	158 (0.52)	0.52	268 (0.88)	0.88	323 (1.06)	1.06
5	-281 (SM)	293 (0.96)	1570	(98)	39	41	0.65 (2.13)	174 (0.57)	0.59	174 (0.57)	0.59	283 (0.93)	0.97

1/ Permeability calculated from data taken from velocity head loss graph and adjusted for depth.

2/ h - head loss between manometers No. 3 and 7.
i - hydraulic gradient for specimen depth between manometers No. 3 and 7.

For data point 9, somewhat catastrophic results occurred to the sand specimen. A horizontal crack formed, worked upward toward the surface, contacted the surface, and formed a violent sand boil. Bulking of the sand specimen was about 15 mm (0.6 in), and the water became very turbid with fines flushed from the sand specimen. Some fluidization of the sand was observed at the face of the box. For data point 10 fluidization increased, and for data point 11 (off the graph) the entire sand specimen appeared fluidized. Conditions for data point 11 were 5.7×10^{-4} m/s (18.7×10^{-4} ft/s) velocity, 0.27 m (0.88 ft) head loss, and 35 mm (1.4 in) bulking. When the discharge was shut off, the sand settled. The sand specimen depth was 300 mm (0.99 ft) or 12 mm (0.04 ft) higher than before the test.

Dry density of the sand specimen had changed to 1520-kg/m^3 (95-lb/ft^3) density, which was close to the desired 1505-kg/m^3 (94-lb/ft^3) density. Therefore, a second upward flow test was made July 31 (fig. 7). For data point 6, a small crack was noticed near the bottom of the specimen. With the next increase of discharge (data point 7), a large sand boil started working upward, and broke out on the surface. Boiling was more extensive for data point 8, and for data point 9 (off the graph) considerable fluidization occurred. Conditions for data point 9 were 6.7×10^{-4} m/s (21.9×10^{-4} ft/s) velocity, 0.26 m (0.85 ft) head loss, depth of the sand specimen was 340 mm (1.12 ft), and the upward flow operated 1 hour. Velocity was sufficient to fluidize some sand from the upper filter layer. After stopping the flow, segregation of the sand specimen was observed through the plastic sides. The largest sand particles were at the bottom and the smallest particles at the top.

Shapes of the July 30 and 31 data curves show extensive failure of the sand specimen. When the curves become horizontal, a failure gradient had been exceeded, and upward flow had destroyed structural integrity of the sand specimen. Bulking of the sand specimen had occurred to such an extent that sand grains were not rigidly interlocked, but were partially in suspension. A subsequent appreciable discharge increase produced a slightly greater separation of the sand grains allowing water to readily flow through without an increase of head loss. For practical purposes, failure of the test specimen occurred before complete fluidization, thus flow discharge would be limited for subsequent tests.

Test 2

Sand was placed at a dry density of 1698 kg/m^3 (106 lb/ft^3). The sand specimen did not settle when filling with water. Data of the flow tests are shown in figure 8. At data point 7, the sand specimen expanded 1 or 2 mm (0.04 to 0.08 in) and a small horizontal fracture was noticed. At data point 8, the first small boil was observed on the sand surface and boil activity increased for data points 9 and 10. Dilation was 4 mm (0.16 in) for data point 10. The deviation of data points 9 and 10 from the straight line of the previous points show flow resistance of the specimen has changed, suggesting that dilation and boils have started failure of the specimen. For data point 11, considerable failure activity occurred. Numerous fracture cracks formed, some at levels of the 38-mm (1-1/2-in) lifts. A large horizontal crack formed 75 mm (3 in) above the bottom of the sample. With the next discharge increase (data point 12), the crack increased in extent and vertical opening. The opening was 10 to 20 mm (1/2 to 3/4 in), and below the crack fluidization of the specimen occurred. The crack moved upward through the specimen until breaking out on the surface with a large boil. More fluidization of the sample occurred at data point 13, and the entire sand specimen appeared fluidized for data point 14 (off the graph). Conditions for data point 14 were 5.61×10^{-4} m/s (18.4×10^{-4} ft/s) velocity, 0.26 m (0.85 ft) head loss, and depth of the sand specimen was 365 mm (1.2 ft).

Test 3

Sand was placed at a dry density of 1505 kg/m^3 (94 lb/ft^3) and during filling the sand specimen settled 7 mm (0.02 ft). Numerous small air bubbles were present throughout the specimen, more than for any other test. Only upward flow tests were made, figure 9. Initial dilation of 1 mm (0.04 in) was noted at data point 2. The dilation increased to 3 mm (0.01 ft) at data point 4, and possible formation of small horizontal hairline cracks was noted. Some cracks appeared as a stratum of excessive air bubbles. The first indication of fines purging from the specimen was noticed at data point 9 and the dilation was 5 mm (0.02 ft). The dilation increased to 10 mm (0.03 ft) for data point 10 and 35 mm (0.11 ft) for data point 11. Only for data point 11 did noticeable sand movement occur at the sides of the plastic box. Cracks formed slanting upward. Sand boiled and fluidized beneath a crack and moved numerous small bubbles upward to the crack. The collection of bubbles worked gradually up the slant and spewed from the sand surface.

Test 3 was a repeat of test 1 for the purpose of obtaining data closer to failure. Data points 9 and 10 (fig. 9) deviate from the straight line, suggesting failure may be somewhat gradual and not an abrupt phenomenon. Test specimen reaction was different than in the previous two tests, small non-violent-type boils were not as prevalent on the sand surface. Permeabilities were different for specimens 1 and 3. Even adjusting for temperature difference between 19 and 24 °C (66 and 75 °F), the permeability of specimen 3 was considerably less than specimen 1. The entrapped air bubbles were believed to hinder waterflow and it was decided future tests should have air removed from the test specimen.

Test 4

Sand was to be placed at 70 percent RD 1738 kg/m^3 (108.5 lb/ft^3). Even with considerable tamping, the desired density was not obtained. After filling with water, the test specimen was 315 mm (1.03 ft) deep, resulting in a 1682-kg/m^3 (105-lb/ft^3) dry density. Numerous minute air bubbles were present throughout the specimen.

Downward flow was directed through the test specimen for 5 days to remove the air bubbles. The air bubbles could not be removed by flow velocities but instead were removed by a leaching process whereby air was dissolved into the flowing water. The top one-third of the specimen was cleared during the second day and the middle one-third the third day. Also on the third day, a considerable amount of air was observed to have moved downward into the filter beneath the specimen. The air had increased to such an extent that instead of individual air bubbles, air interconnected interstices of the gravel particles. Some air in the gravel filter was removed by draining a water-air mixture through piezometer tap No. 2. At the end of the fifth day, no air bubbles were observed in the test specimen and very few in the filter. Discharge and head loss data were taken during the leaching process and permeabilities computed for the sand specimen between piezometer taps (fig. 11). As air was removed from the successive quarter layers, permeability stabilized across the specimen.

Data from the upward flow tests are shown on figure 10. For the November 7 test the first dilation was noted at data point 3. Boils and fractures developed at data point 6. Pronounced failure of the specimen occurred progressively for data points 8, 9, and 10. Immediately after the November 7 upward flow test the specimen was operated with downward flows. The seepage discharge was progressively increased until 2.4 m (8 ft) head loss occurred across the specimen. During seepage, the fractures closed. Another upward flow test was made November 10 with results similar to the November 7 test.

Test 5

Sand was placed at a dry density of 1505 kg/m^3 (94 lb/ft^3), and during filling the sand specimen settled 5 mm (0.02 ft). The specimen operated with downward flow for 7 days, and an additional 7 mm (0.02 ft) settlement occurred. Permeability of the specimen, between piezometer taps, is shown in figure 13.

Data from the upward flow tests are shown on figure 12. For the December 10 test and at data point 4, an approximate 1-mm (0.04-in) dilation appeared in the middle of the specimen. At data point 5, 1-mm (0.04-in) dilation occurred at the sides of the plastic box with greater dilation, or doming, in the middle of the sample. The dilation of the specimen appeared inhibited by friction from the sides. Cracks and boils occurred at data point 5 and progressively increased for the later data points. Another test was made December 12, and close scrutiny detected slight sand movement on some boils left from the earlier test. By turning the inflow valve down in increments, the boiling stopped at data point 6. The inflow valve was turned off, and back on in increments until boiling occurred again (December 12, second run). Thus after partial failure of the test specimen (December 10), boiling occurred at a lower hydraulic gradient (December 12).

FLUIDIZATION

The test program was patterned from tests described by C. A. Mockmore and John W. Dougherty in Volume 100, page 1396, Transactions of the ASCE, 1935. Data of their tests indicated that considerable fluidization of the sand specimen had occurred. Thus it was thought that the specimens in this test program should be subjected to extreme fluidization.

Their tests were made in an effort to verify an equation defining the "flotation gradient." The "flotation gradient" being where the hydraulic gradient in the sand is great enough to make the sand unstable, and was likened to quicksand, sand boils, and piping. The equation is

$$F_c = \frac{\Delta h}{\Delta l} = (1-n)(s-1)$$

where Δl = length of the sand specimen
Δh = head loss for the length
n = porosity of the sand
s = specific gravity of the sand

The basis for this equation was that head loss caused by flowing water can create enough force to lift the unrestrained sand. A theoretical illustration of the "flotation gradient" is given in figure 14.

A "flotation gradient" was computed for each test specimen using the formula. Also computed was a corresponding "flotation gradient" head loss between piezometers No. 3 and 7 for each specimen. Both computed values for each specimen are given in table 1 and head loss (HFc) marked on figures 7 through 12. Data of tests 1 through 5 are close to the HFc values; however, as the test program progressed, it appeared some failure of the sand specimen occurred before fluidization of the test specimen. Also for tests 1 and 2 the hydraulic gradient with considerable fluidization was slightly less than what the test specimen sustained prior to fluidization. Thus full fluidization of the sand test specimen was dropped as an objective of the test program.

Another difficulty was making a sharp distinction about fluidization. For example, when does a sand boil become fluidization? In an earlier filter study made in the plastic test box, fluidization implied a very complete movement of all sand grains. Fluidization was a process where all the sand grains were placed in agitated suspension and upward flowing water cleaned fine sediment from the filter. Thus fluidization or fluidizing may not be an appropriate phenomenon when looking for incipient failure of the sand test specimen.

MODES OF SAND MOVEMENT

For most tests, sand boils formed on the surface of the test specimen. The appearance of the boils could vary depending upon the magnitude of the upward flow. At times, the first detection of the sand boils required close, attentive observation, and only observers with keen eyesight could see movement of the fine sand grains. Over a period of time, a very small mound deposited on the sand surface as find sand grains were purged from the specimen (fig.3a). Other times, the boils would become inactive or if the boil did continue, the deposit could increase in size (fig. 3a, large mound). A crater would exist in the boil and have the predominant sand grain movement. Sometimes the crater grains appeared somewhat larger, almost in a state of suspension, but offering too great a resistance to be purged away from the crater. If upward waterflow was great enough, a very definite boiling bubble of sand occurred (fig. 3b). At other times, the boil would be larger and more violent, but this was much less frequent and extensive failure of the sand test specimen had occurred.

Sometimes the boils formed immediately against plastic sides of the box, and piping action beneath the boil could be observed. A pipe with volcanic-like upward movement of sand grains toward the surface occurred. This type of piping action was deceiving because one would expect sand grain removal to create a void; instead, a suspension-type movement of larger-size sand grains occurred where the grains could not be completely purged from the pipe. However, a general upward passage of smaller-size sand grains occurred along the pipe. In other instances, the pipe could be a void (fig. 4b). A high-velocity waterflow occurred in the pipe and occasional sand grains were flushed through the pipe. In this instance (fig. 4b), flow was from left to right. In the dark area on the right end, the pipe turned into the specimen and probably upward, and was believed the cause of the boil shown in the corner of figure 3b.

Various types of fractures and cracks occurred in test specimens; some fractures were on the lift lines. Generally, the first detection of a fracture for a test was a hairline crack, similar to the left end of the fracture, shown on figure 4a. Another hairline fracture is shown on figure 4b, just below the left end of the pipe. With increased discharge of upward flow, the crack would widen or in the instance of figure 4b, a pipe formed. In some cases, the crack width was 5 to 10 mm (1/2 in), and the specimen above the crack was being hydraulically lifted. Some portion of the crack could slant upward to the surface and within a short time break out in a sand boil.

Some variation occurred in the tests as to whether fracture cracks or boils were first noticed. Boils were first noticed for one test, cracks were noticed first for two tests, and cracks and boils were noticed at the same time for two tests. The test conditions during which the cracks or boils occurred are shown on figures 7 through 12.

FAILURE OF THE TEST SPECIMEN

Dilation, fracture cracks, sand boils, and fluidization were forms of failure. Fluidization was a very obvious failure; however, cracking and boiling occurred with different intensities. Some argument may exist as to what should be defined as failure of the test specimen, especially when trying to relate laboratory results to a field failure.

One failure definition could be where test data deviate from the straight line relationship (figs. 7 through 12), an indication that flow resistance had been lowered by weakening of the specimen because of dilation, boils, and/or fracture cracks. Another failure definition could be where dilation starts or a given amount of dilation takes place. Incipient dilation of the specimen was very difficult to determine and was a judgment by the observer. A measurable amount of dilation would be easier to determine.

One concern about the tests was how a horizontal crack in the test specimen could change hydraulic flow within the specimen. At lower discharges, the extent of an individual crack was small and, for the most part, water appeared to flow vertically through the crack. However, at increased discharges extent of the crack increased and in a few instances horizontal pipes developed. Once a weakness of flow resistance was found above the crack, failure could rapidly progress. Piping action vented water to the surface and the crack acted like a collection reservoir and funneled waterflow to the pipe.

Possibly the method of performing these tests influenced failure. Would the test specimen fail at a higher or lower gradient if operation was for days instead of minutes? Would a longer operation time allow some fracture cracks to heal themselves or induce failure? In these tests, the upward flow discharge was a constant and the hydraulic gradient a variable. For example, after setting a new and higher discharge, the head loss attained its highest value. Then as boils and cracks developed, the head loss lowered. Possibly a more definitive test would be to load the test specimen with a constant hydraulic head and let the discharge vary. Then possibly, as failure occurred, the discharge would increase and cause more extensive failure.

Although similar testing has been done before (Mockmore and Dougherty, ASCE Transactions, 1935), this type of testing has been limited and the literature does not have reports of similar tests. In addition, volume changes and neutral stresses were not observed. No data are available to provide confidence regarding at what point test failure corresponds to a condition of field failure. The fact that the failure phenomenon did not repeat itself exactly each time and can vary indicates that it does not have an exact value but some range of values. Thus, caution should be used in interpreting test results for the hydraulic gradient that causes incipient instability of the sand foundation. The five tests performed in this series show that extensive research remains to be done.

CRITICAL REVIEW OF THE TEST APPARATUS

The apparatus was designed for different tests with a much higher discharge, but provided the economy of a ready-to-go test facility. Should future tests of this nature be made, this evaluation of the test facility may be useful.

The plastic box with transparent sides was a definite advantage to allow observation of the sand test specimen. The water system should be designed for the discharges that will be needed for the tests. With the high flow system that was available for these tests, a pump bypass line was needed to prevent overheating of the pump motor at small discharges. The bypass flow caused excessive turbulence in the storage box. Particulate matter was believed entrained in the water and caught in the extremely small inflow valve openings causing a slight decrease of inflow discharge over 10- to 30-minute time periods.

Flowmeters would be desirable if they are sufficiently accurate at very small discharges. Accuracy problems occurred at the low test discharges with the volume-time interval method of discharge measurement because of the time required to reach discharge equilibrium. The open system (as water overflowed the box and through a pipe to the storage box) had a time lag before reaching equilibrium. Also, people moving could jiggle the box affecting the flow over the weir at small discharges. A closed-type system would be more responsive and provide accurate discharge measurements.

Water temperature affects viscosity of the water which, in turn, influences head loss of waterflow through the sand. Although not absolutely necessary, better temperature control of the water may be helpful.

A better method of sand placement and control of compaction may be desirable. Air bubbles are inherent when filling the specimen with water. Some investigation is needed to determine when the specimen has stabilized and is representative for the desired test.

A manometer system connected to piezometers in fine sand has a time lag after a pressure change occurs. Some time is required for water to flow from the sand through the small tap and reach the correct level in the manometer. In data of the tests, a few instances occurred where the head loss dropped slightly before the discharge measurement could be made. A pressure transducer with a closed system would have a faster response.

D. L. King

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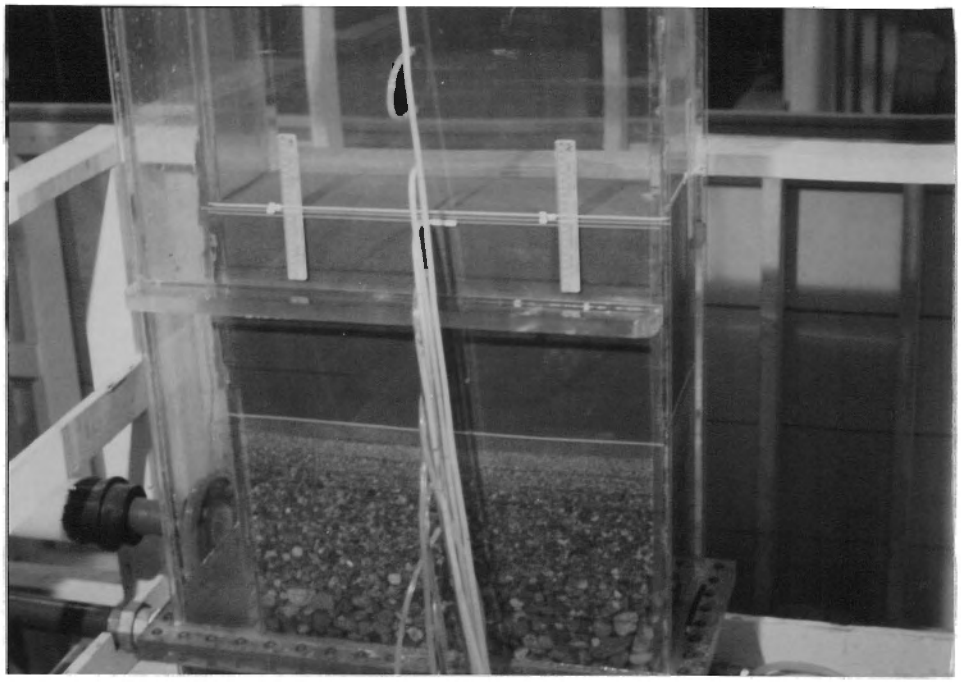


a. Sand test specimen in the plastic box.

b. Filling sand test specimen box with water, note piezometer taps on front face of the plastic box.

Figure 1. - The test apparatus.

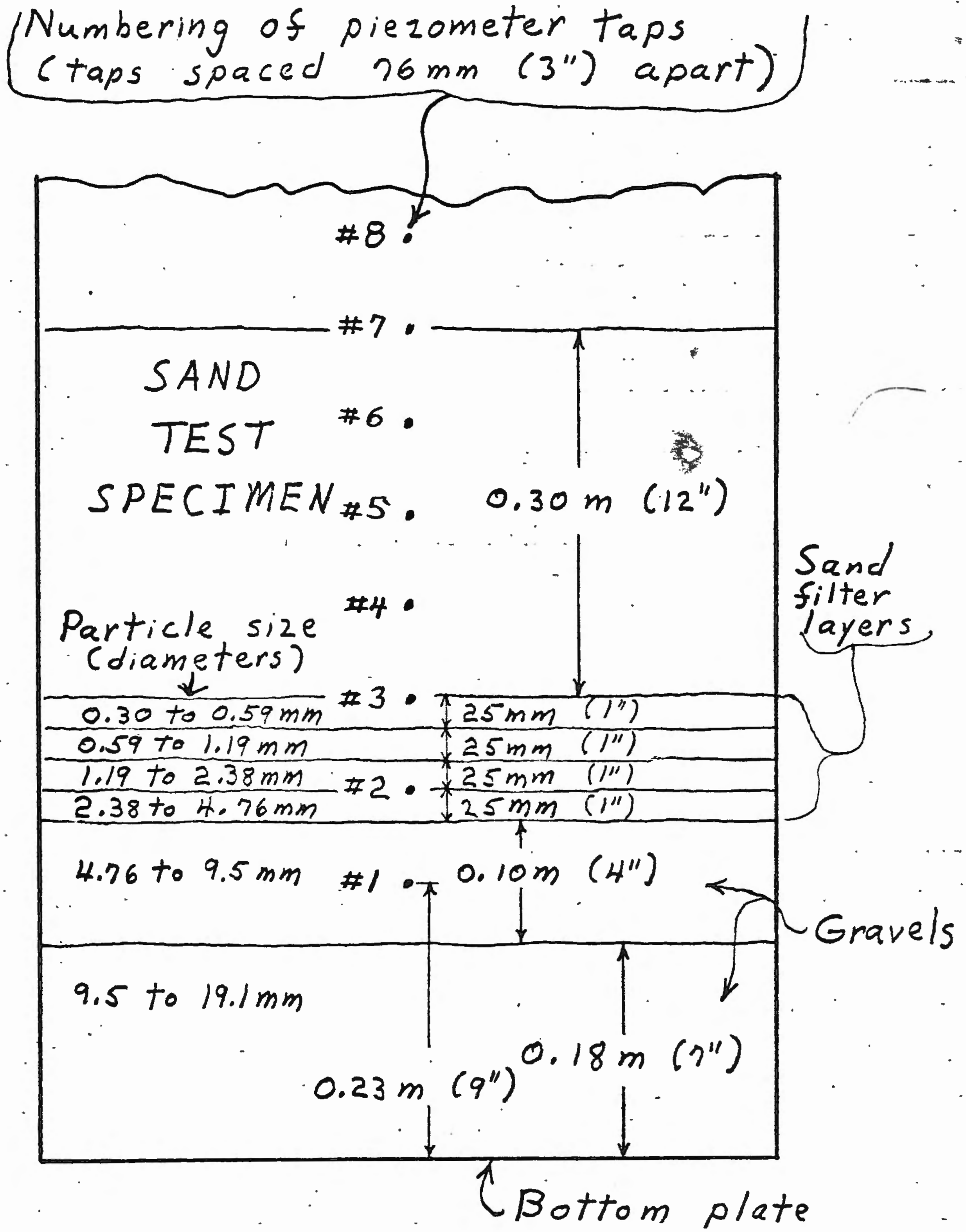
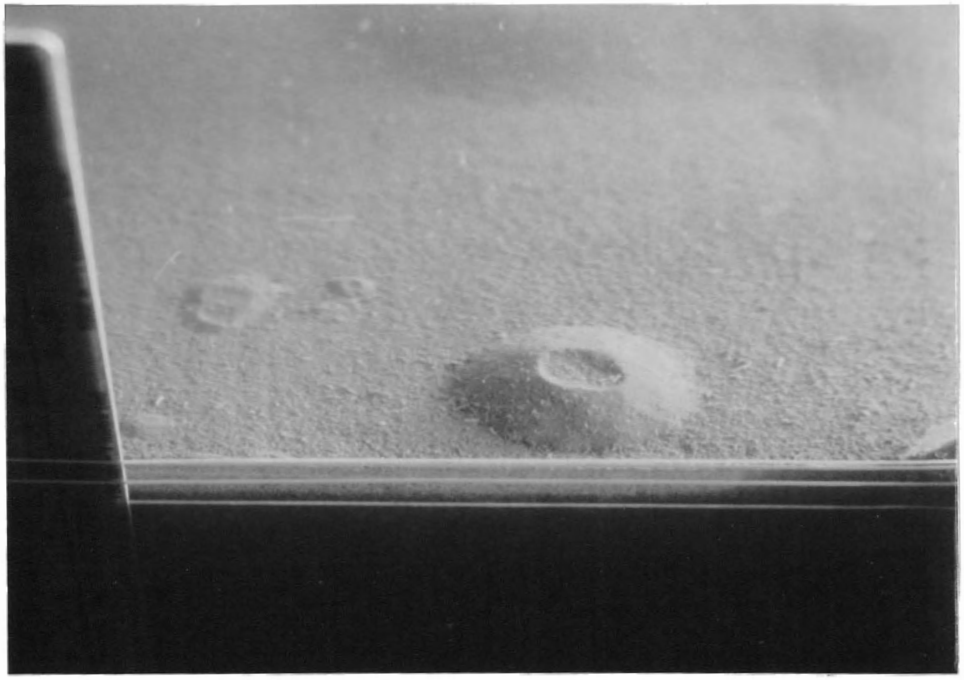


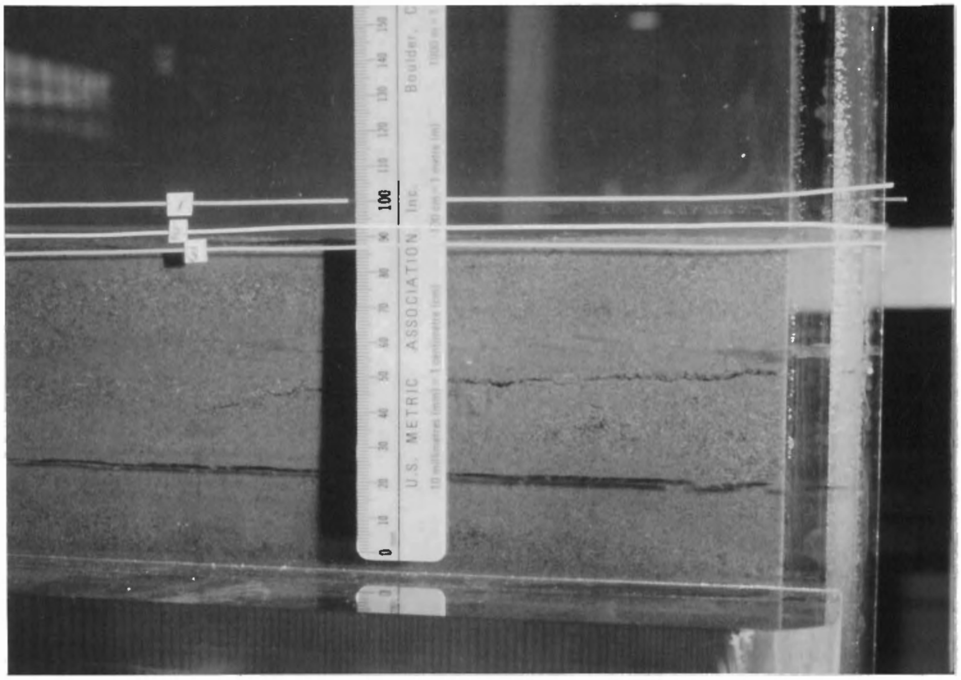
Figure 2. - Filter dimensions and locations of piezometer taps.



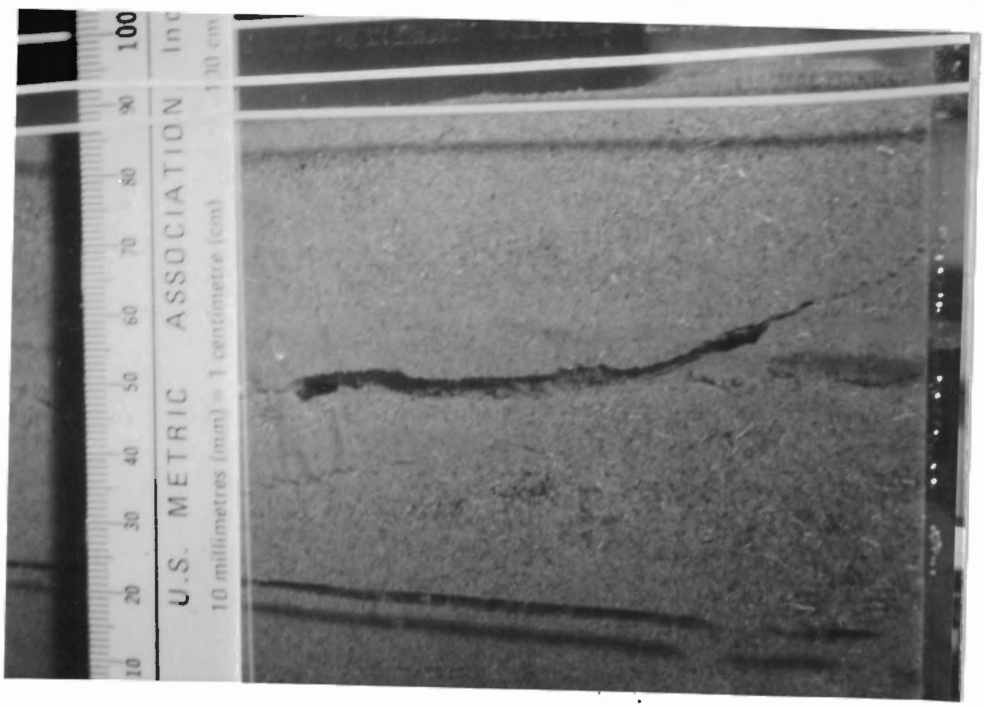
a. Sand boils.

b. More active sand boil, with boiling action of sand in the center.

Figure 3. - Sand boils on surface of the test specimen.



a. Fracture crack.

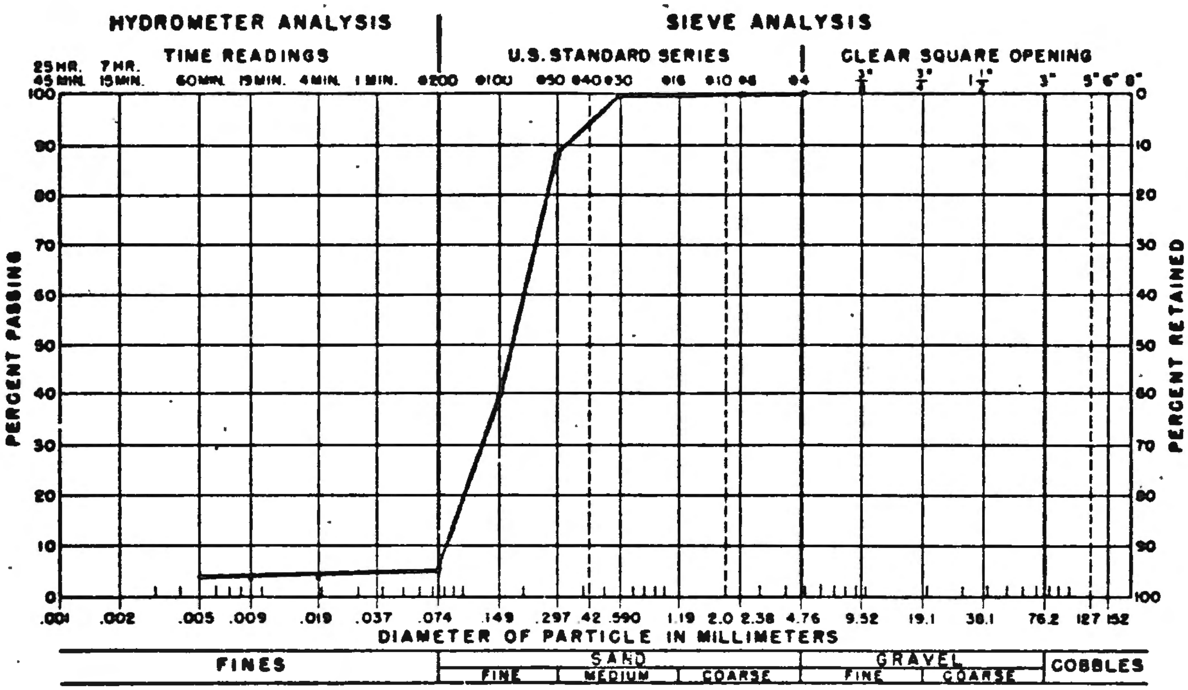


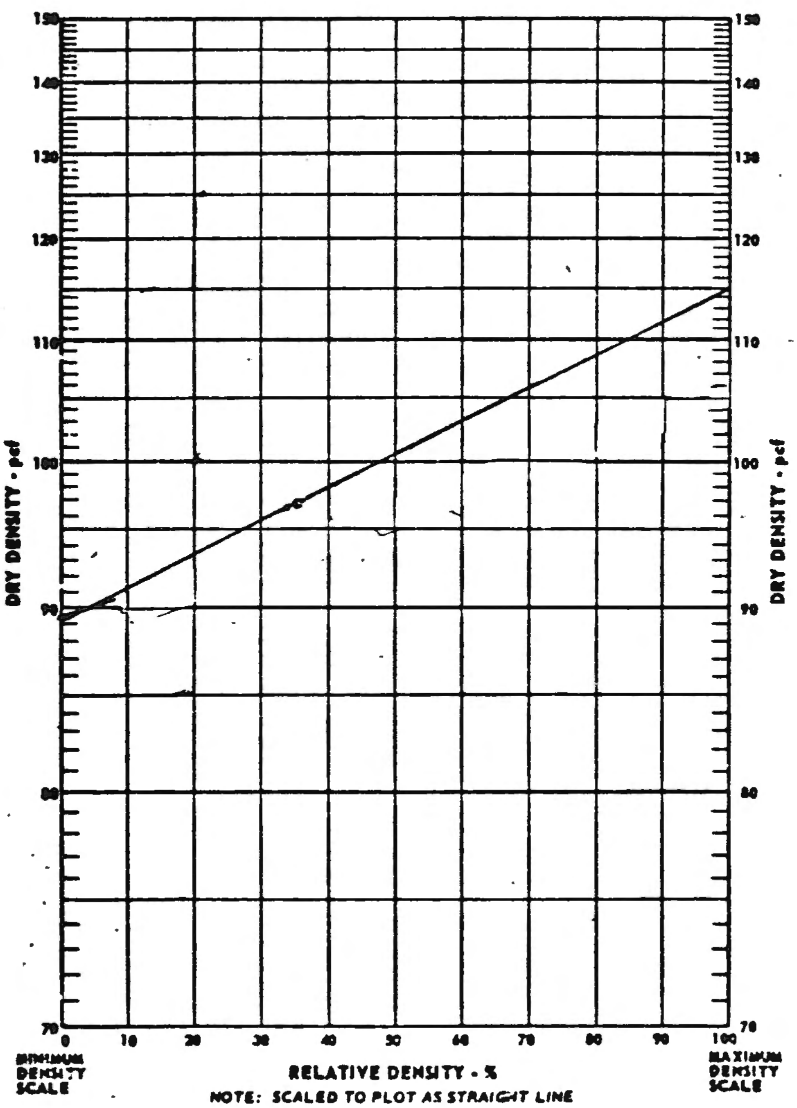
b. Horizontal pipe.

Figure 4. - Fracture cracks and pipe.

7-1742 (8-70)
Bureau of Reclamation

PHYSICAL PROPERTIES SUMMARY PLOT (Relative Density)





LABORATORY Classification Symbol SP-SM

Gradation Summary

- Gravel 0 %
- Sand 94 %
- Fines 6 %

Atterberg Limits

- Liquid Limit ______ %
- Plasticity Index NP* %
- Shrinkage Limit ______ %

Specific Gravity

- Minus No. 4 2.65
- Plus No. 4
- Bulk ______
- Apparent ______
- Absorption ______ %

Relative Density

- Minimum Density 89.4 PCF (______ gm/cm³)
- Maximum Density 114.8 PCF (______ gm/cm³)
- In-place Density ______ PCF (______ gm/cm³)
- Percent Relative Density ______

Permeability Settlement

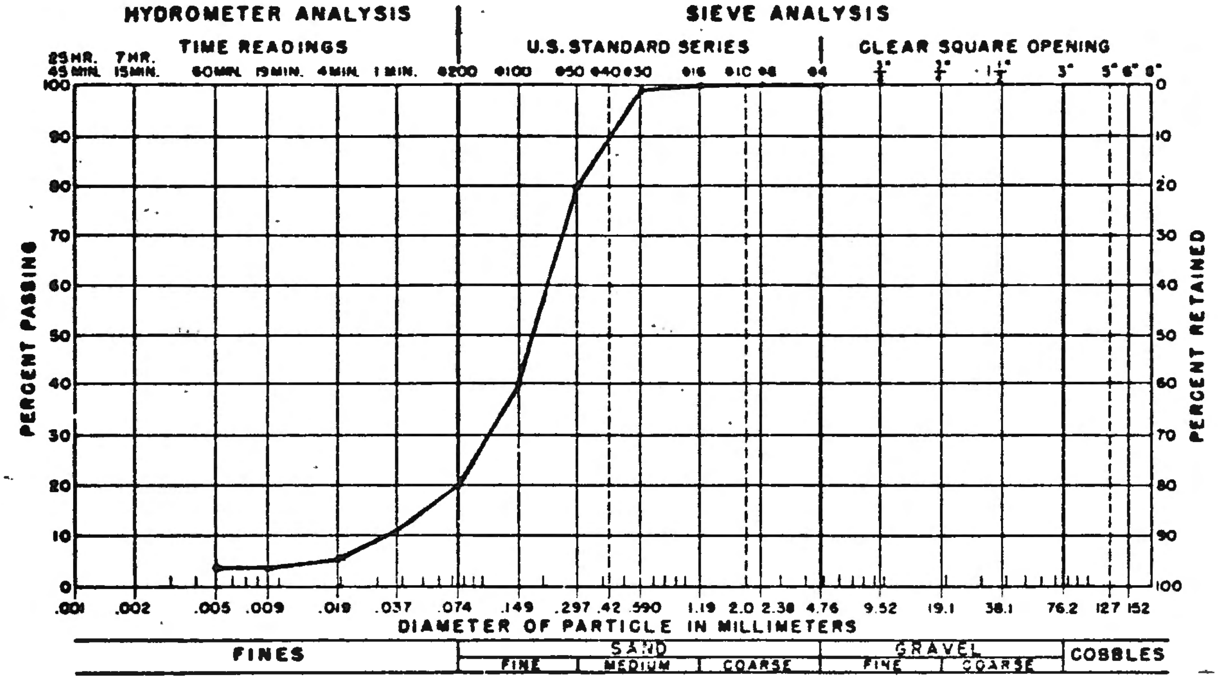
- Placement Condition ______
- Coef of Permeability ______ ft/yr (______ cm/sec)
- Settlement Under ______ psi Load ______ % (______ kg/cm²)

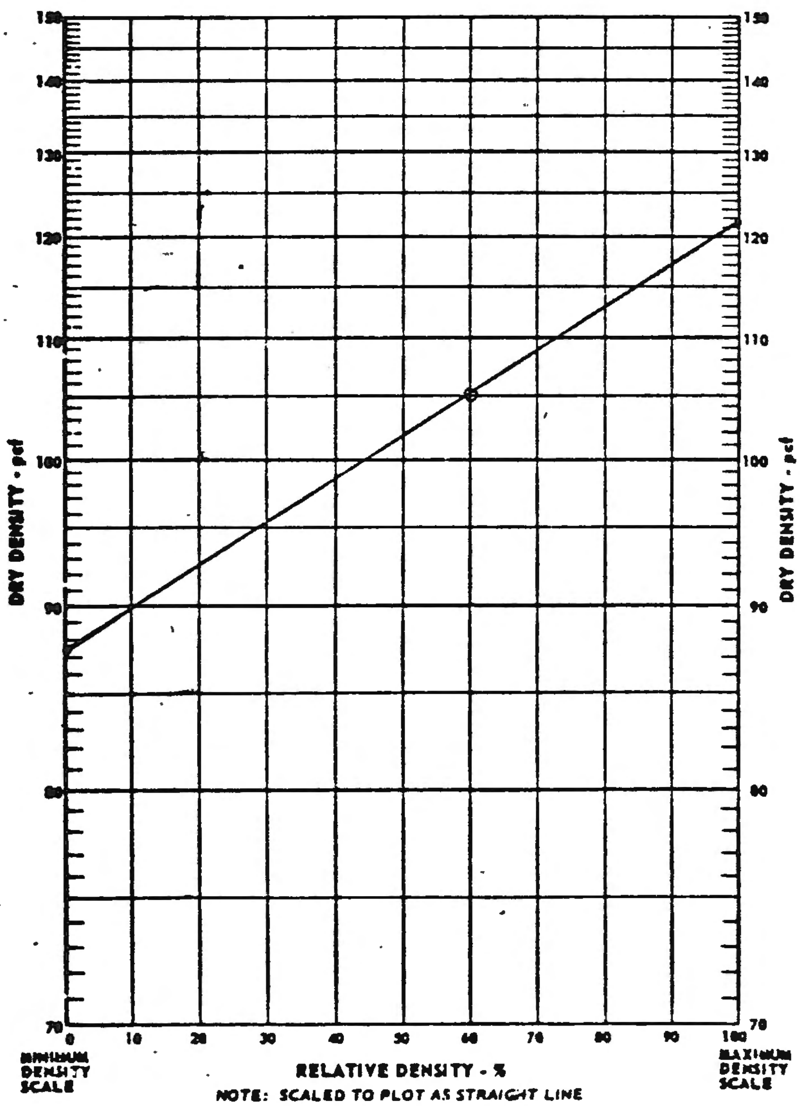
Notes: * VISUALLY DETERMINED

Sample No. 57U-279 Hole No. AQ-6 Depth 0-5.0 ft (______ m)

7-1742 (8-70)
Bureau of Reclamation

PHYSICAL PROPERTIES SUMMARY PLOT (Relative Density)





LABORATORY Classification Symbol SM

Gradation Summary

- Gravel 0 %
- Sand 80 %
- Fines 20 %

Atterberg Limits

- Liquid Limit ____ %
- Plasticity Index NP * %
- Shrinkage Limit ____ %

Specific Gravity

- Minus No. 4 2.63
- Plus No. 4
- Bulk ____
- Apparent ____
- Absorption ____ %

Relative Density

- Minimum Density 87.5 PCF (____ gm/cm³)
- Maximum Density 121.4 PCF (____ gm/cm³)
- In-place Density ____ PCF (____ gm/cm³)
- Percent Relative Density ____

Permeability Settlement

- Placement Condition ____
- Coef of Permeability ____ ft/yr (____ cm/sec)
- Settlement Under ____ psi Load ____ % (____ kg/cm²)

Notes: * VISUALLY DETERMINED

Sample No. 57U-281 Hole No. DD-47 Depth 0-3.0 ft (____ m)

Figure 6. - Physical properties, sand sample No. 57U-281

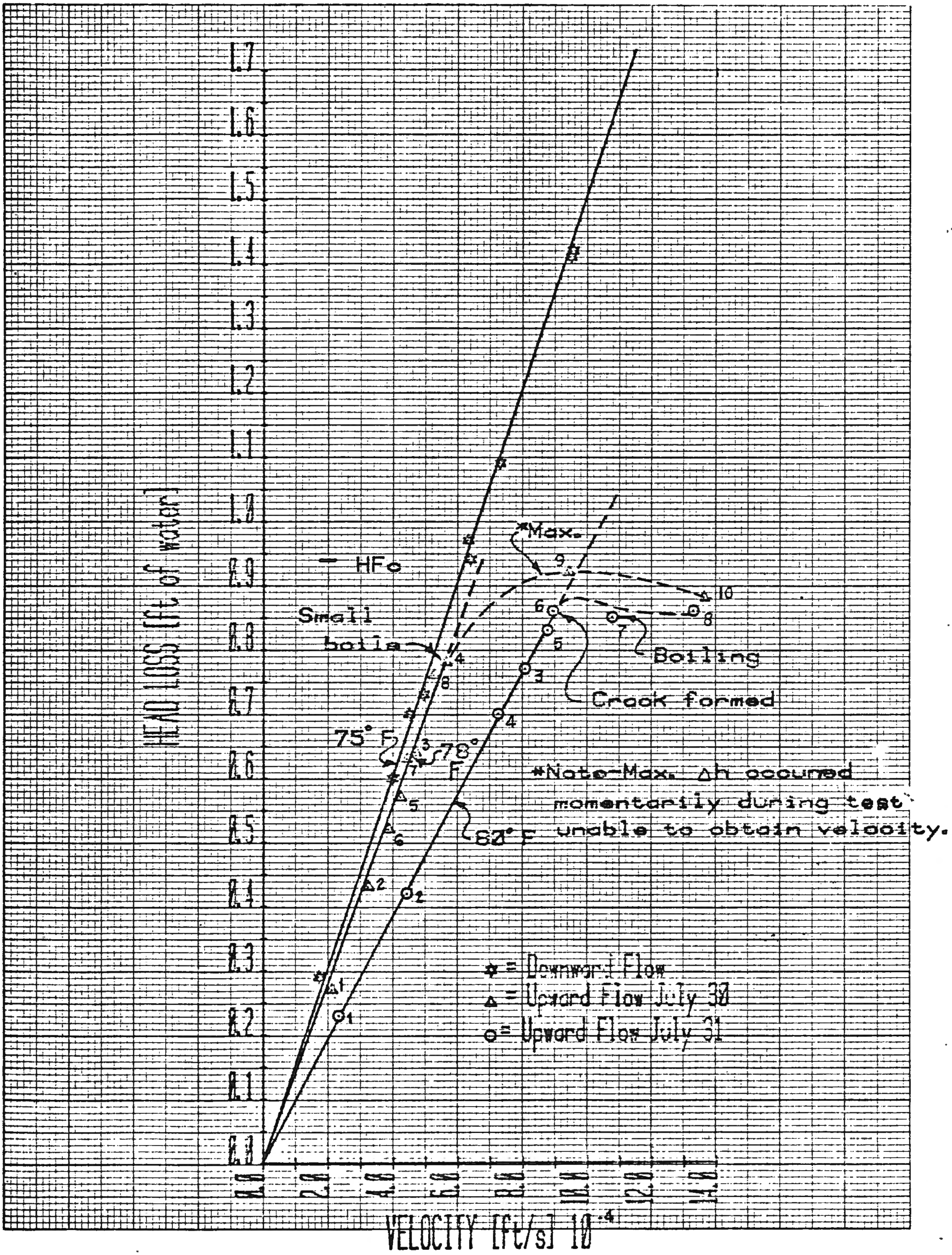


Figure 7. - Head loss versus velocity, test No. 1.

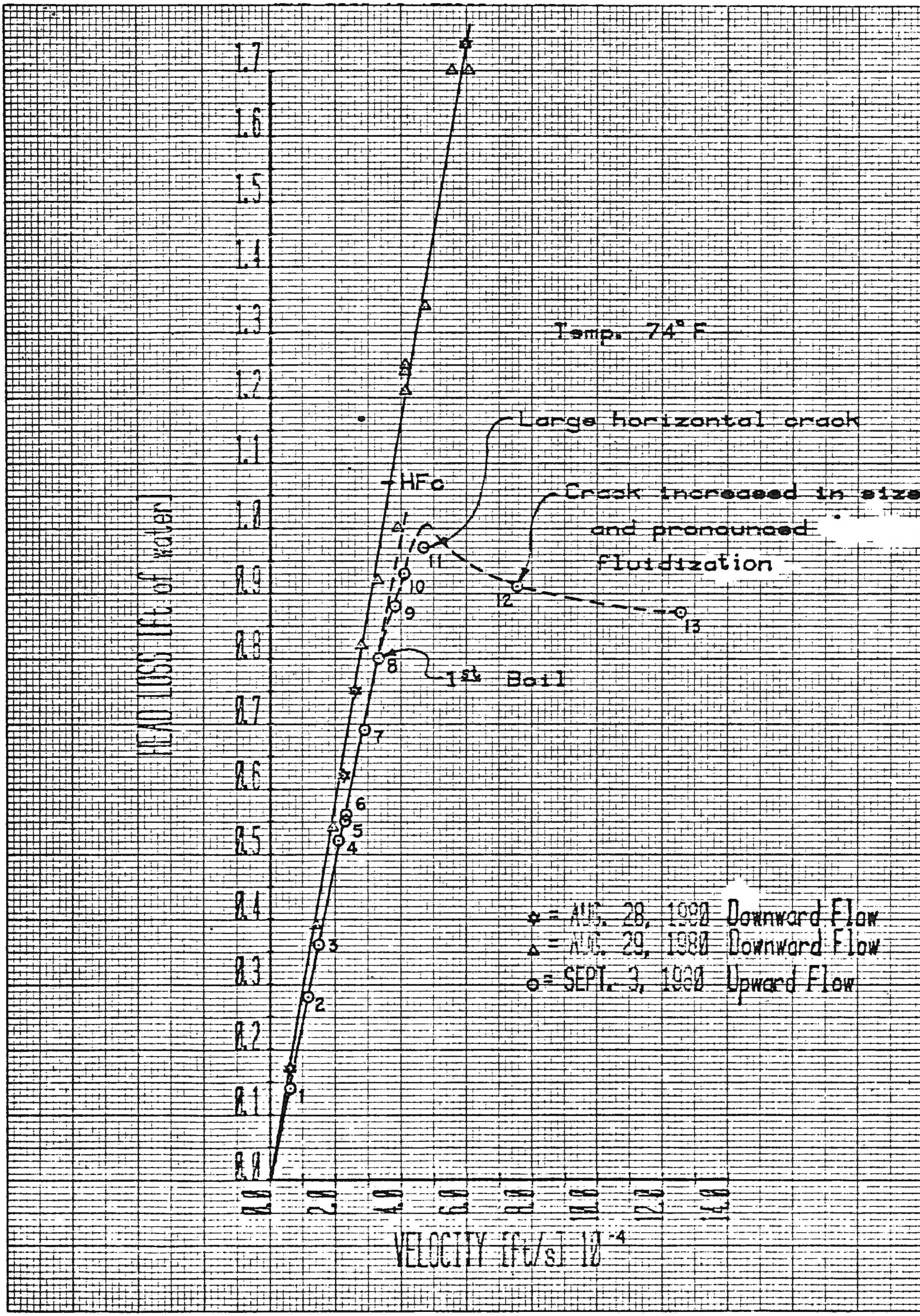


Figure 8. - Head loss versus velocity, test No. 2.

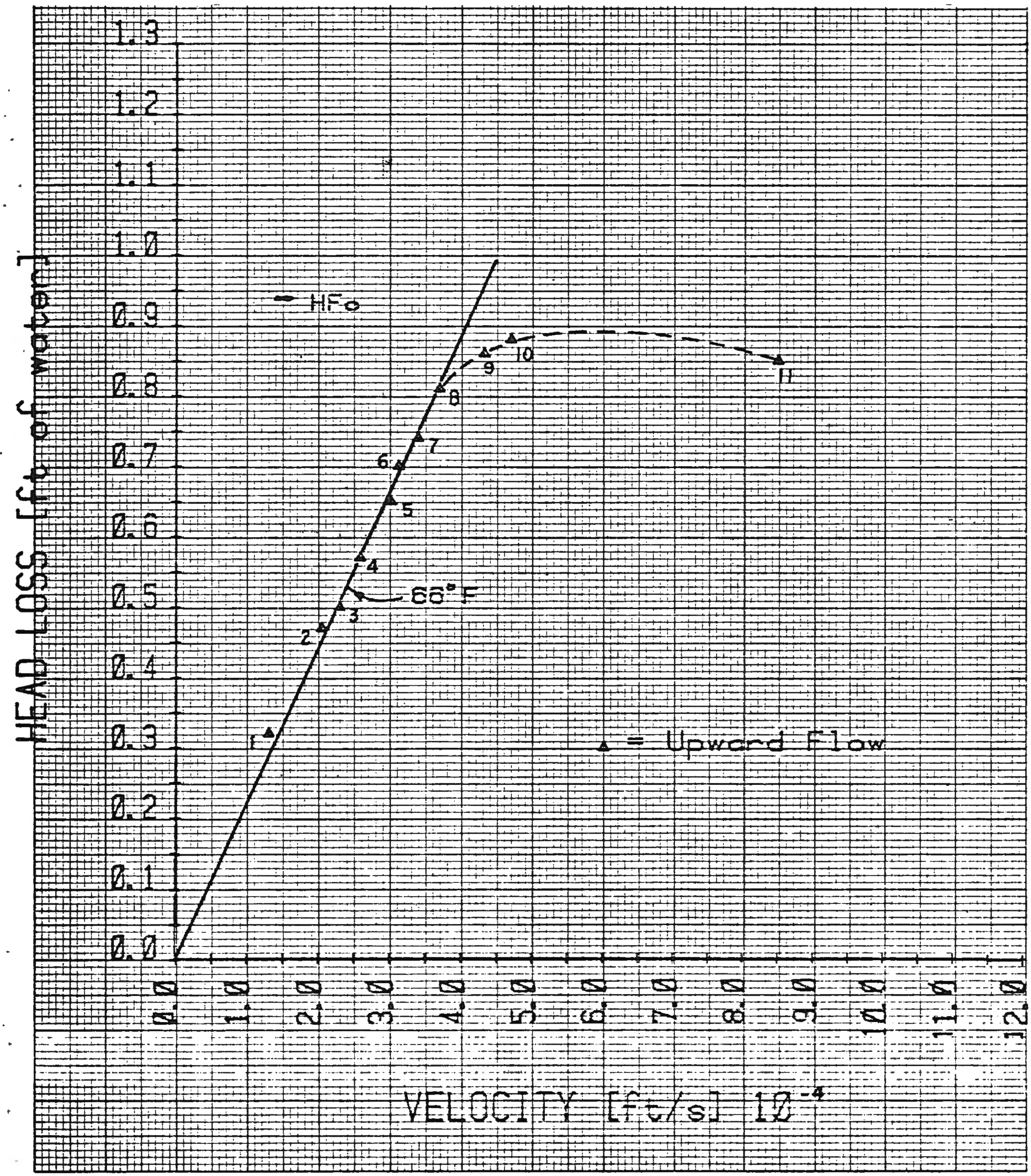


Figure 9. - Head loss versus velocity, test No. 3.

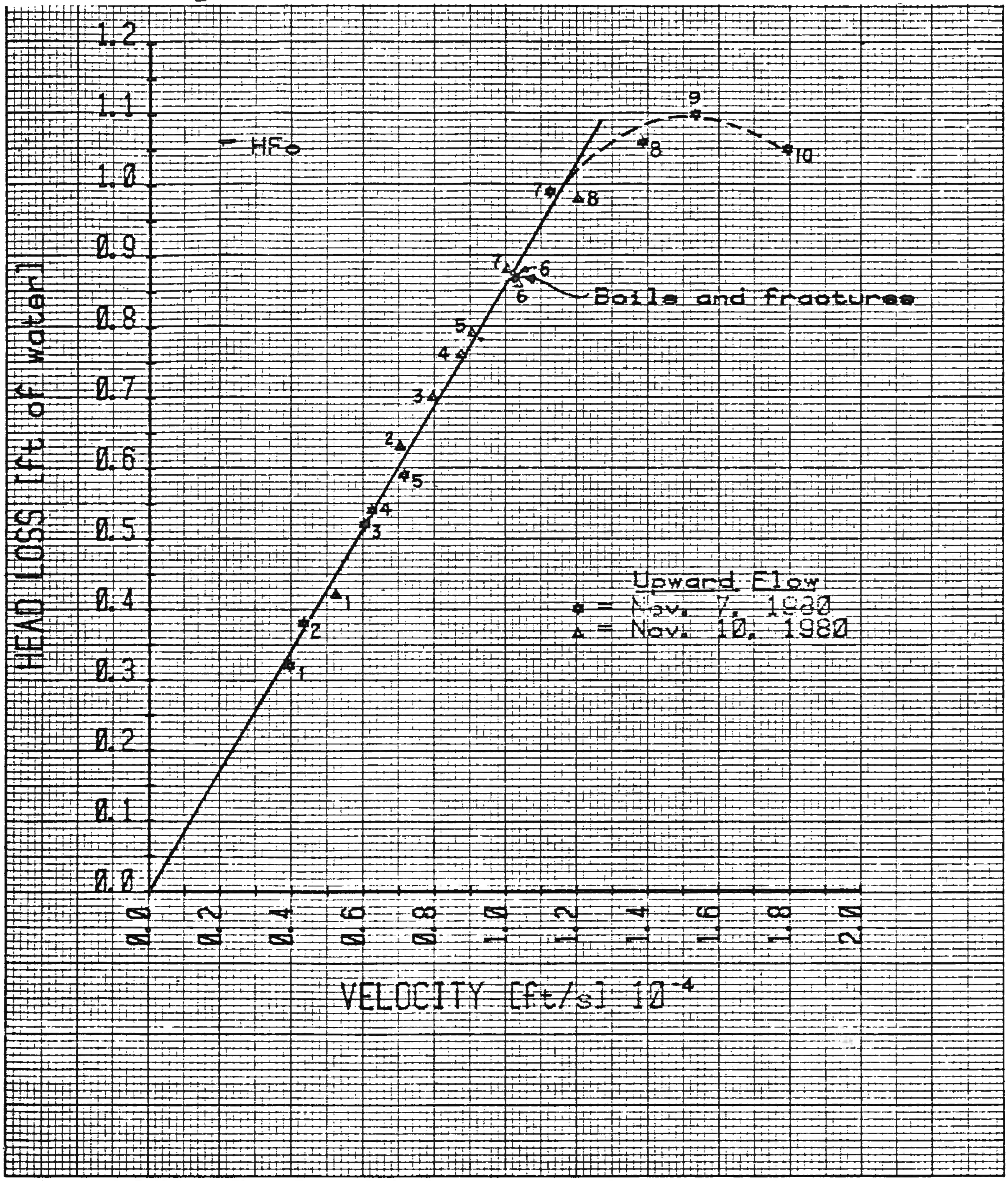


Figure 10. - Head loss versus velocity, test No. 4.

Figure 11. - Seepage permeability, test No. 4

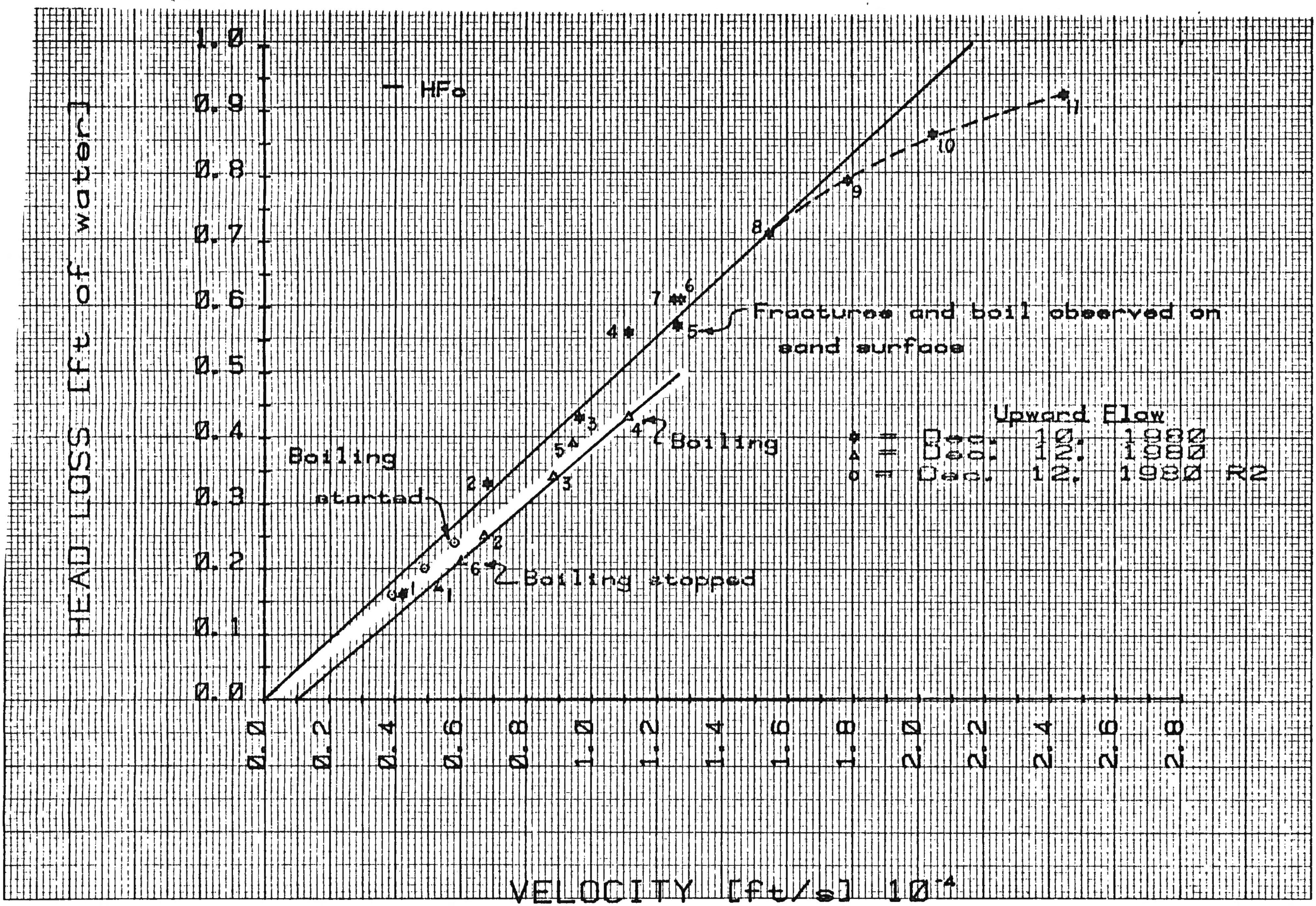


Figure 12. - Head loss versus velocity, test No. 5.

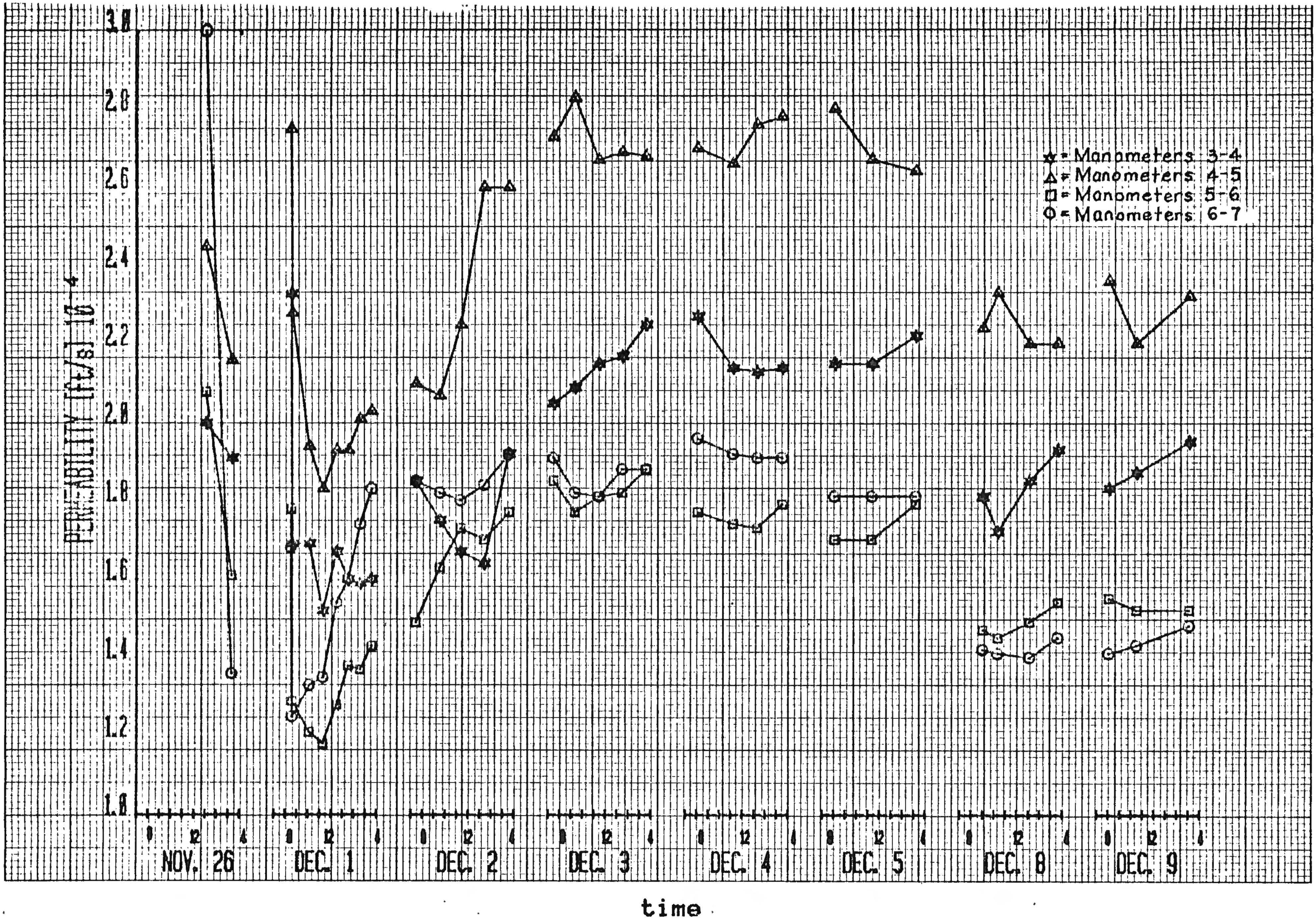
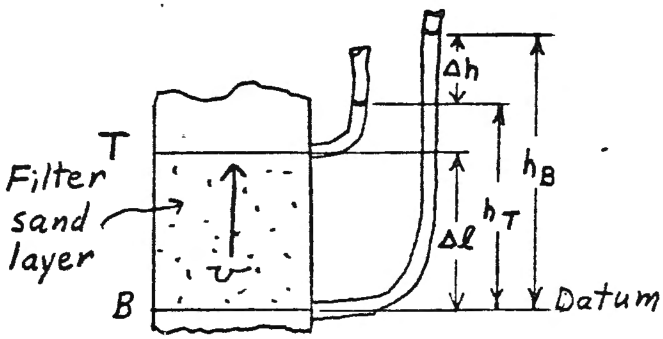


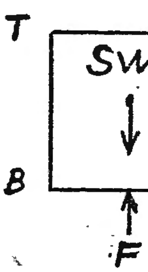
Figure 13. - Seepage permeability, test No. 5.



(a) Resistance of flow through the sand test specimen

$$v = Ki = K\frac{\Delta h}{\Delta l}$$

- v - velocity
- K - coefficient of permeability
- i - hydraulic gradient
- Δh - head loss
- Δl - length over which head loss occurs
- h - piezometric head
- γ - specific weight water
- P - pressure
- A - area
- SW - submerged weight sand
- F - force
- S - specific gravity sand
- n - porosity sand
- F_c - flotation gradient



$$P_T = h_T\gamma$$

$$P_B = h_B\gamma$$

$$F = PA$$

$$F = (P_T - P_B)A = \Delta h\,\gamma A$$

$$SW = \text{Volume}\,[\text{Unit weight/volume}]$$

$$SW = \Delta l\,A\,[\gamma(1-n)(S-1)]$$

(b) Force acting on the sand test specimen and submerged weight of the sand

$$F = SW$$

$$\Delta h\,\gamma A = \Delta l\,A\gamma(1-n)(S-1)$$

$$F_c = \frac{\Delta h}{\Delta l} = (1-n)(S-1)$$

(c) Flotation gradient where force is equal to submerged weight

Figure 14. - Fluidization or flotation gradient.

TEST NOTES

CALAMUS DAM

CRITICAL GRADIENT AND VELOCITY TEST #1
SAMPLE NO. 57U-279 (SP), γ_d = 94 lb/ft^3

7-28-80 SAMPLE PLACEMENT

Box wt 25.5 lbs

Pouring can wt 1.0 lb

Preliminary Test - 2 ft^3 box

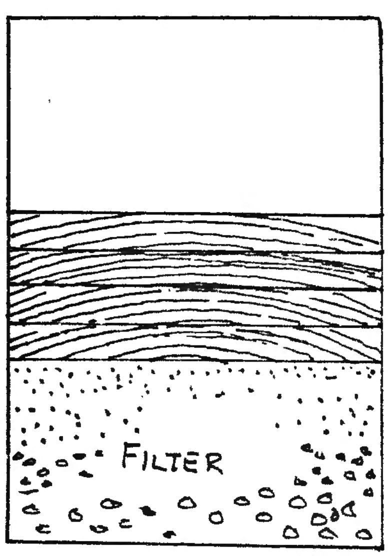
- Pour using RD pouring can, try to obtain minimum soil placement

  Box + Sand 201.5
  \- 25.5
  176.0 lbs/2 = 88 pcf

- Pour sand from bucket

  Box + Sand 202.5
  \- 25.5
  177.0 lbs/2 = 88.5 pcf

Since we obtained minimum by pouring from bucket we poured first trial from bucket - strata visible from side - two layers tamped slightly to get density at life lines. $\gamma_d \approx$ 94 pcf.



- Density gradient exists because sample was poured from bucket - this may be totally unacceptable.

- Material may have to be placed using RD can and funnel, or place in 1.5 inch lifts, rake each lift to reduce strata.

- The strata problem may be a problem at low densities only.

7-29-80 FILLING WITH WATER

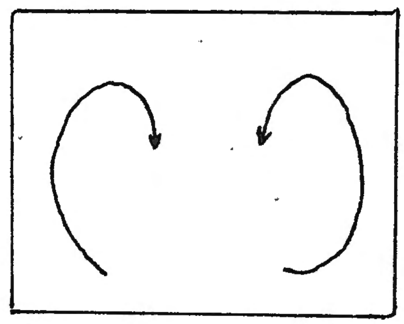
Time	COMMENTS
9:20	Saturation rate - too fast - several horizontal soil fractures, lifting through bottom layer; developed only in bottom lift - see photo's.
	Air bubbles visible trapped in sample
	0.02' settlement
	$0.02 \times 2 = 0.04$ ft^3 V = 1.96 ft^3
10:45	System saturated, piezometers being de-aired
	Specimen settled additional .01 to .02'

7-30-80 UPWARD FLOW TESTING

Time	Δ h (ft)	COMMENTS
9:00		No additional settlement occurred from the previous day
	0.3'	No visible evidence of anything
	0.7'	No visible evidence of anything
	0.8'	Air bubbles (some), small changes in surface,small ½ dia boils beginning, minute dilation (1 mm in NW corner)
	0.7'	Return h = 0.7 to see if boiling stops
	0.54'	Sand movement stopped - specimen settled
	0.56'	No movement, very small dilation (less than 1 mm in NW corner)
	0.53'	No movement
	0.63'	Sand boiling; ½ mm dilation ($-E^3$)
	0.75'	Continued boiling, largest boil getting larger dilation (E^3)

7-30-80 cont.

Time	Δ h (ft)	COMMENTS
	0.95'	Massive boiling, plumes of fines observed rising; cracks up to ¼ inch rising - large boils, 3-4" in diameter, cloudy due to fines
		Dropped to 0.85 after failure
	0.80' to 0.90'	Sand fluidizing in corners of cylinders, heavy flow, water cloudy, circular flow of sand from side to middle of tank



FLOW PATTERN

Fluidizing 1.065* 1.063* 1.050* 1.075*

h = 0.88' - 0.89' - Fluidizing is function of flow, not head

* Approximate surface elevations above 2 co ft line

7-31-80 UPWARD FLOW TESTING

Time	Δ h (ft)	COMMENTS
8:00		The specimen settled back to something less than 94 pcf. Fines settled to 2-4 mm thick layer across surface. Filter intrusion minimal and confined to small areas - several photos taken by E[3] - We decided to rerun critical gradient test since the density is approximately 94 pcf.*

Time	Δ h (ft)	COMMENTS
8:00	0.48' or 0.49'	Surface fines going into suspension, ½ inch cloud over surface of specimen
		(5 min after start) cloud of suspended solid 1½ to 2 inches thick
		Small pipes and particle motion visible in silt layer (indications that it's boiled or fluidized)
		(10 min) cloud extending to 4 to 5 inches above specimen
10:00		Q and h dropped from 8.50 test
	1.11 - 0.68 = 0.43'	Water is rather turbid throughout tank
		Fine silt and top most fine sand still piping (difficult to see)
	1.36 - 0.51 = 0.85'	Initial surface cloud 1" thick, several small pipes in top ¼ to ½" fine sand - water too turbid to see into interior surface
	1.36 - 0.54 = 0.82'	t = 3.0 min
	1.38 - 0.66 = 0.72'	t = 12 min piping slowing down
	1.40 - 0.70 = .70'	t = 20 min
	1.50 - .62 = .88'	Pipes appear to begin deeper in the specimen (¼ -½") (still can't see in specimen)
	1.50 - 0.66 = 0.84'	t = 3 min
12:30	1.84 - 1.06 = 0.78'	Continued boiling in upper ½" of specimen; water clearing slightly
12:50	1.92 - 1.06 = 0.86'	Surface became slightly more murky, small pipes still boiling, slightly more active
	1.93 - 1.07 = .86'	t = 4 to 5 min
	1.94 - 1.08 = .86'	t = 3 min
		Same as above; separation observed 1" above filter sand, 2-3" long, both sides of tank
	0.85'	Hydrofac
	0.90'	Hydrofac
	0.86'	Boiling and shearing
		*Soil completely mixed except for fines which settled on surface

CALAMUS DAM

CRITICAL GRADIENT AND EXIT VELOCITY TEST #2
SAMPLE NO. 57U-279 (SP), γ_d = 106 lb/ft^3

8-27-80 SAMPLE PLACEMENT

8-29, 9-2 DOWNWARD FLOW TESTING Specimen percolated, edges disturbed from testing settled approximately 2 to 5 mm/disputable

9-3-80 UPWARD FLOW TESTING

Stage	Time	Δ h (ft)	COMMENTS
	8:11	1.06 - .85 = 0.21'	Head changes slowly
	8:21	1.24 - 1.08 = 0.16'	
	8:26	1.33 - 1.18 = 0.15'	
	8:30		Manometer system developed air leak, system shut down for repairs
	8:44	9.93 - 9.61 = 0.32'	Target h = 0.25 ft
	8:54	9.93 - 9.64 = 0.29'	
	8:59	9.93 - 9.65 = 0.28'	Air leak stopped
	9:04	9.97 - 9.67 = 0.36'	
	9:07	10.00 - 9.59 = 0.41'	
	9:17	10.00 - 9.61 = 0.39'	
	9:22	9.99 - 9.62 = 0.37'	
	9:25	10.06 - 9.53 = 0.53'	
	9:28	10.07 - 9.53 = 0.54'	
	9:35	10.07 - 9.55 = 0.52'	
	9:42	10.07 - 9.55 = 0.52'	
	9:43	10.10 - 9.51 = 0.59'	
	9:53	10.10 - 9.52 = 0.58'	Slight increase in specimen volume possibly apparent
	9:58	10.10 - 9.52 = 0.58'	
	10:05	10.13 - 9.49 = 0.64'	
	10:15	10.11 - 9.53 = 0.58'	

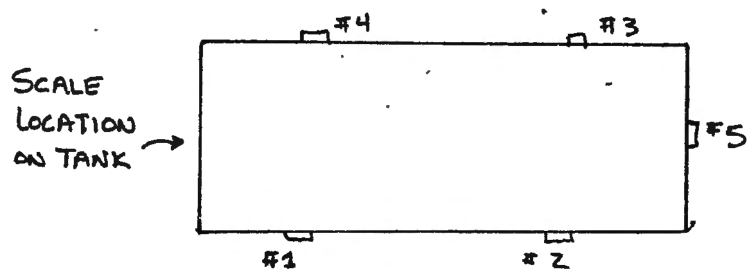
9-3-80 UPWARD FLOW TESTING cont.

Time	Δ h (ft)	COMMENTS
10:20	10.10 - 9.54 = 0.56'	
	10.10 - 9.55 = 0.55'	Decreasing head
10:29	10.20 - 9.44 = 0.76'	Fracture approximately 0.5 inch deep, boiled and stopped; No other boils noted, dilation apparently present, (approximately 1 to 1½ mm longitudinally through specimen)
10:39	10.18 - 9.46 = 0.72'	No additional piping or cracks, dilation 1 to 1½ mm
10:44	10.17 - 9.48 = 0.69'	
10:57	10.17 - 9.48 = 0.69'	Small cracks (previously opened) reopening, piping
10:59	10.23 - 9.42 = 0.81'	
11:02	10.24 - 9.42 = 0.82'	Boils appearing predominantly around edges, one boil formed 1 inch from edge; water essentially clear
11:09	10.23 - 9.43 = 0.80'	Boils appearing predominantly around edges, one boil formed 1 inch from edge; water essentially clear
11:14	10.23 - 9.43 = 0.80'	Approximately 2 mm dilation, several small boils appeared, not very active
11:20	10.29 - 9.38 = 0.91'	Cracks and boils appearing on all faces, several more surface boils, fines visible blowing out of boils
	10.30 - 9.38 = 0.92'	Large oblong boil comprised of several pipes
11:30	10.29 - 9.38 = 0.91'	
11:35	10.28 - 9.40 = 0.88'	3 mm dilation
11:38	10.31 - 9.37 = 0.94'	Old boils boiling, side boils more predominant and illustrative
		4 mm dilation, cracks appearing 1½ to 2 inches deep
11:48	10.30 - 9.37 = 0.93'	Deep cracks, 9 inches down from surface, boiling, fines being blown out of specimen; more small pipes evident; Cracking extensively deep in specimen, 6 mm dilation;

9-3-80 UPWARD FLOW TESTING cont.

Time	Δ h (ft)	COMMENTS
		large surface distortions (local) evident; cracks moving upward to surface; large boils appearing
12:07	10.34 - 9.35 = 0.99'	
12:12	10.33 - 9.35 = 0.98'	
12:18	10.34 - 9.35 = 1.01'	Massive crack ½ to 3/4 inch wide moving up through specimen; large boil broke; shear distortion on surface evident
	10.35 -10.37 = 0.98'	Piezometer 7 below surface of specimen

Scale
- #1 - 33 mm
- #2 - 13 mm
- #3 - 3 mm (ruler)
- #4 - 4 mm
- #5 - 30 mm



Time	Δ h (ft)	COMMENTS
12:31	1.01'	Fluidizing on left end, fines blowing out on right end, water is murky on surface of specimen
	10.28 - 9.33 = 0.95'	#1 - 50 mm #2 - 38 mm #3 - 46 mm (scale) #4 - 41 mm #5 - 48 mm
12:38	10.29 - 9.33 = 0.96'	
	10.28 - 9.31 = 0.97'	Increased Q, but no increase in h; entire sample fluidized #1 - 60 mm #2 - 58 mm #3 - 63 mm (scale) #4 - 60 mm #5 - 51 mm

CALAMUS DAM

CRITICAL GRADIENT - VELOCITY TEST #3
SAMPLE NO. 57U - 279, γ_d = 94 lb/ft^3

10-20-80 SAMPLE PLACEMENT

Specimen placed at $_d$ = 94 pcf (eight - 1½ inch lifts) - No compaction required.

10-21-80 FILLING WITH WATER

Time	Δ h (ft)	COMMENTS
9:00		Begin wetting filter
9:35		Small volume decrease in specimen induced by capillary stress.
9:45		Volume decrease corresponding to 2 - 3 mm drop in specimen height
	6.67 - 5.86 = -0.81'	Check capillary stress (negative head)
9:55	6.03 - 5.93 = -0.10'	Check capillary stress (negative head)
9:57	6.67 - 5.77 = -0.90'	Check capillary stress (negative head)
10:35		Specimen saturated; approximately 7 mm of settlement

10-22-80 UPWARD FLOW TESTING

Stage	Time	Δ h (ft)	COMMENTS
	8:30	--	Test specimen appeared to have settled an additional 1 mm overnight (marked with yellow line below white)
			Videotaped entrapped air and small bumps on surface of specimen
			R_1 = 92 mm R_2 = 92 mm R_3 = 92 mm
1	8:51	9.57 - 9.27 = 0.30'	Manometers constant - no visible effects
	9:04	9.55 - 9.27 = 0.28'	Ditto
	9:06	9.54 - 9.27 = 0.27'	Ditto
2	9:12	9.64 - 9.27 = 0.48'	Had trouble with inflow valve; no visible effects or changes in specimen
	9:18	9.64 - 9.17 = 0.47'	1 to 2 mm volume increase (roughly)
			R_1 = 93 mm R_2 = 92 mm R_3 = 93 mm

10-22-80 UPWARD FLOW TESTING cont.

Stage	Time	Δ h (ft)	COMMENTS
	9:27	9.63 - 9.17 = 0.46'	
3	9:33	9.65 - 9.15 = 0.50'	No changes; no additional volume change; possible crack forming
	9:40	9.65 - 9.15 = 0.50'	
	9:48	9.65 - 9.15 = 0.50'	
4	9:48	9.68 - 9.11 = 0.57'	Additional small volume increases
			R_1 = 96 mm R_2 = 94 mm R_3 = 95 mm
			Approx. 2 to 3 mm volume increase
	10:03	9.70 - 9.13 = 0.57'	No visible changes; outline crack areas; (yellow)
			R_1 = 95+ mm R_2 = 94+ mm R_3 = 95+ mm
5	10:05	9.73 - 9.07 = 0.66'	No major changes evident; volume expansion remaining
	10:13	9.75 - 9.10 = 0.65'	Fairly constant from last gradient. Crack consisting of air trapped in soil voids seems to be expanding
	10:20	9.77 - 9.10 = 0.67'	
6	10:25	9.78 - 9.07 = 0.71'	No major changes evident, small volume increase noted
			R_1 = 95+ mm R_2 = 96 mm R_3 = 95+ mm
	10:32	9.78 - 9.08 = 0.70'	Appear to be small volume increase; more bumps on surface seem to be appearing
	10:40	9.78 - 9.09 = 0.69' VALVE TROUBLE	Several small air bubbles rose
7	10:55	9.83 - 9.05 = 0.78'	No visible changes; bubbles apparent along lift lines
	11:03	9.78 - 9.05 = 0.73'	Ditto
	11:05	9.78 - 9.05 = 0.73'	Ditto
8	11:06	9.82 - 9.01 = 0.82'	Very small volume increase - cracks appear to have widened; no visible particle movement

10-22-80 UPWARD FLOW TESTING cont.

Stage	Time	Δ h (ft)	COMMENTS
			Bubble burst surface, small ring of turbidity appeared around exit
	11:23	9.82 - 9.01 = 0.81'	
9	11:30	9.84 - 8.97 = 0.84'	Volume expansion 2 mm
	11:40	9.85 - 9.00 = 0.85'	R_1= 98 mm R_2 = 97 mm R_3 = 97 mm
			No other visible changes; bubbles appearing, plumes of fire
	11:45	9.85 - 9.01 = 0.84'	
10	11:55	9.86 - 8.97 = 0.89'	Cracks appear to widen;
			R_1 = 100 mm R_2 = 99+ mm R_3 = 98+ 100
	12:00	9.85 - 8.97 = 0.88'	Specimen dilating slowly; (almost at original volume)
			Specimen is doming in center; numerous bubbles appearing
	12:05	9.85 - 8.98 = 0.87'	R_1 = 102 mm R_2 = 102 mm R_3 = 101 mm
	12:10	9.85 - 8.98 = 0.87'	
11	12:15	9.85 - 8.95 = 0.90'	R_1 = 122 mm R_2 = 112 mm R_3 = 110 mm
			Extreme dilation, bubbling, many bubbles, major pipe by outfall -- specimen boiling fines, sand and bubbles
	12:16	9.83 - 8.99 = 0.84'	Simultaneous; small cracks boiling; water becoming turbid; outfall - massive fluidizing bubbles blowing out along cracks, fines and sand piping
			R_1 = 134 mm R_2 = 123 mm R_3 = 125 mm
			(top yellow strip)
			Air moving up pipe holes
	12:20	9.83 - 9.00 = 0.83'	
	12:30	9.84 - 8.98 = 0.85'	Massive boiling tailing off - air mostly out of system; small pipes still evident; lower ¼ of specimen still contains some air bubbles, top 3/4 of specimen homogenized

CALAMUS DAM

CRITICAL GRADIENT AND EXIT VELOCITY TEST #4
SAMPLE NO. 57U-281 (SM), γ_d = 105.5 lb/ft^3

10-28-80 SAMPLE PLACEMENT

10-30 FILLING WITH WATER

Time	Δ h (ft)	COMMENTS
8:57	--	Zero in TV camera
9:12		Water in
9:36		P-1 - P-4
9:42	P_1 = 7.13 P_2 = 6.02 P_3 = 6.12 P_4 = 6.2	
10:06		Wetting front at top of specimen
10:08		Free water at top of specimen
10:22		$\pm$ mm volume expansion

11-7-80 UPWARD FLOW TESTING

Stage	Time	Δ h (ft)	COMMENTS
1	8:15		R_3 = 95 R_2 = 96 R_1 = 95
	8:20	8.88 - 8.60 = 0.28'	
	8:25	8.90 - 8.59 = 0.31'	
	8:33	8.92 - 8.60 = 0.32'	
	8:35	8.92 - 8.60 = 0.32'	
2	8:40	8.95 - 8.55 = 0.40'	No visible changes
	8:45	8.93 - 8.55 = 0.38	
	8:50	8.95 - 8.57 = 0.38'	
3	8:55	9.98 - 9.50 = 0.48'	
	9:00	9.00 - 8.48 = 0.52'	

11-7-80 UPWARD FLOW TESTING cont.

Stage	Time	Δ h (ft)	COMMENTS
3	9:05	9.01 - 8.49 = 0.51'	
	9:10	9.02 - 8.50 = 0.52'	Very subtle dilation noticed; specimen is doming slightly in middle
	9:15	9.02 - 8.50 = 0.52	
4	9:17	9.03 - 8.46 = 0.57	
	9:22	9.03 - 8.47 = 0.56'	
	9:27	9.03 - 8.49 = 0.54'	
	9:35	9.03 - 8.51 = 0.52'	
5	9:38	9.08 - 8.47 = 0.61'	Approx. 1 mm dilation, appears as though the center of specimen is doming
	9:43	9.06 - 8.45 = 0.61'	
	9:48	9.05 - 8.46 = 0.59'	
6	9:56	9.19 - 8.34 = 0.85'	
	10:00	9.22 - 8.30 = 0.92'	Three 6 inch longitudinal cracks appeared in upper 3 inch layer, two small pipes appeared, two good boils recorded
	10:06	9.19 - 8.30 = 0.89'	Continued boiling, approx. 2 mm dilation
	10:12	9.19 - 8.30 = 0.89'	R_3= 97 mm R_2 = 97 mm R_1 = 96 mm
7	- The test will now be controlled by Q; not manometers - they will be recorded.		
	10:17	9.18 - 8.30 = 0.88'	Cracks healing
	10:22	9.21 - 8.25 = 0.96'	Boiling continuing; no new boils observed, cracks reopened.
	10:23	9.23 - 8.25 = 0.98'	R_3 = 97 R_2 = 97 R_1 = 97
	10:32	9.23 - 8.24 = 0.99'	
8	10:34	9.27 - 8.20 = 1.07'	R_3 = 99 R_2 = 99 R_1 = 98
	10:37	9.28 - 8.19 = 1.09'	Cracks opened up; boils occuring all over, deep crack 3 inches long, 2 inches from filter

11-7-80 UPWARD FLOW TESTING cont.

Stage	Time	Δ h (ft)	COMMENTS
8	10:39	9.28 - 8.19 = 1.09'	
	10:47	9.28 - 8.21 = 1.07'	Continued boiling
9	10:52	9.29 - 8.19 = 1.10'	Continued boiling; deep cracks are opening up - considerable amount of fines going into suspension
			R_3 = 99 R_2 = 100 R_1 =
	11:02	9.29 - 8.19 = 1.10'	
10	11:10	9.30 - 8.19 = 1.11'	Continued piping; increased Q is relieved through existing pipes; water is flowing through pipes with considerable velocity
			Deep fracture getting larger; pipes blowing lots of fines
	11:15	9.25 - 8.22 = 1.03'	Large boil tapped from deep crack; crack healed as stress was relieved
			R_3 = 100 R_2 = 100 R_1 = 100

11-10-80 UPWARD FLOW TESTING

Stage	Time	Δ h (ft)	COMMENTS
1			R_1= 95 mm R_2 = 95 mm R_3 = 95 mm
			On line 3 am line 3 = line 4 Rerun on h - .5 = .85
1	8:12	9.01 - 8.50 = 0.51'	Volume change approx. .05 mm
	8:20	9.00 - 8.57 = 0.43'	
2	8:23	9.10 - 8.48 = 0.62'	Volume change approx. 1.5 mm
	8:31	9.10 - 8.48 = 0.62'	Some turbidity
3	8:34	9.14 - 8.44 = 0.70'	Volume change approx. 2.0 + mm Plume turbidity from large crater
4	8:45	9.18 - 8.41 = 0.79'	Very fine particles suspended in water Volume change approx. 3.0 mm
	8:54	9.17 - 8.42 = 0.75'	

11-10-80 UPWARD FLOW TESTING cont.

Stage	Time	Δ h (ft)	COMMENTS
5	8:56	9.19 - 8.39 = 0.80'	Volume change + 3.0 mm
	9:05	9.18 - 8.41 = 0.77'	
6	9:06	9.23 - 8.36 = 0.87'	Pipe active in crater; slight settlement at floping fines - .074 mm
	9:13	9.23 - 8.37 = 0.86'	
7	9:17	9.25 - 8.35 = 0.90'	Sand flow in crater and left boil Volume change - 4.0 mm
8	9:23	9.29 - 8.32 = 0.97'	Boiling in crater; horizontal cracks - front line crack .1 to .3 mm entire specimen side; volume change 5 mm
	9:34	9.29 - 8.32 = 0.97'	

CALAMUS DAM

CRITICAL GRADIENT AND VELOCITY TEST #5
SAMPLE NO. 57U-281, γ_d = 94 lb/ft^3

11-26-80 FILLING WITH WATER

Stage	Time	Δ h (ft)	COMMENTS
	8:15		Maintained from .2 to .4 ft head R_3 = 98 R_2 = 97 R_1 = 96
	8:30		Reading at time surface became wet
	8:40		3 mm over decrease

11-26-80 DOWNWARD FLOW TESTING

Date	Time	COMMENTS
	2:45	R_3 = 93 R_2 = 89 R_1 = 96 Downward flow;
12-1-80	8:00	No change
12-2-80	8:15	R_3 = 89 R_2 = 89 R_1 = 90 Hydrofractures have closed
12-3-80	8:00	R_3 = 88 R_2 = 88 R_1 = 89 No changes

12-10-80 UPWARD FLOW TESTING

Stage	Time	Δ h (ft)	COMMENTS
1	8:50	9.16 - 8.95 = .21	No visible changes
	8:55	9.14 - 8.96 = .19	No visible changes
	9:00	9.12 - 8.96 = .16	No visible changes
2	9:05	9.21 - 8.86 = .35	No visible changes
	9:10	9.20 - 8.87 = .33	No visible changes
	9:16	9.20 - 8.87 = .33	No visible changes
3	9:20	9.30 - 8.80 = .50	No visible changes; specimen may have begun to dilate, doming in center;
	9:25	9.29 - 8.79 = .50	
	9:30	9.28 - 8.80 = .48	

12-10-80 UPWARD FLOW TESTING cont.

Stage	Time	Δ h (ft)	COMMENTS
4	9:35	9.34 - 8.78 = .56	Approx. 1 mm doming in middle of specimen; "Reduction of head seems to be due to redistribution of flow through specimen caused by dilation"
	9:40	9.34 - 8.78 = .56	
	9:45	9.35 - 8.79 = .56	Doming evident in center of specimen
5	9:50	9.38 - 8.76 = .62	Approx. 1 mm dilation; Doming evident to do side friction effects
			Pipe developed 2 inches into specimen (6 in horizontal, 2 in vertical) crack extends from pipe
			3 small pipes on backside of specimen
5	9:58	9.34 - 8.76 = .60	Approx. 6 small boils (3/4 in diameter) active on back side of specimen
			R_3 + 1 mm R_2 + 1 mm R_1 + 1 mm
			Domed in center
	10:05	9.34 - 8.76 = .60	
6	10:08	9.34 - 8.72 = .64	Boils on front and back active, pumping considerable amount of fines into suspension; no deep cracks apparent; approx. 1 + mm volume change; back pipe extremely active (1 in diameter); 2 mm + dilation Numerous small pipes appearing
	10:13	9.34 - 8.73 = .63	
	10:18	9.36 - 8.74 = .64	
7	10:22	9.40 - 8.71 = .69	Crack widening on right end; good boil developed; most cracks in upper 4 inches of specimen; some boils have healed
		9.38 - 8.75 = .60	Approx. 2 mm dilation

12-10-80 UPWARD FLOW TESTING cont.

Stage	Time	Δ h (ft)	COMMENTS
8	10:30	9.41 - 8.70 = .71	Well defined pipe on side of specimen (particle movement seen) 5 mm dilation in center of specimen, 1 mm on sides
	10:35	9.41 - 8.70 = .71	Ditto
	10:40	9.42 - 8.70 = .72	Ditto
9	10:45	9.46 - 8.66 = .80	Renewed boil; additional boils appearing in center of specimen; specimen volume change erratic
	10:50	9.46 - 8.66 = .80	
10	10:53	9.49 - 8.63 = .86	Big pipe in center of tank; (2+ inch diameter) other pipes continuing; no deep fractures visible; "Apparently seems as though specimen must have well developed flow channels through specimen because volume change very minor (2-3 mm)"
10	11:00	9.50 - 8.62 = .92	Continued piping
	11:05	9.48 - 8.63 = .85	Continued piping
11	11:07	9.54 - 8.59 = .95	Pipes in central specimen (2 in diameter) Numerous small pipes Deep cracks appearing; 4 mm + dilation
	11:12	9.54 - 8.58 = .96	Cracked (horizontal) through entire model
	11:23	9.53 - 8.59 = .94	