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R. J. Carle

J. C. Kable

THE EFFECT OF SPUR DIKES ON FLOOD FLOWS THROUGH HIGHWAY BRIDGE ABUTMENTS

A report for

C.E.422 - HYDRAULIC RESEARCH (3 & 4 Credit Hours)

by

ROBERT J. CARLE and JAMES C. KABLE

Submitted to

PROFESSOR JOHN B. HERBICH

Hydraulics Division

Fritz Engineering Laboratory

Department of Civil Engineering

LEHIGH UNIVERSITY

Bethlehem, Pa.

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SUMMARY

(1) Scouring of bridge piers and abutments is a source of expense to highway departments, especially during floods when millions of dollars worth of damage can be caused by the collapse of highway bridges. To date, research on this problem has been spasmodic and limited.

(2) The investigations carried out in this report consisted of tests on a 45° wingwall type abutment placed in a fixed bed. Velocity distribution and depth constituted the primary criteria for comparison between tests.

(3) A series of tests was run using four discharges, 1 c.f.s, 2 c.f.s., 3 c.f.s., and 4 c.f.s. The abutment width was varied from a minimum of 9" to a maximum of 71", a total of 6 separate openings in all. The data from these tests was compared and Test No. 4 was chosen as the most representative of all the tests.

(4) Spur dikes were then placed in the tank and further runs made to determine the effect of the dikes upon the scouring potential of each flow.

The data obtained from these runs was then compared with the original tests. Based upon these comparisons, the following conclusions and recommendations were made.

(a) The 45° wingwall type abutments are inferior in design and are, in fact, conducive to scour. Separation occurs on both the upstream and downstream corners at comparatively low flows and circumferential velocities due to eddying and turbulence are high. Thus the "flow through" type of abutment is far superior.

(b) Spur dikes placed upstream from the abutments along the streamlines are an effective way of preventing upstream separation and provide a smooth transition, thus maintaining a constant velocity distribution across the abutment opening and preventing high localised velocities, a prime cause of scour.

(c) Small stub dikes placed downstream of the vertical abutment wall prevent the downstream separation and eliminate the hydraulic jump on the downstream side of the abutments.

NOMENCLATURE

Symbol	Definition	Unit
A	area	ft^2
A_r	area ratio	-
C_d	coefficient of discharge ≈ 0.98	-
g	acceleration due to gravity	ft/sec^2
Δh	manometer differential	ft
L	length	ft
L_r	length ratio	-
N_f	Froude number $= \frac{V}{\sqrt{gL}}$	-
n	Manning's constant	$ft^{1/6}$
Q	discharge	cfs
Q_r	discharge ratio	-
q	unit discharge	cfs/ft
V	velocity	ft/sec
V_r	velocity ratio	-
y_c	critical depth	ft

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1.0 INTRODUCTION

1.1 General

In highway engineering, increasing emphasis is being placed on the hydraulic design of bridge piers, abutments and the general location of bridges. It has been the case in the past that bridge superstructures have been designed meticulously from the structural point of view while the hydraulic design of the piers and abutments has been approximate only. The results of this are disastrous. In the State of Connecticut alone, during floods which occurred in August and October of 1955, over $30,000,000 worth of damage was caused, primarily by collapse of bridge piers and abutments due to scour and its effects.

Undermining of structures because of scour is still very much a problem, especially with the present trend towards high approach embankments to bridges, with consequent deep flood plain flow. It has been ascertained that scour is especially noticeable at the piers of bridges which are badly located, and especially <u>at points of severe stream curvature</u>, resulting in deep scouring at the outside of the bend.

The spur dike offers definite advantages in this connection. A spur dike is a projection extending from the bridge abutment and which serves to channel the flow of water smoothly through the opening between the abutments. (See Fig. 1)

The proper design of spur dikes, therefore, would

(a) reduce the chances of scour at bridges ;

(b) avoid excessive backwater with its accompanying damage, especially in built-up areas ;

(c) permit the design of approach roadway embankments to keep the highway above selected floods and also provide relief for the bridge opening by permitting floods of greater magnitude to flow over the embankments.

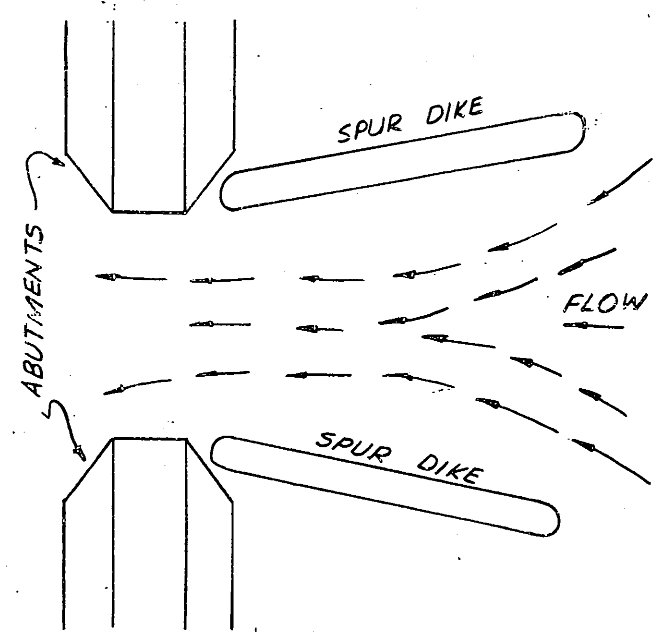


FIGURE 1

Typical Spur Dike

1.2 Objectives

Although some research on the hydraulic aspects of bridge design has been conducted, a variety of problems is still unsolved, including a study of the actual effect the placing of spur dikes in a stream will have upon the abutments of a bridge. Many of the studies undertaken so far have been sponsored by the Highway Departments of various States and interest is growing in view of the large dollar damage to bridges during floods. One of the most intensive studies is being carried out by the University of Colorado, using spur dike models in a moveable bed. One progress report on this work has already been published, but the literature generally available is limited.

With these considerations in mind, it is the objective of these tests to determine the shape and size of dikes necessary for more or less generalised conditions, consistent with typical field conditions. The tests were carried out in a fixed bed, using velocity distribution as the criterion for comparison with the work already carried out by the University of Colorado. In this way, optimum conditions for the establishment of the dikes could be evaluated and, particularly, easily run tests on <u>any</u> fixed bed model would indicate the probable resulting effect due to various velocities and the means to overcome the scour problem.

1.3 Limitations

The limitations of these tests are as follows -

(a) the secondary effect of backwater was negligible, and, in any case, measurement of backwater in front of the abutment was not contemplated in view of the length of the tank, 35 ft.;

(b) the width of the tank was 10 ft. and was not altered during the complete testing program; however, although a limitation, the results were certainly indicative and typical of many of the prototype bridges constructed and/or under construction.

Keeping the above points in mind, it was felt that study and examination on spur dikes in a fixed bed model would be particularly valuable, in view of the fact that a parallel study was being carried out by the University of Colorado, with a moveable bed model and because of the lack of previous pertinent literature on the subject of spur dikes.

2.0 HISTORICAL BACKGROUND

2.1 General

As stated previously, the amount of literature on spur dikes is very limited, although there have been published several reports regarding flow through abutments and prevention of scour. Construction of spur dikes is a means of overcoming, to a large extent, this problem of scour and hence the study of of the flow of water through abutments needs to be studied concurrently with the larger overall problem of spur dikes.

2.2 Previous Studies

The earliest laboratory study of the problem of scour around abutments was a report written in 1894 by Engles in Germany, although reference was made here to previous work carried out in France by Durand-Claye in 1873. The Engles study was confined to narrow limits, however, and no attempt was made at generalisation nor prediction of scour patterns.

Investigation in this field seems to have lapsed for some years and it was not until 1949 that a theoretical approach to the problem was attempted. The United States Department of Agriculture published in April of that year a paper entitled "Flow Through Diverging Open Channel Transitions".(1) This was followed by an investigation by the United States Department of the Interior on "Computation of Peak Discharge at Contractions"(2) in 1953.

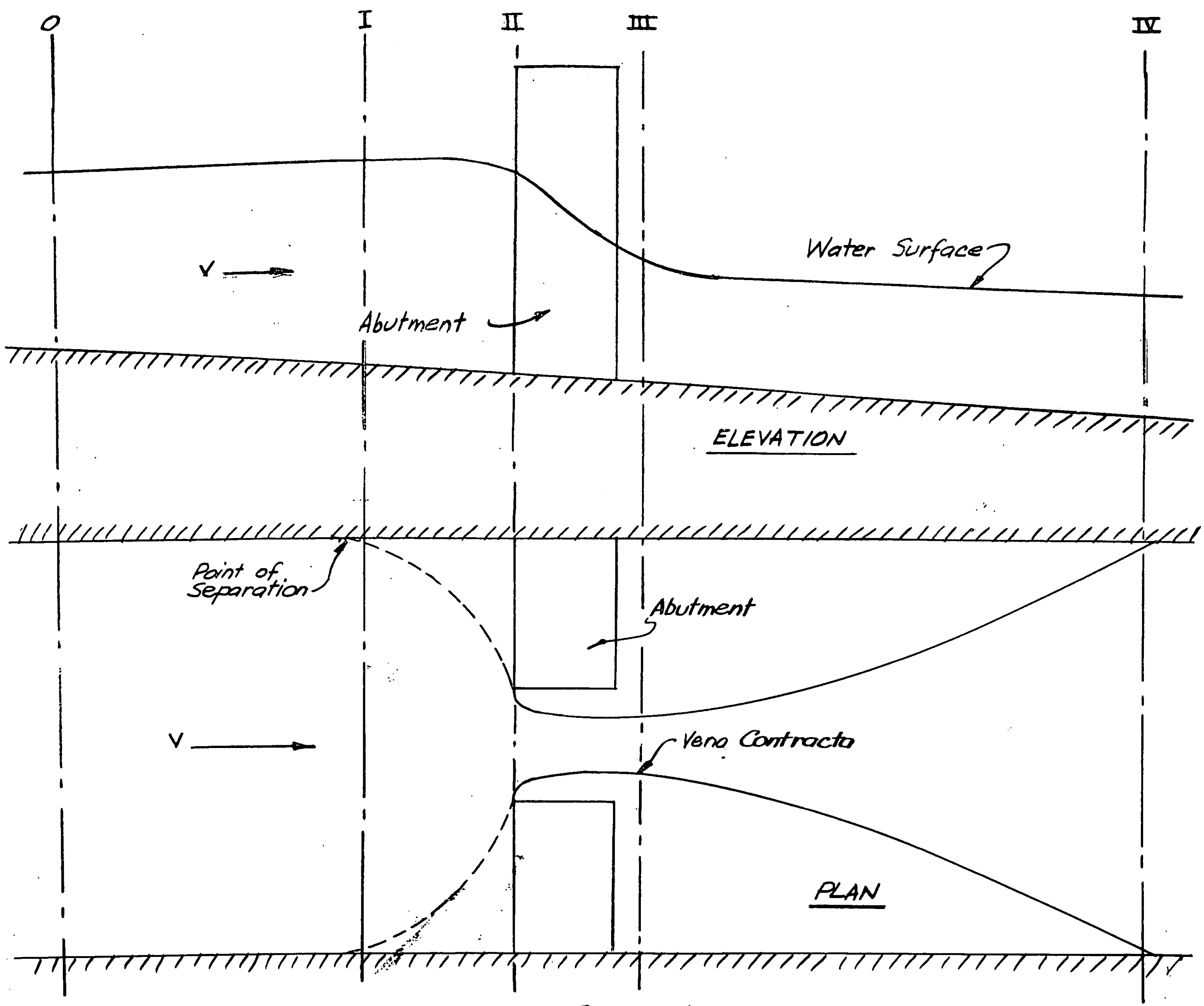
After the publication of the data obtained from these studies, the State University of Iowa, under the auspices of the Iowa State Highway Commission, began investigations into "Scour Around Bridge Piers and Abutments".[3] This work by Emmett M. Laursen and Arthur Toch in 1956 was concerned solely with scour and it was not until January 1959 that the University of Colorado[4] began its program on spur dikes, using a moveable bed model.

3.0 THEORETICAL ANALYSIS

3.1 Flow Through Constrictions

Since great depths of scour have been observed at bridge abutments during flood flows, a sketch of such flows would probably indicate the areas of greatest concern. The figure on the following page[4] is divided into four significant areas. At section O the flow is almost unaffected by the constriction. The depth of flow increases to a maximum at section I, and then begins to decrease through section II where the maximum contraction occurs. A minimum flow area is reached at section III, and then the depth begins to increase toward normal at section IV.

The plan view shows the upstream flow separating from the sidewalls and converging toward the opening. A zone of separation, zone A, is formed by the wall and the outer stream line. The streamline next separates at the sharp entrance to the constriction and forms the zone of separation shown as zone B. A very strong eddy is formed at the beginning of zone B, whereas a large circling mild eddy was formed in zone A. Since the outer streamlines leave the walls of the constriction, the narrowest width of flow is less than the width of waterway. Between sections III and IV the flow diverges back to natural width and depth. If the constriction were sufficiently great to cause supercritical flow, the above zones of separation would be even more distinct and a hydraulic jump would be



DEFINITION SKETCH OF SIMPLE NORMAL CROSSING
TAKEN FROM "BACKWATER EFFECTS OF PIERS & ABUTMENTS"
by LIU, BRADLEY AND PLATE

formed between sections III and IV.

The energy losses in the constricted channel differ from the losses in a natural channel in the following manner: the loss is less than the normal energy loss between sections 0 and I; between sections I and II the losses are almost identical; the energy drop is greater than the normal loss between sections II and III; and between sections III and IV the energy loss is much greater due to the boundary resistance and also to the lateral mixing of the jet with the eddying currents.

It seems apparent from the above discussion that there are certain areas in a constricted section that would be subjected to violent hydrodynamic action which would cause erosion and ultimate structural failures. The most pronounced of these areas is the upstream corner of the constriction. An exact mathematical analysis of this action is not possible at this time because of the many unknown facets of fluid dynamics and because of the complex nature of resistance due to constrictions in open channel flow. Since the problem is so complex, many engineers have attacked it from the experimental side and have evolved workable empirical formulae for such things as depth of scour and height of backwater.

3.2 Backwater Due to Constrictions

Any convergence of the banks of a stream will cause backwater upstream from the narrowed reach. The increased upstream stage is especially noticeable when the constriction is at right angles to the direction of flow, and the backwater increases with decreasing waterway. The Colorado Report[4] classifies backwater as (a) contraction backwater and (b) resistance backwater. When the flow is critical at the contraction, the backwater is called contraction backwater, otherwise it is called resistance backwater. Regardless of the type, backwater has greater potential energy than normal depth water, and the release of this energy through the opening causes high velocities which result in excessive scour.

3.3 Scour at Abutments

A constriction in the stream will increase the velocity and hence increase the sediment carrying capacity of the stream. If the capacity of a stream is increased, scour will occur; if it is decreased, sedimentation will occur. Although this phenomenon seems rather simple, the laws which govern sediment transportation are very complex. According to Butler[5] the depth of scour at equilibrium is independent of both the velocity of flow and the sediment particle size. However the rate of scour is dependent on both these factors. The depth of scour will increase with the depth of flow.

It is important to note that scour is not caused only by high velocities. Distortions in the flow pattern will lead to separations and eddying which cause much additional scour and usually effect the critical part of a bridge foundation.

To confirm this reasoning, Laursen and Toch[3] have found that the scour hole was centered at the upstream corner of the bridge abutment, and that the maximum depth of scour increased with increasing contraction. Moderate rounding of the upstream corners reduced the scour about 15 percent. To minimize scour at abutments it is important to have low velocity and undistorted flow, both of which are not attained with present abutment design.

3.4 Theory Behind Tests

The steel tank which was available for use in this project was 35 ft. long, 10 ft. wide, and 2 ft. deep and would serve as the flood plain across which a constriction could be placed. The normal depths and velocities were established for various discharges as shown in the table below and the critical depths were calculated using the following formula:

$$y_c = \sqrt{\frac{q^2}{g}}$$

Flow in cfs	Velocity in fps	Normal Depth in ft.	Critical Depth in ft.
1	0.31	0.144	0.068
2	0.81	0.193	0.108
3	1.07	0.235	0.141
4	1.24	0.266	0.172

The slope of the bed was negligible since the tank was placed in a horizontal position, and Manning's "n" value was assumed to be 0.015 ft $^{1/6}$. In designing the equipment, no particular prototype was considered since the project was purely research. This does not mean, however, that this study could not be applied to one or several existing structures. Assuming a flood plain of 300 ft. the length ratio would then be 30.1. since the Froude Number, $N_f = \frac{V}{\sqrt{gL}}$, is the controlling factor in open channel flow the following scales have been calculated:

Dimension	Ratio	Scale
Length	L_r	30:1
Area	$A_r = L_r^2$	900:1
Velocity	$V_r = L_n^{\frac{1}{2}}$	5.5:1
Discharge	$Q_r = L_n^{5/2}$	4930:1

<u>3.41 Abutments</u>

Considering the above length ratio and a two lane highway, an abutment one foot long would be a reasonable length. A depth of one foot was also selected so that many constrictions could be tested without over-topping the embankment. Although flow-through type abutments are used quite often, vertical board forty-five degree wing-wall abutments are also used by many state highway agencies. It was decided that vertical board abutments should be used for simplicity of construction and for more reliable correlation of test results since the mechanics of flow through this type of abutment are more readily understood than those for flow-through abutments. A sketch of the abutments can be seen in Figs. 7, 8 and 9.

3.42 Spur Dikes

Since spur dikes are essentially transitions, a logical approach to design would be an investigation of the design of such transitions. When hydraulic principles are the primary concern in the design of a structure, it is important that the structure be streamlined and not have any sharp breaks in the surface. Based on the streamline design, the dike should then be placed along the flow lines giving continuity of flow and avoiding separation. Unfortunately exact streamlining leads to much higher velocities along the boundary than would exist with a different shape. However, it is desirable to place the dike right at the upstream corner of the abutment to avoid the sharp boundary change which causes separation.

The spur dike should not be placed directly along the streamline because of increasing velocity along the boundary. Neither should it extend directly back across the flow lines since this would create a situation almost identical to the original constricted flow with respect to separation. The most desirable shape would probably be one which gradually intercepts the highly convergent outer streamlines near the embankment and then turns more sharply toward the edge of the flood plain as the length of dike increases. This design should have the following effects: (1) a dike tangential to the abutment should eliminate separation and eddying at the abutment; (2) a curved dike should prevent separation at the beginning of the dike itself; (3) the velocity should become more nearly uniform through the abutment; and (4) if the dike can be properly designed from test results the velocity might be increased at the center of the waterway, thereby causing scour in the middle of the stream which would not damage the abutments.

Studies of backwater due to piers[6] have shown that piers with round corners upstream cause only 37% of the backwater caused by piers with square corners. Since it is desirable to reduce backwater, the spur dikes should also have round corners upstream.

With the above potential design factors in mind, a testing program was established in an attempt to verify the theory.

4.0 DESCRIPTION OF EQUIPMENT

4.1 General

All the tests performed in this report were carried out in Fritz Engineering Hydraulic Laboratory at Lehigh University. Reference is made here to Figure 2 which shows the flow diagram. This set-up was used throughout the complete investigation and the individual units were as follows.

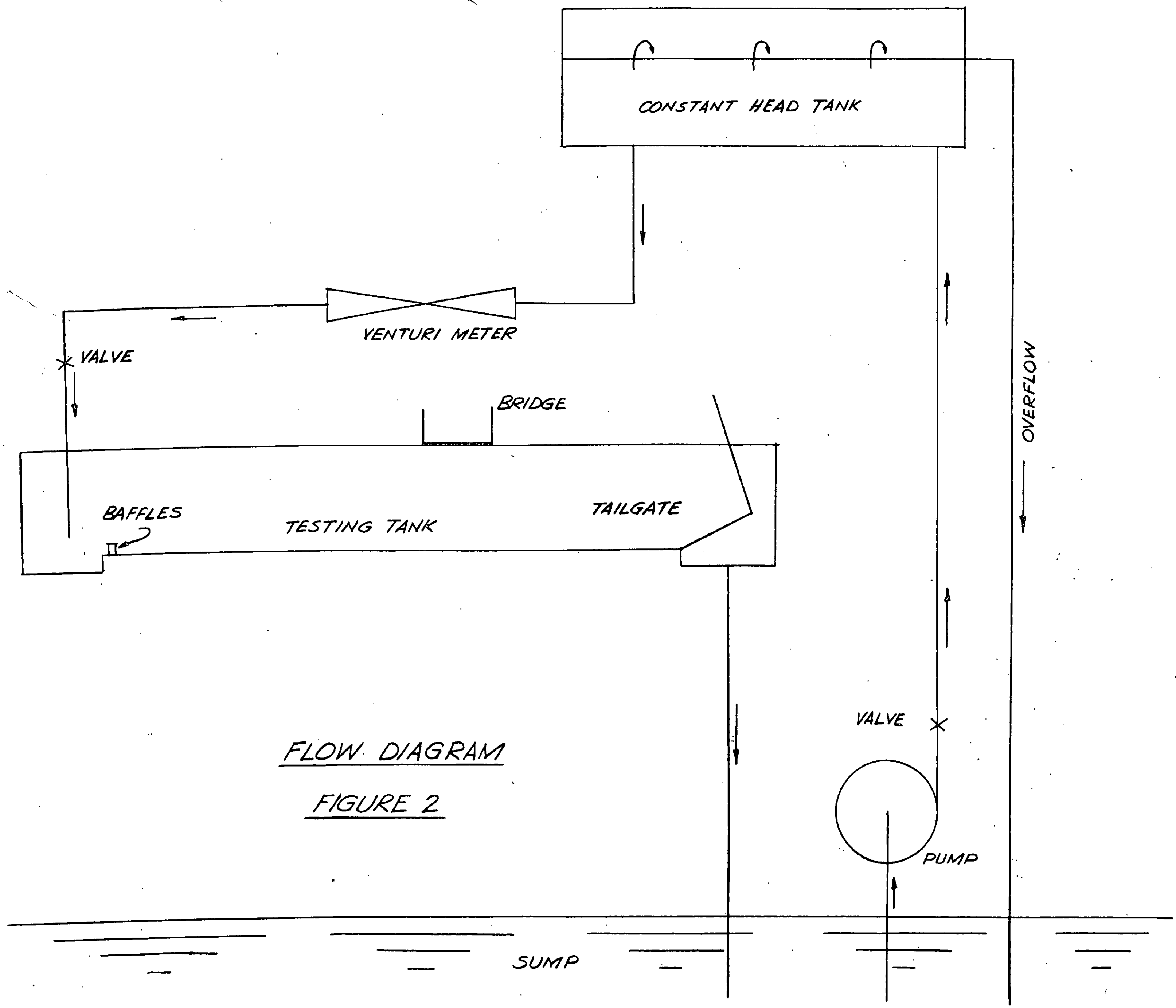
4.2 Motor and Pump

The motor used was a 25 H.P. Westinghouse model HF with a maximum of 1720 rpm. A variable speed control allowed considerable adjustment in the speed of the motor, the speed depending on the quantity of water required for each particular test.

The motor was used to drive a De Laval, model 10/8 pump, with a maximum of 1750 rpm. The rated maximum flow was 1800 gpm. against a head of 70 feet. Although another pump and motor were available for use, it was found that the one unit was ample for the limits of the investigation. The characteristic curve for the pump is shown in Figure 3.

4.3 Head Tank

The head tank supplied water by gravity to the testing tank. A constant head was maintained in the head tank by the use of an elevated overflow channel which led directly to the sump. The overflow was a 12 inch diameter spun iron pipe.



FLOW DIAGRAM

FIGURE 2

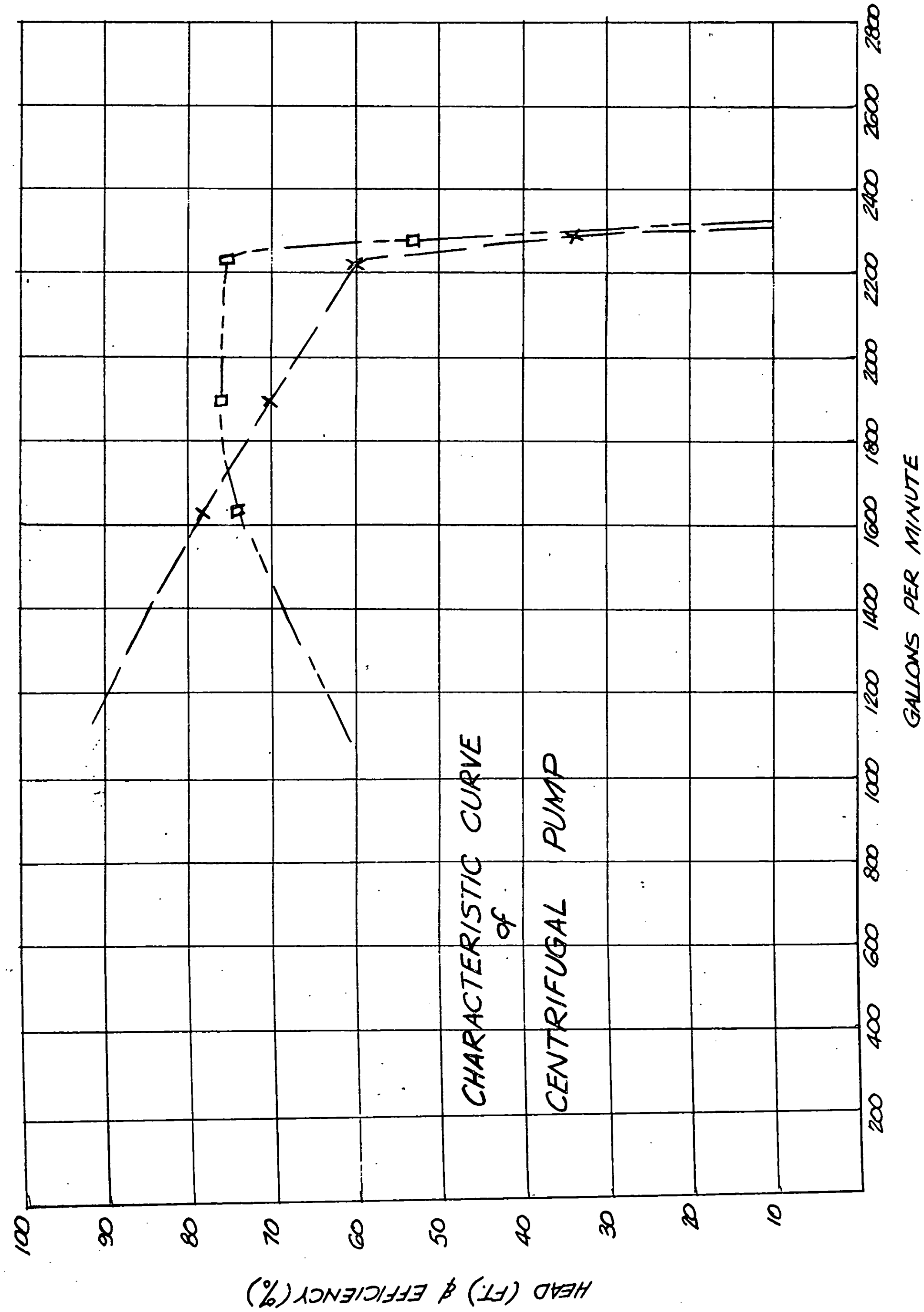


FIGURE 3

□———□ EFFICIENCY CURVE

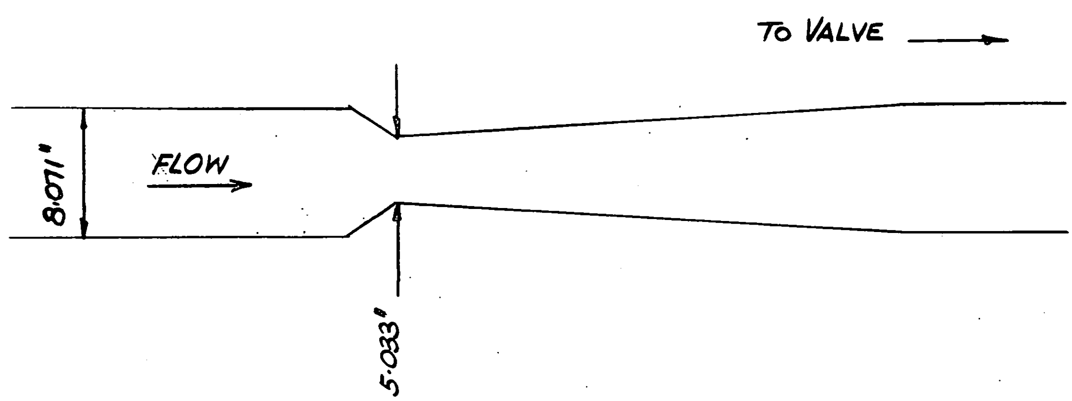
×- - - -× HEAD CURVE

4.4 Piping

Spun iron pipes were used throughout the system. A 6" valve was available for use on the downstream side of the pump, with a 6" x 8" reducer which carried the water in 8" spun iron to the head tank, a lift of approximately 28 feet.

4.5 Venturi Meter

From the head tank, an 8" spun iron pipe led into an 8" x 5" venturi meter, located adjacent to the testing tank. (See Fig. 4)



VENTURI METER

FIGURE 4

The meter was calibrated to read $Q = 1.17 \sqrt{\Delta h}$, where

Q = quantity of water flowing

Δh = height differential in feet of water

Coefficient of discharge, C_d = 0.98 with little variation.

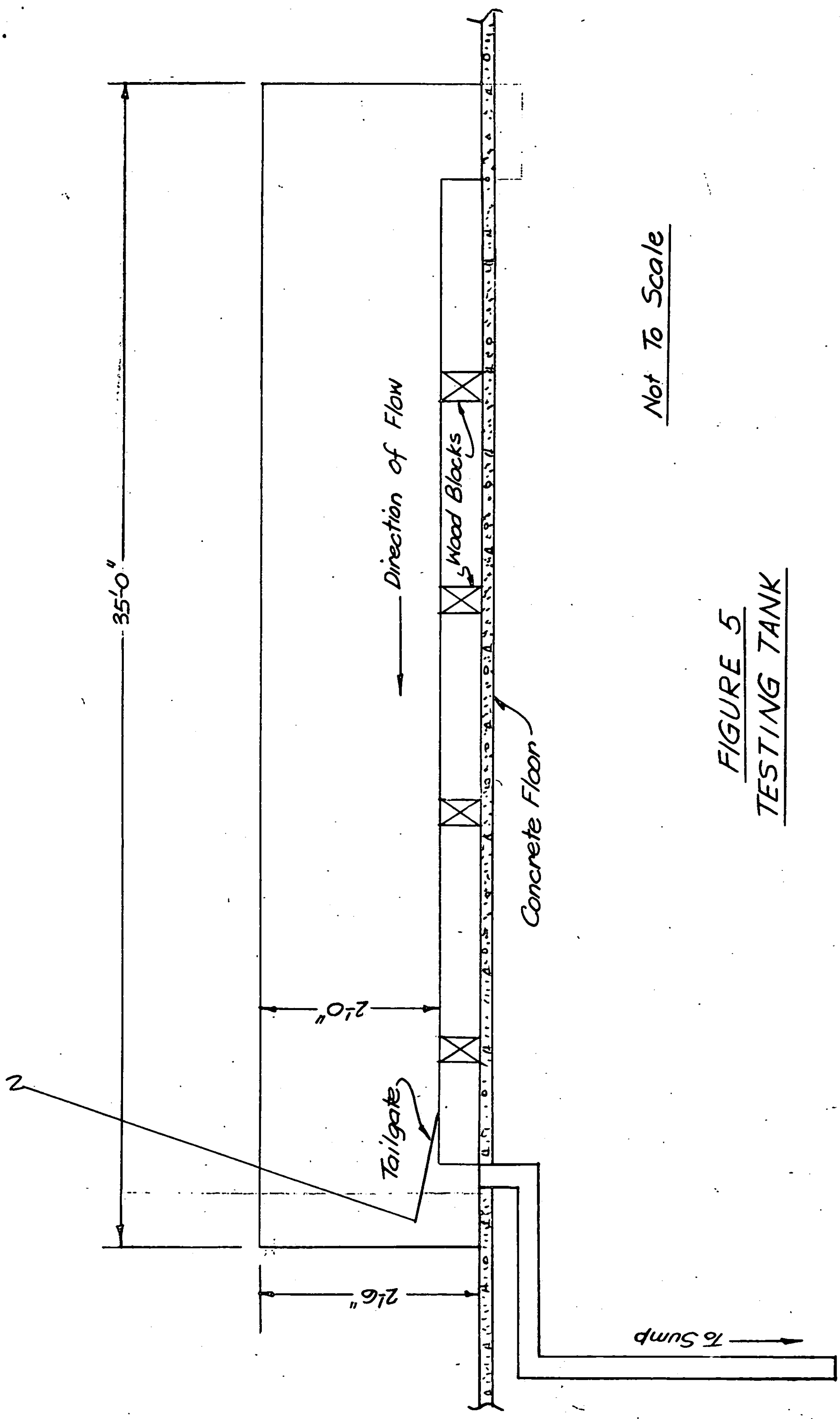


FIGURE 5
TESTING TANK

4.6 Manometer

The manometer, manufactured by Meriam Instrument Company, had a maximum differential of 100 ins., calibrated in inches and tenths. The manometer liquid was also supplied by the same company and had a specific gravity of 2.95.

4.7 Entrance Valve and Baffles

To control the quantity of water, an 8" valve was placed downstream of the venturi meter and the water then discharged directly into the testing tank.

A series of brick and concrete baffles was placed in the tank in order to provide a constant velocity distribution across the tank width.

4.8 Testing Tank

The testing tank was constructed of 3/8" steel plates welded together and measured 35' by 10' overall. A channel was provided at the inlet end, the depth of which was 2'6", in contrast with the remainder of the tank which was 2 ft. in depth. A tailgate was used at the downstream end to regulate the level of the water and the discharge flume, of rectangular section, led directly to the sump. (See Fig. 5)

4.9 Bridge

In order to facilitate taking readings and measurements, a moveable "bridge" was provided over the tank and placed into position as needed. This bridge may be seen in several of the photographs included in the rear of this report.

4.10 Point Gauge

Attached to the bridge was a point gauge, used to measure the depth of water in the tank. The gauge was calibrated to read to 0.001 ft., all center readings being taken from the bridge itself.

4.11 Current Meter

The midget current meter was manufactured by Leupold, Volpel and Company and consisted of a small propeller which was placed into the flow of water. The number of revolutions of the propeller was recorded electrically by counting the pulsations on a meter connected into the circuit. The meter was firmly screwed to the body of the point gauge and could thus be raised and lowered easily with the point gauge adjusting wheel.

A calibration supplied with the midget current meter converted revolutions per second into c.f.s. (See Fig. 6)

4.12 Abutments and Spur Dikes

The abutments were made from 20 gauge galvanised iron to a shape typically used by the Pennsylvalia State Highways Department. Sections were provided to alter the distance between abutments (see Figs.

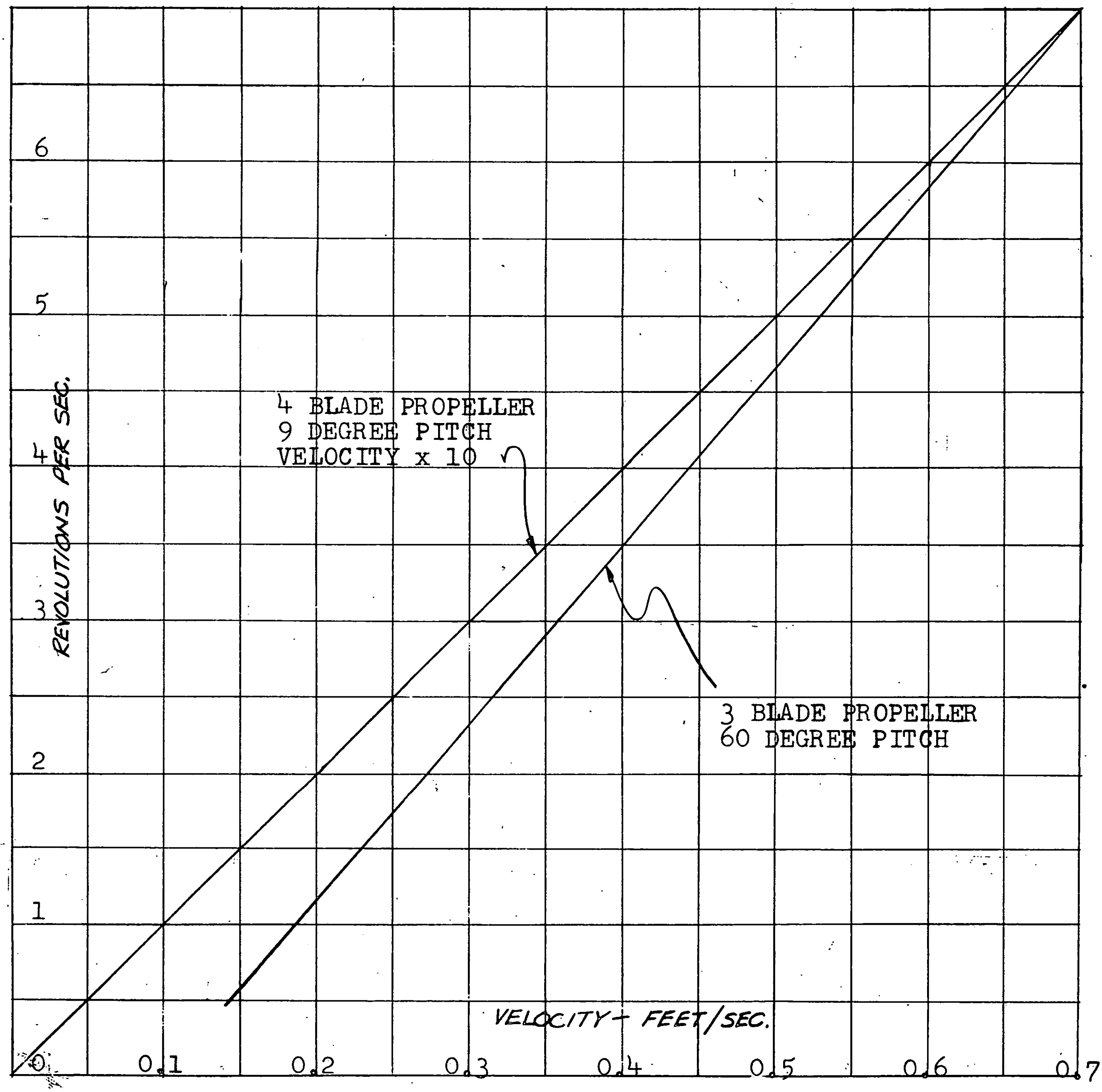
7, 8 and 9) and they were fastened to the abutment piece itself by means of small nuts and bolts.

The whole assembly was securely attached to the bottom of the tank with shaped steel straps bolted to the floor of the tank with 2½" bolts.

The spur dikes, of various shapes, were constructed of concrete and placed into different positions as the experiments required.

4.13 Sump

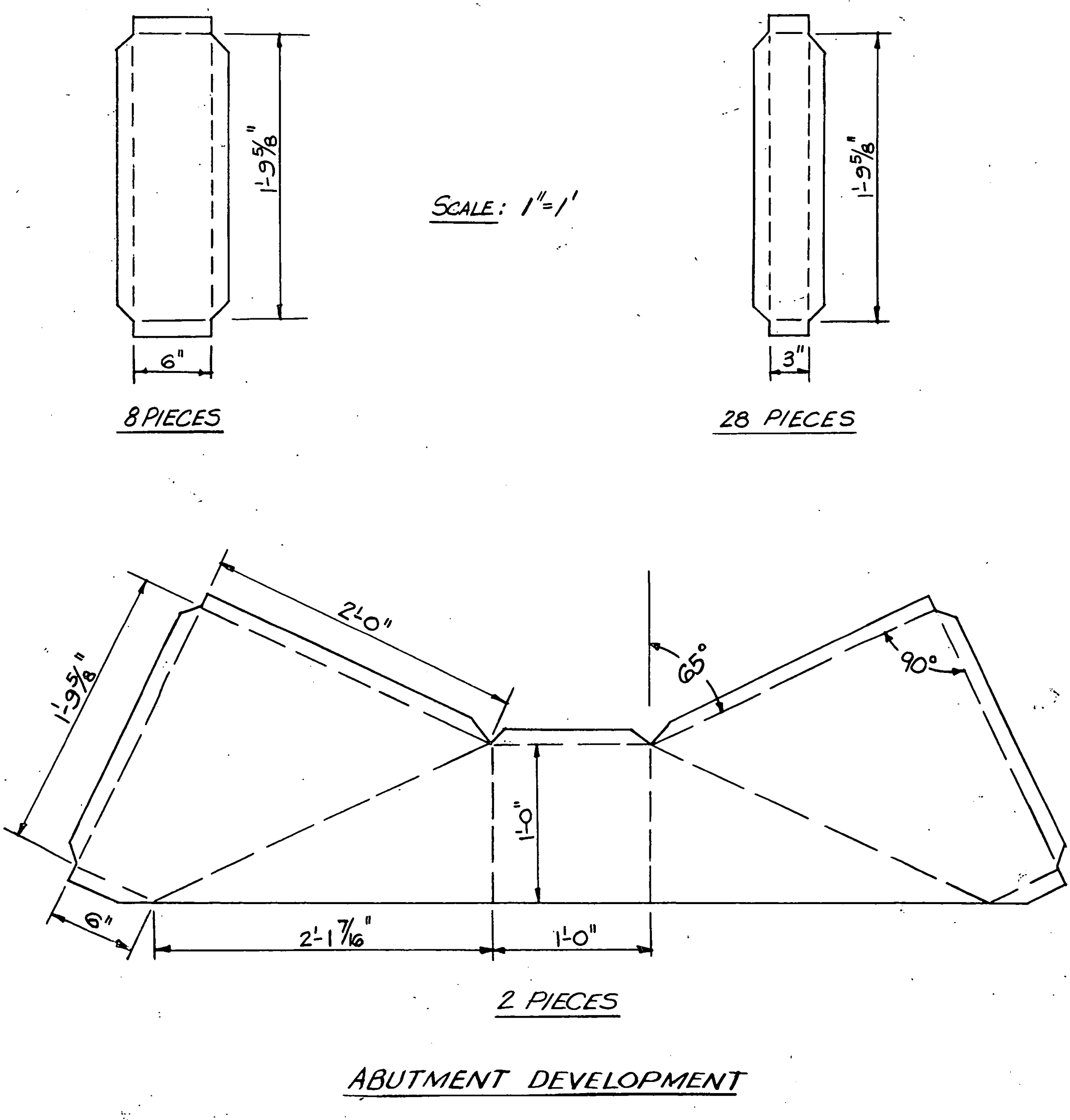
The final unit in the flow diagram was the sump which was an integral part of the basement of the hydraulics laboratory and with ample capacity to carry out the investigations successfully. The sump was drained often and cleaned in order to prevent the bottom of the testing tank from collecting rust and grit, which would interfere with the very sensitive contact on the current meter.



CALIBRATION GRAPH

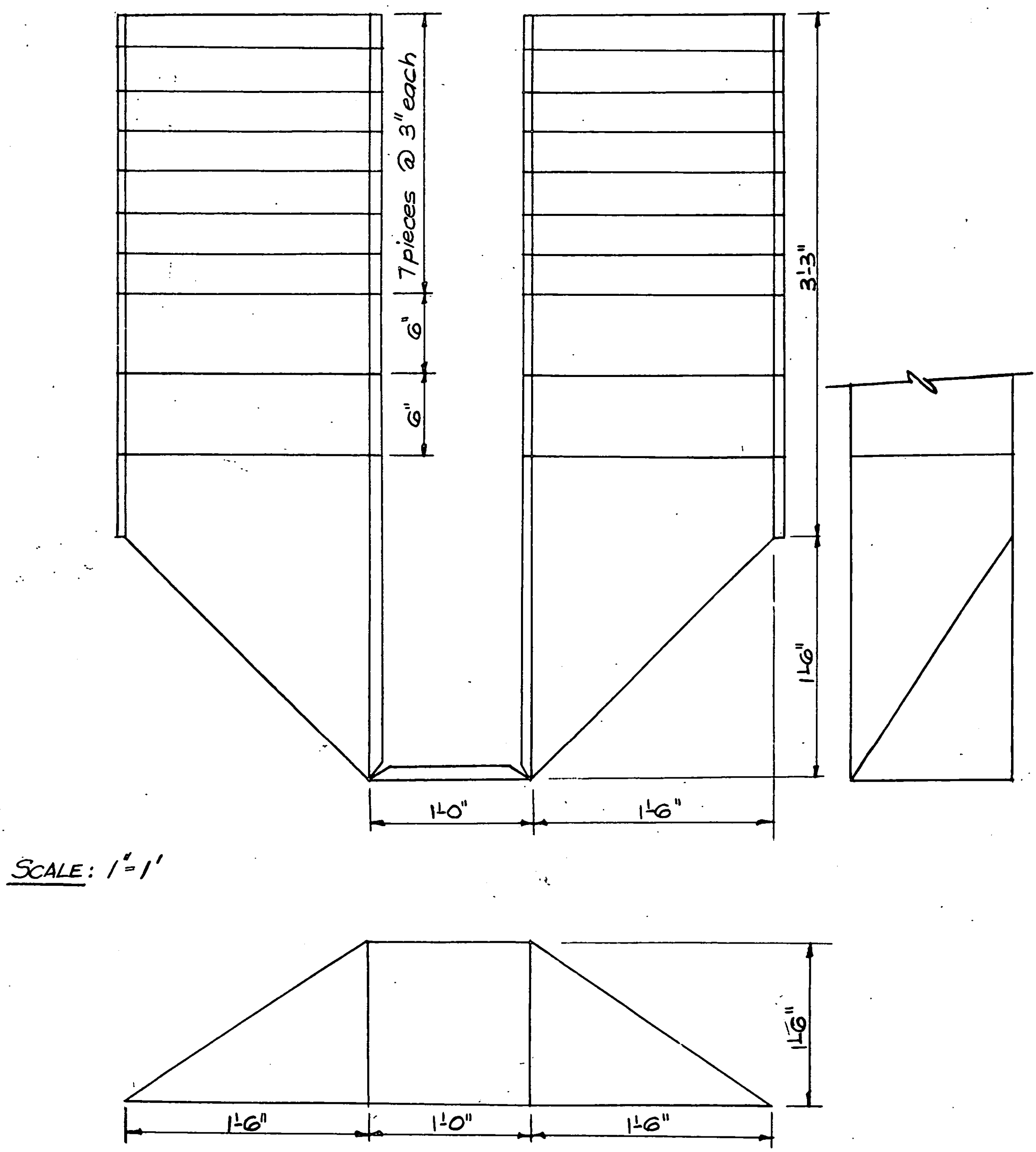
MIDGET CURRENT METER

FIGURE 6



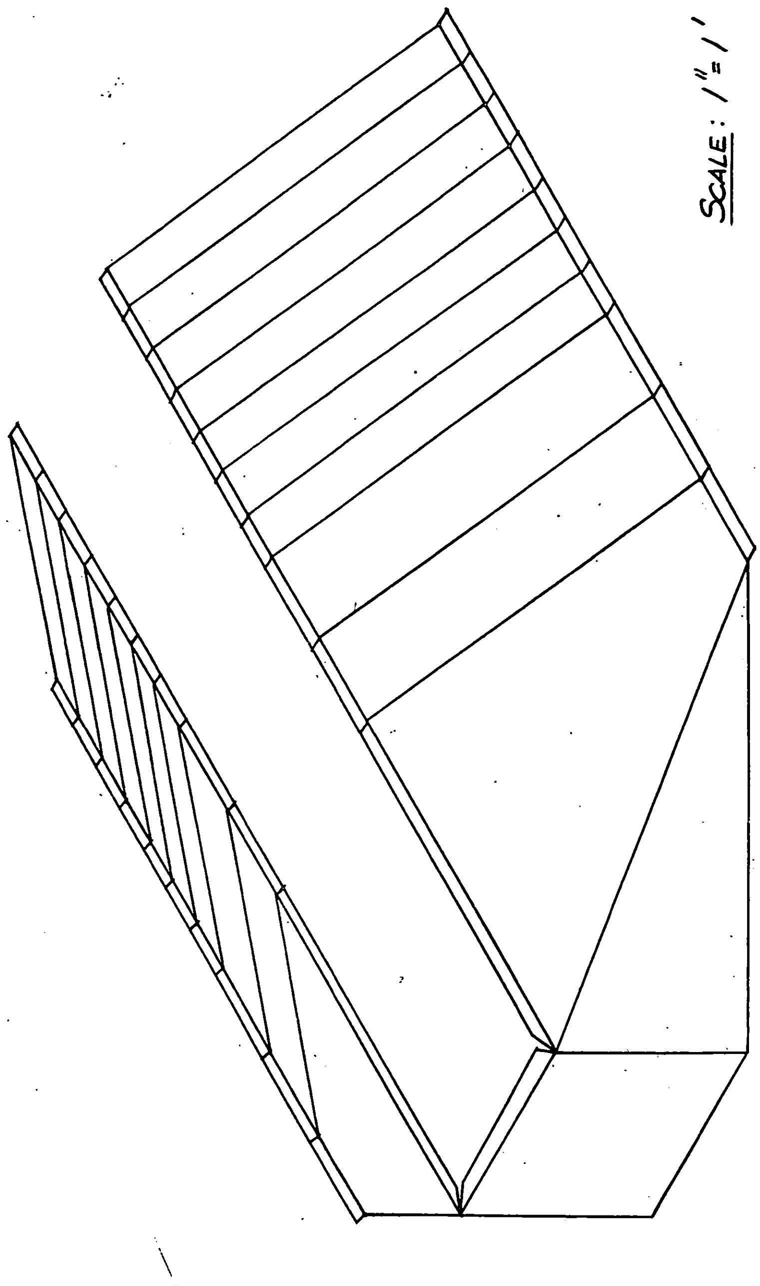
ABUTMENT DEVELOPMENT

FIGURE 7



VERTICAL WALL ABUTMENT

FIGURE 8



SCALE: 1" = 1'

ISOMETRIC SKETCH

FIGURE 9

5.0 DESCRIPTION OF TESTS

5.1 Establishment of Datum

The first investigation was to determine the level of the bottom of the testing tank in order to establish a datum to use throughout the succeeding experiments. To do this, the tank itself was marked off to form a grid and in this way, easy recognition of sections was made. The grid pattern with its associated section numbers is shown in Figure 10 below and reference is also made to the Data Sheets, pps. 99 and 100 showing the actual readings taken.

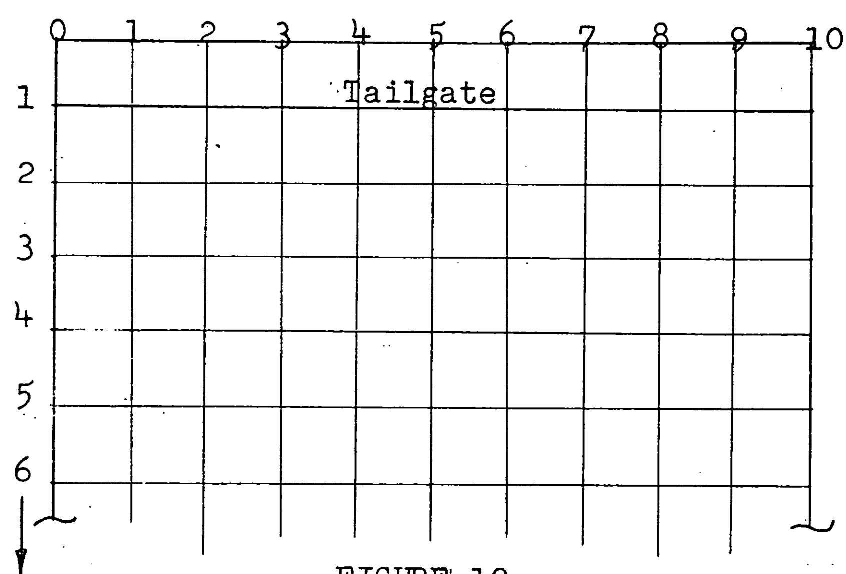


FIGURE 10

Grid Pattern and Sections on Tank

The bridge was moved into position and a check made on the deflections across the span of 10 ft. However, with two operators and equipment, the deflection was zero, or, at least, could not be measured with the point gauge. As the tank itself had been levelled previously during installation, the bridge and hence the point gauge attached to it, were perfectly level. This was checked periodically during the tests and found to be accurate.

The datum was thus established and the level of the tank bottom checked. As can be seen by reference to the Data Sheets mentioned above, the values were all within 0.01 ft. of each other, discounting the major discrepancies in readings which were found to be those near welds. The bottom of the tank was constructed of 3/8" M.S. plate, butt welded together and in the vicinity of each weld, the plate tended to buckle downwards. This was also true of the outside edge where the sides were also welded to the floor. It was recognized that the side discrepancies were of little concern but it was felt that better results would be obtained if the model abutments were placed in a position away from a longitudinal floor weld if possible and preferably in an area where the bottom of the tank was level. As the exit channel and tailgate induced a decided draw-down, the section chosen also had to be placed as far upstream as possible, and yet be far enough downstream that the baffles would effectively smooth out the flow of water before reaching the abutments. A compromise was eventually made by choosing, tentatively, Section 7.*

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* Unless otherwise stated, section numbers referred to as such eg. "Section 7", refer to sections across the width of the tank.

In this position, the difference between maximum and minimum floor levels was 0.008 ft., discounting side weld discrepancies, and, having found the exact level of the tank bottom to 0.001 ft., the actual depth of flow at any section could be easily computed.

A tentative position for the abutments was thus chosen and a test was made to determine the effect of backwater at this section.

5.2 Backwater Check

The tank was filled with water and a flow established representing the maximum flow anticipated to be used during the succeeding tests ie. 4c.f.s. The manometer readings were as follows -

$$h = 22.5 + 25.5 = 48'' = 4 \text{ ft.}$$

$$\text{Height of Equivalent Water Column} = 4 \times 2.95 = 11.80 \text{ ft.}$$

$$\text{Thus, } Q = 1.17\sqrt{\Delta h} = 1.17\sqrt{11.80} = 4.02 \text{ c.f.s.}$$

The tailgate was then raised so that the water level increased to a depth of approximately 8". After the flow had stabilized, surface level readings were taken and accurate depths established. The results are shown in Figures 11a and 11b and on Data Sheet, p. 101. As can be seen, the backwater effect was negligible at Section 7; that is to say, the water surface levelled off approximately at Section 5 and remained constant at this one depth far beyond Section 7. Also, the depth across Section 7 was nearly constant and, in view of these results, this section was chosen as the centerline of the abutments.

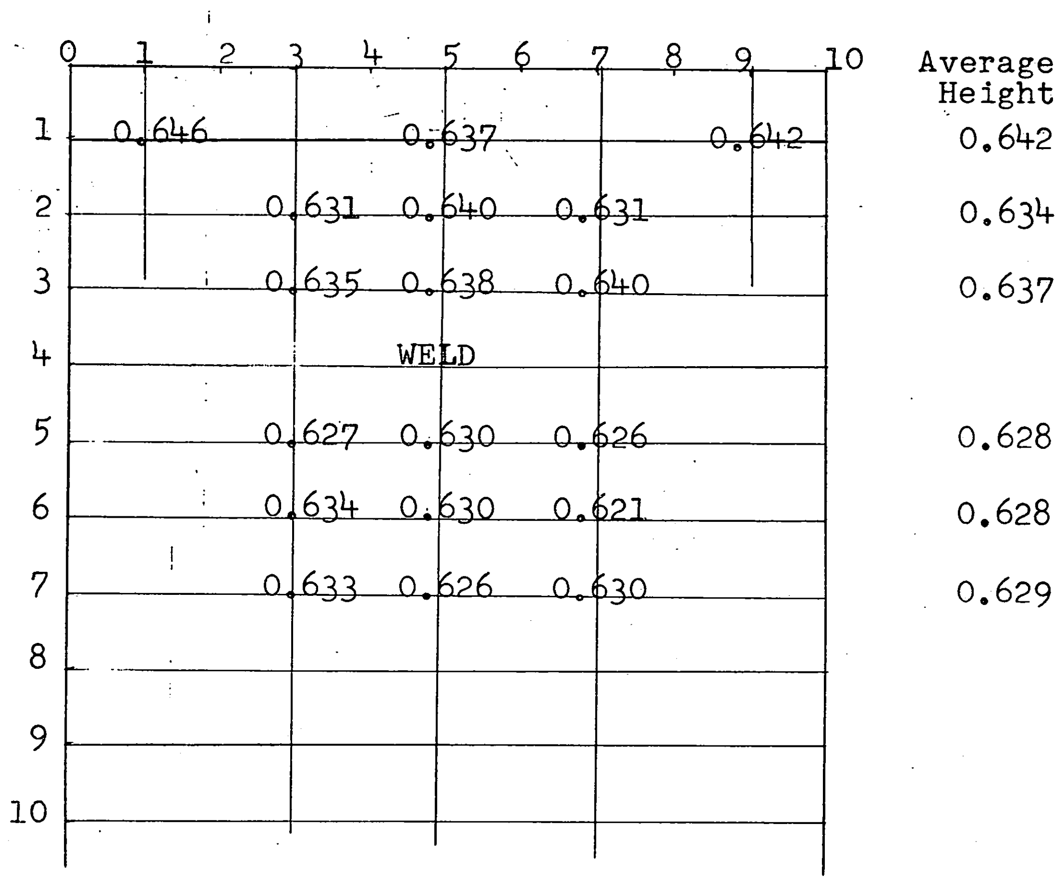


FIGURE 11a - Depths Behind Tailgate

5.3 Determination of Uniform Velocity Distribution

Before any tests could be run on the abutments, a constant velocity distribution across the width of the tank was necessary in order to avoid the local effects of eddies, turbulent flow etc. usually associated with this kind of test, especially as the water entered at one point viz. at the center of the entrance channel (See Fig. 2). To accomplish this uniform distribution, a system of baffles had to be devised which would disperse the highly concentrated entering flow.

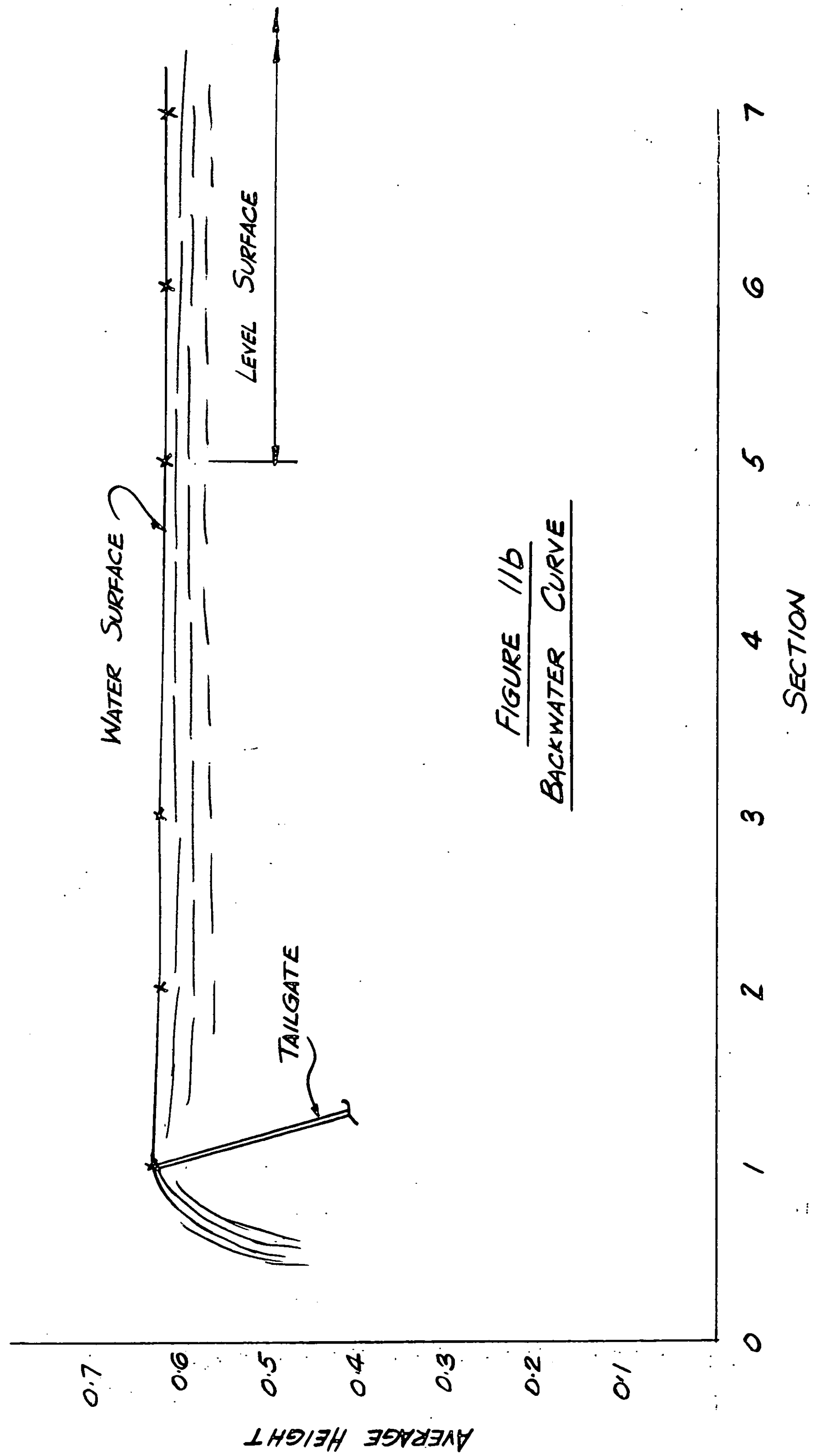


FIGURE 11b
BACKWATER CURVE

Furthermore, the flow had to be dispersed across the width of the tank.

As a first approximation, three rows of common bricks were placed, staggered between rows, at the upstream end of the tank but a check on the velocities along Section 7, the abutment section, showed a decided short-circuiting along one side of the tank. In fact, the velocity on this side was over twice as high as that on the other side. (See Fig. 12 and Data Sheets, pp. 102 - 105)

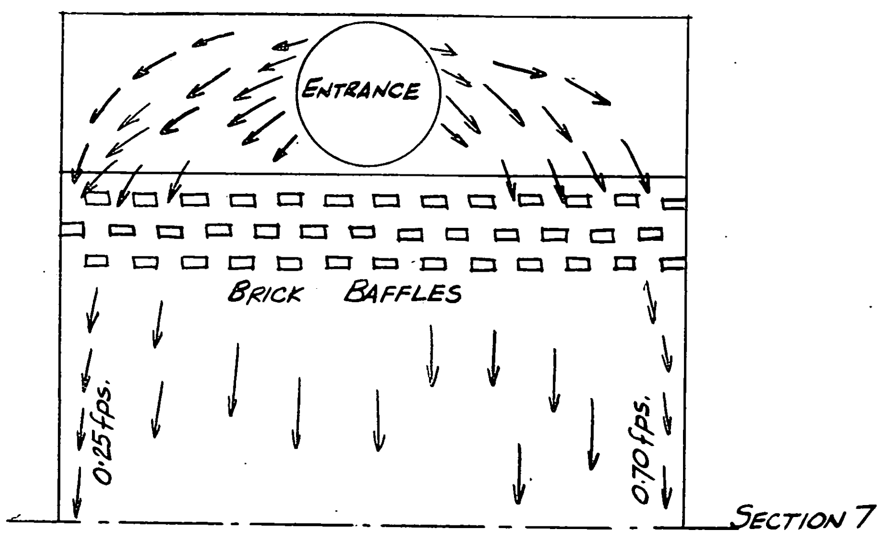


FIGURE 12 - Baffles, Run No. 1

It was then decided to place extra baffles in the entrance channel itself in order to prevent the flow of water along this one side and four 6" x 6" concrete blocks were placed as shown in the Data Sheets referred to above. Two runs were made, with the blocks in different positions and the velocities checked each time. Once again, however, the velocity distribution across the tank at Section 7 was unsatisfactory.

Another four blocks were then placed in the entrance channel in an effort to block off the excess flow and six more runs were made, varying the position of the blocks at each run. Only velocities across Section 7 were checked each time, except for the final run where Sections 2 and 12 were also included.

After positioning the concrete blocks for Run 9, a close approximation to uniform flow was established and it was decided then to leave the concrete baffles as they were but to add extra bricks in front of the three rows already placed, wherever the velocity needed to be lowered. It was found that, after four more runs, the velocity distribution at Section 7 was very nearly constant, there being a difference of only 0.067 fps. across the full width of the tank. A check on velocities at Sections 2 and 12 showed the same constant distribution. It was decided to continue with the tests, using the baffles in this one position. (See Fig. 13)

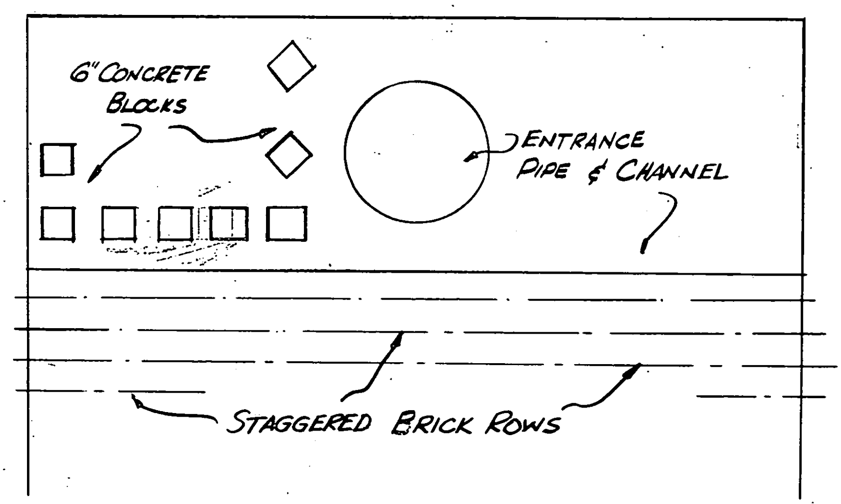


FIGURE 13 - Final Baffle Arrangement

5.4 Normal Depth and Velocity

Having established a constant velocity distribution across the tank, consideration was given to the number of flows required and the normal depth and velocity of these flows. The maximum flow available from the head tank was approximately 4.5 c.f.s. and so a maximum of 4 c.f.s. for the purpose of the tests was decided upon. In order to provide as wide a range of tests as possible, keeping in mind the information required, flows of 1 c.f.s, 2 c.f.s. and 3 c.f.s. were used to augment the maximum flow and these flows were thus used to determine normal depth and velocity through the tank.

To ensure complete accuracy, the flows were controlled using the discharge valve and the height differential of the manometer.

$$Q = 1.17\sqrt{\Delta h}$$

The following table indicates the manometer differential required for each flow.

Q c.f.s.	$\sqrt{\Delta h}$, water ft.	Δh, water ft.	Δh, liquid ft.
1	0.854	0.728	0.248
2	1.71	2.94	1.00
3	2.56	6.58	2.22
4	3.42	11.65	3.97

TABLE 1

Manometer Differentials

All readings were taken along Sections 3 and 15, the former being well downstream of the abutment section (but away from the drawdown effect of the tailgate) and the latter being well upstream of the abutments (but away from the unstable baffling effect near the entrance channel). Three readings for depth and velocity were taken at three points across each section and the results have been tabulated in Table 2. Note that the velocity distribution across these sections shows the effectiveness of the baffles for all flows. At maximum flow, the highest discrepancy in velocity across the complete area of the testing tank is 0.16 fps. in 1.35 fps. or 1.18%, while at minimum flow, this difference is 1.91%, making an average error of approximately 1½%, well within the accuracy required for the intended investigation.

A temperature check on the water showed this value to be 19° C. (70° F.) and remained constant throughout the complete series of tests. As standard conditions require evaluation to a temperature of 68° F., it was felt unnecessary to make any calculations and/or alterations in this regard.

5.5 Scour Around Abutments

The first step in the evaluation of the usefulness of spur dikes was to set up in the testing tank models of the bridge abutments which were to be investigated. The models have been discussed in Section 4 of this report and reference is made to Figures 7, 8 and 9.

TABLE 2

Normal Height and Velocity

Flow c.f.s.	Section	Velocity rpm.	Height ft.
1	3	17, 18, 18	0.492, 0.489, 0.489
	15	18, 21, 19	0.490, 0.491, 0.492
	Average	18.5	0.490
2	3	48, 51, 47	0.541, 0.548, 0.543
	15	49, 51, 46	0.540, 0.541, 0.540
	Average	48.7	0.542
3	3	62, 64, 64	0.585, 0.582, 0.590
	15	64, 71, 61	0.570, 0.570, 0.574
	Average	64.3	0.578
4	3	69, 81, 77	0.635, 0.630, 0.630
	15	75, 74, 71	0.620, 0.618, 0.617
	Average	74.5	0.625

In order to be able to test a complete range of abutment openings, six series of tests were carried out - from a minimum opening of 9" to a maximum of 71". As the prime purpose of the investigation is to discuss the effects of flood flows, the narrow opening was used to represent the worst possible condition that could be found in a prototype. Although drastic, the results are indicative of possible conditions under severe flooding.

In all the six test runs made on the abutments, a system of numbering was adhered to, indicating the positions at which depth and velocity readings were taken. These numbers are used extensively in the Data Sheets and the following figure (Fig. 14) shows the position of each number in relation to the grid already established and to the abutments. The use of Figure 14 in conjunction with all succeeding figures in this section of the report will facilitate the reading of these figures.

In all cases, the letter following the number of each test indicates the flow through the abutments as follows- (a) 1 c.f.s.; (b) 2 c.f.s.; (c) 3 c.f.s.; (d) 4 c.f.s. Identification of each run can thus be made easily.

5.51 Test 1

The opening between the abutments was adjusted to 9" and the abutment sections securely bolted to the floor of the tank. The head tank was filled and a flow of 1 c.f.s. was diverted into the testing tank (Run a). After the flow had stabilized, height and velocity readings were taken (see Data Sheets pp. 106 - 108) and the heights plotted as a profile (see Fig. 15). An examination was also made of the water profile through the abutments in order to determine the possibility of scour.

This procedure was followed for Runs (b) and (c) and the profiles also plotted for comparison in Figure 15. Because of the backing up of the water behind the abutments, Run (d) could not be made without overtopping of the model and so only three runs were attempted.

As can be seen in Fig. 15, there was a large variation between the heights behind the abutments depending on the flow. However, several features in common are to be noted.

(a) The profiles are remarkably alike, with a very sharp drawdown between the abutments.

(b) Backing up of the water behind the abutments is very pronounced, producing a decided backwater, apparently extending beyond Section 18, especially as the normal height was not reached (see Table 2).

(c) The downstream levels are identical, irrespective of flow. However, the height of water in the center is far lower than that at the edges of the tank indicating, as is to be expected, a higher velocity through the abutments.

Examination of the flow showed a violent separation both on the upstream and downstream corners of the wingwall type abutments. Velocities were very high and an hydraulic jump was formed in all runs, moving farther downstream as the flow increased. Turbulence was produced along the abutment walls and it was obvious that excessive scouring would take place in a prototype under these conditions.

POSITIONS OF VELOCITY AND DEPTH READINGS

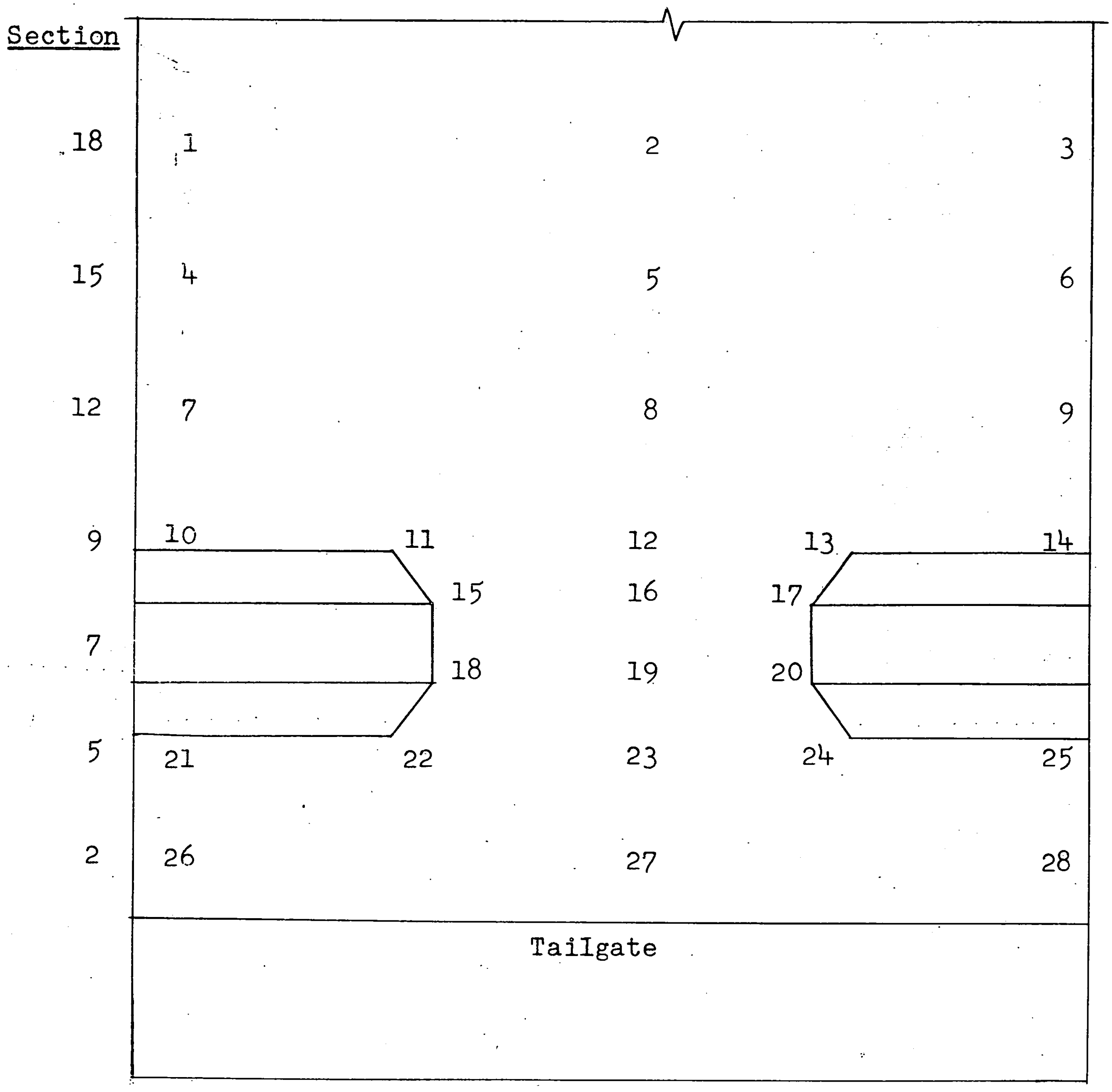
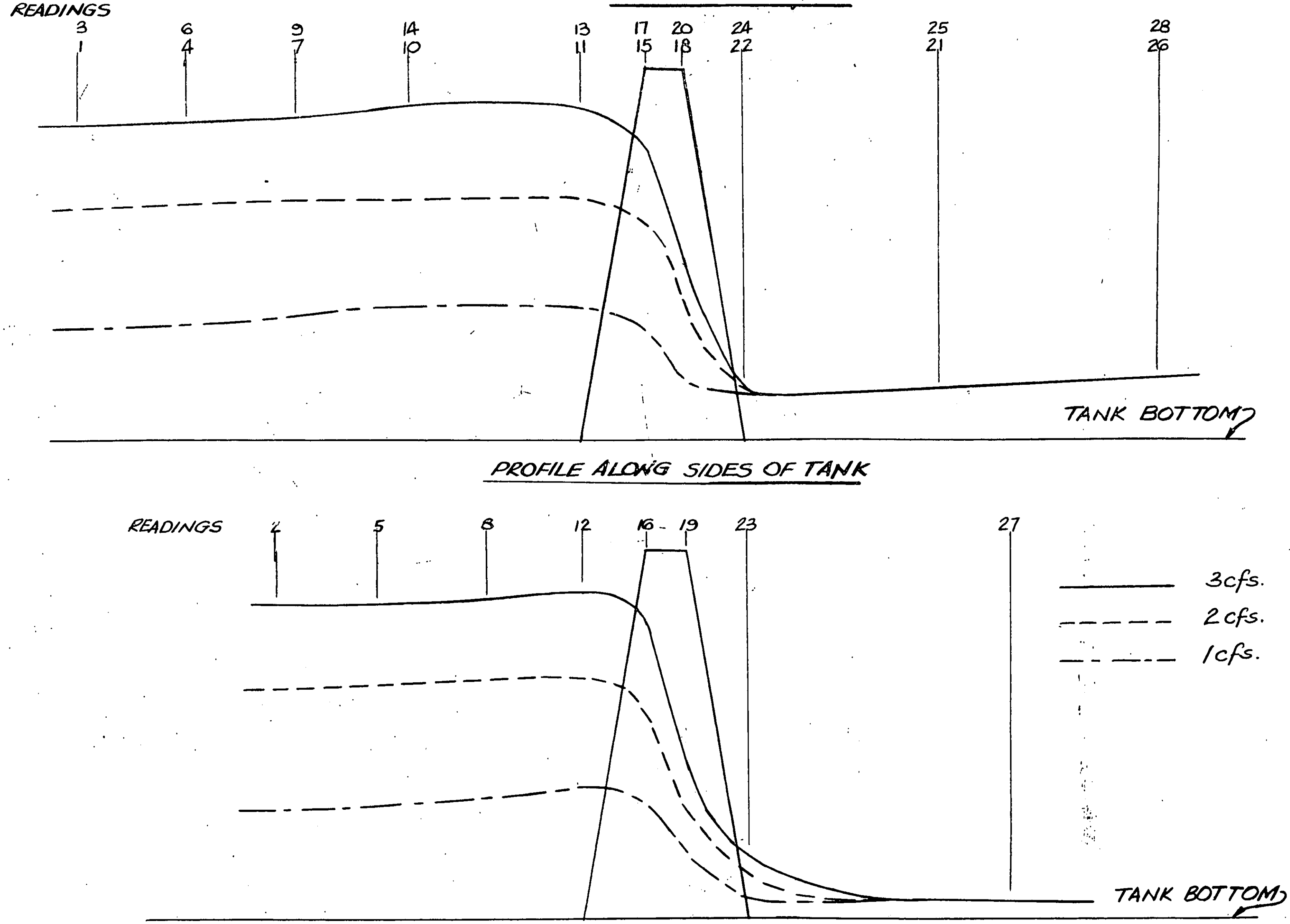


FIGURE 14

TEST RUN NO. 1



PROFILE ALONG ℄ OF TANK

FIGURE 15

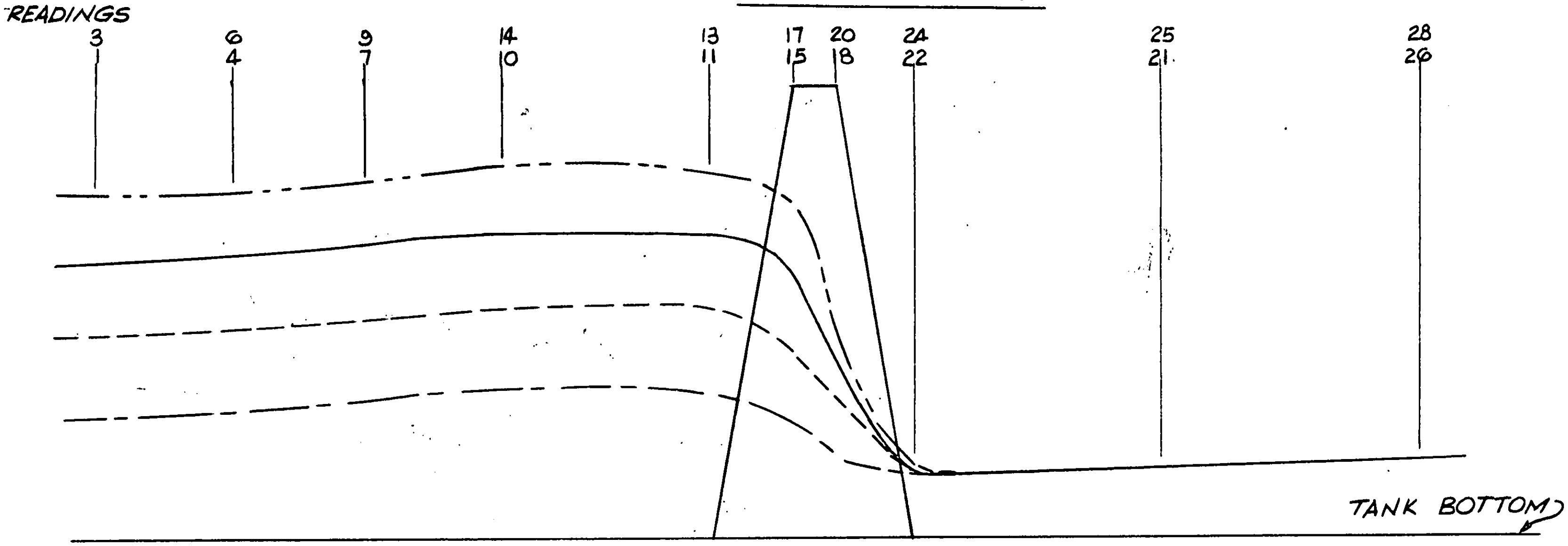
Scouring, then, is caused mainly by localized high velocities accompanied by eddying, turbulence and/ or separation. It was felt that the prime purpose of a spur dike was to minimise and, if possible, prevent altogether, these effects. The combination of all four conditions above was so violent in Test 1 that undermining of the most accurately designed abutments would have been inevitable without some remedial action taken to lower the velocities along the abutments. The high velocity was the prime consideration; without it, eddies, turbulence and separation could be controlled.

5.52 Test 2

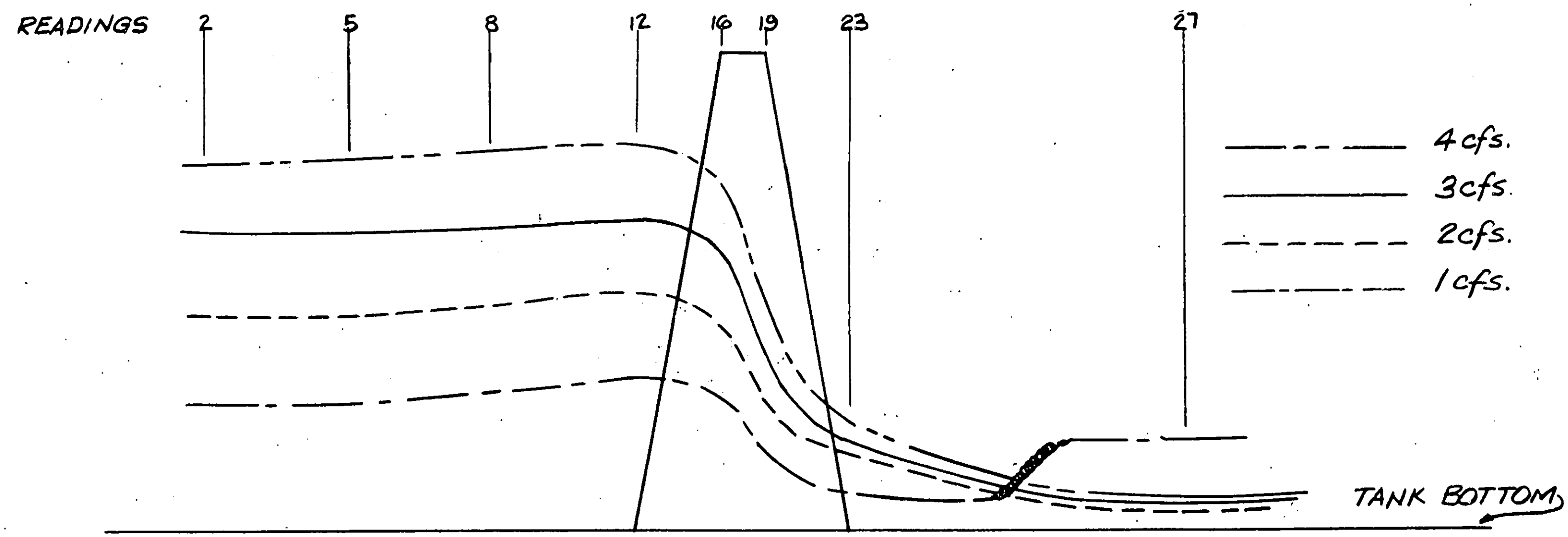
In view of the fact that only three runs could be made in Test 1, the abutment width was increased very slightly for Test 2. The new dimension was 15½" and this allowed a flow of 4 c.f.s. to be used without overtopping the model. Apart from this, a study of the profiles in Figure 16 will show that the outcome of this test was almost identical to Test 1.

The height of water, of course, was lower but the comments noted above for Test 1 apply equally as well for Test 2. The biggest contrast was that the hydraulic jump in Run (a) had moved up very close to the abutments. This can be clearly seen in the photographs included in the rear of this report. It is obvious that, as the flow decreases and/or the abutment width increases, so the jump will move back towards the constriction with the decrease in velocity until, eventually, the jump will be unable to form.

TEST RUN NO. 2



PROFILE ALONG SIDES OF TANK



PROFILE ALONG ℄ OF TANK

FIGURE 16

In this test, separation and turbulence were violent, indicating again the instability of any structure under these conditions of flood flow.

5.53 Test 3

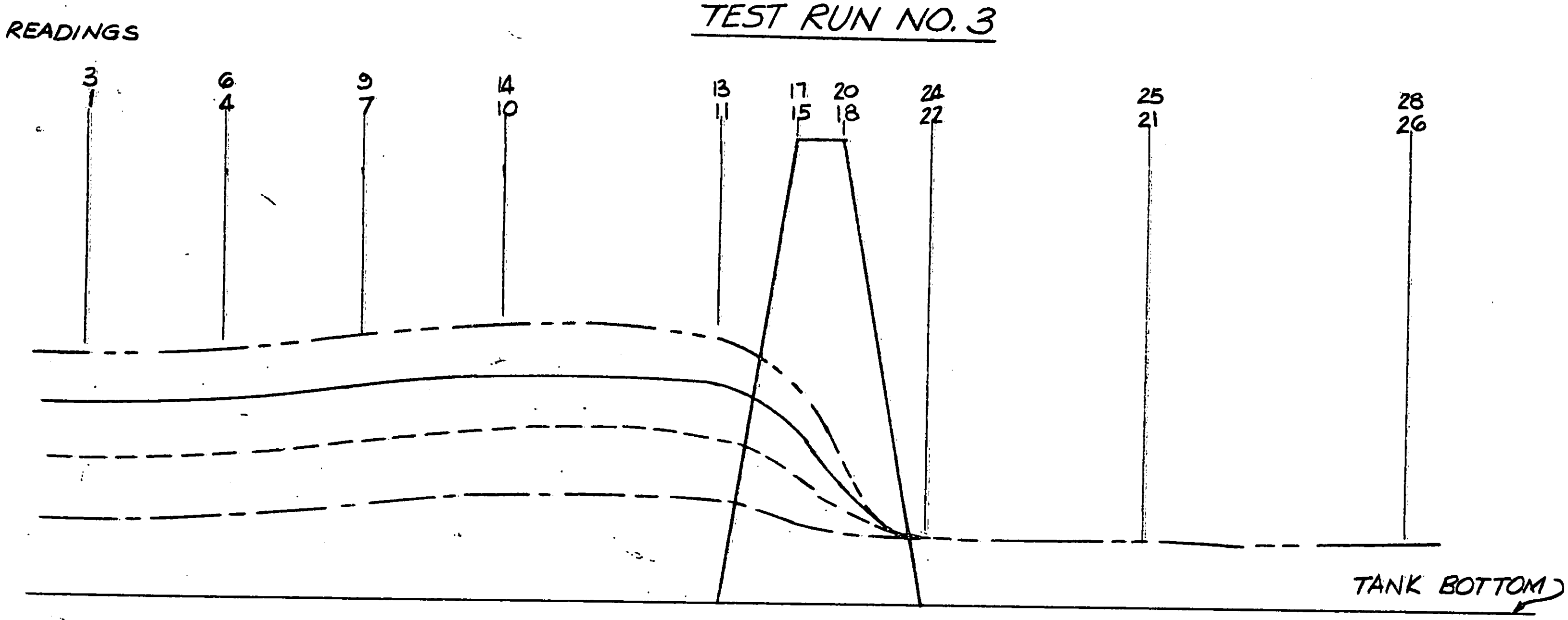
The abutment width in this test was 27 7/8" and the increase was enough over the opening in Test 2 to make a definite change in the water surface profile. The height of water behind the abutments was considerably lower and, most important, eddying and turbulence became the prime consideration in scour effects in Runs (b) and (c). Although separation occurred on both upstream and downstream corners, eddying prevented several velocity readings from being taken.

Also, an hydraulic jump was recorded close to the abutments in both Runs (a) and (b). The backwater curve was still very prominent and seemed to be caused primarily by the sloping walls of the abutments where surface tension allowed the water to "cling" to the sides much more readily than if the walls were vertical. However, the backwater curve cannot be discounted altogether; its presence, even along the center line of the tank, is proof enough that backing up of water could be disastrous during floods, especially in built-up areas. To be completely successful, a spur dike should help alleviate this condition also. Figure 17 shows very clearly the profile curves of this test with the backwater.

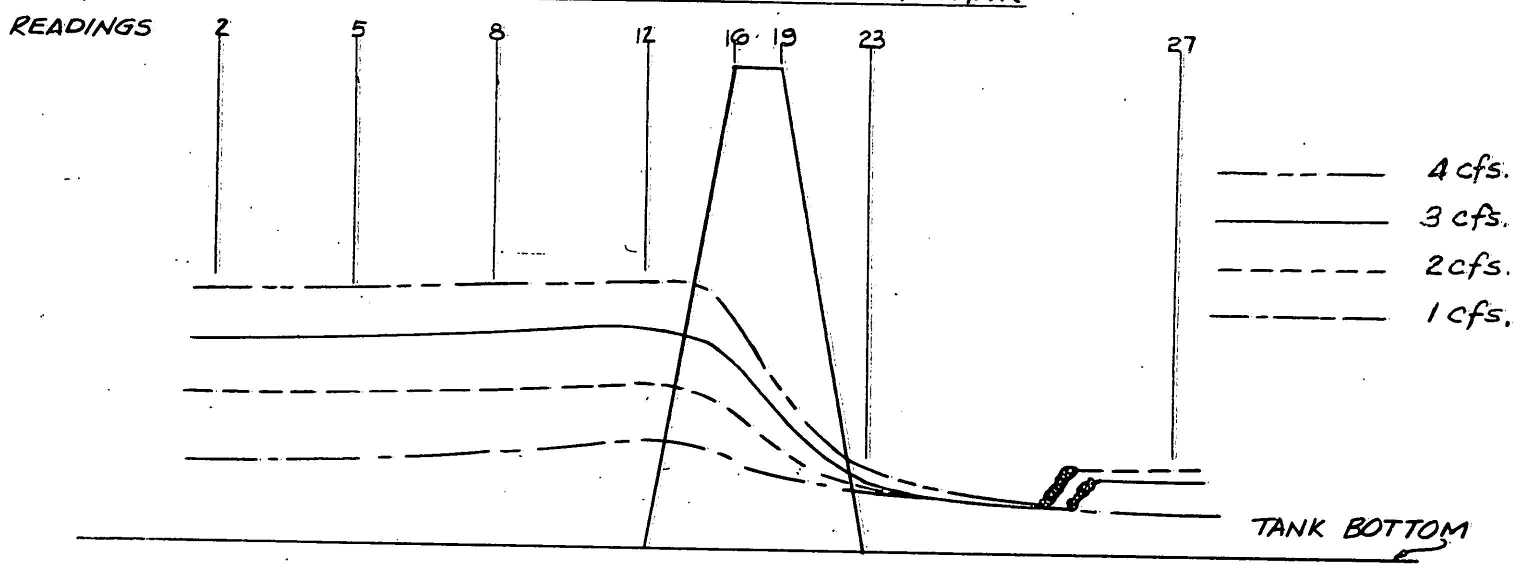
5.54 Test 4

With an abutment width of 40¼", this test was noted for one important fact - the variation in conditions between Run (a) and Run (d).

TEST RUN NO. 3



PROFILE ALONG SIDES OF TANK



PROFILE ALONG ℄ OF TANK

FIGURE 17

The water surface profile in Figure 18 does not give a full indication of the instability encountered nor of the difference between runs. Study of the Data Sheets for this test (pp. 117 - 120) will indicate a greater accuracy of information.

The following comments are noted-

(a) There was no hydraulic jump formed for Run (a). In fact, the surface levels upstream and downstream of the abutments varied very little. Separation on this run was negligible and the only possible cause of scour would be the eddies which still prevailed at the wingwalls. Velocities were low and conditions generally stable.

(b) Run (b) was unstable. Surges were common and the velocity not quite high enough to form a jump. Separation only at the upstream corner of the abutments occurred but severe eddying and instability would cause scour.

(c) Runs (c) and (d) correspond more closely to previous tests. Separation occurred at both corners as before and eddying and turbulence again made scouring inevitable.

(d) This particular test proved to be the most interesting insofar as different conditions were concerned. Not the least important was the fact that Run (b) was the unstable change-over between the high velocity-separation-hydraulic jump type of flow of the pervious tests and the low velocity-smooth profile type of flow, typical of future tests. As explained fully later, this was one of the reasons why it was decided to concentrate experiments on Test 4 and consider the effect of the spur dikes on this abutment width first.

TEST RUN NO. 4

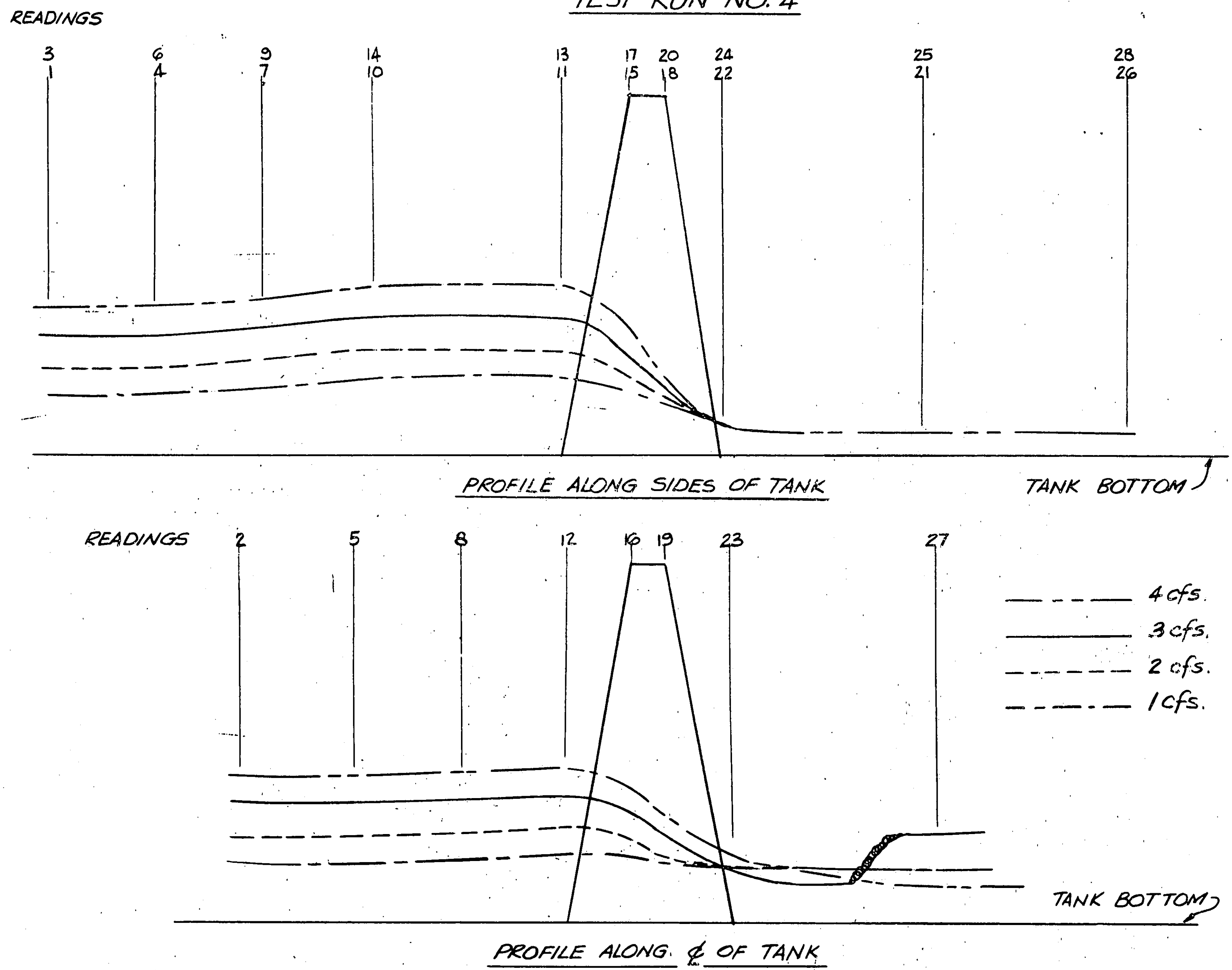


FIGURE 18

In order to describe more effectively the change in conditions in Test 4, reference is made to the photographs included in the rear of this report.

5.55 Test 5

The abutment opening for this test was 52½" and the water surface profiles are plotted in Figure 19. Although the upstream profile still showed a backwater curve, the downstream side, except for some instability in Run (d), was smooth. In fact, the water levels in Run (a) were very nearly constant, indicating that control of velocity is an important criterion in preventing scour patterns.

Run (c) was inclined to be turbulent, with eddies forming on the wingwalls but complete separation was noticeable only on Runs (c) and (d).

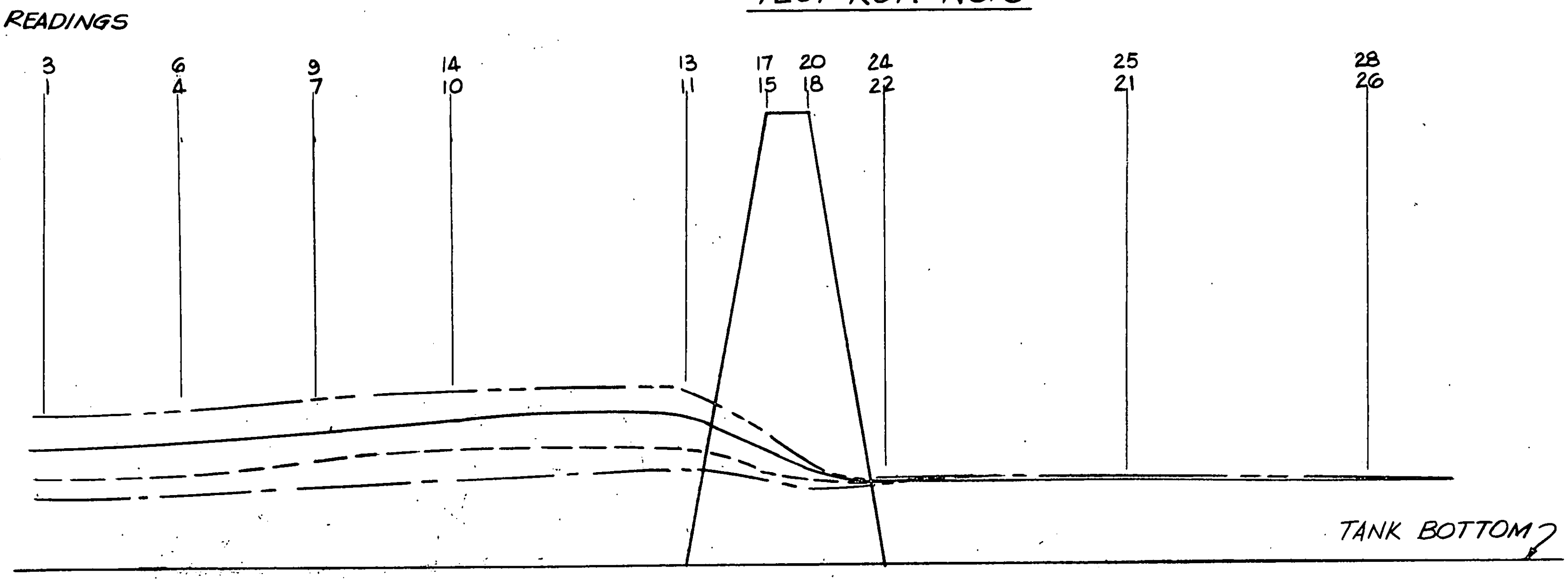
5.56 Test 6

Reference is again made to the photographs in the rear of this report and the contrast between this opening of 71" and that of Test 1, 9", is apparent.

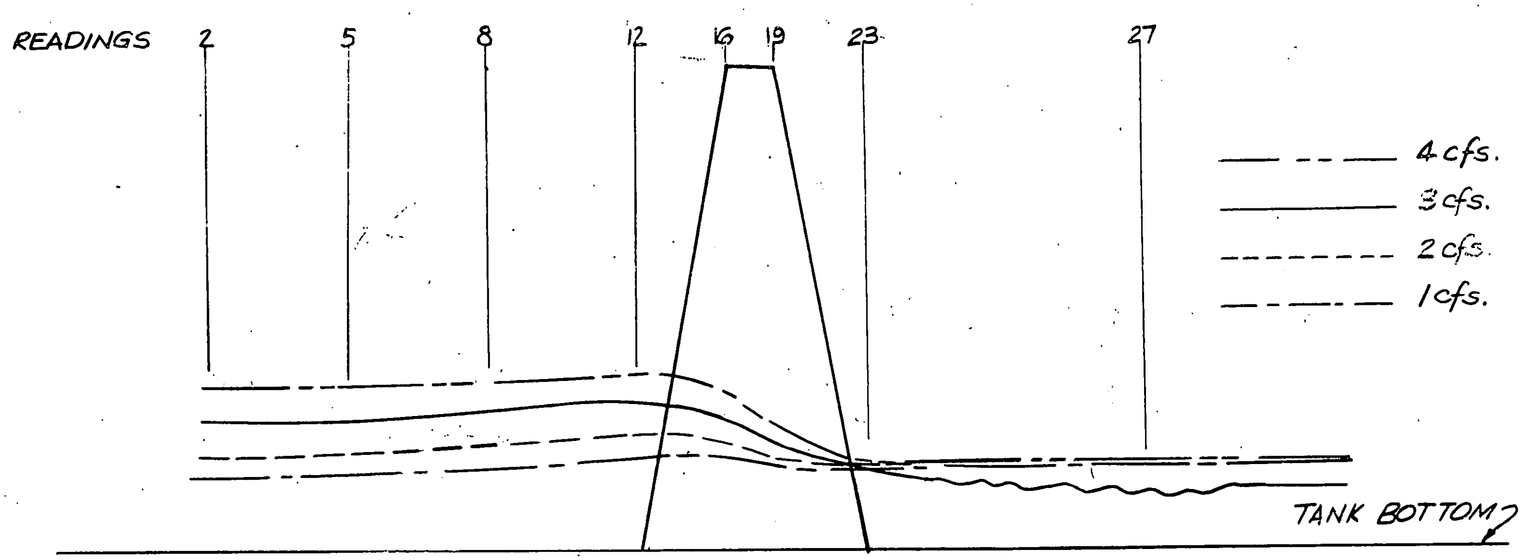
The profiles in Figure 20 show the stable conditions prevalent throughout the full range of this test. Although separation did occur in Runs (c) and (d), especially the latter, eddying was the prime consideration. Linear velocities were low but the circumferential eddy velocities appeared high, high enough to cause some scouring action at the abutments.

However, water level differences over the whole tank were low and only Run (d) showed any signs of real drawdown through the abutment opening.

TEST RUN NO. 5



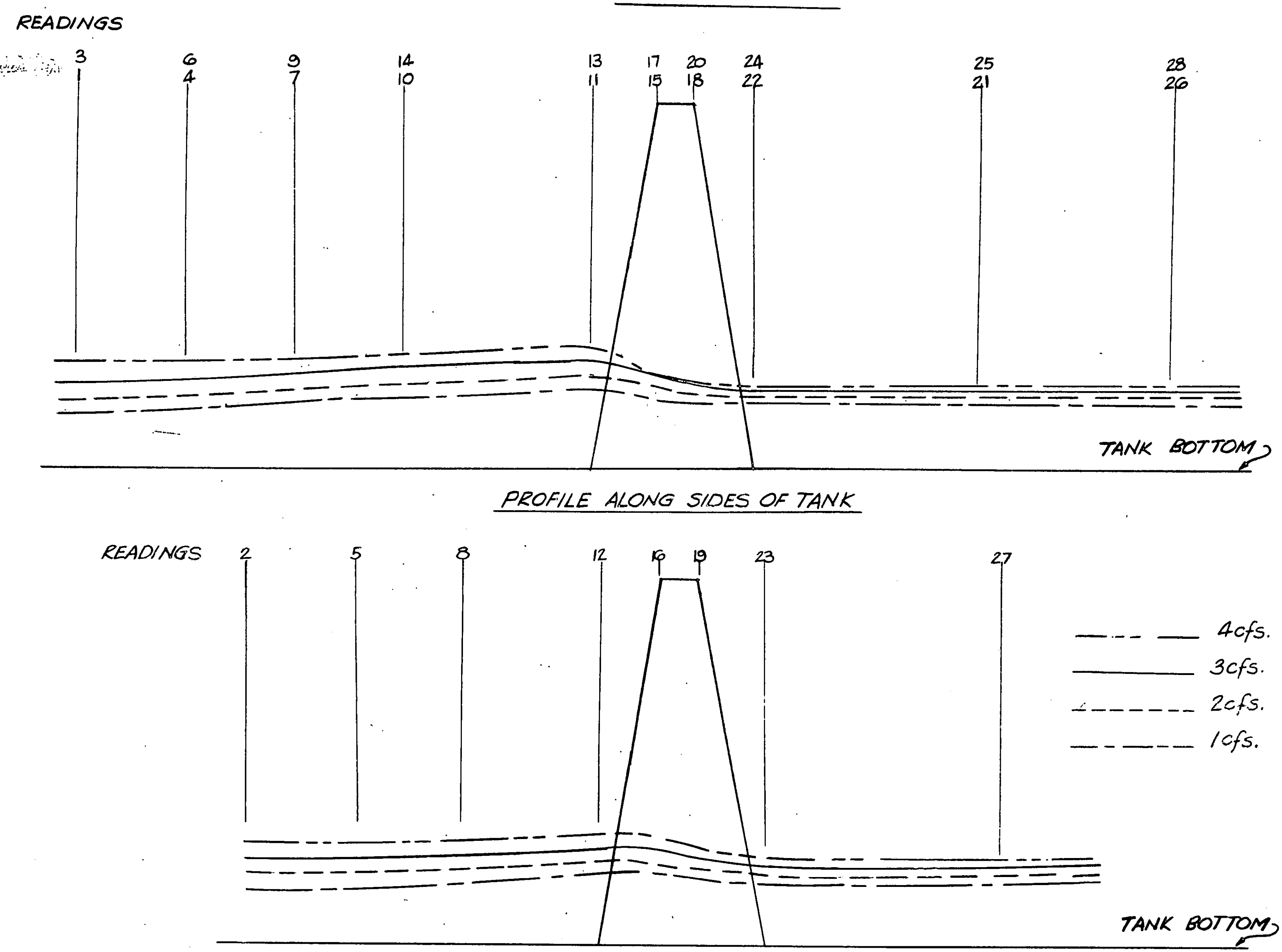
PROFILE ALONG SIDES OF TANK



PROFILE ALONG ℄ OF TANK

FIGURE 19

TEST RUN NO. 6



PROFILE ALONG ℄ OF TANK

FIGURE 20

5.57 Resumé

The purpose of this series of tests was two-fold --

(a) to determine the velocities and depths for various flows through abutments of various widths;

(b) to establish the most useful abutment width upon which to base further experiments.

Comparison between each of the tests carried out above showed that Test 4 was an ideal condition. It represented the extremes found in all the other tests as well as provide the unique intermediate situation explained above. Using the data obtained in Test 4 as a datum, then, further experiments using the spur dikes were carried out.

As can be seen from the Data Sheets, the tailgate height was kept constant at 1 3/4 inches throughout the tests. This was the lowest height available and it was found unnecessary to raise the gate any further as the difference in depth between all Runs was found to be adequate.

6.0 SPUR DIKE EXPERIMENTS

6.1 General

The test run chosen as the most indicative was Test 4, Runs (a) through (d). A recapitulation of conditions for this test is tabulated below in Table 3.

Test	Tailgate Height	Opening	Run	Q
4	1 3/4"	40¼"	a	1 c.f.s.
			b	2 c.f.s.
			c	3 c.f.s.
			d	4 c.f.s.

TABLE 3 - Test 4

Before trying to determine the effect that the placing of the spur dikes would have upon the abutments, the data obtained for Test 4 was plotted as follows -

(a) a contour plot of Runs 4a and 4b;

(b) a streamline plot of Test Run 4d.

(a) Figure 21 shows the contour plot of Run 4a and at once several determinations may be made. As was to be expected with the low flow, the contours are rather wide apart but show very clearly the drawdown through the abutments. More important, however, is the contour of 0.520 ft. which shows as a "loop" around the downstream corner of the abutment. Comparison with the photograph of this Run and the comments on page 52 indicates that this loop represents an area of eddying and possible scour. Similarly, the contours show clearly the areas in which zero velocity was recorded i.e. directly behind and in front of the wingwalls.

In contrast with this is the contour plot of Run 4b, shown in Fig. 22. This plot shows the formation of a more pronounced drawdown between the abutments and the general elongation of the contour lines, indicating that the effect of the drawdown is appreciable, even well upstream of the abutments. This is typical of both succeeding runs viz. Runs 4c and 4d and no attempt has been made to plot these as separate patterns.

The only pronounced difference between these tests is in the proximity of the contour lines. The pattern is the same and this is the important criterion when the placing of the spur dikes is concerned.

Once again, this plot shows clearly the pockets of zero velocity.

(b) More important from the dike placement point of view is the streamline pattern in Fig. 23. This plot has been made directly from the photographs included in the rear of this report and is a typical streamline pattern for all tests. As was expected and verified by the photographs, the streamlines converged towards the abutment opening as the velocity increased.

The information obtained from the contour and streamline plots can be used as a guide in placing the spur dikes effectively. The purpose of the dikes, as stated previously, is to decrease velocity through the abutments as well as provide a smooth transition in order to prevent separation.

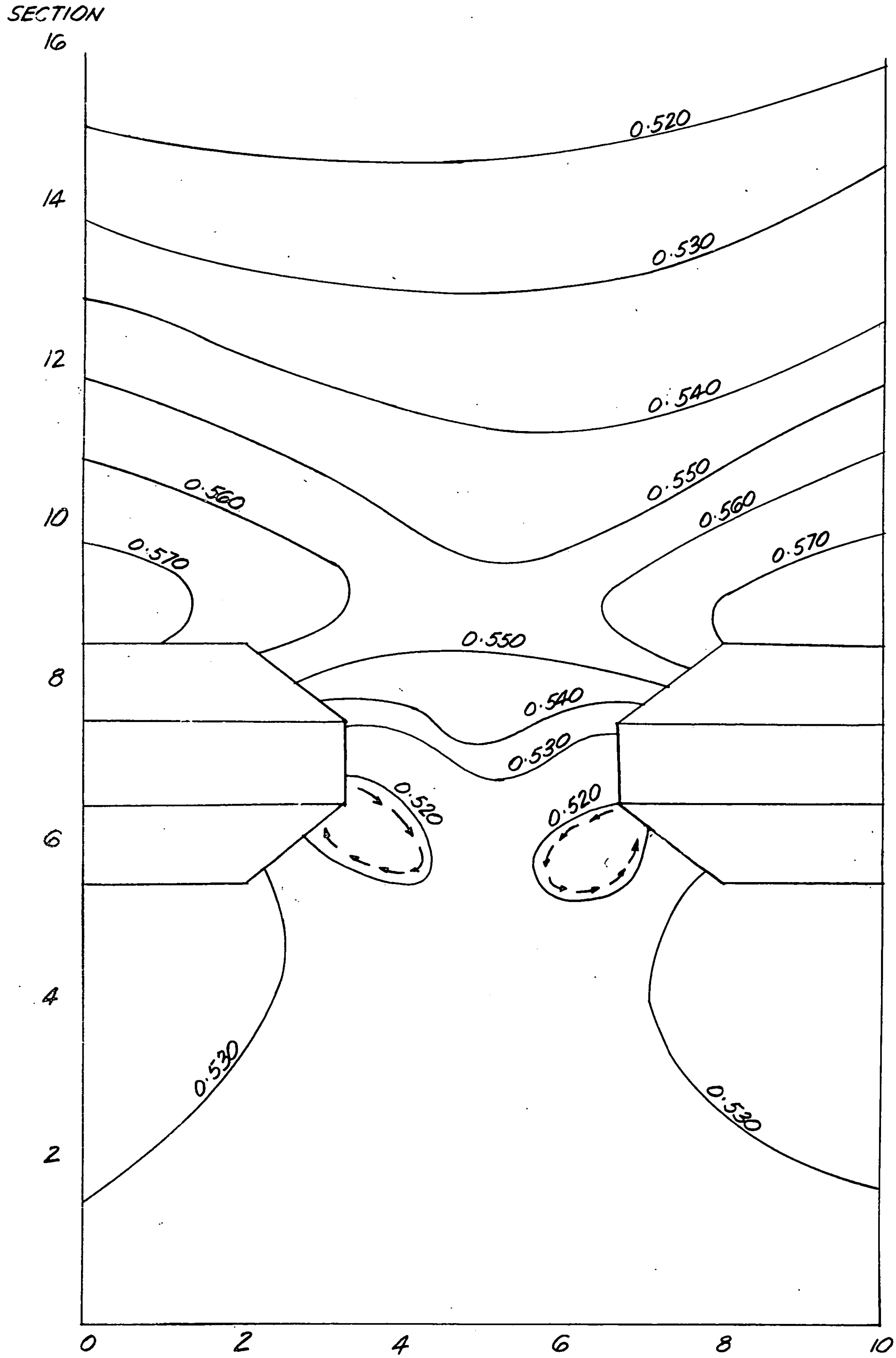


FIGURE 21

CONTOUR TEST 4A

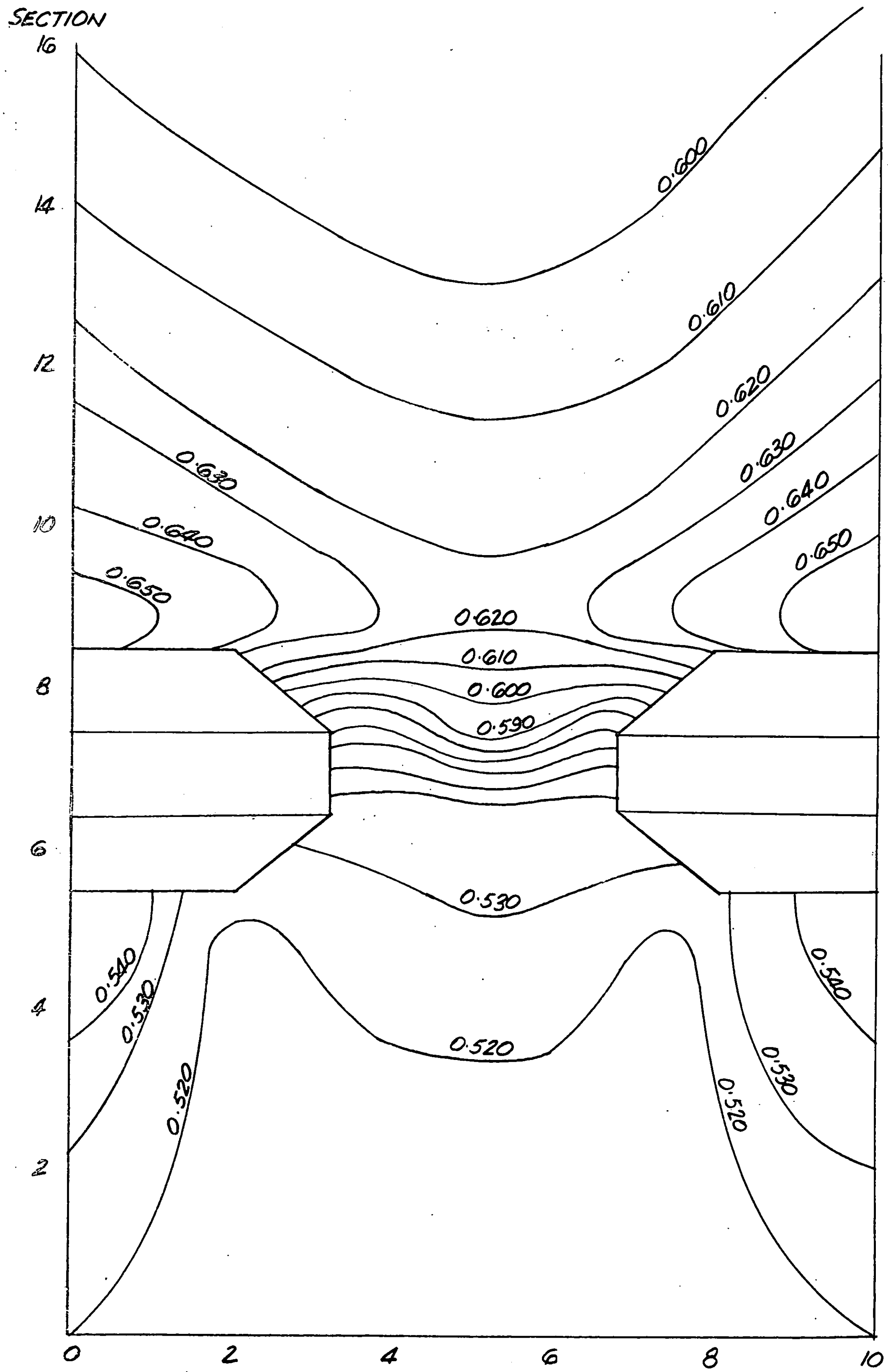


FIGURE 22

CONTOUR TEST 4B

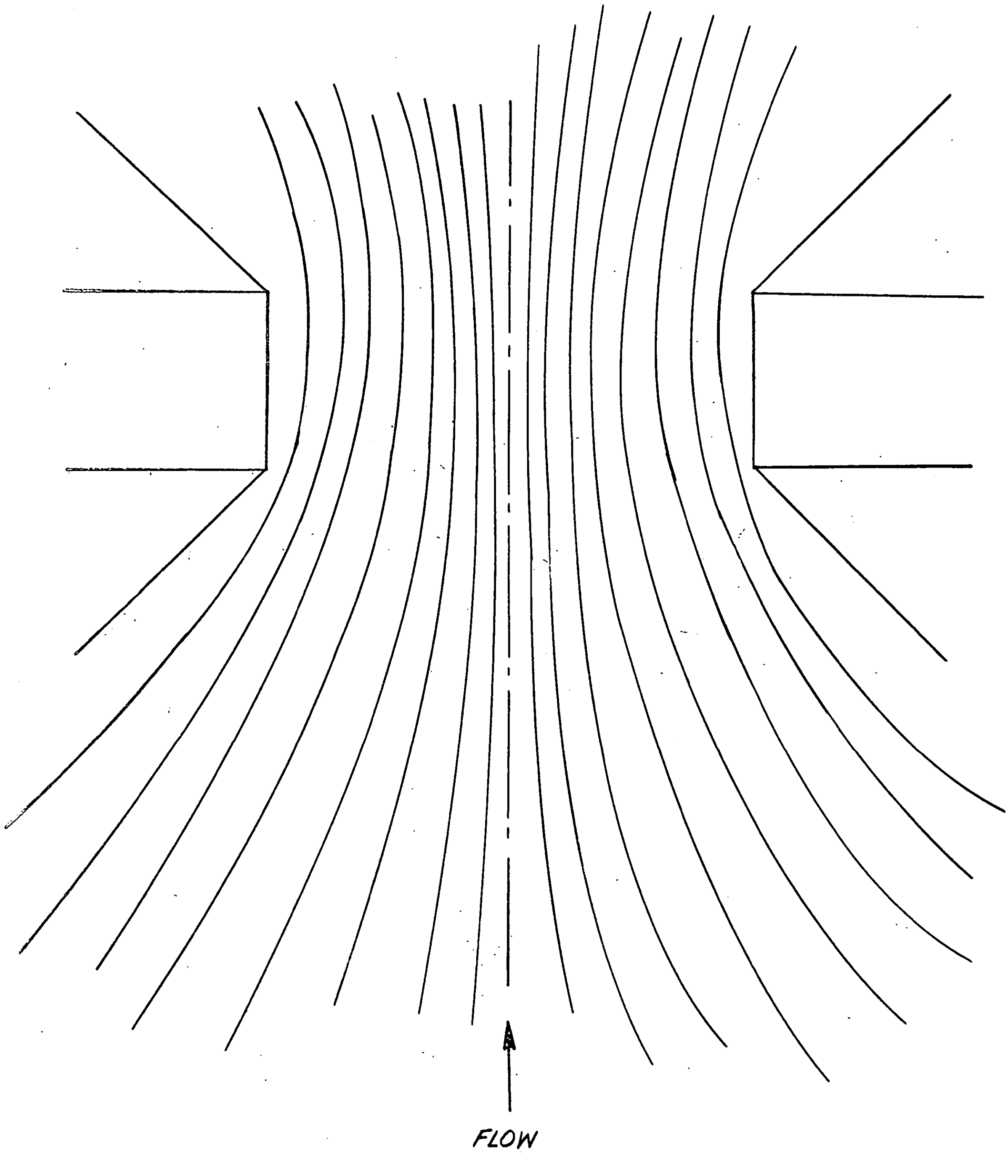


FIGURE 23

STREAMLINES OF TEST 4D

(Taken directly from photograph)

An increase in the height of water through the abutments would decrease the velocity and thus, using the contour plots in conjunction with the velocity distribution across the tank, would indicate the height of water required. Similarly, by placing the dikes parallel to the streamlines, the flow could be diverted smoothly towards the abutment opening.

6.2 Placing of Spur Dikes

The immediate problem in placing the dikes was to prevent the separation on the upstream corner of the abutment. The model dikes consisted of concrete blocks, 6" x 6" in section, which could be moved individually according to the position required. As a first approximation, the dikes were placed as close as possible to the streamlines as indicated in Fig. 23 and in the position as shown in Fig. 24a below.

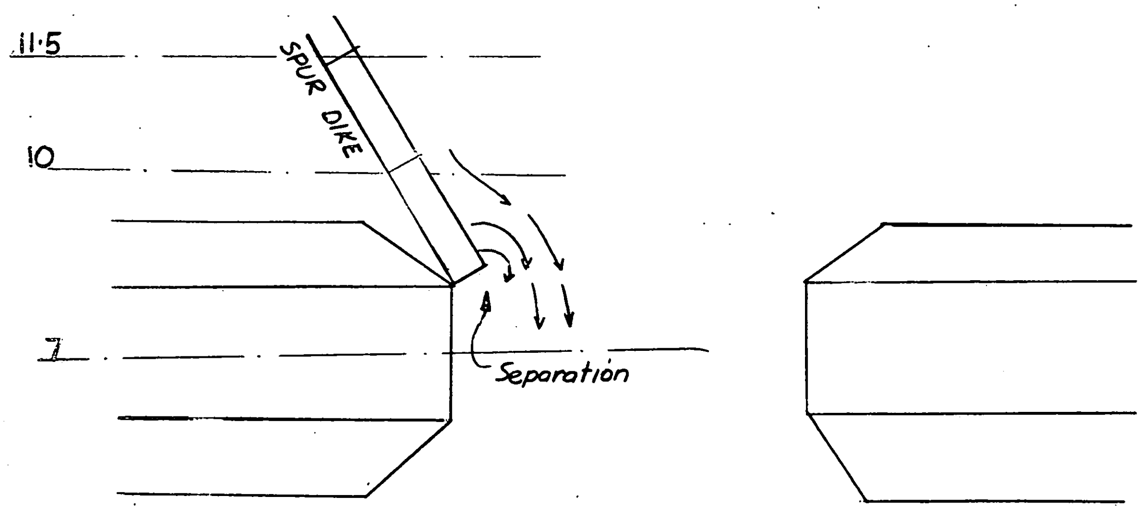


FIGURE 24a

Position of Dikes

In this position, however, separation occurred on the upstream corner of the abutment when a flow of 4 c.f.s. was maintained. Turbulence and eddying were worse than when the test was run without dikes and it was obvious that the downstream end of the dike had to be placed to form a continuation of the parallel vertical sides of the abutments. Figure 24b shows the new position, again following the streamlines as closely as possible.

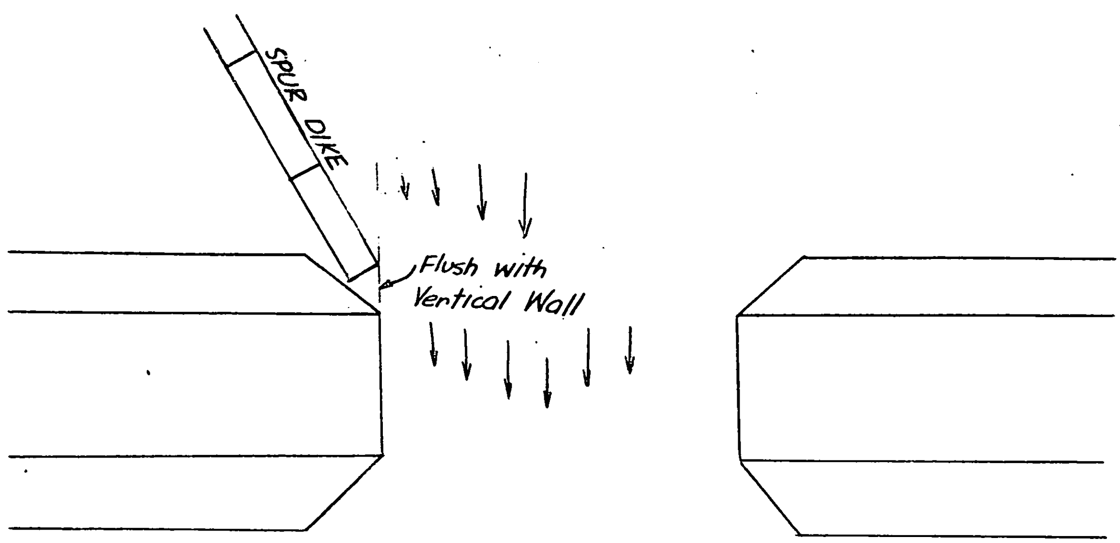


FIGURE 24b

Revised Position of Dikes

The flow of 4 c.f.s. was kept constant for these runs as the maximum flow available and thus representing the most severe condition. After the re-positioning of the dikes, the upstream separation disappeared although there still was turbulence in the area between the end of the dike and the abutment wingwall. This, then, led to the following observations:

(a) A more effective abutment would have a wingwall which followed the streamlines upstream - probably a circular shape would be sufficiently approximate to channel a smooth flow of water through the opening, preventing separation entirely.

(b) Failing this, (and a circular shaped wingwall would be expensive to construct) the spur dike must be shaped to "fit into" the abutment and provide a smooth transition.

These arrangements are shown diagrammatically as follows-

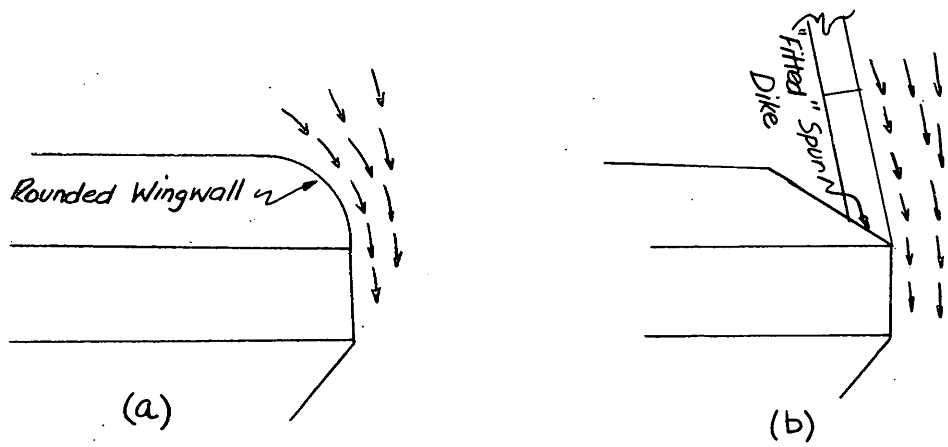


FIGURE 25

Means of Preventing Upstream Separation

Thus, in general, the dike should be flush with the vertical wingwall and constructed upstream approximately along the streamlines. In fact, the abutment with a 45° wingwall is not only ineffective <u>but conducive to scour</u> providing as it does a corner which promotes separation on the upstream side. Thus, existing abutments of this type could be improved with the addition of a small spur dike.

Having established this fact, a small triangular shaped concrete block was constructed which could be placed in such a way as to provide a smooth transition. Reference is made to the photographs in the rear of this report. Tests made using this small block showed that the upstream separation was prevented totally, although the downstream separation still persisted at the high flow (4 c.f.s.)

The next step in the investigation was to determine the minimum length of dike necessary to overcome scour entirely.

6.3 Length of Spur Dike

Use of the small triangular dike successfully prevented separation at the upstream corner of the abutment but transferred the separation to the upstream corner of the dike. Thus, scouring of the dike would cause its collapse and the abutment would soon follow. To prevent this, the dikes would have to be extended upstream, where the lower velocity would not be able to cause separation.

As a first approximation, the dikes were extended upstream from the abutments to Section 12, making a model length of 4 ft. for a prototype length of 120 ft. Working on the assumption that a circular section on the upstream side would help prevent separation (as was seen previously when considering the abutment), a circular block was placed at the upstream end of one of the dikes. For comparison, the other dike was left unprotected. The results of the tests have been tabulated in the following tables and show conclusively the effects of the rounded approach section. In all cases, separation, eddying and turbulence were more pronounced on the unprotected corner.

Three series of tests were run in all --

Series I - Dike Length, 4'-0"

Series 2 - Dike Length, 2'-6"

Series 3 - Dike Length, 1'-0"

The results were as follows:

TABLE 4 - Series I Tests

Dike Length	Q	Comments	
		Rounded Dike	Square Dike
4'-0"	1 c.f.s.	No scour	No scour
	2 c.f.s.	No scour	No scour
	3 c.f.s.	No scour	Minor eddying and turbulence
	4 c.f.s.	No scour	Minor eddying and turbulence

TABLE 5 - Series 2 Tests

Dike Length	Q	Comment	
		Rounded Dike	Square Dike
2'-6"	1 c.f.s.	No scour	Minor eddying and turbulence
	2 c.f.s.	Minor eddying	Severe eddying and turbulence
	3 c.f.s.	Minor eddying and turbulence	Severe eddying and minor separation
	4 c.f.s.	Minor eddying and turbulence	Minor separation

TABLE 6 - Series 3 Tests

Dike Length	Q	Comments	
		Rounded Dike	Square Dike
1'-0"	1 c.f.s.	Minor eddying and turbulence	Severe eddying and turbulence. Severe drawdown
	2 c.f.s.	Severe eddying and drawdown	Separation
	3 c.f.s.	Severe eddying and drawdown	Large separation
	4 c.f.s.	Minor separation and turbulence	Large separation

It can be seen that, in all cases, the dike with the rounded end upstream prevented the formation of scour producing conditions. It is obvious, also, that a dike length of 4 ft. was far too long* and that a length of 1 ft. was too short to prevent scouring of the dike. Hence the intermediate, Series 2 length, was adopted. This model length of 2'-6" represented a prototype length of 75 ft., well within the economic limitations of this investigation. The minor eddying and turbulence noted on the rounded dike in this case would be very unlikely to cause scour around the dike, even at the maximum flow available.

----

*Although ideal from a scour point of view, it is desirable to use the most economical length possible. The comparable prototype length for Series 1 is 120 ft.

6.4 Determination of Separation Velocity

The economical length of spur dike available to prevent upstream scour of abutments depends upon many conditions but primarily upon the velocity of the water. Irrespective of the size of opening or quantity of water flowing, if the spur dike can be built to intercept the flow at a certain maximum velocity, then separation, eddying and turbulence could be prevented. There is little use in constructing a spur dike, only to have scouring occur around the dike and, after its collapse, around the abutment.

In order to determine the velocity at which scour appeared likely, a series of tests was carried out in which the velocity at the end of the dikes was checked for the same length of dike and the same flows indicated in the previous tables. The following information was obtained, presented in the table below.

TABLE 7 - Velocities at End of Dike

Dike Length	Q	Velocity, rpm.	
		Square End	Round End
4'-0"	1 c.f.s.	19	16
	2 c.f.s.	35	34
	3 c.f.s.	42	41
	4 c.f.s.	44	44
2'-6"	1 c.f.s.	33	33
	2 c.f.s.	61	61
	3 c.f.s.	66	66
	4 c.f.s.	70	70

TABLE 7 (Cont'd)

Dike Length	Q	Velocity, rpm.	
		Square End	Round End
1'-0"	1 c.f.s.	39	39
	2 c.f.s.	74	74
	3 c.f.s.	82	82
	4 c.f.s.	90	90

A comparison of the comments made in Tables 4, 5 and 6 shows that the approximate "velocity of separation" is 60 rpm. or 1 fps. This, of course, <u>is</u> only approximate and applicable only to the rather idealized conditions of this report. However, it is a guide and a most important one in determining the approximate length of the dike. The above figure of 1 fps. in the model would be equivalent to 5.5 fps. in a hyperthetical prototype.

Using this criteria - the velocity - it should be possible to determine an empirical formula to calculate the necessary length of dike.

$$L = f(V)$$

$$V = f(\text{abutment width}, Q)$$

Therefore, $L = f(\text{abutment width}, Q)$

Unfortunately, this particular problem is outside the limitations of this investigation but could be studied at length at some other time.

6.5 Discontinuous Dike

In order to economise, a predetermined dike length could be built up, using separate, small blocks placed some distance apart from each other as shown in Fig. 26 below.

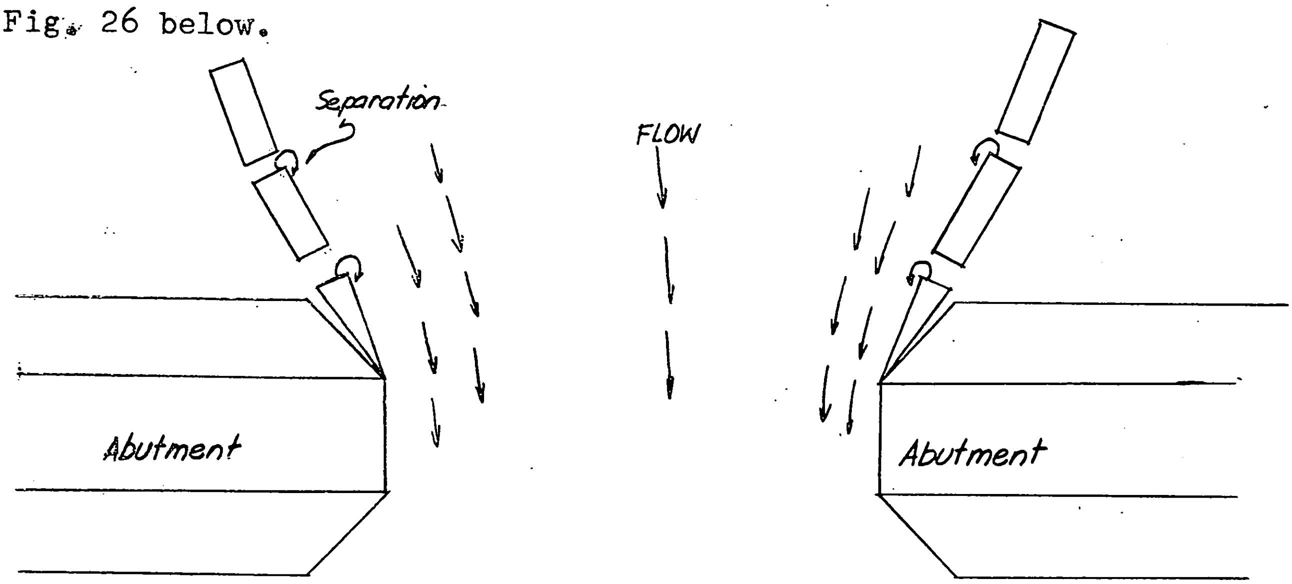


FIGURE 26

"Separate Block" Dike

Experiments were carried out using this principle but were unsuccessful. Eddying and separation occurred on each corner of each block, thus multiplying the effect of scour. Rounded blocks could, of course, be used at some expense but this was not considered of sufficient practical value and no further work was done on this aspect of the investigation.

6.6 Prevention of Downstream Separation

The use of a small dike upstream successfully prevented separation on the upstream corner of the abutment but the downstream separation persisted.

In order to overcome this latter separation which was very severe at high flows, small "stub dikes" were placed flush with the vertical sides of the abutments and extending downstream, thus directing the flow of water smoothly away from the 45° wingwalls. The effect of these stub dikes was most encouraging.

Separation around the downstream corner was prevented and the hydraulic jump, so prominent in all previous tests, was also eliminated, indicating that the velocity had apparently been lowered. Comparison between the photographs taken of this test and Test Run 4d shows the change in the flow pattern with and without dikes.

Having determined the criteria for the position, length and type of spur dikes and with the success of the stub dike, a complete range of flows was then used. The arrangement of dikes is shown in Fig. 27 below.

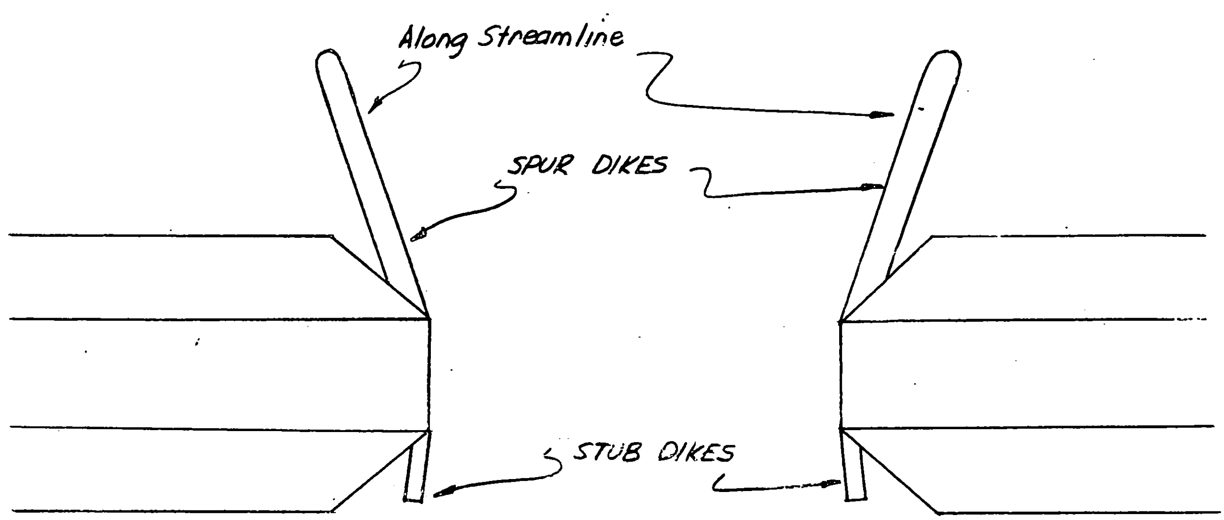


FIGURE 27

Completed Dike Arrangement

In all flows, the results showed a vast improvement over the corresponding previous tests. The drawdown was smoother, separation was prevented entirely and the violent eddying and turbulence, so typical of the higher flows, was also prevented.

However, scouring is primarily a function of the velocity and before any final recommendations could be made, a further series of tests was undertaken to determine whether there had been any change in velocity and depth near the abutment walls.

6.7 Overall Effect of Dikes

Depth and velocity readings were taken in the same positions as were used in all previous tests (See Fig. 14, p. 46) except that readings 11 and 13 were moved towards the center of the tank, on the inside of the spur dikes. For the first series of tests, the only readings taken were numbers 11 through 20, as comparison of these results with the previous tests would indicate a definite trend. In order to compare the results more accurately, the following extra readings were taken -

15a - Between Nos. 15 and 16
16a - Between Nos. 16 and 17
18a - Between Nos. 18 and 19
19a - Between Nos. 19 and 20

After the dikes had been removed, velocity and depth readings at these positions were checked as representing the original tests i.e. with abutments only. Reference is made to the Data Sheets pp. 131 - 134 , which show the tabulated results.

6.71 Test 4aI

Allowance had to be made in all velocity readings for the direction of flow for readings 11 and 13. In the original tests, the current meter was set parallel to the flow and this standard was used in all the readings taken near the spur dikes, thus making the results comparable.

In this test, the depths decreased as the water entered the dikes but tended to increase through the abutments thus raising the velocity in the vicinity of the dikes and lowering the velocity through the abutments. The difference is slight, however, and not very indicative.

6.72 Test 4bI

This test shows a similar result but the difference between readings is more pronounced. In fact, the dike has the effect of "flattening out" the drawdown thus increasing velocity upstream and decreasing velocity through the abutments. This is precisely the effect desired and correct placement of the dikes through experimentation would indicate the optimum position having regard to the streamlines.

6.73 Test 4cI

The same remarks apply here as for Test 4bI.

6.74 Test 4dI

In this test, the velocities became a little higher, although remained constant across each section. It appeared that at the higher flow, the effect of the dikes was overcome and thus the opposite condition prevailed - an increase in velocity instead of the required decrease.

Thus, it was decided to move the dikes a little, making the shape more in compliance with the streamline pattern of Fig. 23 and another series of tests was carried out on this altered position. Spot checks of velocity and depth showed that the velocities were much the same as the previous readings (See Table 8) but there was a tendency to become lower. This being the case, another run was made with the dikes in the new position (See Fig. 28).

TABLE 8

Spot Check on Tests 4aI - 4dII

Test	Section	Depth (ft.)	Velocity (rpm.)
4aI	12	0.543	61
	16	0.530	82
	19	0.525	92
4aII	12	0.546	60
	16	0.539	82
	19	0.530	88
4bI	12	0.614	82
	16	0.569	128
	19	0.547	150
4bII	12	0.612	82
	16	0.579	125
	19	0.554	142
4cI	12	0.684	94
	16	0.640	144
	19	0.595	166

TABLE 8 (Cont'd)

Test	Section	Depth (ft.)	Velocity (rpm.)
4cII	12	0.675	96
	16	0.634	142
	19	0.592	170
4dI	12	0.745	108
	16	0.694	174
	19	0.642	196
4dII	12	0.747	110
	16	0.695	160
	19	0.648	194

6.75 Test 4aII

The velocities in this run were slightly lower than the corresponding velocities of Test 4aI and generally lower than Test 4a. The comments for Test 4aI apply equally in this case.

6.76 Test 4bII

Once again, the pattern is the same - a slightly lower depth between the dikes and a decrease in velocity between the abutments. This series of tests, with the dikes closer to the streamlines, seems to improve conditions a little, indicating that the change is in the right direction. There is certainly a decrease in velocity between Test 4b and 4bII at the abutment wall which is the important criterion.

6.77 Test 4cII

This test appears to be approximately the same as Test 4cI although there is a small increase in velocity throughout accompanied by a decrease in depth. The reason for this is difficult to determine, especially as there is no definite pattern, as there has been previously. Further investigation is required but is outside the scope of this report.

6.78 Test 4dII

Velocities in this run are lower than in Test 4dI but still above the original velocities of Test 4d. However, the distribution across the abutment opening is nearly constant which indicates an efficient transition and local changes in velocity, an important contributing factor towards scour, have been eliminated. Once again, though, further investigation is required to determine the position of dike necessary to decrease the velocity.

Note that decrease in velocity alone, of course, is not the only requirement in preventing scour. Scouring can be caused at relatively low velocities, depending upon the stream bed and its transporting capacity. However, the lower the velocity, the less likelihood there is of scour and this criterion has been kept in mind throughout this report. All the readings for the foregoing tests have been tabulated for easy reference in Tables 9, 10, 11 and 12. Figure 28 shows the position of the dikes for the Series II tests.

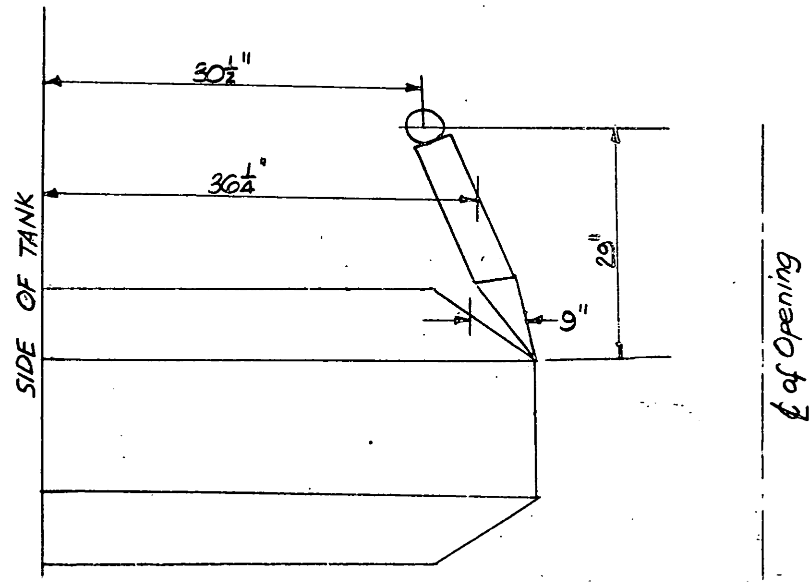


FIGURE 28

Position of Dikes for Series II Tests

6.8 Resumé

After establishing Test 4 as the most indicative, dikes were placed in the tank and a series of tests conducted. These tests showed that -

(a) Placing spur dikes upstream of the abutments formed a smooth transition for the water, preventing separation completely and maintaining a constant velocity distribution across the abutment opening. These dikes were placed as close as possible parallel to the streamlines.

(b) Placing stub dikes downstream from the vertical wall of the abutment prevented the formation of the downstream separation and eliminated the hydraulic jump which formed in previous tests.

TABLE 9

Comparison of "a" Results - 1 c.f.s.

Reading	4a		4aI		4aII	
	Depth	Velocity	Depth	Velocity	Depth	Velocity
11	0.565	0	0.541	61	0.546	44
12	0.554	39	0.543	61	0.546	60
13	0.570	0	0.540	64	0.552	41
15	0.531	58	0.523	80	0.562	80
15a	0.536	42	0.529	84	-	82
16	0.545	80	0.530	82	0.539	82
16a	0.536	60	0.530	86	-	84
17	0.536	68	0.524	86	0.532	80
18	0.517	Eddy	0.523	94	0.524	86
18a	0.520	100	0.523	94	-	82
19	0.525	96	0.525	92	0.530	88
19a	0.524	96	0.526	92	-	88
20	0.520	Eddy	0.527	94	0.528	80

Note: All depth readings are in feet

All velocity readings are in rpm.

TABLE 10

Comparison of "b" Results - 2 c.f.s.

Reading	4b		4bI		4bII	
	Depth	Velocity	Depth	Velocity	Depth	Velocity
11	0.642	18	0.612	80	0.603	90
12	0.624	74	0.614	82	0.612	82
13	0.647	21	0.614	84	0.610	86
15	0.570	70	0.559	126	0.565	132
15a	0.585	60	0.567	122	-	130
16	0.592	108	0.569	128	0.579	125
16a	0.582	114	0.568	126	-	140
17	0.568	90	0.560	130	0.569	128
18	0.534	158	0.544	148	0.546	146
18a	0.487	162	0.544	140	-	146
19	0.534	166	0.547	150	0.554	142
19a	0.497	150	0.545	142	-	148
20	0.534	158	0.543	138	0.548	146

Note: All depth readings are in feet

All velocity readings are in rpm.

TABLE 11

Comparison of "c" Results - 3 c.f.s.

Reading	4c		4cI		4cII	
	Depth	Velocity	Depth	Velocity	Depth	Velocity
11	0.727	18	0.684	90	0.679	100
12	0.707	82	0.684	94	0.675	96
13	0.732	24	0.683	88	0.687	88
15	0.633	100	0.621	150	0.610	148
15a	0.651	122	0.635	144	-	156
16	0.669	140	0.640	144	0.634	142
16a	0.651	156	0.636	148	-	144
17	0.640	108	0.625	152	0.615	154
18	0.558	178	0.596	158	0.559	194
18a	0.523	190	0.590	160	-	188
19	0.594	172	0.595	166	0.592	170
19a	0.523	180	0.595	158	-	182
20	0.563	174	0.589	164	0.560	184

Note: All depth readings are in feet

All velocity readings are in rpm.

TABLE 12

Comparison of "d" Results - 4 c.f.s.

Readings	4d		4dI		4dII	
	Depth	Velocity	Depth	Velocity	Depth	Velocity
11	0.818	50	0.745	102	0.747	100
12	0.783	90	0.745	108	0.747	110
13	0.820	60	0.747	98	0.750	84
15	0.714	54	0.678	172	0.674	154
15a	0.716	90	0.690	172	-	156
16	0.735	134	0.694	174	0.695	160
16a	0.716	120	0.688	176	-	164
17	0.718	78	0.676	180	0.676	160
18	0.578	172	0.642	200	0.612	206
18a	0.552	190	0.630	198	-	210
19	0.660	176	0.642	196	0.648	194
19a	0.557	180	0.628	194	-	196
20	0.586	180	0.640	210	0.619	200

Note: All depth readings are in feet

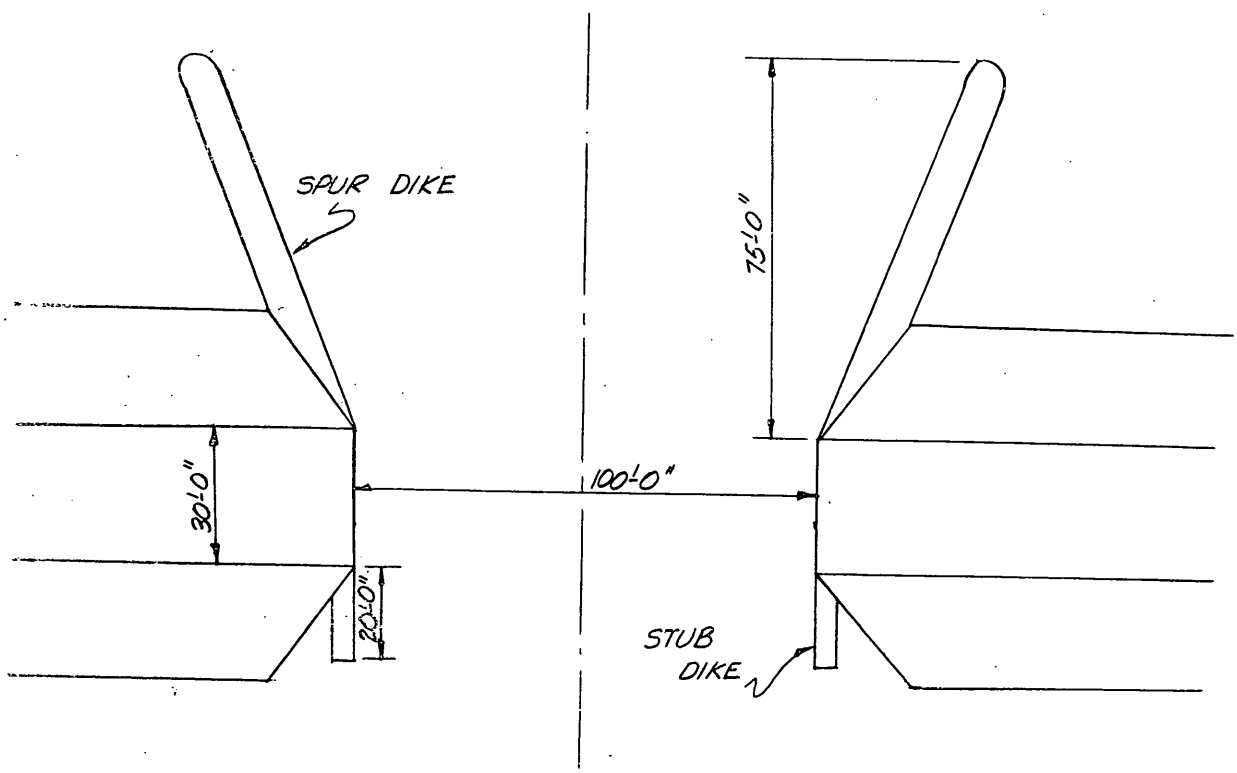
All velocity readings are in rpm.

7.0 CONCLUSION

Much work still has to be done on the problem of scour around abutments. The tests carried out in this investigation showed that the 45° wingwall type abutment was not a particularly good design in that it was conducive to the formation of eddies, turbulence and separation, especially at high flows and thus susceptible to scour.

However, spur dikes and stub dikes helped prevent these high localized velocities, although further investigation needs to be done in an effort to lower the linear velocities through the abutments.

In conclusion, then, the following diagram represents a hyperthetical prototype of a bridge abutment, span 100', carrying a dual carriageway of 30' width and modified according to this report to minimize the effect of scour due to flood flows.



8.0 RECOMMENDATIONS FOR FUTURE RESEARCH

Recommendations for future research, based on the investigations contained in this report are as follows -

(a) Determination of the effect of changing the abutment opening width. This may indicate the minimum width available before appreciable scouring conditions are formed - a most important condition where the length of bridge superstructures is concerned.

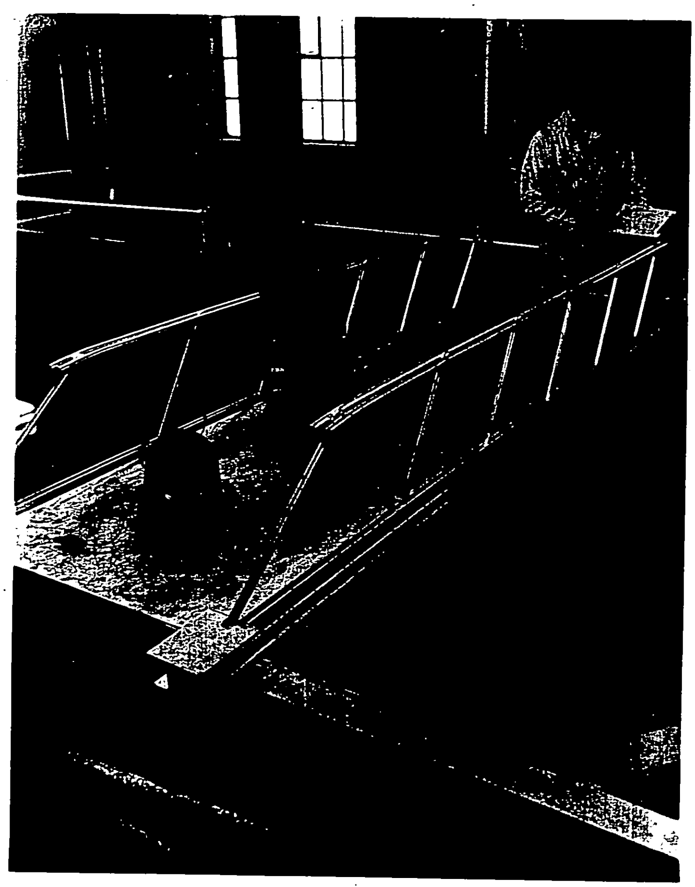
(b) Calculation of an empirical formula for the length of spur dike required to prevent separation and scour around the dike itself.

(c) Determination of the spur dike shape. The shape should be as close as possible to the streamlines and yet provide ease of construction and economy.

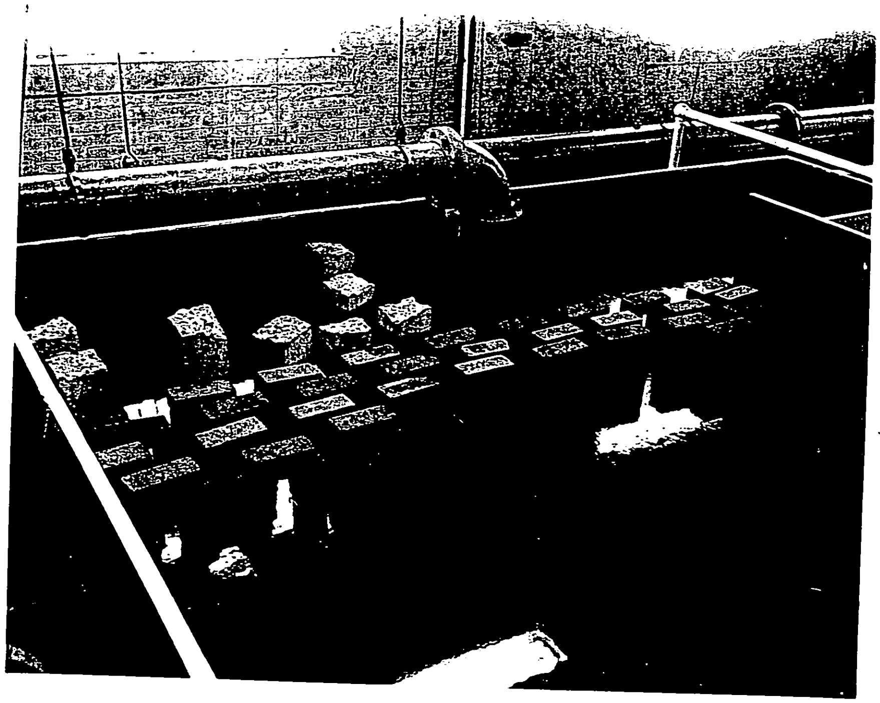
(d) Investigation of the stub dike. The tests on this downstream dike were very encouraging and require a more detailed study.

APPENDIX 1

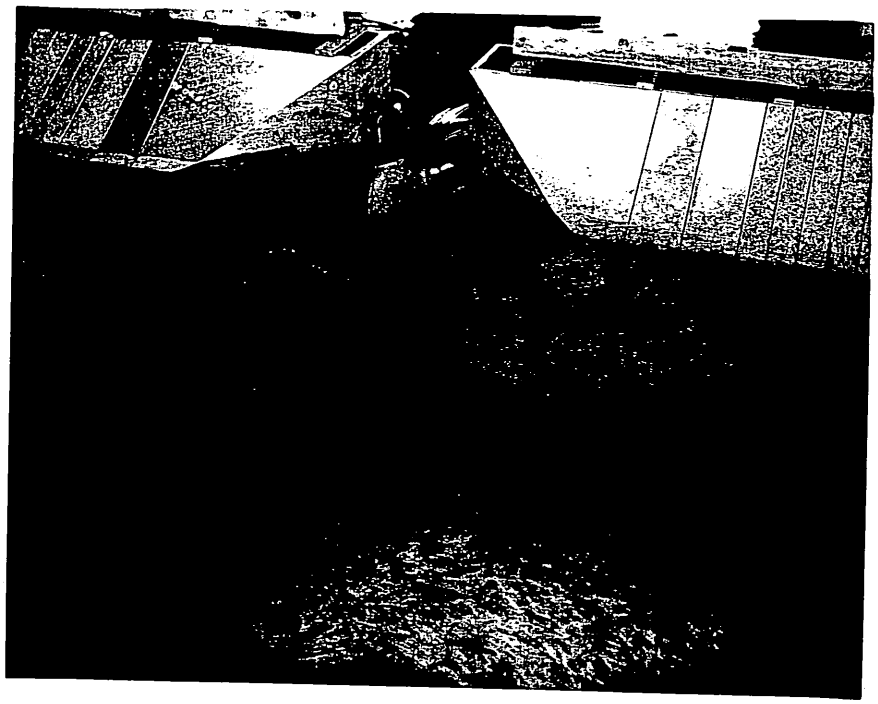
PHOTOGRAPHS



1. VIEW OF EQUIPMENT SHOWING BRIDGE, MIDGET CURRENT METER, ELECTRIC TIMER AND VOLTMETER.

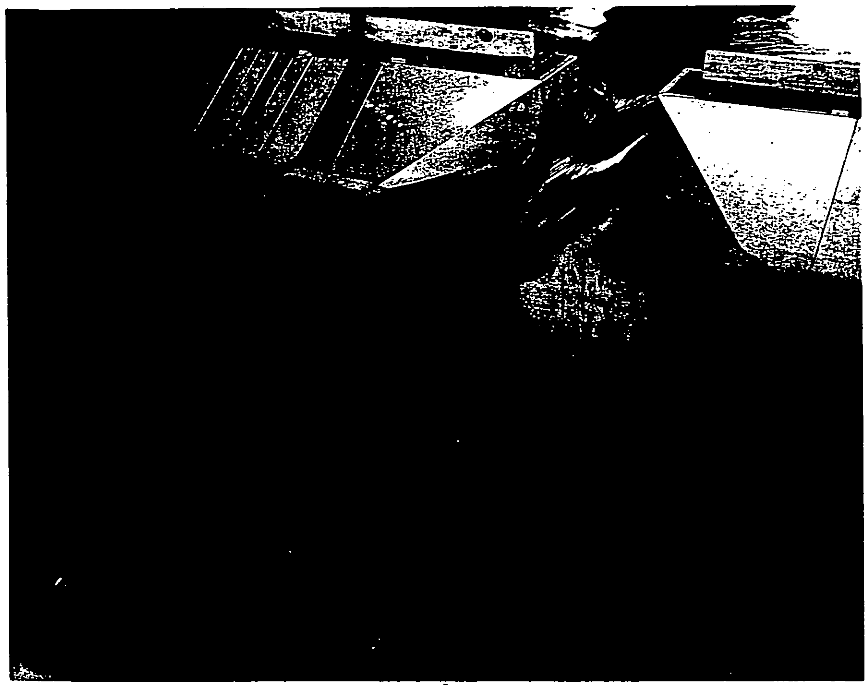


2. ARRANGEMENT OF BAFFLES AT TANK INLET

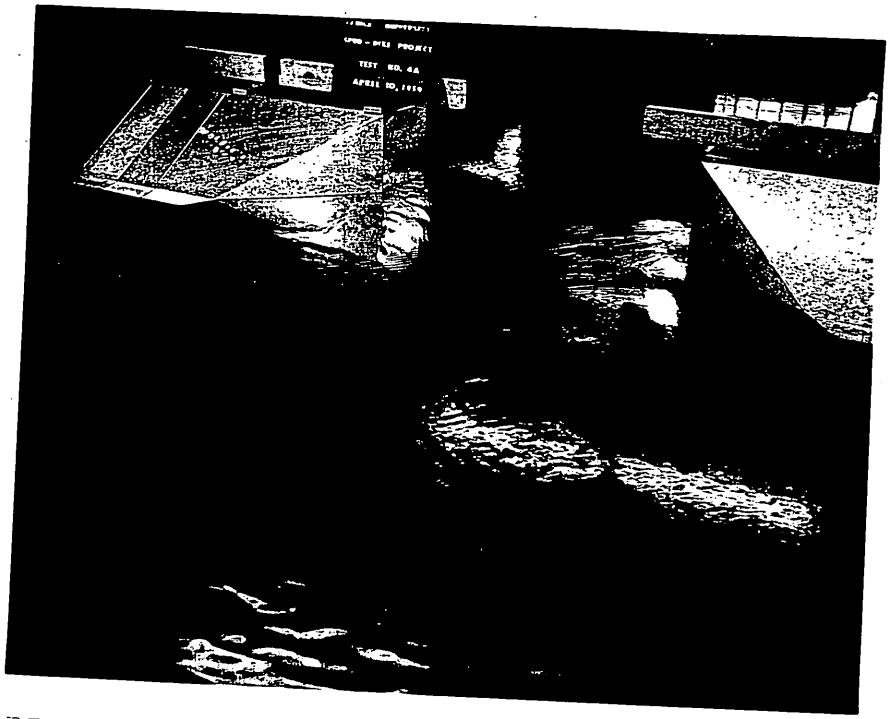


3. TEST 2a

4. GENERAL VIEW OF TANK AND TEST 2b

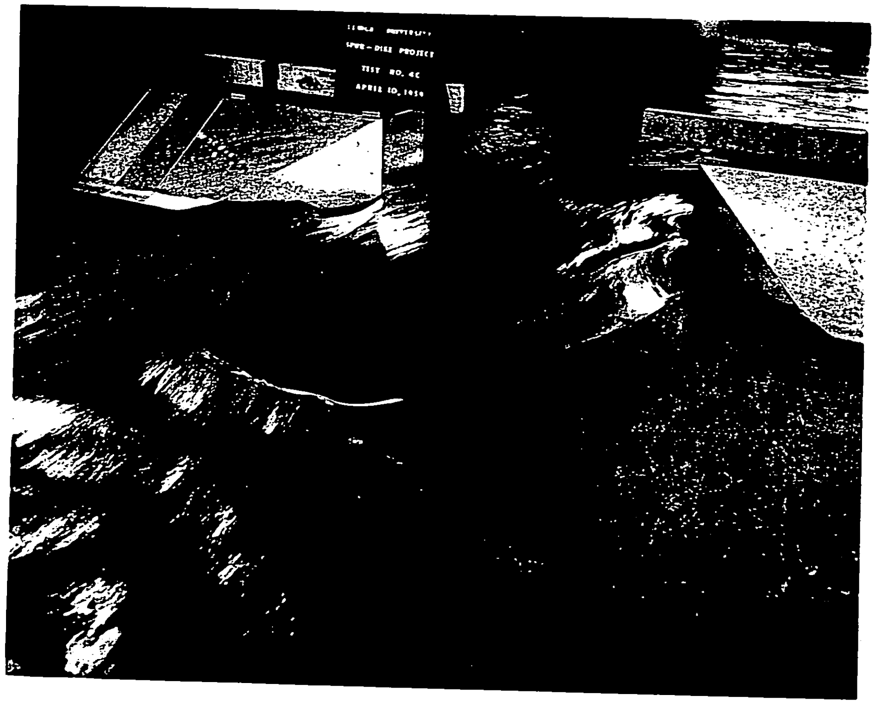


5. TEST 2d



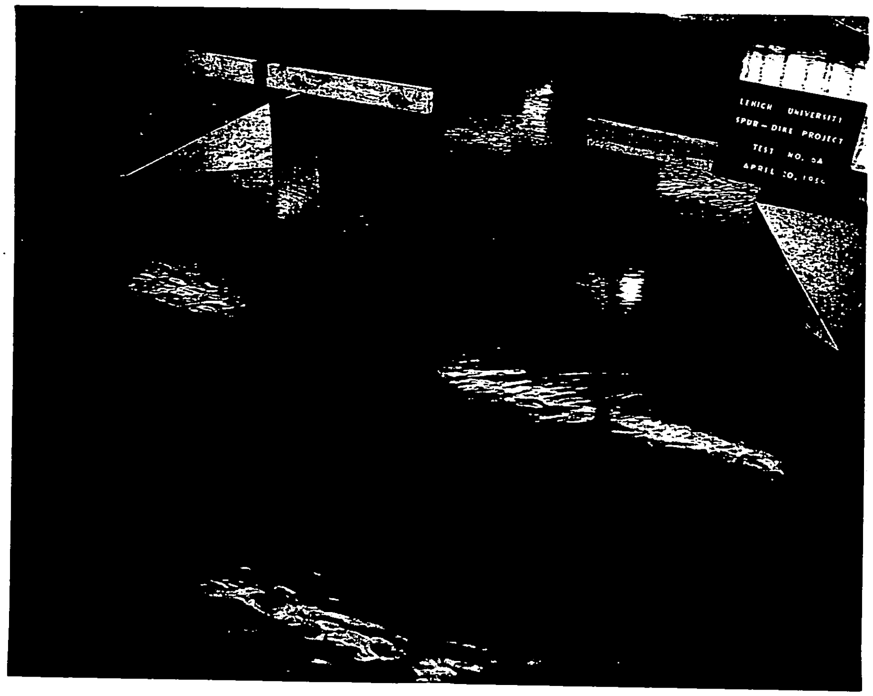
6. TEST 4a

7. TEST 4b

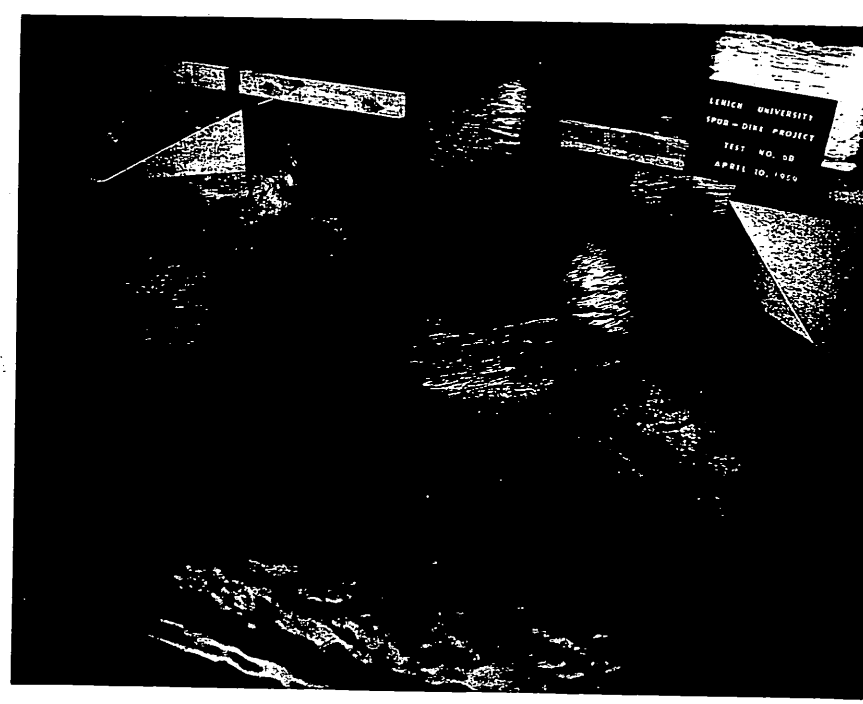


8. TEST 4c

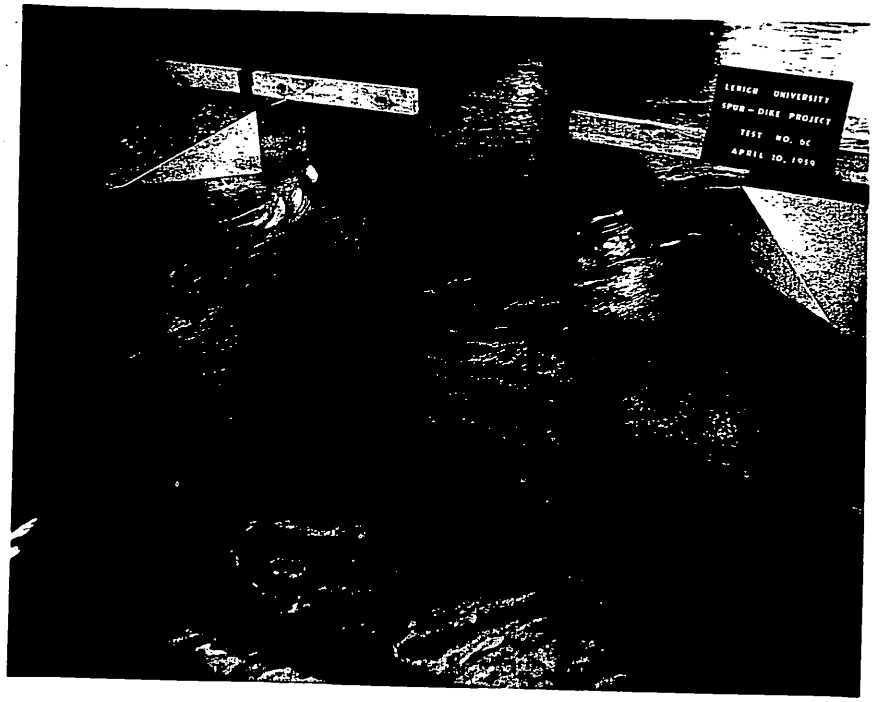
9. TEST 4d



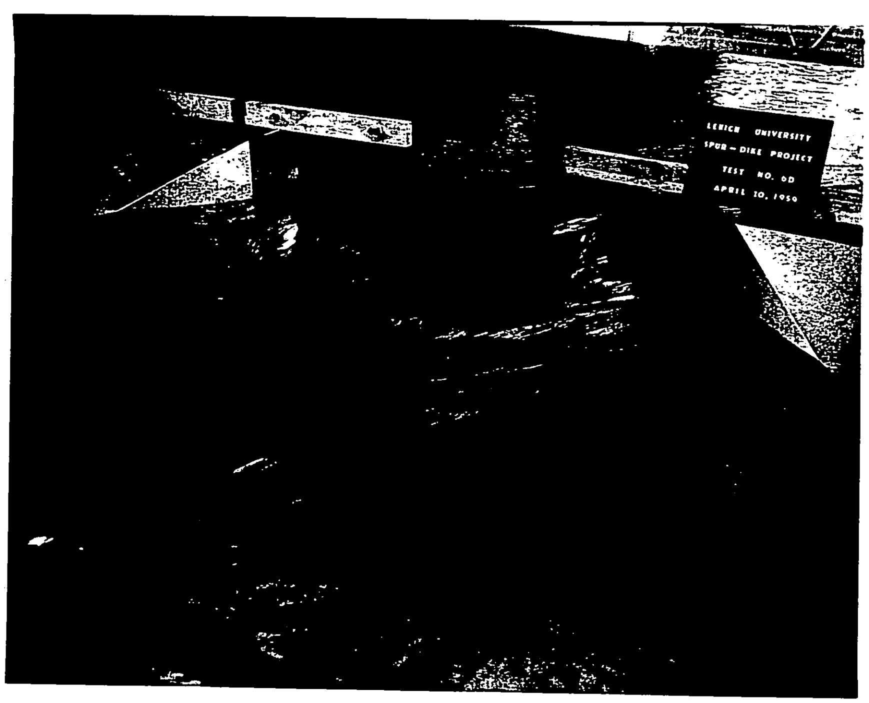
10. TEST 6a



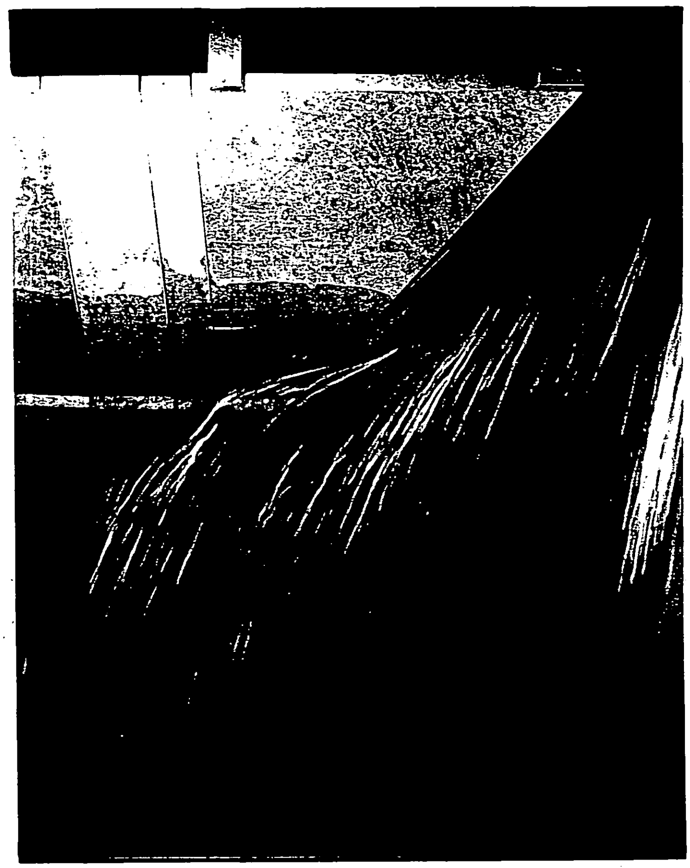
11. TEST 6b



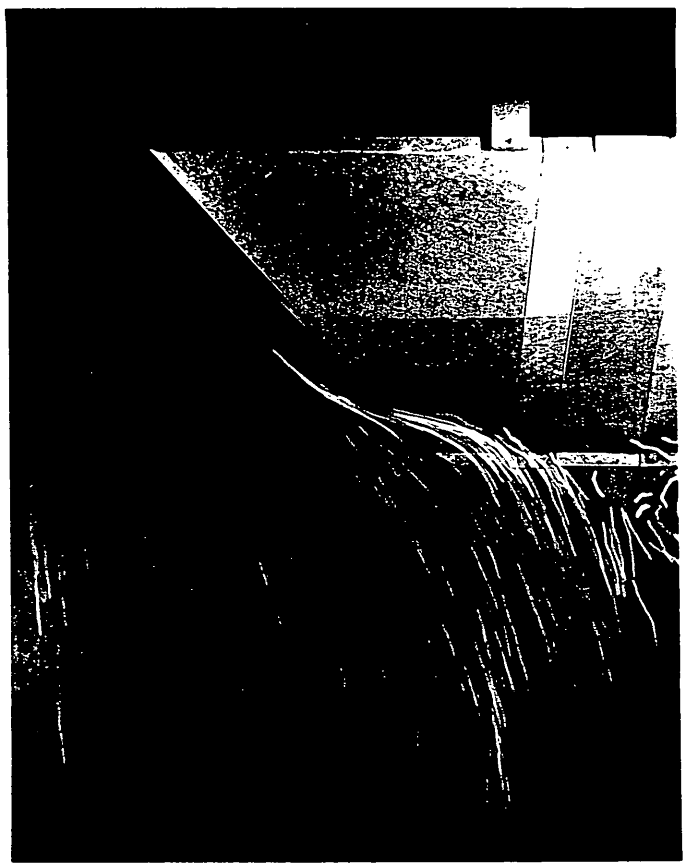
12. TEST 6c



13. TEST 6d

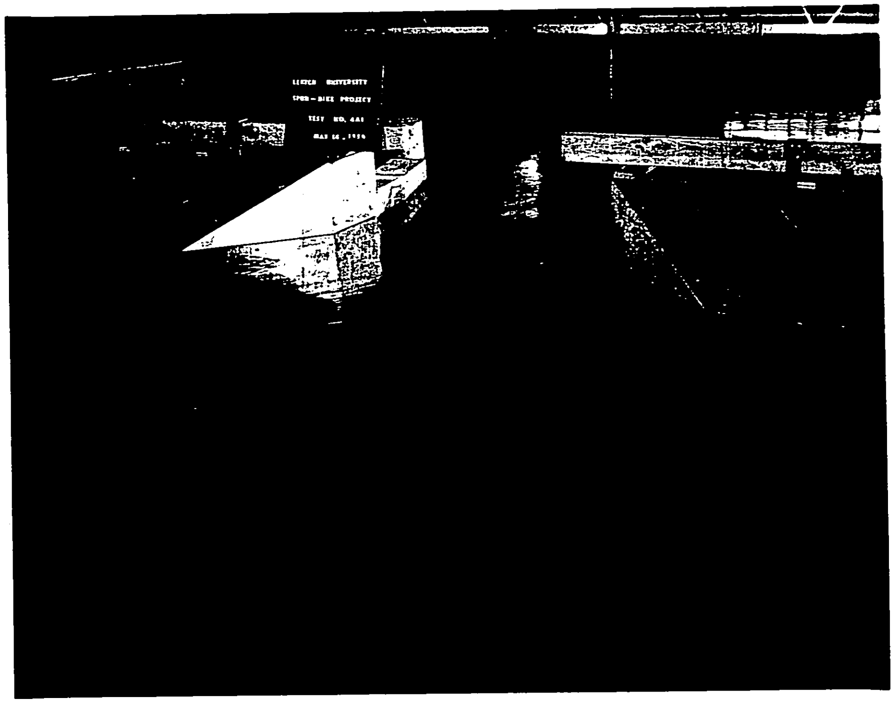


14. TEST 4b SHOWING STREAMLINES
AROUND ABUTMENT

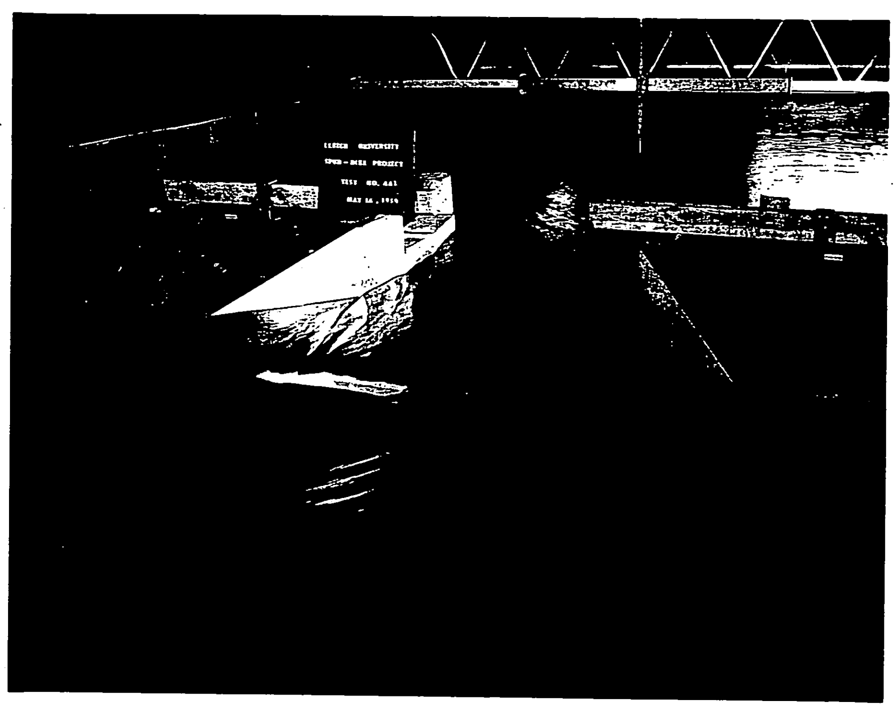


15. TEST 4b SHOWING STREAMLINES
AROUND ABUTMENT

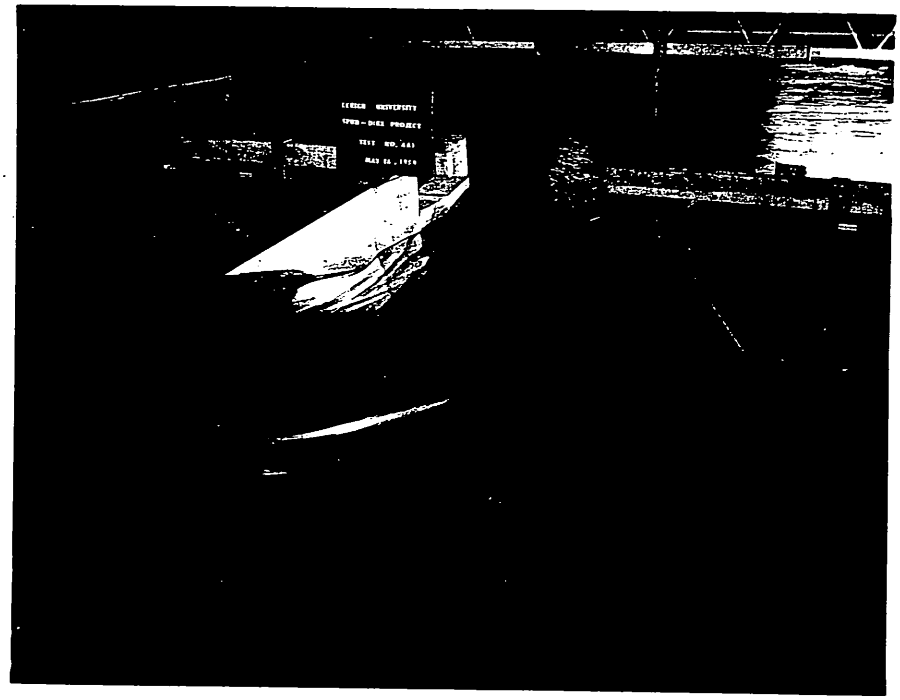
16. TEST 4d SHOWING STREAMLINES
THROUGH ABUTMENT OPENING



17. TEST 4 - 1 cfs. - SHOWING EFFECTS OF DIKE S



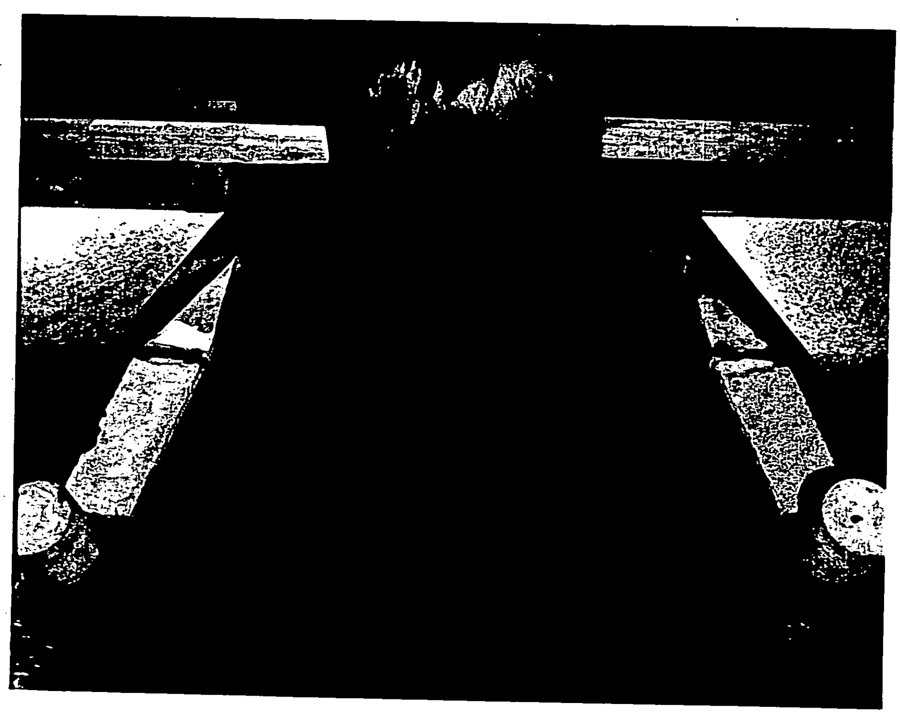
18. TEST 4 - 2 cfs. - SHOWING EFFECTS OF DIKES



19. TEST 4 - 3 cfs. - SHOWING EFFECTS OF DIKES

20. TEST 4 - 4 cfs. - SHOWING EFFECTS OF DIKES

21. TEST 4 - 4 cfs. - EFFECT OF STUB DIKE
COMPARE PHOTO NO. 9



22. ARRANGEMENT OF DIKES

APPENDIX 2

DATA SHEETS

DATA SHEET

Level of Tank Bottom

	0	1	2	3	4	5	6	7	8	9	10
0											
1	0.352	0.356	0.358	0.351	0.347	0.342	0.349	0.353	0.354	0.353	0.353
2	0.354	0.360	0.361	0.360	0.353	0.344	0.348	0.350	0.353	0.350	0.352
3	0.352	0.360	0.362	0.355	0.347	0.344	0.342	0.342	0.352	0.352	0.354
*4	0.351	0.357	0.357	0.350	0.340	0.330	0.333	0.334	0.341	0.342	0.344
5	0.354	0.358	0.359	0.358	0.356	0.355	0.355	0.356	0.356	0.354	0.352
6	0.354	0.357	0.360	0.359	0.358	0.355	0.355	0.361	0.360	0.355	0.351
7	0.354	0.356	0.358	0.360	0.358	0.356	0.354	0.352	0.354	0.352	0.348
8	0.355	0.358	0.359	0.359	0.357	0.353	0.354	0.356	0.357	0.355	0.352
9	0.352	0.355	0.355	0.356	0.355	0.341	0.336	0.335	0.334	0.343	0.343
*10	0.333	0.332	0.318	0.303	0.315	0.335	0.333	0.329	0.327	0.327	0.328
11	0.339	0.336	0.331	0.331	0.330	0.333	0.348	0.343	0.335	0.332	0.332
12	0.334	0.333	0.335	0.333	0.338	0.340	0.342	0.338	0.335	0.331	0.330
13	0.327	0.329	0.333	0.333	0.331	0.330	0.331	0.328	0.327	0.326	0.330
*14	0.330	0.325	0.322	0.321	0.326	0.322	0.318	0.316	0.323	0.325	0.330

Sections marked thus * were coincident with welds.

Tailgate at horizontal section zero.

Distance between adjacent vertical and adjacent horizontal sections is one foot.

DATA SHEET

Level of Tank Bottom (cont'd)

	0	1	2	3	4	5	6	7	8	9	10
15	0.340	0.338	0.314	0.302	0.317	0.318	0.317	0.315	0.315	0.319	0.324
*16	0.328	0.327	0.332	0.332	0.315	0.312	0.310	0.308	0.317	0.325	0.330
17	0.337	0.340	0.333	0.324	0.304	0.304	0.304	0.302	0.310	0.322	0.322
18	0.325	0.320	0.310	0.299	0.290	0.298	0.286	0.289	0.307	0.318	0.325

Sections marked thus * were coincident with welds

Tailgate at horizontal section zero.

Distance between adjacent vertical and adjacent horizontal sections is one foot.

DATA SHEET

Backwater Check

Manometer Differential = 22.5 + 25.5 = 48" = 4 ft.

Height of Water Column = 4 x 2.95 = 11.80 ft.

$$Q = 1.17\sqrt{\Delta h} = 1.17\sqrt{11.80}$$

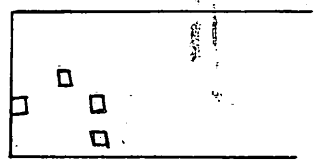
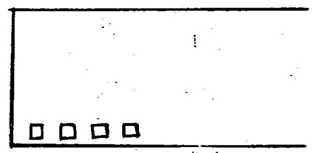
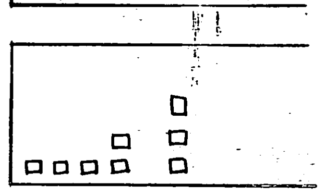
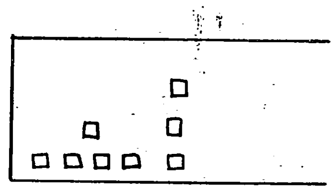
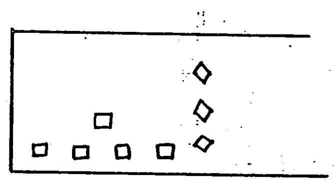
$$= 4.02 \text{ c.f.s.}$$

Section	3	5	7
1	1.000	0.984	1.000
2	0.991	0.984	0.981
3	0.990	0.982	0.982
4	0.990	0.981	0.981
5	0.985	0.985	0.982
6	0.993	0.985	0.982
7	0.993	0.982	0.982
8	-	-	-
9	-	-	-

Section chosen for placement of abutments - Section 7

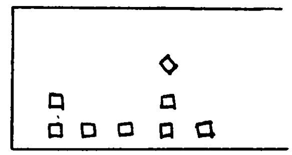
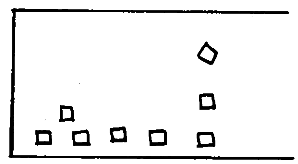
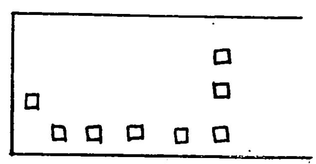
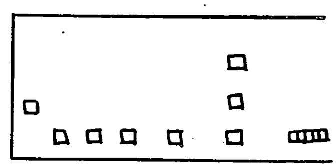
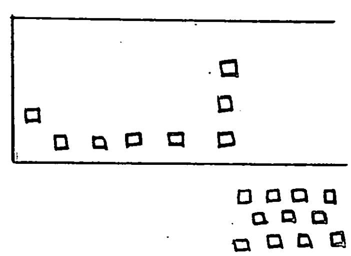
DATA SHEET

Velocity Distribution

RUN	SECTION	METER	TIME	VELOCITY	PATTERN
1	3-7	15	1 min.	0.25 fps.	NO BAFFLES
	5-7	22	"	0.37 fps.	
	7-7	38	"	0.70 fps.	
2	7-7	42	1 min.	0.70 fps.	
	5-7	22	"	0.37 fps.	
3	7-7	38	1 min.	0.70 fps.	
4	7-7	27	1 min.	0.45 fps.	
	5-7	26	"	0.43 fps.	
	3-7	30	"	0.50 fps.	
5	3-7	27	1 min.	0.45 fps.	
	5-7	24	"	0.40 fps.	
	7-7	29	"	0.48 fps.	
6	1-7	45	1 min.	0.75 fps.	
	2-7	32		0.53 fps.	
	3-7	26		0.43 fps.	
	5-7	27		0.45 fps.	
	7-7	32		0.53 fps.	
	8-7	33		0.55 fps.	
	9-7	37.		0.63 fps.	

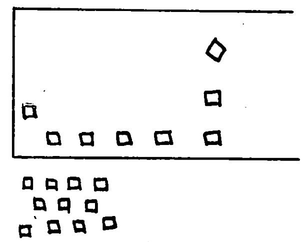
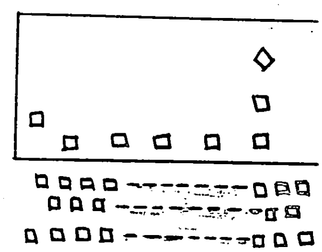
DATA SHEET

Velocity Distribution (cont'd)

RUN	SECTION	METER	TIME	VELOCITY	PATTERN
7	3-7	39	1 min.	0.65 fps.	
	5-7	36	"	0.60 fps.	
	7-7	34	"	0.57 fps.	
	8-7	34	"	0.57 fps.	
	9-7	29	"	0.48 fps.	
8	1-7	49	1 min.	0.82 fps.	
	2-7	34	"	0.57 fps.	
	3-7	31	"	0.52 fps.	
	5-7	29	"	0.48 fps.	
	7-7	35	"	0.58 fps.	
9	1-7	46	1 min.	0.77 fps.	
10	1-7	23	1 min.	0.38 fps.	
	2-7	28	"	0.47 fps.	
11	1-7	33	1 min.	0.55 fps.	
	2-7	30	"	0.50 fps.	
	3-7	29	"	0.48 fps.	
	5-7	32	"	0.53 fps.	
	7-7	45	"	0.75 fps.	
	8-7	43	"	0.72 fps.	
	9-7	43	"	0.72 fps.	

DATA SHEET

Velocity Distribution (cont'd)

RUN	SECTION	METER	TIME	VELOCITY	PATTERN
12	1-7	33	1 min.	0.55 fps.	
	2-7	32	"	0.53 fps.	
	3-7	31	"	0.52 fps.	
	5-7	34	"	0.57 fps.	
	7-7	40	"	0.67 fps.	
	8-7	36	"	0.60 fps.	
	9-7	33	"	0.55 fps.	
13	1-7	36	1 min.	0.60 fps.	
	2-7	33	"	0.55 fps.	
	3-7	33	"	0.55 fps.	
	5-7	35	"	0.58 fps.	
	7-7	36	"	0.60 fps.	
	8-7	34	"	0.57 fps.	
	9-7	37	"	0.62 fps.	
14	1-2	34	1 min.	0.57 fps.	Same as RUN 13
	2-2	33	"	0.55 fps.	
	3-2	32	"	0.53 fps.	
	5-2	33	"	0.55 fps.	
	7-2	36	"	0.60 fps.	
	8-2	33	"	0.55 fps.	
	9-2	33	"	0.55 fps.	

DATA SHEET

Velocity Distribution (cont'd)

RUN	SECTION	METER	TIME	VELOCITY	PATTERN
15	1-12	35	1 min.	0.59 fps.	
	2-12	31	"	0.52 fps.	Same as RUN 13
	3-12	33	"	0.55 fps.	
	5-12	34	"	0.57 fps.	
	7-12	36	"	0.60 fps.	
	8-12	36	"	0.60 fps.	
	9-12	36	"	0.60 fps.	

DATA SHEET

TEST 1a

Abutment Width - 9"; Tailgate Height - 1 3/4" ;

Q - 1 c.f.s. ; Δh - 0.248'

Height		Velocity, rpm.	
1. 0.685	15. 0.655	1. 4	15. 73
2. 0.654	16. 0.664	2. 5	16. 117
3. 0.667	17. 0.654	3. 4	17. 123
4. 0.665	18. 0.515	4. 3	18. 197
5. 0.661	19. 0.536	5. 4	19. 205
6. 0.683	20. 0.521	6. 4	20. 212
7. 0.692	21. 0.506	7. 3	21. 0
8. 0.684	22. 0.499	8. 4	22. 18
9. 0.697	23. 0.406	9. 3	23. 188
10. 0.720	24. 0.511	10. 0	24. 16
11. 0.715	25. 0.507	11. 0	25. 0
12. 0.713	26. 0.510	12. 20	26. 0
13. 0.725	27. 0.500	13. 0	27. 180
14. 0.728	28. 0.516	14. 0	28. 0

DATA SHEET

TEST 1b

Abutment Width and Tailgate Height same as Test 1a

Q - 2 c.f.s. ; Δh - 1.00'

Height				Velocity, rpm.			
1.	0.984	15.	1.030	1.	4	15.	88
2.	0.980	16.	1.067	2.	6	16.	132
3.	1.003	17.	1.050	3.	4	17.	136
4.	0.997	18.	0.716	4.	4	18.	206
5.	0.994	19.	0.650	5.	6	19.	220
6.	1.008	20.	0.720	6.	4	20.	218
7.	1.020	21.	0.498	7.	5	21.	0
8.	1.014	22.	0.481	8.	8	22.	Turb.
9.	1.025	23.	0.471	9.	4	23.	266
10.	1.053	24.	0.488	10.	0	24.	Turb.
11.	1.040	25.	0.505	11.	0	25.	0
12.	1.035	26.	0.515	12.	52	26.	21
13.	1.055	27.	0.386	13.	36	27.	Hyd. Jump
14.	1.062	28.	0.510	14.	0	28.	0

DATA SHEET

Test 1c

Abutment Width and Tailgate Height same as Test 1a

Q - 3 c.f.s.; Δh - 2.22'

Height				Velocity, rpm.			
1.	1.215	15.	1.147	1.	11	15.	64
2.	1.213	16.	1.160	2.	13	16.	148
3.	1.217	17.	1.150	3.	12	17.	140
4.	1.217	18.	0.850	4.	13	18.	214
5.	1.209	19.	0.793	5.	11	19.	246
6.	1.219	20.	0.854	6.	11	20.	204
7.	1.234	21.	0.506	7.	5	21.	0
8.	1.227	22.	0.475	8.	10	22.	Turb.
9.	1.236	23.	0.510	9.	3	23.	276
10.	1.262	24.	Turb.	10.	0	24.	Turb.
11.	1.258	25.	0.504	11.	16	25.	0
12.	1.247	26.	0.530	12.	64	26.	0
13.	1.260	27.	0.398	13.	56	27.	Hyd. Jump
14.	1.276	28.	0.520	14.	0	28.	0

DATA SHEET

Test 2a

Abutment Width - 15½" ; Tailgate Height - 1 3/4" ;

Q - 1 c.f.s. ; Δh - 0.248'

Height				Velocity, rpm.			
1.	0.628	15.	0.614	1.	6	15.	94
2.	0.622	16.	0.626	2.	7	16.	124
3.	0.645	17.	0.617	3.	5	17.	160
4.	0.635	18.	0.530	4.	5	18.	184
5.	0.628	19.	0.503	5.	8	19.	174
6.	0.640	20.	0.538	6.	4	20.	176
7.	0.656	21.	0.512	7.	0	21.	0
8.	0.645	22.	0.508	8.	9	22.	0
9.	0.662	23.	0.432	9.	0	23.	228
10.	0.690	24.	0.512	10.	0	24.	0
11.	0.670	25.	0.512	11.	13	25.	0
12.	0.670	26.	0.513	12.	44	26.	0
13.	0.688	27.	Turb.	13.	32	27.	168
14.	0.687	28.	0.512	14.	0	28.	0

DATA SHEET

TEST 2b

Abutment Width and Tailgate Height same as Test 2a

Q - 2 c.f.s. ; Δh - 1.00'

Height				Velocity, rpm.			
1.	0.809	15.	0.799	1.	10	15.	92
2.	0.813	16.	0.788	2.	9	16.	134
3.	0.819	17.	0.775	3.	8	17.	122
4.	0.818	18.	0.650	4.	10	18.	200
5.	0.811	19.	0.597	5.	11	19.	218
6.	0.820	20.	0.661	6.	9	20.	192
7.	0.840	21.	0.515	7.	9	21.	0
8.	0.828	22.	0.503	8.	19	22.	Turb.
9.	0.840	23.	0.516	9.	9	23.	210
10.	0.872	24.	0.496	10.	0	24.	Turb.
11.	0.864	25.	0.515	11.	17	25.	0
12.	0.853	26.	0.521	12.	57	26.	0
13.	0.866	27.	0.390	13.	52	27.	256
14.	0.874	28.	0.520	14.	0	28.	0

DATA SHEET

TEST 2c

Abutment Width and Tailgate Height same as Test 2a

Q - 3 c.f.s.; Δh - 2.22'

Height				Velocity, rpm.			
1.	0.975	15.	0.928	1.	19	15.	Separ'n 92
2.	0.981	16.	0.937	2.	18	16.	156
3.	0.990	17.	0.926	3.	16	17.	Separ'n 98
4.	0.980	18.	0.720	4.	18	18.	232
5.	0.980	19.	0.686	5.	17	19.	232
6.	0.987	20.	0.740	6.	15	20.	208
7.	1.000	21.	0.502	7.	14	21.	0
8.	0.994	22.	0.492	8.	20	22.	Turb.
9.	1.008	23.	0.535	9.	12	23.	258
10.	1.033	24.	0.502	10.	0	24.	Turb.
11.	1.020	25.	0.506	11.	42	25.	0
12.	1.010	26.	0.513	12.	78	26.	0
13.	1.033	27.	0.406	13.	69	27.	300
14.	1.046	28.	0.522	14.	0	28.	0

DATA SHEET

Test 2d

Abutment Width and Tailgate Height same as Test 2a

Q - 4 c.f.s.;   Δh - 3.97'

Height				Velocity, rpm.			
1.	1.125	15.	1.100	1.	21	15.	120
2.	1.125	16.	1.073	2.	18	16.	154
3.	1.135	17.	1.091	3.	19	17.	Separ'n 110
4.	1.130	18.	0.796	4.	22	18.	186
5.	1.130	19.	0.796	5.	20	19.	188
6.	1.135	20.	0.840	6.	18	20.	186
7.	1.157	21.	0.521	7.	17	21.	0
8.	1.150	22.	Turb.	8.	22	22.	Turb.
9.	1.156	23.	0.573	9.	15	23.	264
10.	1.199	24.	Turb.	10.	0	24.	Turb.
11.	1.175	25.	0.530	11.	43	25.	0
12.	1.160	26.	0.546	12.	88	26.	0
13.	1.193	27.	0.423	13.	61	27.	-
14.	1.205	28.	0.544	14.	0	28.	0

DATA SHEET

Test 3a

Abutment Width - 27 7/8" ; Tailgate Height - 1 3/4"

Q - 1 c.f.s.; Δh - 0.248'

Height				Velocity, rpm.			
1.	0.527	15.	0.526	1.	13	15.	74
2.	0.528	16.	0.546	2.	14	16.	102
3.	0.535	17.	0.530	3.	13	17.	118
4.	0.534	18.	0.515	4.	11	18.	130
5.	0.533	19.	0.506	5.	14	19.	140
6.	0.539	20.	0.512	6.	9	20.	126
7.	0.560	21.	0.520	7.	7	21.	0
8.	0.549	22.	0.516	8.	24	22.	0
9.	0.562	23.	0.500	9.	7	23.	144
10.	0.590	24.	0.519	10.	0	24.	0
11.	0.575	25.	0.522	11.	10	25.	0
12.	0.573	26.	0.512	12.	44	26.	0
13.	0.581	27.	0.505	13.	22	27.	126
14.	0.588	28.	0.515	14.	0	28.	0

DATA SHEET

Test 3b

Abutment Width and Tailgate Height same as Test 3a

Q - 2 c.f.s.; Δh - 1.00'

Height				Velocity, rpm.			
1.	0.659	15.	0.637	1.	23	15.	94
2.	0.678	16.	0.655	2.	22	16.	116
3.	0.680	17.	0.633	3.	21	17.	104
4.	0.669	18.	0.562	4.	21	18.	182
5.	0.670	19.	0.562	5.	25	19.	176
6.	0.688	20.	0.562	6.	20	20.	178
7.	0.694	21.	0.520	7.	16	21.	0
8.	0.686	22.	0.518	8.	30	22.	Eddy
9.	0.700	23.	0.472	9.	17	23.	202
10.	0.723	24.	0.521	10.	0	24.	Eddy
11.	0.716	25.	0.524	11.	46	25.	0
12.	0.701	26.	0.516	12.	72	26.	0
13.	0.730	27.	0.533	13.	53	27.	144
14.	0.735	28.	0.526	14.	0	28.	0

DATA SHEET

Test 3c

Abutment Width and Tailgate Height same as Test 3a

Q - 3 c.f.s.; Δh - 2.22'

Height				Velocity, rpm.			
1.	0.781	15.	0.732	1.	30	15.	102
2.	0.785	16.	0.750	2.	31	16.	110
3.	0.795	17.	0.735	3.	30	17.	108
4.	0.788	18.	0.616	4.	30	18.	152
5.	0.782	19.	0.634	5.	29	19.	132
6.	0.801	20.	0.620	6.	28	20.	144
7.	0.810	21.	0.503	7.	28	21.	0
8.	0.802	22.	0.503	8.	34	22.	Turb.
9.	0.808	23.	0.503	9.	26	23.	216
10.	0.839	24.	0.510	10.	0	24.	Turb.
11.	0.830	25.	0.510	11.	50	25.	0
12.	0.812	26.	0.512	12.	67	26.	0
13.	0.831	27.	0.437	13.	56	27.	240
14.	0.842	28.	0.510	14.	0	28.	0

DATA SHEET

Test 3d

Abutment Width and Tailgate Height same as Test 3a

Q - 4 c.f.s.; h - 3.97'

Height				Velocity, rpm.			
1.	0.888	15.	0.828	1.	34	15.	Separ'n 94
2.	0.891	16.	0.852	2.	35	16.	132
3.	0.903	17.	0.830	3.	34	17.	Separ'n 98
4.	0.895	18.	0.647	4.	34	18.	200
5.	0.891	19.	0.704	5.	33	19.	190
6.	0.905	20.	0.660	6.	32	20.	198
7.	0.921	21.	0.520	7.	32	21.	0
8.	0.906	22.	0.518	8.	40	22.	Turb.
9.	0.923	23.	0.540	9.	30	23.	232
10.	0.948	24.	0.520	10.	0	24.	Turb.
11.	0.930	25.	0.528	11.	68	25.	0
12.	0.910	26.	0.533	12.	88	26.	10
13.	0.938	27.	0.450	13.	74	27.	252
14.	0.954	28.	0.531	14.	0	28.	14

DATA SHEET

Test 4a

Abutment Width - 40¼" ; Tailgate Height - 1 3/4" ;

Q - 1 c.f.s. ; Δ h - 0.248'

Height				Velocity, rpm.			
1.	0.510	15.	0.531	1.	14	15.	58
2.	0.516	16.	0.545	2.	17	16.	80
3.	0.518	17.	0.536	3.	8	17.	68
4.	0.517	18.	0.517	4.	17	18.	Eddy
5.	0.518	19.	0.525	5.	21	19.	96
6.	0.522	20.	0.520	6.	13	20.	Eddy
7.	0.543	21.	0.532	7.	11	21.	0
8.	0.535	22.	0.529	8.	27	22.	Eddy(0)
9.	0.540	23.	0.522	9.	9	23.	106
10.	0.572	24.	0.535	10.	0	24.	Eddy(0)
11.	0.565	25.	0.534	11.	0	25.	0
12.	0.554	26.	0.528	12.	39	26.	0
13.	0.570	27.	0.526	13.	0	27.	86
14.	0.575	28.	0.530	14.	0	28.	0

DATA SHEET

Test 4b

Abutment Width and Tailgate Height same as Test 4a

Q - 2 c.f.s. ; Δh - 1.00'

Height				Velocity, rpm.			
1.	0.589	15.	0.570	1.	29	15.	70
2.	0.588	16.	0.592	2.	37	16.	108
3.	0.603	17.	0.568	3.	26	17.	90
4.	0.599	18.	0.534	4.	28	18.	158
5.	0.592	19.	0.534	5.	39	19.	166
6.	0.606	20.	0.534	6.	24	20.	158
7.	0.618	21.	0.540	7.	22	21.	0
8.	0.605	22.	0.520	8.	48	22.	Eddy
9.	0.623	23.	Hyd. Jump	9.	20	23.	190
10.	0.650	24.	0.530	10.	0	24.	Eddy
11.	0.642	25.	0.545	11.	18	25.	0
12.	0.624	26.	0.521	12.	74	26.	168
13.	0.647	27.	Hyd. Jump	13.	21	27.	Hyd. Jump
14.	0.653	28.	0.522	14.	0	28.	0

NOTE: All downstream readings were effected by a surging, unstable area, typical of this particular test.

DATA SHEET

Test 4c

Abutment Width and Tailgate Height same as Test 4a

Q - 3 c.f.s. ; Δh - 2.22'

Height				Velocity, rpm.			
1.	0.679	15.	0.633	1.	37	15.	100
2.	0.682	16.	0.669	2.	41	16.	140
3.	0.695	17.	0.640	3.	38	17.	108
4.	0.683	18.	0.558	4.	43	18.	178
5.	0.682	19.	0.594	5.	46	19.	172
6.	0.694	20.	0.563	6.	39	20.	174
7.	0.703	21.	0.525	7.	35	21.	0
8.	0.695	22.	0.525	8.	50	22.	Eddy
9.	0.707	23.	0.497	9.	33	23.	200
10.	0.740	24.	0.535	10.	0	24.	Eddy
11.	0.727	25.	0.535	11.	18	25.	0
12.	0.707	26.	0.525	12.	82	26.	0
13.	0.732	27.	0.604	13.	24	27.	Turb.
14.	0.741	28.	Jump 0.528	14.	0	28.	0

DATA SHEET

Test 4d

Abutment Width and Tailgate Height same as Test 4a

Q - 4 c.f.s.; Δh - 3.97'

Height				Velocity, r.p.m.			
1.	0.759	15.	0.714	1.	46	15.	Separ'n 54
2.	0.759	16.	0.735	2.	45	16.	134
3.	0.765	17.	0.718	3.	44	17.	Separ'n 78
4.	0.770	18.	0.578	4.	44	18.	172
5.	0.762	19.	0.660	5.	47	19.	176
6.	0.782	20.	0.586	6.	42	20.	180
7.	0.786	21.	0.531	7.	39	21.	0
8.	0.773	22.	0.524	8.	50	22.	0
9.	0.793	23.	0.537	9.	39	23.	206
10.	0.828	24.	0.527	10.	0	24.	0
11.	0.818	25.	0.535	11.	50	25.	0
12.	0.783	26.	0.535	12.	90	26.	0
13.	0.820	27.	0.461	13.	60	27.	224
14.	0.834	28.	0.538	14.	0	28.	16

DATA SHEET

Test 5a

Abutment Width - 52½" ; Tailgate Height - 1 3/4" ;

Q - 1 c.f.s. ; Δh - 0.248'

Height				Velocity, r.p.m.			
1.	0.503	15.	0.533	1.	19	15.	58
2.	0.505	16.	0.545	2.	20	16.	62
3.	0.513	17.	0.540	3.	17	17.	60
4.	0.506	18.	0.525	4.	19	18.	Eddy
5.	0.508	19.	0.532	5.	24	19.	72
6.	0.519	20.	0.528	6.	18	20.	Eddy
7.	0.530	21.	-	7.	16	21.	-
8.	0.521	22.	0.536	8.	28	22.	0
9.	0.530	23.	0.531	9.	15	23.	86
10.	-	24.	0.538	10.	-	24.	0
11.	0.556	25.	-	11.	0	25.	-
12.	0.546	26.	0.524	12.	44	26.	72
13.	0.560	27.	0.528	13.	0	27.	0
14.	-	28.	0.522	14.	-	28.	

DATA SHEET

Test 5b

Abutment Width and Tailgate Height same as Test 5a

Q = 2 c.f.s. ; Δh = 1.00'

Height				Velocity, r.p.m.			
1.	0.550	15.	0.552	1.	36	15.	70
2.	0.552	16.	0.575	2.	40	16.	112
3.	0.553	17.	0.556	3.	34	17.	72
4.	0.560	18.	0.546	4.	37	18.	Turb. 56
5.	0.555	19.	0.548	5.	44	19.	124
6.	0.562	20.	0.548	6.	35	20.	Turb. 52
7.	0.590	21.	-	7.	30	21.	-
8.	0.570	22.	0.548	8.	55	22.	0
9.	0.591	23.	0.542	9.	30	23.	140
10.	-	24.	0.550	10.	-	24.	0
11.	0.612	25.	-	11.	Eddy 12	25.	-
12.	0.592	26.	0.537	12.	76	26.	0
13.	0.617	27.	0.545	13.	Eddy 18	27.	124
14.	-	28.	0.539	14.	-	28.	0

DATA SHEET

Test 5c

Abutment Width and Tailgate Height same as Test 5a.

Q = 3 c.f.s. ; Δh - 2.22'

Height				Velocity, r.p.m.			
1.	0.618	15.	0.600	1.	42	15.	110
2.	0.621	16.	0.623	2.	42	16.	120
3.	0.622	17.	0.607	3.	40	17.	112
4.	0.627	18.	Surge 0.555	4.	43	18.	144
5.	0.625	19.	0.580	5.	48	19.	160
6.	0.626	20.	Surge 0.558	6.	41	20.	140
7.	0.651	21.	-	7.	37	21.	-
8.	0.636	22.	0.540	8.	58	22.	Eddy
9.	0.654	23.	0.508	9.	37	23.	180
10.	-	24.	0.542	10.	-	24.	Eddy
11.	0.690	25.	-	11.	Eddy	25.	-
12.	0.656	26.	0.526	12.	80	26.	0
13.	0.693	27.	Unstable	13.	Eddy	27.	154
14.	-	28.	0.529	14.	-	28.	0

NOTE: All downstream readings were effected by a surging, unstable area, typical of this particular test.

DATA SHEET

Test 5d

Abutment Width and Tailgate Height same as Test 5a

Q - 4 c.f.s. ; Δh - 3.97'

Height				Velocity, r.p.m.			
1.	0.689	15.	0.644	1.	53	15.	Separ'n 96
2.	0.691	16.	0.685	2.	54	16.	132
3.	0.702	17.	0.648	3.	54	17.	Separ'n 108
4.	0.698	18.	0.555	4.	50	18.	192
5.	0.695	19.	0.620	5.	54	19.	156
6.	0.700	20.	0.563	6.	48	20.	184
7.	0.723	21.	-	7.	48	21.	-
8.	0.708	22.	0.532	8.	60	22.	Eddy
9.	0.728	23.	0.539	9.	48	23.	202
10.	-	24.	0.540	10.	-	24.	Eddy
11.	0.736	25.	-	11.	Eddy 10	25.	-
12.	0.715	26.	0.527	12.	88	26.	0
13.	0.745	27.	0.485	13.	Eddy 25	27.	222
14.	-	28.	0.530	14.	-	28.	5

DATA SHEET

Test 6a

Abutment Width - 71"; Tailgate Height - 1 3/4"

Q - 1 c.f.s.; Δh - 0.248'

Height				Velocity, rpm.			
1.	0.490	15.	0.534	1.	20	15.	42
2.	0.488	16.	0.546	2.	24	16.	46
3.	0.492	17.	0.541	3.	21	17.	44
4.	0.496	18.	0.534	4.	20	18.	Eddy
5.	0.500	19.	0.532	5.	24	19.	52
6.	0.505	20.	0.541	6.	19	20.	Eddy
7.	0.517	21.	-	7.	16	21.	-
8.	0.510	22.	0.535	8.	30	22.	0
9.	0.520	23.	0.532	9.	15	23.	56
10.	-	24.	0.538	10.	-	24.	0
11.	0.559	25.	-	11.	0	25.	-
12.	0.549	26.	0.528	12.	34	26.	0
13.	0.561	27.	0.529	13.	0	27.	48
14.	-	28.	0.530	14.	-	28.	0

DATA SHEET

Test 6b

Abutment Width and Tailgate Height same as Test 6a

Q - 2 c.f.s.; Δ h - 1.00'

Height				Velocity, rpm.			
1.	0.536	15.	0.560	1.	33	15.	Turb. 70
2.	0.538	16.	0.574	2.	33	16.	80
3.	0.545	17.	0.568	3.	30	17.	Turb. 60
4.	0.544	18.	0.550	4.	36	18.	Eddy -17
5.	0.539	19.	0.561	5.	45	19.	92
6.	0.552	20.	0.555	6.	35	20.	Eddy -15
7.	0.566	21.	-	7.	33	21.	-
8.	0.555	22.	0.561	8.	54	22.	0
9.	0.564	23.	0.555	9.	33	23.	100
10.	-	24.	0.564	10.	-	24.	0
11.	0.600	25.	-	11.	0	25.	-
12.	0.585	26.	0.545	12.	60	26.	0
13.	0.608	27.	0.555	13.	0	27.	90
14.	-	28.	0.550	14.	-	28.	0

DATA SHEET

Test 6c

Abutment Width and Tailgate Height same as Test 6a

Q - 3 c.f.s.; Δh - 2.22'

Height				Velocity, rpm.			
1.	0.579	15.	0.594	1.	48	15.	Separ'n 88
2.	0.579	16.	0.602	2.	52	16.	102
3.	0.584	17.	0.600	3.	49	17.	Separ'n 92
4.	0.585	18.	0.585	4.	49	18.	Eddy 34
5.	0.581	19.	0.584	5.	54	19.	118
6.	0.586	20.	0.582	6.	49	20.	Eddy 48
7.	0.605	21.	-	7.	50	21.	-
8.	0.596	22.	0.570	8.	57	22.	Eddy
9.	0.606	23.	0.563	9.	49	23.	132
10.	-	24.	0.574	10.	-	24.	Eddy
11.	0.643	25.	-	11.	0	25.	-
12.	0.624	26.	0.555	12.	78	26.	0
13.	0.643	27.	0.577	13.	0	27.	122
14.	-	28.	0.558	14.	-	28.	0

DATA SHEET

Test 6d

Abutment Width and Tailgate Height same as Test 6a

Q - 4 c.f.s.; Δh - 3.97'

Height				Velocity, rpm.			
1.	0.628	15.	0.598	1.	55	15.	88
2.	0.624	16.	0.638	2.	58	16.	126
3.	0.628	17.	0.609	3.	55	17.	100
4.	0.624	18.	Turb. 0.575	4.	56	18.	Turb. 120
5.	0.624	19.	0.614	5.	65	19.	148
6.	0.630	20.	Turb. 0.586	6.	57	20.	Turb. 118
7.	0.643	21.	-	7.	55	21.	-
8.	0.638	22.	0.597	8.	80	22.	0
9.	0.641	23.	0.594	9.	57	23.	156
10.	-	24.	0.601	10.	-	24.	0
11.	0.681	25.	-	11.	Eddy	25.	-
12.	0.654	26.	0.575	12.	90	26.	Eddy 6
13.	0.684	27.	0.594	13.	Eddy	27.	144
14.	-	28.	0.581	14.	-	28.	Eddy 10

DATA SHEET

Test 4cI

Abutment Width and Tailgate Height same as Test 4a

Q - 3 c.f.s.; Δh - 2.22'

Height				Velocity, rpm.			
11.	0.684	17.	0.625	11.	90	17.	152
12.	0.684	18.	0.596	12.	94	18.	158
13.	0.683	18a.	0.590	13.	88	18a.	160
15.	0.621	19.	0.595	15.	150	19.	166
15a.	0.635	19a.	0.595	15a.	144	19a.	158
16.	0.640	20.	0.589	16.	144	20.	164
16a.	0.636			16a.	148		

Test 4dI

Abutment Width and Tailgate Height same as Test 4a

Q - 4 c.f.s.; Δh - 3.97'

Height				Velocity, rpm.			
11.	0.745	17.	0.676	11.	102	17.	180
12.	0.745	18.	0.642	12.	108	18.	200
13.	0.747	18a.	0.630	13.	98	18a.	198
15.	0.678	19.	0.642	15.	172	19.	196
15a.	0.690	19a.	0.628	15a.	172	19a.	194
16.	0.694	20.	0.640	16.	174	20.	210
16a.	0.688			16a.	176		

DATA SHEET

Test 4aI

Abutment Width and Tailgate Height same as Test 4a

Q - 1 c.f.s.; Δh - 0.248'

Height				Velocity, rpm.			
11.	0.541	17.	0.524	11.	61	17.	86
12.	0.543	18.	0.523	12.	61	18.	94
13.	0.540	18a.	0.523	13.	64	18a.	94
15.	0.523	19.	0.525	15.	80	19.	92
15a.	0.529	19a.	0.526	15a.	84	19a.	92
16.	0.530	20.	0.527	16.	82	20	94
16a.	0.530			16a.	86		

Test 4bI

Abutment Width and Tailgate Height same as Test 4a

Q - 2 c.f.s.; Δh - 1.00'

Height				Velocity, rpm.			
11.	0.612	17.	0.560	11.	80	17.	130
12.	0.614	18.	0.544	12.	82	18.	148
13.	0.614	18a.	0.544	13.	84	18a.	140
15.	0.559	19.	0.547	15.	126	19.	150
15a.	0.567	19a.	0.545	15a.	122	19a.	142
16.	0.569	20.	0.543	16.	128	20.	138
16a.	0.568			16a.	126		

DATA SHEET

TEST 4aII

Abutment Width and Tailgate Height same as Test 4a.

Q - 1 c.f.s.; Δh - 0.248'

Height				Velocity, rpm.			
1.	0.510	16.	0.539	1.	20	16.	82
2.	0.510	16a.	-	2.	18	16a.	84
3.	0.516	17.	0.532	3.	-	17.	80
4.	0.518	18.	0.524	4.	13	18.	86
5.	0.518	18a.	-	5.	20	18a.	82
6.	0.520	19.	0.530	6.	9	19.	88
7.	0.538	19a.	-	7.	0	19a.	88
8.	0.529	20.	0.528	8.	33	20.	80
9.	0.540	21.	0.535	9.	0	21.	0
10.	0.569	22.	0.532	10.	0	22.	0
11.	0.546	23.	0.524	11.	44	23.	92
12.	0.546	24.	0.535	12.	60	24.	0
13.	0.552	25.	0.535	13.	41	25.	0
14.	0.570	26.	0.528	14.	0	26.	0
15.	0.526	27.	0.531	15.	80	27.	80
15a.	-	28.	0.533	15a.	82	28.	0

DATA SHEET

TEST 4bII

Abutment Width and Tailgate Height same as Test 4a.

Q - 2 c.f.s.; Δh - 1.00'

Height				Velocity, rpm.			
1.	0.591	16.	0.579	1.	27	16.	125
2.	0.594	16a.	-	2.	31	16a.	140
3.	0.595	17.	0.569	3.	23	17.	128
4.	0.599	18.	0.546	4.	25	18.	146
5.	0.592	18a.	-	5.	39	18a.	146
6.	0.601	19.	0.554	6.	27	19.	142
7.	0.624	19a.	-	7.	12	19a.	148
8.	0.605	20.	0.548	8.	54	20.	146
9.	0.621	21.	0.536	9.	15	21.	0
10.	0.650	22.	0.530	10.	0	22.	0
11.	0.603	23.	0.502	11.	90	23.	186
12.	0.612	24.	0.538	12.	82	24.	0
13.	0.610	25.	0.538	13.	86	25.	0
14.	0.653	26.	0.515	14.	0	26.	0
15.	0.565	27.	0.525	15.	132	27.	154
15a.	-	28.	0.516	15a.	130	28.	0

DATA SHEET

TEST 4cII

Abutment Width and Tailgate Height same as Test 4a

Q - 3 c.f.s.; Δh - 2.22'

Height				Velocity, rpm.			
1.	0.669	16.	0.634	1.	32	16.	142
2.	0.665	16a.	-	2.	35	16a.	144
3.	0.672	17.	0.615	3.	32	17.	154
4.	0.675	18.	0.559	4.	32	18.	194
5.	0.678	18a.	-	5.	40	18a.	188
6.	0.678	19.	0.592	6.	33	19.	170
7.	0.697	19a.	-	7.	26	19a.	182
8.	0.680	20.	0.560	8.	54	20.	184
9.	0.699	21.	0.535	9.	30	21.	0
10.	0.726	22.	0.535	10.	0	22.	0
11.	0.679	23.	0.526	11.	100	23.	214
12.	0.675	24.	0.540	12.	96	24.	0
13.	0.687	25.	0.540	13.	88	25.	0
14.	0.736	26.	0.542	14.	0	26.	0
15.	0.610	27.	0.598	15.	148	27.	Hyd. Jump
15a.	-	28.	0.550	15a.	156	28.	0

DATA SHEET

TEST 4dII

Abutment Width and Tailgate Height same as Test 4a

Q - 4 c.f.s.; Δh - 3.97'

Height				Velocity, rpm.			
1.	0.750	16.	0.695	1.	39	16.	160
2.	0.750	16a.	-	2.	40	16a.	164
3.	0.760	17.	0.676	3.	37	17.	160
4.	0.755	18.	0.612	4.	33	18.	206
5.	0.755	18a.	-	5.	43	18a.	210
6.	0.758	19.	0.648	6.	37	19.	194
7.	0.777	19a.	-	7.	24	19a.	196
8.	0.762	20.	0.619	8.	62	20.	200
9.	0.785	21.	0.540	9.	26	21.	0
10.	0.819	22.	0.540	10.	0	22.	Eddy
11.	0.747	23.	0.560	11.	Eddy	23.	266
12.	0.747	24.	0.540	12.	110	24.	Eddy
13.	0.750	25.	0.540	13.	Eddy	25.	0
14.	0.822	26.	0.530	14.	0	26.	0
15.	0.674	27.	0.458	15.	154	27.	280
15a.	-	28.	0.550	15a.	156	28.	0

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