A LABORATORY STUDY OF FLOW AROUND BENDS AND BANK STABILIZATION

Vol. I.

A Thesis

Presented to

The Faculty of Engineering

The University of Manitoba

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Civil Engineering

by

David A. Pashniak

March, 1966

SYNOPSIS

A two part laboratory study was undertaken to investigate, in Part I, the helical flow phenomenon, and the associated features of water flowing around meander bends, and, in Part II, the effects of several types of stabilizing measures on helical flow and the erosion patterns of an erodable sinuous channel.

The conclusions, in Chapter VIII are supported by the laboratory observations presented in Volume II, and Chapters IV, and VII of Volume I.

ACKNOWLEDGEMENT

I wish to express my gratitutde to the National Research Council in providing the funds necessary for the investigation, and also Professor G.A. Russell and Professor A.J. Carlson for their advice and encouragement. I also acknowledge Professor E. Kuiper for stimulating my interest in this field of hydraulics.

To Barb

TABLE OF CONTENTS

VOLUME I

CHAPTER PAGE

PART II

CHAPTER PAGE

VOLUME I

LIST OF FIGURES

VOLUME II

PART I

PART II

PART II (Cont'd)

PART II (Cont'd)

LIST OF SYMBOLS

a_{CB} - acceleration of bottom currents in ft/sec^2

a_{CS} - acceleration of surface currents in ft/sec^2

C - a constant (see definition of Law of Areas).

g - acceleration of gravity in ft/sec^2

θ - angular deviation of bottom centreline velocities in ft/sec

1/n - transverse water surface slope

P - wetted perimeter in feet

R_e - Reynold's Number

r_c or R_c - radius of curvature of channel centreline in feet

r_1 or R_1 - radius of concave bank in feet

r_2 or R_2 - radius of convex bank in feet

R - radius of curvature of surface velocities in feet

r - radius of curvature of bottom velocities in feet

V_{av} - average velocity in a channel in ft/sec

V_n - superficial velocities in ft/sec

V_s - surface velocities in ft/sec

V_B - bottom velocities in ft/sec

V_T - tangential velocities in ft/sec

V_r - radial (transverse) velocities in ft/sec

w - weight of an element of water in lbs.

z - super elevation of the water surfaee in feet.

DEFINITIONS

Apex (axis) of a curve - the mid point of the length of curve.

Convex and concave bank - see Plate 1, page 1, Volume II.

Degree of curvature - the sharpness of a curve.

Helical flow - flow patterns around meander bends resembling a helix.

Normal depth - the depth attained by water flowing in an open channel at a given discharge on a constant channel slope. The magnitude of normal also depends on the channel cross-section and its relative roughness.

Relative roughness - The magnified surface profile of a channel bottom (and sides) is composed of irregular peaks and valleys. The ratio of the effective heights, of these irregularities, to the hydraulic radius of the channel is called the relative roughness. (Hydraulic radius is the area of flow divided by lengths of the wetted sides in cross-section).

Sinuosity - See Plate 1, page 1, Volume II.

Stage - the water surface elevation.

Point bar - the shoal formation on the convex bank downstream of the apex of a curve.

CHAPTER I

INTRODUCTION

The encroachment of meandering streams upon the homes, roadways and industries of our expanding communities is becoming an increasingly great problem.

When stabilization of meanders is considered, a knowledge of the effects of stabilizing measures on the hydraulic processes and channel material in a meander bend is essential. Basically, any form of stabilizing measure is a foreign obstacle placed in the path of on-coming flow with the purpose of either disrupting the flow direction or protecting the banks containing the flow. Therefore, it is apparent that the installation of stabilizing measures could cause one of two results to occur. The river channel could either be checked in its lateral and downstream movement, thereby saving valuable property, or over a period of time the stabilizing measures could worsen the situation by causing the river to take an entirely new course and cause many times more damage than it would have done, otherwise.

The following thesis is divided into two parts:

Part I will briefly study the hydraulics processes and resulting phenomena of water flowing around meander bends in a laboratory channel.

Part II will briefly attempt to consider the effects of several "basic" forms of stabilization on the flow of water around the meander bends in a laboratory channel. Part II will also entail:

A. Briefly examining the effects of basic forms of stabilization on the bed material of a sinuous channel.

B. Briefly examining the effects of basic forms of stabilization on the bed and bank materials of an erodable sinuous channel.

The "basic" stabilizing measures used were in forms of spur dykes, jetties and revetments.

PART I

CHAPTER II

THE RESULTS OF PREVIOUS INVESTIGATIONS IN FLOW AROUND BENDS

GENERAL STATEMENT

> "The most characteristic feature of all stream channels, regardless of size, is the absence of long straight reaches and the presence of sinuous reversals of curvature".
>
> \- Leopold & Wolman[3]

With the extensive number of bends existing in any river reach, the study of the hydraulic processes occurring therein is of utmost importance when river training is considered.

TWO THEORIES - PARALLEL FLOW & NON PARALLEL FLOW

At the turn of the twentieth century, two trends of thought described the movement of water in an open channel.

The first postulation was called the "Parallelist Theory". It maintained that water streamlines flowed essentially parallel to the boundaries of a channel as well as parallel to each other. The other theory, which is now accepted, was called the"Non Parallelist Theory". It stated that in a curvilinear channel, no contiguous streamlines are ever parallel.

The latter theory was introduced by J. Thomson[2] in 1879. The theory did not gain recognition at that time. However, his claim that transverse circulation (i.e. helical flow) existed in open channels was physically correct.

In the beginning of the twentieth century, a number of investigators advocated Thomson's theory. This group included, M. Muller[4] in 1906, N.S. Leliavsky[2][5] in 1908, and O.Fargue[5][2] in 1908.

A brief chronological review of the views of these men will follow in the next paragraphs.

After Thomson introduced his theory of helical flow, F. Grashot[2][5] in 1879 presented an equation for the transverse water surface slope occurring in a river bend. Muller (1906) experimented with surface and bottom currents. He presented an equation for transverse slope which was modified by Lyapin[5] in 1954. O. Fargue (1908) conducted field observations on the Garonne River. His conclusions from the study led to the Fargue Laws which are still used in Europe, both in research and design. N.S. Leliavsky (1908) improved on Muller's work. He also confirmed Fargue's Laws with measured data.

From the studies of Muller, Grashof, Fargue, Leliavsky and others, the two following postulates constitute the basis of the "Non Parallelist Flow Theory". (a) In a natural channel, any adjacent flow lines are non-parallel except in the zones near the bank. (Leliavsky). (b) The greater the curvature of the horizontal projection of stream flow lines, the deeper the scour below them. (Fargue).

This new concept could not be substantiated because the empirical relationship did not give a physical reason for the phenomenon. The first of the above mentioned postulates, (a), was impossible to explain due to the presence of fluctuating turbulence.

> "The absence of parallel flow indicates average velocities rather than instantaneous velocities".
>
> \- Kondratev[5]

The second postulate remained. Boussinesq, Thomson and Fargue each attempted to relate channel depth to increased curvature.

Boussinesq[7] used a closed pipe analogy by employing pressure losses. The equation he derived has been criticized for the excessive number of assumptions.

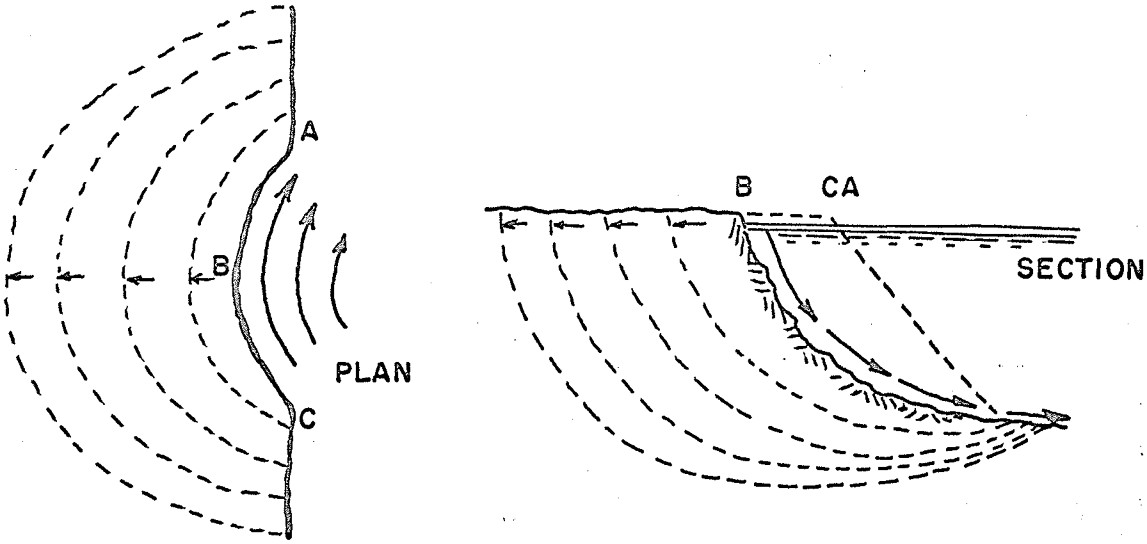
Fargue[5][2] again proposed empirical relationships from previous observations on the Garonne River. (The equations were further expanded by Yasmund[5] with data obtained from other rivers in central Europe). The Fargue Laws resulted from his observations. Although they are recognized, they are not laws from a scientific viewpoint, since they are empirically derived.

TRANSVERSE CIRCULATION PHENOMENON

F. Grashof[5][2] and M. Muller[4] considered Thomson's idea of transverse circulation. Subsequently, this work was more full developed by other investigators. Their equations for the transverse slope of the water surface in a bend of an open channel gave strong physical proof for the existence of non-parallel flow. Their theories also gave a logical approach to the cause of meandering in natural streams.

MATHEMATICAL RELATIONS FOR TRANSVERSE SLOPE

Meandering is attributed basically to scour and deposition. When a channel is disrupted in some manner, the streamlines are forced to deviate from their initial paths. (see Fig. 1, page 7). Gradually they become increasingly curved in plan. As the boundaries of the channel increase in curvature, the water flowing around the disruption develops a centrifugal force. This force increases with the growing curvature. An outward movement set up by the centrifugal force causes the water to be "piled" against the concave bank. Transverse circulation takes place as water is forced down the bank and along the bottom towards the convex bank.



DEVELOPMENT OF A MEANDER

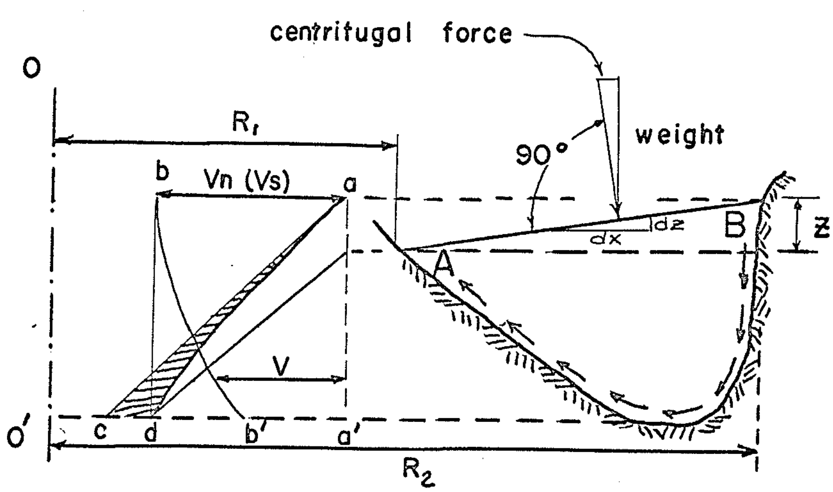
Figure 1

In this downward motion material is removed from the concave bank and partially carried to the convex side where deposition occurs. This continuous action propagates the meander.

(a) Grashof's Equation For Transverse Slope

Grashof[2] reasoned that the transverse slope resulted from the piling effect caused by the centrifugal force.

Consider a cross-section, A B, of a channel curved in plan. Let 0 0' be the vertical axis of curvature, (i.e. the centre of the curve).



TRANSVERSE WATER SURFACE SLOPE IN A MEANDER AND THE MECHANICAL MODEL OF HELICAL FLOW

Figure 2

The centrifugal force on a surface element would be:

$$\frac{W\ V_n^{\ 2}}{g\ R} \qquad \text{....(1)}$$

where: W = weight of element

V_n = superficial velocity

g = constant of gravity

R = distance of element to centre of curve.

The water surface slope is equal to the ratio of centrifugal force to weight. (Fig. 2)

or

$$\frac{dz}{dx} = \frac{\frac{W\ V_n^{\ 2}}{g\ R}}{W} \qquad \text{....(2)}$$

integrating equation (2)

$$gz = V_n^{\ 2} \log_e R + \text{constant} \qquad \text{....(3)}$$

where: z = super elevation.

Because no super-elevation exists on the left side, it follows that:

$$gz = 0 = V_n^{\ 2} \log_e R_1 + \text{const} \qquad \text{....(4)}$$

where: R_1 = radius to convex bank.

Thus the difference in water levels between the concave bank and convex bank is

$$z = \frac{V_n^{\ 2}}{g} \log_e \frac{R_2}{R_1} \qquad \text{....(5)}$$

where: R_2 = radius to concave bank

R_1 = radius to convex bank.

In order to ascertain the existence of transverse currents, consider the cross-section A B shown in Fig. 2. In the Grashof equation, only the surface velocity is considered. If the velocity distribution had been uniform, no secondary currents could exist. In that case, all streamlines would be parallel and the hydrostatic force diagram would be represented by the area "c a a'",(with line "c a" inclined at 45°). Because the velocity decreases with depth, it follows that the centrifugal force will also diminish. Hence, the pressure on the concave bank would be treated as hydrodynamic rather than hydrostatic, as indicated by the curved line "a d" in Fig. 2. The excess in hydrostatic pressure (shaded in Fig. 2) is unbalanced. This produces movement on the bottom in form of the helical cross currents shown by the arrows A to B. The directions of surface and bottom currents are not completely radial as shown, but are deflected in the downstream direction by the advancing longitudinal flow. This results in a helical or screw pattern of flow.

(b) The Muller Equation for Transverse Slope

Muller[4] observed the transverse slope of the free surface in an open channel when he discovered the existence of helical flow. The general flow pattern was plotted from velocity readings. By attaching a thread to the point of velocity measurement, the resultant direction was obtained. No method was given for the measurement of angles. Realizing that the resultant velocities in any bend are directed toward the concave bank, he deduced that the transverse components were, in effect, the centrifugal acceleration.

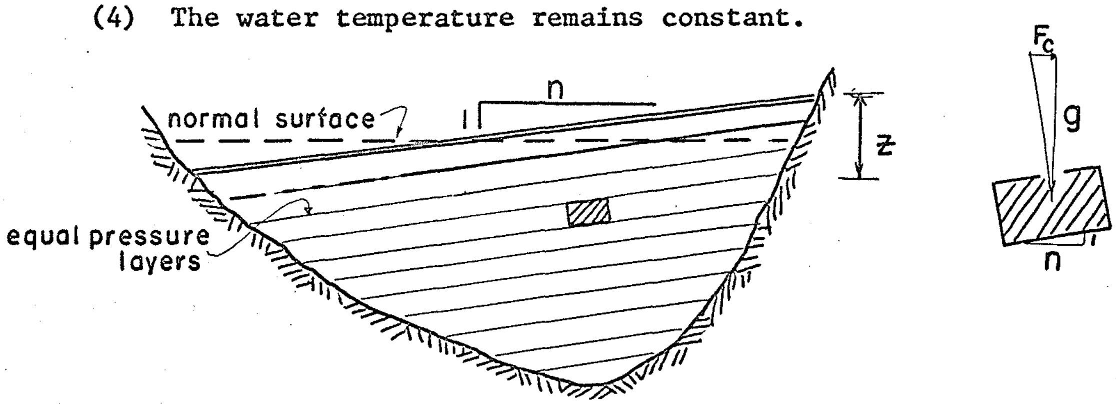
Muller[4] simulated basic natural flow conditions in a laboratory flume. The channel, although rectangular and sloped, had such a cross-section that bed friction influenced the vertical velocity distribution. Hence the magnitude and direction of surface and bottom currents had distinct values. He concluded that the surface currents, being the greater, would develop a much larger centrifugal force. In the derivation of the equation, Muller[4] made the following assumptions:

(1) The piling effect of the water in a bend not only causes the transverse slope but also inclined parallel planes of equal pressure existing to the channel bottom. (See Fig. 3).

(2) If any vertical acceleration exists it is of no consequence.

(3) The average of the surface current radius and bottom current radius is equal to the centreline radius of the channel.

(4) The water temperature remains constant.



MULLER'S ASSUMPTION OF TRANSVERSE WATER SLOPE IN A MEANDER

Figure 3

Muller[4] reasoned that the transverse component of gravity of all elements in each pressure layer would be

$$F_c = \frac{1}{n} g \qquad \ldots.(6)$$

where: $\frac{1}{n}$ = transverse slope.

In reaction, this force would equal the centrifugal acceleration.

For surface velocities $a_{CS} = \frac{V_S^2}{R}$ ....(7)

where: a_{CS} = acceleration of surface currents

R = radius for curvature for surface velocities.

For bottom velocities, $a_{CB} = \frac{V_B^2}{r}$ ....(8)

where: a_{CB} = acceleration of bottom currents

r = radius of curvature for bottom velocities.

"By averaging surface and bottom velocities, a fair estimate of the average velocity in the cross-section is obtained".

– Muller[4]

Thus: $$\frac{1}{n} g = \frac{V_s^2}{R} = \frac{V_B^2}{r} = \frac{V_{av}^2}{R_C}$$ ....(9)

and $$\frac{1}{n} = \frac{V_{av}^2}{g\ R_C}$$ ....(10)

or $$z = \frac{V_{av}^2}{g\ R_C}(r_2 - r_1)$$ ....(11)

where: z = super elevation

$\frac{1}{n} = \frac{z}{r_2 - r_1}$

$(r_2 - r_1)$ = width of cross-section

or r_1 = radius of convex bank

r_2 = radius of concave bank.

Equation (11) was compared to measured values, but the result were never published.

(c) <u>The Lyapin Equation for Transverse Slope</u>

Lyapin[5] in 1954, developed an equation similar to that of Muller[4] by considering:

(1) centrifugal force;

(2) pressure difference on the side walls of the water element under consideration;

(3) bottom friction.

The basic assumption in the derivation was that pressures along the vertical follow the hydrostatic law.

Summation of the above mentioned forces produced equation (12).

$$\frac{1}{n} = \alpha_o \frac{V_{av}^2}{R_c} \qquad ....(12)$$

$$z = \alpha_o \frac{V_{av}^2}{R_c} (r_2 - r_1) \qquad ....(13)$$

where: α_o = a coefficient

R_c = radius of the centre-line of the channel.

Equation (13) resembles equation (11) except a coefficient, α_o, has been introduced to take into account the irregular velocity distribution in the vertical. Equation (13) also assumes that the tangential velocities across the section are constant. This was later proved incorrect in field and laboratory studies conducted by Rozovskii[5] and Mockmore[5][3].

(d) The Shoutri Equation for Transverse Slope

Shoutri[5] modified equation (13) by assuming that the distribution of velocity of the advancing flow follows the Law of Areas.

That is $V_T\, r = C$ ....(14)

where: C = a constant

V_T = a tangential velocity

r = distance of V_T to centre of curvature.

Applying this to equation (13), the following expression is obtained for the super elevation.

$$z = \frac{C^2}{2\, g\, r_2^2\, r_1^2} (r_2^2 - r_1^2) \qquad ....(16)$$

Shoutri[5] and Rozovskii[5] both checked equation (16) with measured values of super-elevation and found it to be quite accurate.

CONVERGING AND DIVERGING CURRENTS

The separations of surface and bottom currents have been studied by several previous investigators.

Muller[4] measured velocities and directions in a bend in a laboratory flume. His results were plotted but the conclusions were incomplete.

N.S. Leliavsky[2] conducted a similar study on a bend of river. He presented a theory which stated that converging currents (concave bank) produce erosion, and diverging currents (convex bank and points of inflection) produce deposition.

Prus-Chassinsky[3][5] and Rozovskii[5] studied flow around bends in some detail. The empirical relationships for angular deviation of bottom centreline velocities presented by these two investigators comprise the majority of the formulae that presently exist in this topic of fluvial hydraulics.

(a) Prus-Chassinsky Equation for Angular Deviation of Bottom Centreline Velocities

Prus-Chassinsky[5] obtained expressions, for angular deviation of bottom centreline currents, for channels of rectangular and triangular cross-sections.

The formula that will be compared to the measured results of this thesis is given as:

$$\text{Tan } \Theta = \frac{P}{(R_e)^{0.25}(R_c)} \qquad \ldots(17)$$

where: Θ = magnitude of angular deviation

P = wetted perimeter

R_e = Reynold's number

R_c = Centre-line radius of curvature.

Prus-Chassinsky restricts the use of equation (17) to the following conditions:

(1) The angle subtended at the centre of the curve by the extent of the curve be at least 33°.

(2) The Reynold's number of the flow must lie between 2,000 and 15,000.

(b) <u>The Rozovskii Equation for Angular Deviation of Bottom Centre-line Velocities</u>

Rozovskii[5] did not agree with the expressions proposed by Prus-Chassinsky[3][5]. He maintained that the variation of angular deviation of bottom centre-line currents varied only with the depth of flow and the radius of the kind in question. From his laboratory studies, he recommended an empirically derived equation, (equation (18)), which has no restrictions in its use.

$$\text{Tan } \Theta = (10 \rightarrow 12) \frac{h}{R} \qquad \ldots.(18)$$

where: h = depth of flow

R = centre-line radius

Θ = angular deviation of centre-line velocities.

Equation (18) has been questioned in that no consideration is given to the flow characteristics of the channel as in the case of the Prus-Chassinsky Equation (equation (17)), which uses Reynold's Number in this respect.[7] In practical applications, equations (17) and (18) could be used in obtaining the intensity of the transverse flow existing in a river channel for purposes of stabilization.

The preceding pages have briefly outlined several different theories concerning flow around bends in an open channel. Because the present thesis was basically an introduction to a study of the effects of river training measures on flow around beds, only the more outstanding relationships were dealt with. Comparisons of the results of other investigators in this subject, not mentioned in this chapter, will be made in Chapter IV.

CHAPTER III

LABORATORY INVESTIGATION

GENERAL STATEMENT

A series of laboratory experiments were conducted to investigate the phenomena resulting from helical flow in a sinuous channel. Measurements were taken on the transverse water slopes, angular deviation of bottom centre-line currents, as well as general observations.

This phase of testing served to introduce the writer to this field of fluvial hydraulics before the topic of river training was considered (Part II). The apparatus used was constructed and tested over a period of three months in 1965. The laboratory apparatus and testing procedure is briefly outlined in this chapter, but treated in more detail in Appendix A.

Apparatus

The test channel was located in an abandoned hydraulic model. The approximate dimensions of the testing area were, 50 feet in length, and 15 feet in width. (See Fig. 9 , page 80, Appendix A). A waterproofed retaining wall, 3 feet in height surrounded the model. The entire test area was filled with multi-grade mortar sand in which the mortar test channel was set.

A circulating system supplied the water used in the tests. A supply pump, located next to a sump at the downstream end of the model, pumped water to a supply reservoir at the upstream end, which directly supplied water to the test channel by means of a control gate. (See Fig. 9). In order to assure steady flow in the test channel, water was allowed to flow over one side of the supply reservoir into a return channel which flowed into the sump. The amount of water required for a particular test was regulated by the upstream control gate and measured as it passed over a 90° V-notched weir into the testing area.

Before the water reached the test channel, it passed through a series of decreasing diameter pipes which directed the water straight into the channel as well as dampening out any disturbances.

At the downstream end of the channel, a stilling basin and an adjustable tailgate were located. The tailgate was used to vary the depth of water in the channel. The stilling basin was used to settle out debris that could be collected in the channel and carried into the sump.

Two sets of rails straddled the test channel throughout its length. (One set of rails was sloped parallel to the channel bottom, the other set was level). A travelling gauge carriage could be mounted on either set or rails. A secondary carriage carrying electric point gauge and velocity instrument was allowed to run on the main carriage. This arrangement allowed lateral as well as longitudinal movement.

The test channel was formed from a fine mortar cement, (see Sieve Analysis, Appendix B), set in the sand bed of the testing area. In its airline distance of 36 feet, four curves were formed to produce a thalweg distance of 42 feet. (See "Construction of Channel", Appendix A).

Instrumentation

For a detailed description of the construction and operation of the measuring instruments, refer to Appendix A.

Fixed and Variable Conditions

The alignment of the test channel had a sinuosity of 1.2. Four curves of different radii were fitted into the testing area available. The size of curves increased in the downstream direction. (Friedken[1] produced natural meanders in a laboratory flume. The naturally formed channels had a similar shaped alignment and a sinuosity which varied from 1.1 to 1.6). Any channel alignment would have been sufficient as the vagaries of nature allow no set patterns of channel formation. The reason for choosing Friedken[1] as a guide was primarily because the investigation of Bank Stabilization in Part II which is a follow up to his study. A similar channel alignment will be used in Part II. However in that study, the channel shall be completely erodable.

The channel was treated as a portion of a small stream which has a relatively large depth of width ratio. Previous investigators have indicated that this is essential if helical flow is to exist in a laboratory channel.

The final apparatus permitted the following items to be varied:

(1) Discharge: This was regulated by the upstream reservoir gate and measured by the 90° V-notch weir. (Fig. 9)

(2) Water Depth: This is directly associated with discharge. The normal depths for all discharges studied was set by regulating the tail-water level with the tailgate and hook gauge. (See Fig. 9)

(3) Radius of Curvature: Four radii of curvature were formed in the channel. Increasing in magnitude in the downstream direction, the radii distances were; 4.13 feet, 4.39 feet, 6.77 feet, and 7.21 feet.

The fixed conditions of the apparatus were as follows:

(1) Slope: The fixed bed channel was set at a slope of 0.0006. This value for slope was chosen as it produced optimum depths of flow as well as normal depth velocities in the range of the velocity instrument used.

(2) Channel Dimensions: The channel was trapezoidal in section with dimensions as follows; 0.5 feet bottom width, 1:1 side slopes and 0.5 feet depth.

(3) Channel Roughness: The mortar mixture used produced a test channel with a relative roughness value of 0.014. The effects of channel roughness was not a part of this study.

Testing Procedure

The testing procedure was conducted in the following manner. Having primed and started the pump, the valve at the upstream reservoir was set to allow approximately 2 to 3 inches of overflow into the return channel. To obtain the discharge required, the upstream reservoir gate was adjusted to conform to the water level reading required, over the 90° V-notch weir. (This reading sas set on a hook gauge immediately upstream of the weir. See Fig. 9 , Appendix A).

When the required discharge was flowing in the channel, the normal depth was obtained by adjusting the tail-water gate. This setting was made to the reading set on the tail-water hook gauge which was zeroed to the channel bottom.

With the flow running steady and at a normal depth for the conditions present, testing commenced. Velocities and transverse slope readings were taken at observations stations which were set at one foot intervals along the centre-line of the channel. Additional observations were recorded on photographs and notes.

CHAPTER IV

DISCUSSION OF TEST RESULTS

GENERAL STATEMENT

The laboratory testing was based on the following considerations.

(1) The tests would be conducted on a test channel, the alignment of which, was such that the variation of curvature would allow sufficient comparison of the effects of the radii of curvature of the helical flow phenomena.

(2) In order to study the effects of the helical flow phenomena, the channel cross-section would have to contain a relatively large depth to width ratio in order that the helical flow phenomena would exist at the different depths to be observed.

(3) The channel slope was fixed so that with maximum discharge, the cross-section of the channel would be completely filled and yet contain velocities that would be within the measuring range of the instrument used.

(4) No modelled or scaled relationships would be used in these studies. The test channel would be treated as a section of a small stream but fixed by the aforementioned conditions.

Previous investigators in this subject have placed a great deal of emphasis on the qualitative observations. This could be due to the complexity of the helical flow phenomena which would result in a lack of theoretical and empirical relationships with which to compare results. This thesis will not deviate from that standard and will present the discussion of results in the following manner. By comparison of the present results with past studies, the initial section will deal with the overall existence of helical flow. This will be followed by the flow features that arise as a result of helical flow, for example, super-elevation, deviation of bottom centre-line currents, effect of helical flow on bottom material, etc.

The Presence of Helical Flow

Plate 2, Volume II, shows the detailed distribution of surface and bottom velocities which were recorded during maximum conditions in the test channel. (These maximum conditions were at a flow of 0.3 cubic feet per second and a depth of flow of 0.4 feet). The centre-line of the test channel was sub-divided into one foot station lengths. The velocity readings taken on the surface and bottom at these stations have been plotted in vector form. The solid vectors represent the surface velocities and the dashed vectors represent the bottom velocities. The direction of each velocity vector has been referred to radial lines joining the centre of a particular curve to the station on the curve.

Plate 2 clearly indicates the existence of helical flow in the test channel. Proceeding downstream from Station 0, it is seen that the approach velocities on the surface and bottom are relatively coincident in direction. As the curve is gradually traversed, there is a definite angular separation between the surface and bottom velocities. The surface velocities move toward the concave bank, and the bottom velocities are deflected toward the convex bank. In this process, there occurs a definite decrease in concave velocities over the convex velocities. Associated with the decreased concave velocities would be energy loss, and build-up of radial and vertical components at the concave location.

As the curve is traversed, the outward deflection of surface velocities and the inward deflection of bottom velocities increases until the apex of the curve (Station 3) is reached. At this time, it is apparent that the helix or spiral form of flow has been fully developed and continues if the curve continues or gradually diminishes if the curve ends. By observing the positions and magnitudes of velocity vectors between Stations 4 and 8, it is apparent that as Curve 1 ends, there is a gradual decrease in angular distance between the surface and bottom velocities as well as an increase in vectors showing the concave velocities.

In summary, as the concave velocity approaches its minimum, the helix approaches full development. As the concave velocity increases, the helix pattern disappears. Therefore, helical flow depends upon: the radial component of the resultant concave velocity, the radius and length of the bend.

Leopold[3] and Wolman[3] plotted longitudinal and transverse velocities measured in a natural stream. They noted that in narrow channels, (with relatively large depth to width ratios) the bottom cross currents which were present were directed toward the convex bank.

> "Continuity would therefore require that surface water plunge downward near the concave bank and emerge near the convex bank at the surface".
>
> — Leopold and Wolman[3]

In earlier studies, Thomson[2][7] and Muller[4] observed the plunging action at the concave bank by inserting pulverized coal. They noted there was a complete cross-over from the concave bank to the convex bank. Because of the indicator used, no observations were made as to the emergence of the bottom current to the surface at the convex side;

the coal crossed over and was deposited at the convex bank downstream of the axis of the curve forming a small shoal. In the present study, potassium permanganate dye crystals were placed at the point of inflection between Curves 1 and 2 and on the concave bank of Curve 2. Photographs 1 and 2 of Plate 3, Volume II indicate the flow patterns set up by water stained with these dye crystals. At the point of inflection of Curves 1 and 2, (Photograph 1), the dye pattern shows only partial emergence. It appeared that the oncoming longitudinal flow kept the dye below the top one-quarter depth of flow. When the dye crystals were placed near the apex of Curve 2 (Photograph 2, Plate 3), approximately one quarter of the actual flow crossed over and only partially emerged to one half the depth. (The higher velocities near the convex bank prevented complete emergence.)

The above observations indicate that complete cross-over and emergence is more likely to occur at or near the end of curve where the magnitudes of the oncoming surface velocities on the convex side are somewhat less. Photograph 3, Plate 3, uses the dye to illustrate the higher velocities on the convex side of a curve.

Leopold and Wolman[3] state:

> "The maximum cross channel motion does not exceed perhaps two-thirds of the channel width in any given meander bend".

Friedken[1] does not fully agree with the existence of cross channel movement, he quotes:

> "Material eroded from one bank tends to deposit on a point bar downstream on the same side of the stream".

Although Friedken[1] observed helical flow in some of his experiments, he concludes that the cause of meandering is solely due to the erosion of concave banks and deposition of material on the same bank downstream. Other investigators questioned this conclusion as it was based on meander bends of relatively small degrees of curvature.

Plate 4, page 4 , Volume II is a series of photographs which were taken during a test to study the effects of helical flow on bed material. Silica sand was spread uniformly to a depth of 0.05' throughout the entire length of the test channel. The discharge of 0.3 cubic feet per second used for the plot of Plate 2 was passed through the channel for one hour. On Plate 4, photographs 1, 2 and 3 were taken at the half-hour point. Photographs 4, 5 and 6 were taken at the end of one hour after which the contours shown were traced. The contour datum is the channel bottom which is called 100. The interval is 0.05 feet. Therefore contour 105 represents the initial surface of silica sand.

The erosion and deposition in Curves 2 and 3, (Photographs 4, 5 and 6) indicates that cross channel movement did exist in Photograph 4, Curve 2, which is the sharper of the two curves, shows more build-up at the convex bank than in Cruve 3. (Photograph 5 on Plate 4). Two additional tests were conducted to confirm the erosion and deposition patterns. These additional tests produced patterns identical to those shown on Plate 4.

The bottom velocities on Plate 2, relate quite well to the erosion zones shown in Photographs 4, 5 and 6 of Plate 4. In regard to Curve 2, the bottom velocities obtained a maximum convex direction in the area between Stations 12 and 15. The erosion "fingers" formed during the test conform to this location (Photograph 4). Referring once again to Plate 2, the deflection of bottom velocities in Curve 3 has already developed by the time Station 19 is reached. The convex deflection remains constant until Station 24. The erosive zone illustrated by Photograph 5 (Plate 4), extends from Station 19 to Station 24. Between Station 26 and 29 the surface and bottom velocities become nearly parallel, this corresponds to areas of deposition as indicated by Photograph 6, (Plate 4).

The results of the above experiment agree with the observations of previous investigators (except Friedken[1]), and indicate that there is an increase in cross channel movement with an increase in bend curvature. Some of the conclusions of previous investigators are listed below.

Leopold and Wolman[3] state:

> "It seems clear that helical flow may play an important part in the process of deposition on a point bar. A building point bar helps to promote bank caving and channel movement".

Kondratev[5] states:

> "The most important cause of erosion of the concave bank is attributed to transverse currents which cause sediment to the transferred from the concave to the convex bank".

Characteristics of Velocity Distribution in a Sinuous Channel

While obtaining the data used in the preparation of Plate 2, it was noted that on the convex bank just downstream of the axis of any curve, irregular and eratic velocities existed. The directions and magnitudes fluctuated so that it was necessary to take a maximum value in all cases. Small amounts of debris that were picked up in the channel were noticed to deposit at these locations. This is a supposed commonplace occurrence as Mockmore[3][5] states:

> "Nearly three-quarters of the way down a bend, an eddy or stagnation zone appears on the convex wall. This leads to the deposition at this location and hence the formation of a shoal".

To illustrate the stagnation zone associated with the convex bank and furthermore the presence of helical flow, Plate 5, (page 5, Volume II), is a photo sequence taken around Curve 2 between Stations 6 and 17. Threads were suspended on the surface and bottom of the channel to correspond to the locations of the velocity readings taken in preparation of Plate 2. (The light threads represent the surface velocity directions and the darker threads are the bottom velocity directions). Photographs 1 and 5, (Plate 5) illustrate the stagnation zones for the convex banks of Curves 1 and 2 respectively. The threads near the convex bank oscillated slowly, while threads at other stations in the curve took a more or less constant alignment.

Features Associated With the Velocity Distribution

Leopold[3] and Wolman[3] state:

> "The velocity in a meander cross-over is symetrically distributed. As would be expected, proceeding downstream from the axis of the bend, the thread of maximum velocity is much closer to the concave bank than to the centre-line of the channel. The high velocity more-over continues to hug this side through the point of inflection of the curve".

Examination of Plate 2 illustrates the above quotation. As the end of any curve is reached, there is an increase in magnitude of velocity on the concave side. After the apex of a curve is passed, the concave bank of this curve actually becomes the convex bank of a following curve. This increase in concave velocities continues until the next curve is nearly passed, after which the change over in magnitudes begins again. With reference to Plate 2, and Plate 6 (Page 6, Volume II) it is seen that the concave velocities begin to increase after maximum super-elevation of the free surface is reached along the curve.

Mockmore[5] states:

"The longitudinal velocity components in the first half of the bend have a higher value near the convex bank than the concave bank".

Rozovskii[5] states:

"As water approaches the bend, the velocities at the convex bank tend to be larger than those of the concave. The minimum concave velocity is associated with a considerable transverse slope. This is followed by a rearrangement of velocities whereby the lines of maximum velocity move over to the concave bank".

It is also concluded that the intensity of the concave and convex velocities depend mainly on the turning process. If the turning process is abrupt, as in a small sharp curve, the velocities (and superelevation), will attain a maximum at possibly one location. However if the turning process is gradual, as in a long small degree curve, the velocity changes associated with the turning process can occur at any number of locations along the curve. (See Fig. 4, page 27). This agrees in part to conclusions arrived by Harbrecht[5], when he proposed a tentative method for determination of erosion zones in a sinuous channel. In Harbrecht's[5] study, he concluded that in the regions where a stream strikes the concave bank, a maximum transverse sope (super-elevation) of the free surface is associated with the reflection of velocities in the turning process. He also showed that several points of the reflections could exist along a curve depending on the length and degree of curvature.

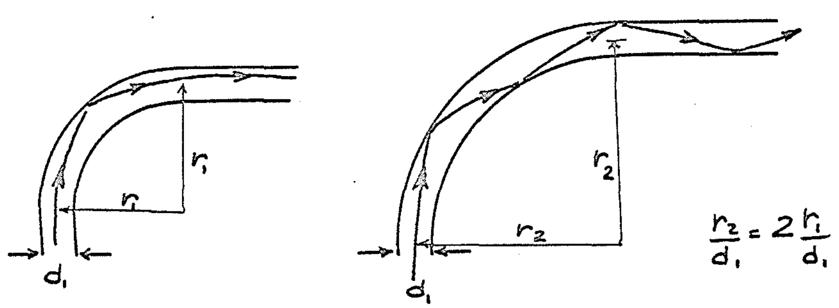


FIGURE 4: HARBRECHT'S REFLECTION THEORY

Piling results when the stream strikes the concave bank. This and a combination of centrifugal force produces a transverse slope (super-elevation) of the free surface. Plates 6, 7 and 8, (pages 6 to 8 , Volume II), which will be discussed in more detail in the following section, shows the variation of super-elevation along the curves of the test channel. Curve 1 of the test channel, which is the sharpest of the four curves tested, developed one maximum super-elevation at the location of the curve's apex. Curves 2, 3 and 4 which are increasingly milder curves, developed as many as three super-elevation maximums. The distances between these maximum values increases as the degree of sharpness decreases. Considering the above observation and Fig. 4 , on page 27 the locations where the water is made to deflect in its movement, around a curve is associated with locations of maximum super-elevation.

Transverse Slope - Super-Elevation

The variations of super-elevation along the test channel for the three discharges studied are shown in Plates 6, 7 and 8, (Pages 6, 7 and 8 , Volume II).

The variation in magnitudes of super-elevation along a sinuous channel takes the form of a sinusoidal curve when plotted. Relative comparison of Plates 6, 7 and 8, indicate that the super-elevation varies with discharge as with the degree of curvature of a meander bend.

Fidman[5] states in his conclusions:

> "Variation of the magnitude of the free surface slope along a stream is represented by a curve of the sinusoidal type".

A number of previous investigators[5] have indicated that the location of maximum transverse slope (i.e. super-elevation) corresponds to the proximity of the curve's apex. The results shown in Plates 6, 7 and 8 do not wholly agree with this theory. Only the maximum super-elevation attained at Curve 1 was located at the apex of the curve when the largest and second largest discharge was studied. (Plates 6 and 7). In the results observed on other curves, as many as three super-elevations were recorded on any one curve.

It can therefore be concluded that the location of the maximum super-elevation of the free surface cannot be generally specified. And in addition, the magnitudes of super-elevation on a curve are dependent on the discharge through the channel, the degree of curvature and the length of curve.

It is generally accepted that super-elevation is associated with a decrease in velocities along the concave bank in a curve. For example this relationship becomes apparent when Plate 2 and Plate 6 are considered. In all cases it is at the points of inflection where the super-elevation approaches zero. As noted previously, the concave velocities begin to increase when a curve ends. In all cases, where a relative decrease in concave velocities occurs, a super-elevation exists.

Rozovskii[5] states:

> "The minimum concave velocity is associated with a considerable transverse slope. This is followed by a rearrangement of velocity whereby the lines of maximum velocity move over to the concave bank. The area of rearrangement occurs near the end of the bend where the transverse slope disappears".

Fidman[5] states:

> "At the point of inflection between bends, almost no effect of centrifugal force is apparent. The cross-section of the free surface can be considered horizontal".

Once again in regard to the Harbrecht Theory of Reflection, it is interesting to note how the water is made to change its direction in a sinuous channel. Plate 3 is a plot of variation of super-elevation along the test channel at the lowest flow studied. Three maximum values of super-elevation were attained when the water passed around Curve 3. The first appearance of super-elevation occurs when the water is first deflected in Curve 3, at Station 18; the second deflection occurs at Station 22. At this time, in the proximity of the apex, due to the small degree of curvature, the channel at this point is, in effect, straight for the moment. The water is then given its final deflection near Station 26. Once again, it is reasonable to say that super-elevation is associated with this deflection. From this observation and those previously mentioned, it is concluded that the transverse slope (super-elevation) is caused by the piling effect of deflected velocities and its accompanying energy losses as well as centrifugal force induced in the water as it passes around a bend.

As mentioned in the Chapter II, Muller[4], Grashof[2][5], Lyapin[5] and Shoutri[5], proposed empirical relationships that would describe the transverse slope (super-elevation) of the free surface as water passed around a bend. All four expressions relate the super-elevation to the water velocity in the channel and the respective radii of the curves passed. All four equations were solved using velocity readings obtained at maximum discharge, (that is at 0.3 cubic feet per second). The solutions for each equation was then superimposed on a plot of super-elevations measured at maximum discharge in the test channel (Plate 6).

The Muller equation (equation 11) relates super-elevation to average velocity and radius of curvature. The equation therefore implies that the super-elevation will be attained immediately as a curve begins and remains at a constant value throughout the curve. As proven in the present investigation, and previous studies, this is not the case. The transverse slope is not developed suddenly, but is gradually and incidentally developed with the helical flow and piling effect of deflected surface velocities. As the super-elevations calculated by the Muller equation are dependent only on the average velocity, the super-elevations measured and plotted in Plate 7 and Plate 8 may also be compared. In all three discharges, (Plates 6, 7 and 8), the magnitudes of super-elevation calculated by the Muller equation fall within reasonable limits of accuracy to the magnitudes of super-elevations measured.

The equation derived by Lyapin[5] (equation 13) and Grashof[2][5] (equation 5) resembles the Muller equation to some extent. The two differ from the Muller equation in that a coefficient is applied to the average velocity which relates the average velocities to the superficial velooities and takes into account the irregular distribution of velocities along the vertical. The Lyapin and Grashof equations differ each other in that one is logarithmic, (equation 5) whereas the other is a straight line function (equation 5). Using the detailed velocity readings obtained at maximum flow, the Lyapin and Grashof equations were evaluated. When superimposed on Plate 6, the magnitudes of super-elevation obtained by the equations came very close to the actual measured super-elevations in the test channel.

When considering the variations of magnitude of super-elevation along any of the curves, the formulae do not produce any set pattern as shown by the measured values. As a definite variation in resultant surface velocities existed throughout any curve, the coefficient that related surface velocity to average velocity was evàluated at each station. This resulted in the irregularity of the calculated values superimposed on Plate 6. Had the coefficients been treated as constant around any curve, the two formulae would have plotted as straight lines, as in the case of the Muller equation, but with slightly larger magnitudes.

The Shoutri[5] equation, (equation 16) was the final equation evaluated and compared to measured values of super-elevation, (Plate 6). Its derivation takes into account the variation of super-elevation around a curve on the assumption that the distribution of velocities of the advancing flow over the stream width follows the Law of Areas, (V_{tan} x R = Constant, see Definitions, page xiv,Volume 1).The constant was evaluated at each station so that the super-elevation at that cross-section could be calculated and plotted on Plate 6. These calculated values of super-elevation were comparable to the measured quantities. Also the pattern of variation of calculated magnitudes agree in part with the pattern of variation obtained through measurement.

In summary, considering the magnitude of the super-elevation, (10^{-3} feet), it is concluded that the comparison of calculated and measured values shows reasonable agreement. However, with the exception of the Shoutri[5] Equation, the patterns of variation of calculated super-elevation along the curves are not in agreement.

Transverse Slope and Channel Bottom Formation

Comparison of Plate 4 (page 4 , Volume II) and Plate 6 (page 6 Volume II) indicates that a relationship between transverse slope and channel bottom formation exists. The areas of maximum scour corresponds to the locations of maximum super-elevation. Fidman[5] indicated, that, in a laboratory flume, there is a connection between free surface slope and channel formation.

Kondratev[5] states:

> "The amount of rise in usual bends (stream bends) does not exceed 5-10 cm. (0.4 ft), which represents a small portion of the depth and cannot therefore, in itself exert a marked influence on the concave bank".

The validity of this statement cannot effectively be proven in a laboratory, and would therefore require a natural stream study.

Angular Deviation of Bottom Centre-line Currents

Plates 9, 10 and 11 are plots of the variation of angular deviation of bottom centre-line currents along the test channels for the three flows considered. These results were compared to the equations developed by Prus-Chassinsky[5] (equation 17, page 13) and Rozovskii[5] (equation 18, page 14).

Although the Prus-Chassinsky equation is for a channel of triangular cross-section, in all cases, the angular values calculated are similar to the measured values of the test channels. As in the cases of expressions describing the variation of super-elevation around a curve, the shortcoming of the Prus-Chassinky equation is that it implies that the angular deviation is constant around a curve. However, if the values calculated for each curve by the formula were treated as maximums of angular deviations, the results would compare favourably to the observed values. On the other hand, the Rozovskii equation states that the angular deviation will occur within a range on any one curve. The range of angular deviations calculated from this formula are larger than those observed in the test channel, especially in the case of higher flows. As well as assuming that the angular deviation will be constant around any curve, the Rozovskii equation fall short because it claims that the angular deviation is dependent only on the depth of flow and radius of curvature. (The Rozovskii equation is plotted on Plates 9, 10 and 11 using two lines to represent the range which angular deviation should occur). Plate 12 (Plates 9, 10 and 11 superimposed) illustrates that the magnitude of angular deviation did not appreciably vary in the three depths of flow studied. The radius of curvature, however, does appear to influence the variation. As the radii of curvature increases the magnitude of angular deviation decreases. On the other hand, the Prus-Chassinky equation takes into consideration the flow characteristics of the channel by regarding the Reynolds Number as well as the wetted perimeter. Examination of Fig. 5 indicates the reason for the lack of variation of angular deviation with depth. As the discharge and normal

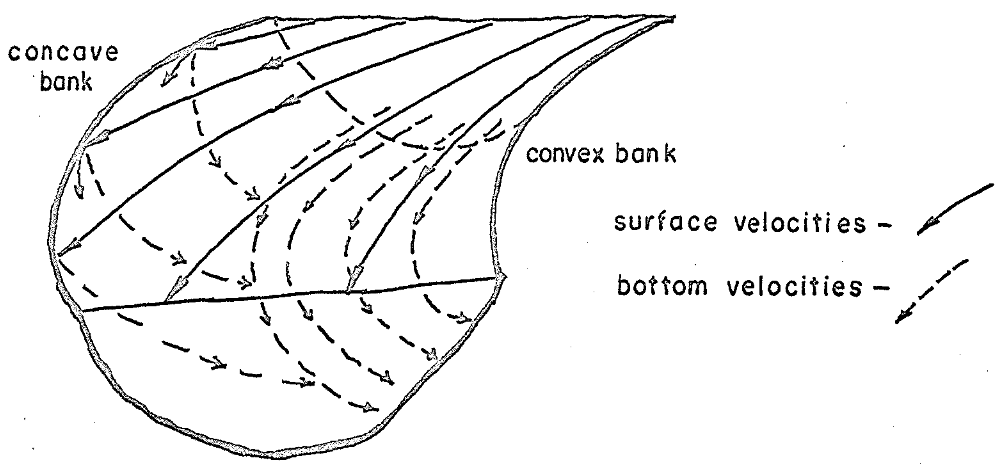
DISCHARGE	DEPTH	R_e
0.30	0.4	15,000
0.18	0.3	11,800
0.084	0.2	7,000

FIGURE 5: VARIATION OF REYNOLDS NUMBER WITH DEPTH AND DISCHARGE

depth were decreased, the corresponding Reynolds Number proportionally decreased. Therefore the flow features in effect were similar at all three depths considered. As Prus-Chassinsky[5] indicates the cause of variation in angular deviation would then be attributed to the crosssection of a channel, as well as the flow features of the channel.

As in the case of super-elevation, the variation of angular deviation of bottom centre-line velocities takes the form of a sinusoidal curve when plotted for the length of the test channel. Due to relative magnitude directions, the plot super-elevation is one phase ahead of the angular deviation plot. By inverting an angular deviation plot and superimposing it on its corresponding super-elevation plot, an interesting observation may be made. (For example, on Plate 13, Plate 9 has been invertėd and superimposed on Plate 6).

In Plate 13, the plots of variation of angular deviation are shifted slightly to the right of the super-elevation plot. From this, it is evident that the super-elevation is formed first and the build-up of angular deviation of bottom currents follows. As mentioned previously, a vertical velocity component is associated with the super-elevation. This vertical component is drawn down the concave bank to the channel bottom causing the oncoming bottom currents to be deflected toward the convex bank. As the super-elevation develops, the vertical component also increases and causes the angular deflection of bottom velocities to increase. The resulting flow pattern in the channel forms a helix.



SKETCH OF HELICAL FLOW

Figure 6

The diagramatic sketch shown in Figure 6 illustrates this phenomenon. Extrapolation of this observation leads to a description of the development of helical flow in a sinuous channel.

PART II

CHAPTER V

REVIEW OF PREVIOUS STUDIES

GENERAL STATEMENT

Few publications exist which consider the effects of different stabilizing methods on the structure of an erodable small scale laboratory channel. However field studies have been conducted to consider a particular river and its stabilizing problem. (Investigators in this area include the U.S. Corps of Engineers, Bureau of Reclamation, and others.)

G.F. Friedken[1] presented a report, "The Laboratory Study of the Meandering of Alluvial Rivers", which investigates experimentally the causes and behaviour of meanders in a river, and the effects of revetments on the structure and flow characteristics of laboratory channels.

The object of this thesis is to examine briefly, not only the effects of parallel type of bank protection, that is, revetments as in the Friedken study, but also to study the effects of bank stabilization measures which protrude into the river (that is, spur dykes and jetties).

A PRECIS OF THE FRIEDKEN[1] STUDY

(a) Friedken[1] states:

> "...the primary requirements of the laboratory meandering river are of course, that the bed material be eroded by flows and that the eroded material be transported by the stream as bed loads. The eroded materials must be transported as bed material and not suspended load in order for bars to develop. The most difficult part of developing laboratory meandering rivers is to obtain the proper relationships between the rate of bank erosion and the rate of material movement."

Extensive tests were conducted on the use of many different materials in the formation of meanders in the laboratory channel. Some of these materials included: fine sand and silt mixtures, coarse sand, granulated coal, and granulated coal and loess, and others. Friedken does not recommend any ideal material that can be used in a small scale meadering river. He suggests that coarse sand with a small percent of binding material (silt or loess) will form natural meanders provided again that good control is kept over the velocities, (bed movement, slope and tailwater level).

(b) Clear Water Tests

In his study of the behaviour and formation of meanders in a small scale stream, Friedken observed that the introduction of bed load affects the sinuosity of the channel formed. The clear water tests, (that is, with no introduction of bed load), produced channels which contained meanders of decreasing degrees of curvature. The channels which were studied with bed load introduction produced meander bends of constant radius of curvature throughout the length of channel considered. In order to simulate natural conditions as much as possible, bed load feed was introduced at the upstream end of all channels considered in the bank stabilization studies.

(c) Testing Procedures

Friedken conducted five stabilization tests with different materials each time. Meanders were allowed to form naturally evolving from a straight channel with impining angle of inflow. After sixty hours, during which time bed load was added at the entrance, the banks were stabilized with revetments. Testing then resumed until such time that bed movement and erosion ceased to exist.

The discharge through the channel was allowed to vary according to assumed hydrographs. This permitted the variation of stages from low water to maximum bank flow situations.

(d) The Results

Due to the use of a different material for each of the five tests mentioned, the resulting sinuosity of the naturally formed streams varied from 1.16 to 1.51. Friedken concluded that the use of revetments as a form of stabilization produced a general deepening of the thalweg as well as confinement of the alignment of the channel. The revetments had little or no effect on the depth of water at the points of inflection.

N.S. Leliavsky[3] states:

> "...it may be regretted that the only layout of bank protection he (Friedken) investigated was the plane parallel type, and that no attempt was made to study the effect of bank protection provided with a tail protruding into the river".

CHAPTER VI

LABORATORY INVESTIGATIONS

GENERAL STATEMENT

The overall apparatus used in this phase of the investigation was basically the same as that used in Part I, (described in Chapter II). The mortar channel used in Part I was used in the erodable bed study of Part II. For the erodable bank and bed studies in Part II, the channel was removed and reformed in a bed of silty-sand.

Scope

Of the many dissertations written on the subject of river training, few are treated from the laboratory standpoint. This thesis will study briefly the effects of several basic methods of stabilization on the structure of a laboratory stream. Consideration will be given only to type of stabilizing measure and angular position. No attempt was made to conduct experiments on optimum spacing and protruding distance.

APPARATUS

A. Erodable Bed Study - Effects of Stabilizing Measures on Bed Material

As mentioned, the fixed test channel used in Part I was again used in this study. The circulating water system and all other appurtances described previously were also employed.

Silica sand (size: passing #60 sieve and retained on #100 sieve) was used to simulate bed material. The stabilizing measures used were in form of jetties, and spur dykes. Jetties were simulated by using expanded metal (90% void area) and spur dykes were formed from perforated metal (15% void area). Due to the qualitative nature of this study, the amount of instrumentation was negligible. Photographs and notes recorded all pertinent observations. A timing clock was used for the duration time of each test. At the end of each test, wool yarn was used to trace the contours of the resulting channel bottom formation.

B. Erodable Bank and Bed Study - Stabilization Tests

The initial test channel used in this phase of testing had the same alignment as the mortar channel used previously. In this case it was completely erodable. The erodable channel was formed in a mixture of sand and silt (the sieve analysis is given in Appendix B, page 81, Volume II). Metal rods, anchored in concrete, marked the centres of curvature for each curve. By pivoting a "male" trapezoidal template on these rods, and resting the template on the sloping rails, the initial test channel could be continuously reconstructed for each test. The intial channel was stabilized by jetties and spur dykes simulated by the materials mentioned in (A) above. Revetments were simulated by placing mortar on the banks to be stabilized. Changes in stage was indicated and measured with an electric point gauge which was mounted on a carriage that rode on rails straddling the channel. The test duration and times for stage readings were indicated on a timing clock.

Instrumentation in A and B

The operation and construction of the electric point gauge is described in detail in Appendix A. Rack and pinion hook gauges, mounted as in Fig. 9, page 80, Volume I, were used to measure discharge and adjust tailwater levels for changing stages.

Fixed and Variable Conditions in A and B

Four curves of increasing radii were fitted into the testing area available. The choice of this alignment (sinuosity of 1.2) was based on the results obtained by Friedken[1].

The apparatus permitted the following items to be varied:

(1) Radius of Curvature: Four radii of curvature increased in size in the downstream direction.

(2) Type of Stabilizing Measures: Three basic types of stabilization measures were employed. These included jetties, spur dykes, and revetments. The projecting angle to the flow for the jetties and spur dykes varied from, 45° upstream and downstream, to 90°. (The angular orientation refers to the centreline of the initial channel at the installation points in question).

(3) Number of Stabilizing Measures to Each Curve: Initially four stabilizing measures were installed on each of the first three curves. The last curve downstream, (i.e. Curve 4), was left unstabilized for comparison. When the fifth measure was added to the first and second curve, the sixth and seventh measures were added, thereafter to the third curve. This produced two simple combinations of 5-6,(i.e. 5 measures on Curves 1 & 2, and 6 measures on Curve 3), and 5-7,(i.e. 5 measures on Curves 1 & 2, and 7 measures on Curve 3). The reason for this was due to the length of curve available in Curves 1 and 2.

The fixed conditions that existed are listed as follows:

(a) Discharge: The discharge could be variable, however, due to the intended scope of this study, it was treated as a fixed condition.

(b) Slope: The channel slope was fixed at 0.0006 for all tests. The water surface slope was assumed constant and parallel to the channel bottom and regulated as such, throughout the duration of testing. The end result would be a constant water surface slope with changes in stage due to changes in the relative roughness caused by erosion, deposition and in some causes the type of stabilizing measure.

(c) Spacing of Stabilizing Measures: Originating at the axis of each curve, the spacing of stabilizing measures was set at one foot intervals.

(d) Sediment Load: As mentioned previously, no sediment was introduced at the head of the channel. This condition was left to take place naturally in the channel.

LABORATORY PROCEDURE

A. Erodable Bed Study - Bed Stabilization Tests

Prior to running water in the mortar channel, a 0.05 ft. layer of silica sand was uniformly spread on the channel bottom. When this was completed, the stabilizing measures to be studied were set in place.

The water was turned on and adjusted for the discharge required. During each test, the stage was constantly regulated, so that a slope of 0.0006 was maintained. Regulating the flow stage of the channel was done by adjusting the tailwater gate. (Fig. 7 , page 80; Appendix A.)

At the end of each test, photographs were taken af the contours describing the resulting erosion and deposition patterns. At the completion of each test, the tailwater gate was closed and the supply pump was shut off. This left a reservoir of still water in the channel. Contours of wool yarn were laid along still water lines at intervals of 0.05 feet. The contour datum, called 100, was taken as the bottom of the channel at the downstream end. When a contour elevation has been completely traced, the water level was lowered 0.05 feet, and another contour elevation was established. The water level elevation [illegible] indicated by the tailwater hook gauge, which was zeroed at [illegible]

B. Erodable Bank and Bed Study - [illegible] Stabilization [illegible]

The stabilizing measu[illegible] [illegible]talled after [illegible] initial sinuous channel was formed in the silty-sand bed of the [illegible]

In order to prevent unnatural scour, the channel was filled slowly from downstream. When the channel was full, the circulating water supply was turned on. The discharge was set and the depth of flow was adjusted. (As mentioned previous[illegible] [illegible]ecause of the changing relative roughness of the channel, the dep[illegible] [illegible] flow was constantly changed during the test in order to ma[illegible] [illegible]e initial water surface slope of 0.0006).

Each test lasted four hours. In that time stage readings were recorded at 15 minute intervals. Notes of pertinent observations were recorded.

At the completion of a test, the water was shut off and the channel was slowly drained. Cross-sections at one-half foot intervals, were taken along the channel using a point gauge mounted on the level set of rails. The point gauge was zeroed at datum (1.00), which was the channel bottom at the downstream end of the initial channel. Contour maps were plotted from this hydrographic data.

Pilot Test

In both A and B above, before any stabilizing measures were tested, a Pilot Test, with no stabilizing measures was run. This test was used as an indication of the effectiveness of each type of stabilizing measure.

CHAPTER VII

DISCUSSION OF RESULTS

A. EFFECTS OF STABILIZING MEASURES ON THE BED MATERIAL OF A SINUOUS CHANNEL

General Statement

The tests in this phase were conducted to investigate the effects of different stabilizing measures on the bed material of a sinuous channel. The results are in the form of observations taken during the tests and contour layouts which were established at the completion of each test. The final contour layout of each test was recorded by photographs which accompany the discussion. (The aforementioned photographs are found on Plates 16 to 24, Volume II). The effectiveness of each stabilizing measure will be compared to the Pilot Test, where no stabilization was involved.

Although three of the curves in the fixed sinuous channel used in Part I were stabilized, only two were under consideration. These being Curves 2 and 3.

General Observations

In all of the tests conducted in this phase, it was observed by the use of dye, that the helical flow was hindered in its development as a result of the stabilizing units. Obstruction to flow came in the form of either direct flow deflection (as in the case of the spur dykes), or as an induced form of energy loss with minor flow deflection (as in the case of the jetties). The effectiveness of stabilizing measures in obstructing helical flow was also apparent when the resulting contour pattern of the Pilot Test is compared to any of the contour patterns resulting from the stabilization tests.

As the number of stabilizing measures increased on a curve, the areas of erosion moved downstream into the proximity of the point of inflection. Because of the large percentage of void area, (90 percent), the jetties were very premeable to flow and caused only minor flow deflection. As a result of this, the amount of erosion at the base of each jettie was slight. Except in the case of jetties oriented at 45° to the upstream, the bed material remained almost intact in the stablized portion of the curve.

The spur dykes (15 percent void area) caused extensive flow deflection, producing local erosion "pockets" around the base of each unit. As each test progressed, these erosion pockets expanded into the centre part of the channel. Turbulent zones occurring on the downstream side of each spur dyke as a result of the deflected flow caused deposition to take place. Due to the volume of material moved from the stabilized area of each curve, extensive deposition developed on the convex bank near the point of inflection. By comparing the deposition at the convex banks, Plates 16 to 24, Volume II, it is seen that the amount of cross-channel movement in the jetty tests is far less than in the spur dyke tests. Plate 14 further illustrates the relative intensity of flow deflection resulting from spur dykes and jetties.

As illustrated in Part I of this thesis, the change of flow direction due to the geometry of a sinuous channel, causes a flow pattern resembling a helix to develop.

The introduction of stabilizing measures partially obstructs the development of this helical flow pattern. Even though the turning effect is obstructed in the initial stages, the change in flow direction is inevitable. Rather than occurring gradually as in an unstabilized curve, the change in flow direction is concentrated at one location which is immediately downstream of the stabilized area on the concave bank. As a result of this, a concentrated helix occurs which produced a large erosion zone. This erosion area is common to both the jetties and the spur dykes. In revetment stabilization, (simulated by the Pilot Test, Plate 15), the concave bank is not protected by protrusions and therefore the change in flow direction (and the helical flow pattern) is allowed to take place naturally in the normal confines of the curve. In this case, no concentrated erosion area occurs.

SPUR DYKES AND JETTIES AT 90° TO THE CENTRELINE

Plates 16, 17, and 18 illustrate the contours of erosion and deposition due to the stabilizing measures placed at 90° to the centreline of the channel.

Spur Dykes at 90°

The spur dykes at this angle literally caused the channel to be narrowed by directly obstructing flow. Severe flow deflection occurred which eroded the material from the stabilized side and carried it over to the convex side. As the tests progressed, these eroded areas extended into the centre of the channel. Photographs 1A, 2A, and 3A on Plates 16, 17, and 18 indicate that as the number of spur dykes increased, the amount of deposition on the convex sides increased.

These photographs also show the increasing size of erosion areas downstream of the stabilized zone. Dye streaks showed that only partial development of helical flow occurred. This was located slightly upstream of the curves' axes, but was soon disrupted by the flow deflected off the spur dykes.

Jetties at 90°

The jetties at this angle did not obstruct flow to the extent of the spur dykes. However, the eroding effect of the helical flow was inhibited as seen by Photographs 1A, 2A, and 3A. In the stabilized areas, the bed material stayed in place during the duration of the tests.

Because the jetties allowed some helical flow to exist, the change in flow direction partially occurred inside the stabilized zone. However, as the resulting erosion patterns indicate, the major part of the turning process occurred downstream of the stabilized areas. Compared to the spur dykes tests, the relative sizes of the erosion areas from the jetty tests are much smaller.

The amount of flow deflection resulting from the jetties was much less than in the case of the spur dykes. Plates 16, 17 and 18 illustrate this by the amount of deposition accurring at the convex banks.

SPUR DYKES AND JETTIES AT 45° TO THE CENTRE LINE UPSTREAM

Plates 19, 20, and 21 illustrate the contours of erosion and deposition of bed material at the completion of tests on stabilizing measures orientated at an angle of 45° upstream.

Spur Dykes at 45° to Centreline Upstream

In these tests the concentrated erosion area downstream of the stabilized area existed only when the jetties were considered. Due to the small void area in the spur dykes and the angular orientation upstream, a helical flow pattern was induced at approximately the same location on the curve as it would have occurred had the curve been without stabilizing measures. This induced form of helix was of greater intensity when compared to the naturally formed helical flow around an unstabilized meander bend. A comparison of helical intensity can be made by observing the contour patterns resulting in the Pilot Test and those illustrated by Photographs 1B, 2B and 3B, Plates 19, 20 and 21. Because the helix (which is associated with the change in flow direction in a sinuous channel), was allowed to occur inside the stabilized area, the change in flow direction wqs not concentrated at a location immediately downstream of the stabilized zone. Photographs 1B, 2B and 3B on Plates 19, 20 and 21 respectively, show only minor erosion downstream of the stabilized area. This indicates that only a slight helical flow pattern existed at this point and the turning process had been completed. The above is further confirmed by Plate 14, which illustrates (by use of threads suspended in the flow), the effects of stabilizing measures on the turning process of the water flowing around a stabilized curve.

Jetties at 45° to the Centreline Upstream

The jetties, which have a large percent of void area, allow a relatively large portion of flow to pass through. However with this upstream angular orientation (that is 45° upstream) the jetties induce some flow deflection into the concave banks of the stabilized curve. As in the case of the spur dykes at 45° upstream, but in a much smaller intensity, the helical flow pattern was slightly aided in its development. This caused some concave bank erosion to occur in the stabilized areas, as shown on Photographs 1A, 2A, and 3A, Plates 19, 20 and 21 respectively. The most significant action of the jetties at 45° upstream was in obstructing the overall helical flow development in the stabilized area. Therefore the greater part of the turning process was once again concentrated at one location downstream of the stabilized zone. As shown in Photographs 1A, 2A and 3A, the erosion zones set up by the concentrated turning effect is smaller when compared to the erosion zones produced in the tests with jetties at 45° downstream and 90° to the flow, where nearly complete obstruction to helical flow development was attained.

SPUR DYKES AND JETTIES AT 45° TO THE CENTRELINE DOWNSTREAM

Spur Dykes at 45° to the Centreline Downstream

The contours of erosion and deposition, as illustrated by Photographs 1B, 2B and 3B (Plates 22, 23 and 24) indicate that this angle of orientation did not oppose the flow as much as in the tests with spur dykes at 90° and 45° upstream. (Both of these cases caused extensive base erosion at each measure, which moved into the cenral part of the channel). In the present test, that is, spur dykes at 45° downstream, only minor base erosion at each measure occurred. The bed material inside the stabilized zones remained intact. It was observed that the helical flow was forced against the convex bank as a result of the downstream angle of each stabilizing measure (See Plate 14). The change in flow direction took place downstream of the stabilized area as in previous tests.

As the number of stabilizing measures increased, the erosion zones, produced by change in direction, increased in size and in advancement in the downstream direction.

Jetties at 45° to the Centreline Downstream

As mentioned previously, the larger void area of the jetties, compared to the spur dykes, allowed less flow deflection and greater permeability to flow. As illustrated by Photographs 1A, 2A and 3A, (Plates 22, 23 and 24), the resulting contours of erosion and deposition demonstrate this fact. Observation of dye streaks and threads suspended in the flow (Plate 14) shows that the helix is inhibited its development and slightly deflected to the convex bank. Because the jetties caused greater hindrance to the helical flow development, the change in flow direction again was concentrated downstream of the stabilized zone. The erosion area produced by this concentrated turning process was much larger than the spur dykes. The flow deflection caused by the spur dykes, orientated at 45° downstream, aided the change in flow direction of the channel. Therefore, a less concentrated helix was formed when the turning process occurred downstream of the stabilized zone.

B. THE EFFECTS OF STABILIZING MEASURES ON THE BED AND BANK MATERIALS OF A SINUOUS CHANNEL

General Statement

The purpose of this phase of the investigation was to study the effects of several types of stabilizing measures on the bed and bank materials of a completely erodable, sinuous laboratory channel.

The data used in the discussion of results will be in the form of contour maps, final thalweg profiles, cross-sections at standard locations, photographs at standard locations and plots of variation in flow stage during each test. The effectiveness of each stabilization method will be compared to a Pilot Test where no stabilization existed. Cross comparisons of data will be made for the relative effectiveness of each stabilizing method.

The form of data mentioned (contour maps, thalweg profiles, etc.) accompany the discussion for each stabilization test and can be found in Volume II.

BANK STABILIZATION TEST NO. 1

Jetties Placed at 90° to the Centreline

Plate 31 illustrates the final contour maps of the Pilot Test and the channel stabilized with jetties placed at 90° to the centreline. Respectively, Plates 28, 29 and 30 show photographs at the completion of the test, cross-sections at A A', B B', and C C' and the final thalweg profile.

The variation of flow stages for the test duration is shown on Plate 27, page 30, Volume II. Photographs taken at the completion of the Pilot Test are shown on Plate 25, page 28, Volume II.

Changes in the Channel (Plate 31)

The contour maps indicate that the downstream and lateral movement of the stabilized channel was restricted as a result of the jetty installations. General deepening occurred around the stabilized bends and in the vicinity of the points of inflection. The point bar that occurred on the convex bank in the Pilot Test is not as pronounced.

Changes in the Cross Sections (Plate 29)

Cross-sections A A' and C C', taken on the axes of the second and third curves respectively, illustrated the effectiveness of the jetties in deepening the channel in the meander bends. Cross-section B B' illustrates the deeper point of inflection, resulting from the jetties at 90° by comparison to a cross-section at the same location in the resulting Pilot Test channel.

Change in the Final Thalweg (Plate 30)

As shown on Plate 30, the jetties at 90° were effective in lowering the final thalweg profile. (The final thalweg profile of the Pilot Test is superimposed on Plate 30). The profile was lowered extensively in the areas of stabilization and points of inflection.

The contour maps (Plate 31) show that the jetties kept the location of the thalweg closely aligned to the centreline of the initial channel.

Variations in Flow Stage During the Test (Plate 27)

Explanation of Plate 27: As the erosion and deposition of bed and bank material increases, the relative roughness of the channel also increases. This accordingly causes an increase in the normal depth of the channel. Because it was assumed that the test channel was a small section taken from a long channel, it is safe to assume that the water surface slope of the initial test channel will be constant throughout all tests. Therefore, as the relative roughness changes, so much the depth of flow (i.e. stage) in order to sustain the initial water surface slope. By comparing the changes in stage of a stabilization test, with that of the Pilot Test, the relative effectiveness of a type of stabilizing measure in restricting movement of channel material, can be evaluated.

The initial stage of the Pilot Test is greater than the stage at the start of Stabilization Test No. 1. This was due to the extensive erosion that occurred immediately when the Pilot Test began. The jetties controlled this initial erosion which resulted in a lower initial stage. At the end of the four hour test period, the test channel with the jetties at 90° had long reached equilibrium. The Pilot Test channel, however, was still very active at the end of the four hour testing period. The above indicates that the jetties were quite effective in inhibiting the movement of channel material.

BANK STABILIZATION TEST NO. 2

Jetties Placed 45° to Centreline Downstream

Plate 35 illustrates the final contour maps of the Pilot Test and the channel stabilized with jetties placed at 45° to the centreline downstream. Respectively, Plates 32, 33, and 34 show photographs at the completion of the test, cross-sections at A A', B B' and C C', and the final thalweg profile.

The variation of flow stages for the test duration is shown on Plate 27, page 30, Volume II. Photographs at the completion of the Pilot Test are shown on Plate 25, page 28, Volume II.

Changes in the Channel (Plate 35)

Except for some concave bank erosion in the areas of the points of inflection, the jetties placed at 45° downstream sustained the initial channel alignment.

Minor deepening occurred in the stabilized bends. The points of inflection were free of shoals. Due to the small flow deflection induced by the jetties placed at 45° downstream, slight convex bank erosion occurred. This material was immediately deposited just downstream of the axis of the bend, forming a small shoal.

<u>Changes in the Cross-Sections (Plate 33)</u>

Cross-sections A A' and C C' (taken at the axes of the second and third curves, respectively), indicate that the jetties, placed at 45° downstream, did not appreciably deepen the stabilized bends.

The cross-section at B B' illustrates the relative deepening in the points of inflection and the lateral confinement of the channel boundary.

<u>Change in the Final Thalweg (Plate 30)</u>

The installation of jetties at 45° downstream caused the final thalweg profile to be lower than thalweg profile of the Pilot Test. However, the final thalweg profile of Stabilization Test No. 1 is even lower. From the results of the tests on the effects of stabilizing measures on the bed material, (Part A of this chapter) it was expected that jetties placed at 45° downstream would maintain a relatively deep thalweg. However at the beginning of this test (i.e. Bank Stabilization Test No. 2), the banks of the stabilized bends failed, causing the material to fall to the bottom of the channel and remain in place for the test duration. The bank failures appeared to take place as a result of the minor flow deflection set up by the jetties at this angle (i.e. 45° downstream). The deflected flow caused erosion to occur approximately three quarters of the way down the bank.

The deposition of bank material at the channel bottom of the stabilized curves caused an overall increase in the final thalweg.

Referring again to Plate 35, the resulting contour maps of the test channel, it is seen that the jetties at 45° downstream kept the final thalweg and the centreline of the initial channel quite close together.

Variations in Flow Stage During the Test (Plate 27)

The jetties, placed at 45° downstream, were effective in producing the lowest stage at the completion of the test. The jetties at this angle were also effective in establishing equilibrium of the channel, (that is, when deposition and erosion ceased), long before the end of the testing period.

The initial stage elevation is relatively high. At the beginning of the test, bank failures occurred in the stabilized zones. The material fell to the bottom of the channel causing an increase to the thalweg as well as the flow stage. Because the jetties were effective in holding the failed material intact, no excessive shoal formations occurred that would cause the relative roughness, and therefore the stage, to increase. The contour maps and photographs, (Plates 28 and 31) illustrate the absence of extensive shoals and other irregular erosion and deposition areas.

BANK STABILIZATION TEST NO. 3

Jetties at 45° to the Centreline Upstream

Plate 39 illustrates the final contour maps of the Pilot Test and the channel stabilized with jetties placed at 45° to the centreline upstream. Respectively, Plates 36, 37 and 38 show photographs at the completion of the test, also cross-sections at A A', B B' and C C', and the final thalweg profile.

The variation of flow stages for the test duration is shown on Plate 27, page 30, Volume II. Photographs at the completion of the Pilot Test are shown on Plate 25, page 28, Volume II.

Changes in the Channel (Plate 39)

The resulting contour map of Bank Stabilization Test No. 3 illustrates the general deepening around all stabilizated beds. Compared to the Pilot Test, the areas in the points of inflection are deeper. However, compared to Bank Stabilization Test No. 2, the shoal formations in the convex bank areas are more pronounced.

Because of the angle at which the jetties were placed, (that is, 45° upstream), the oncoming flow was deflected into the concave banks at the location of each jetty. The deflected flow caused erosion at the base of each measure and immediate deposition downstream of each measure, causing a rippled effect to form on the concave banks of the stabilized curves. Bank failures also occurred at several locations as a result of this deflected flow.

Except for concave bank erosion at the points of inflection and some bank failure, the jetties were effective in maintaining the initial channel alignment.

Changes in Cross-sections (Plate 37)

Cross-sections A A' and C C' taken at the axes of the second and third curves respectively, show that channel deepening in the areas of stabilization was much more than in Stabilization Test No. 2. It was also observed that flow deflection in this test was not as extensive as in Stabilization Test #2. This resulted in less bank failure. The jetties in this test are much more effective in restricting the channel width in the bends than the jetties in Stabilization Test No. 2.

Cross-section B B' taken at the point of inflection between the second and third curve, resembles Cross-section B B' of Stabilization Test No. 2, except here the channel width is more. The jetties were very effective in the stabilization and deepening of curves, but failed to restrict the channel in its downstream movement by allowing concave bank erosion in the points of inflection.

Changes in the Final Thalweg (Plate 38)

The jetties, placed at 45° upstream, were very effective in reducing the overall thalweg profile of the channel, especially in the stabilized areas and the points of inflection. Except in the points of inflection , the location of the final thalweg, after stabilization , was coincident to the centreline of the initial channel.

Variations in Flow Stage During the Test (Plate 27)

Due to the upstream orientation of the jetties in this test, the initial flow stage of the channel was slightly more than in Stabilization Test No. 2. Also, because of the increased shoal formation and the "rippled" effect of the stabilized concave banks, the relative roughness of the channel increased. This caused the rate of stage increase to be somewhat larger than in Stabilization Test No. 2. Although Stabilization Test No. 3 reached equilibrium at approximately the same time as Stabilization Test No. 2, the stage of the former test was much higher at the end of the test period.

BANK STABILIZATION TEST NO. 4

Revetments

Plate 43 illustrates the final contour maps of the Pilot Test and the channel stabilized with revetments. Respectively, Plates 40, 41 and 42 show photographs taken at the completion of the test, cross-sections at A A', B B' and C C' and the final thalweg profile.

The variation of flow stages for the test duration is shown on Plate 27, page 30, Volume II. Photographs at the completion of the Pilot Test are shown on Plate 25, page 28 , Volume II.

Changes in the Channel (Plate 43)

The contour maps show that the revetments were extremely effective in fixing the lateral movement of the channel. However, the eroded concave banks at the points of inflection indicate the channel was not restricted in its downstream movement. Although the downstream movement of the stabilized channel was not as extensive as the Pilot Test, it was considerably more than in Stabilization Tests 1, 2 and 3.

Extensive deepening occurred around the stabilized bends. Deposition on the convex banks downstream of the axes of the curve and extending into the points of inflection, caused shallows to exist across most of the channel width.

Changes in the Cross-sections (Plate 41)

Cross-sections A A' and C C' taken on the axes of the second and third curves, illustrate the deepening of the channel around the stabilized curves and the presence of material movement on the convex banks.

Cross-section B B', taken at the point of inflection between the second and third curves, illustrates the shallows occurring at this location. Reference to the photographs on Plate 40 indicates the magnitude of deposition upstream of this point of inflection.

Changes in the Final Thalweg (Plate 42)

Plate 42 indicates the effectiveness of the revetments in lowering the final thalweg when compared to Pilot Test. In view of the extensive deposition in the areas downstream of the stabilized curves, the revetments produced the lowest overall thalweg profile of all stabilizing measures. At several locations along the stabilized curves, the bottom erosion was so great that it extended below the initial channel bottom.

Due to the deep sections at the bases of the revetments, the location of the final thalweg in plan (Plate 43) was considerably removed from the centreline of the initial channel.

Variations in Flow Stage During the Test (Plate 27)

Because the revetment type of stabilization does not obstruct flow, the relative roughness of the channel is not affected. It is for this reason that the initial stage in this test was the lowest recorded in the entire investigation. However, because the helical flow development was not obstructed, as in the other forms of stabilizatioh, extreme erosion and deposition occurred causing the relative roughness (and stage) to increase rapidly once the test was in progress. The final stage at the end of the four hour test period was slightly higher than the lowest final stage recorded, (that is, Stabilization Test No. 2).

Equilibrium (deposition and erosion ceased) occurred before the testing period ended.

Comparison With the Results of the Friedken Study[1]

The results of Stabilization Test No. 4 compared quite favourably with the results obtained in the Friedken Study[1]. As mentioned in Chapter 5, Friedken concluded that the use of revetmentsproduced general deepening of the thalweg in the stabilized zones as well as confinement of the channel to lateral movement. The revetments had little or no effect on the bottom elevations at the points of inflection.

BANK STABILIZATION TEST NO. 5

Spur Dykes Placed at 90° to the Centreline

Plate 47 illustrates the final contour maps of the Pilot Test and the channel stabilzed with spur dykes placed at 90°. Respectively, Plates 44, 45 and 46 show; photographs taken at the completion of the test, cross-sections at A A', B B' and C C' and the final thalweg profile.

The variation of flow stages for the test duration is shown on Plate 27, page 30 , Volume II. Photographs taken at the completion of the Pilot Test are shown on Plate 25, page 28 , Volume II.

Changes in the Channel (Plate 47)

The introduction of the spur dykes at 90° to the centreline caused extensive movement of material. Due to the impervious nature of the spur dykes considerable flow deflection occurred. As a result of flow deflection, eddy currents developed immediately downstream of each spur dyke. Theseeddy currents produced large erosion pockets which exposed large portions of the spur dykes anchored in the concave banks. (See the photographs on Plate 44), also bank failures, occurred between each spur dyke as a result of the eddy currents.

Compared to the Pilot Test, little deepening was evident around the stabilized bends, except at the base of the spur dykes. Due to the amount of erosion in the stabilized zones, deposition occurred in the areas of the points of inflection, causing shallows to develop.

The spur dykes at 90° were relatively ineffective in sustaining the initial channel alignment.

Changes in the Cross-sections (Plate 45)

Cross-sections A A' and C C' taken at the axes of the second and third curves, illustrate the ineffectiveness of the spur dykes in deepening and confining the channel cross-sections. The cross-sections taken at the same locations in the Pilot Test show similar results.

Cross-section B B' taken at the point of inflection between the second and third curve, illustrates resulting shallows in this location. Photographs on Plates 44 better illustrate the relative magnitude of deposition in this area, especially at the downstream end of the stabilized zone.

Changes in the Final Thalweg (Plate 46)

As shown in Plate 46, the introduction of spur dykes at 90° had little or no effect in reducing the final thalweg profile of the channel. In some instances, the final thalweg elevations of the stabilized channel are higher than those of the Pilot Test. This mainly occurred in the stabilized zones, which illustrates the ineffectiveness of the spur dykes, at 90° in checking movement of material. Instead, this form of stabilization induces erosion.

The final thalweg location is removed from the centreline of the initial channel.

Variations in Flow Stage During the Test (Plate 27)

The high initial stage and rapid increase in stage during the test is attributed to the impervious nature of the spur dykes and the flow deflection caused by them. Due to the small percent of void areas, the spur dykes obstructed the flow to such an extent that the magnitude of the initial relative roughness (initial stage), of the channel became very large. As the test progressed, the deflection of flow and resulting eddy currents caused extensive material movement and continually increased the relative roughness. (As mentioned previously, in order to maintain the initial water surface slope of 0.0006, the stage had to be increased with the relative roughness).

As indicated on Plate 27, the channel stabilized with spur dykes at 90° did not reach equilibrium conditions in the prescribed testing period. In fact, the test had to be abandoned after 3-1/2 hours, as the water level had reached the top of the channel.

BANK STABILIZATION TEST NO. 6

Spur Dykes Placed at 45° to the Centreline Downstream

Plate 51 illustrates the final contour maps of the Pilot Test and the channel stabilized with spur dykes placed at 45° downstream. Respectively, Plates 48,49 and 50 show photographs taken at the completion of the test, cross-sections at A A', B B' and C C' and the final thalweg profile.

The variation of flow stages for the test duration is shown on Plate 27, page 30, Volume II. Photographs at the completion of the Pilot Test are shown on Plate 25, page 28, Volume II.

Changes in the Channel (Plate 51)

The introduction of spur dykes at 45° downstream caused the resulting channel to be more confined than in Stabilization Test No. 5. On account of the downstream orientation, and the imperviousness of the spur dykes, flow was deflected toward the convex banks. This resulted in convex bank erosion and subsequent shoal formations downstream in the immediate area of the points of inflection.

Some scour occurred at the anchor locations of the spur dykes. This erosion was not as extensive as in Stabilization Test No. 5. Due to the angular position (45° downstream) the spur dykes developed smaller eddy currents.

The overall effect of the spur dykes placed at 45° downstream was not as effective as the stabilization formed by jetties and revetments, but it was an improvement over Stabilization Test No. 5 (spur dykes at 90°).

Changes in the Cross-sections (Plate 49)

The cross-sections A A' and C C', taken at the axes of the second and third curves illustrate the magnitude of convex bank erosion. These also show the shallowness of the channel in the stabilized bends. The confinement of the channel in the concave direction is good except for some local undermining at each spur dyke location.

Cross-section B B' which is taken at the point of inflection of the second and third curves, illustrates the increased bottom elevation as a result of material removed from the banks of the second curve and deposited at this location. Photographs on Plate 48 also indicate the magnitude of deposition in this area.

Changes in the Final Thalweg (Plate 50)

The spur dykes at 45° downstream, were not effective in checking the movement of material. When compared to the unstabilized Pilot Test, the overall thalweg was lowered by only a small amount. As in Bank Stabilization Test No. 5, the "jagged" form of the profile in the stabilized areas indicates the concentrated erosion and deposition that occurred. As in Bank Stabilization Test No. 5, the location of the final thalweg was removed from the centre of the initial channel.

Variations in Flow Stage During the Test (Plate 27)

In comparison to Bank Stabilization Test No. 5, the downstream orientation of the spur dykes caused less obstruction to flow and therefore a lower initial relative roughness for the channel. However, due to the amount of convex bank erosion on each stabilized curve, a relatively large rate of increase of relative roughness (stage) developed. The final stage at the end of the four hour test period was slightly lower than that of the Pilot Test. Equilibrium had not been reached at the end of the test period.

BANK STABILIZATION TEST NO. 7

Spur Dykes Placed at 45° to the Centreline Upstream

Plate 55 illustrates the final contour maps of the Pilot Test and the channel stabilized with spur dykes placed at 45° in the downstream direction. Respectively, Plates 52, 53 and 54 show photographs taken at the completion of the test, cross-sections at A A', B B' and C C', and the final thalweg profile.

The variation of flow stages for the test duration is shown on Plate 27, page 30, Volume II. Photographs taken at the completion of the

Pilot Test are shown on Plate 25, page 28, Volume II.

Changes in the Channel (Plate 55)

The resulting contour map of Stabilization Test No. 7 indicates the similarity of erosion and deposition with Stabilization Tests 5 and 6. As before, the small percent of void areas in this type of stabilizing measure (spur dykes) caused a great deal of obstruction and deflection to flow. Consequently extensive erosion and deposition patterns developed.

During Test No. 7, dye streaks showed that the spur dykes, placed at 45° to the upstream, caused the helical flow pattern to be compressed (as a compressed spring), and therefore more concentrated. Simultaneously, due to the deflecting nature of the spur dykes, the entire flow pattern was deflected into the convex banks and extensive erosion occurred at the convex bank. The combination of convex bank erosion and local erosion around each measure resulted in extensive deposition in the areas of the points of inflection. As the test progressed, and the convex banks eroded, the major portion of the flow was less influenced by the deflecting spur dykes and some deposition occurred in the channel bottom of the stabilized curves.

Because the spur dykes were placed at 45° upstream, the eddy currents set up immediately downstream of each stabilizing measure were not as intense as those in Stabilization Tests No. 5 and 6. Partly, as a result of this, the portion of the bank anchoring each spur dyke was not eroded to the extent observed in Tests 5 and 6.

Changes in the Cross-sections (Plate 53)

Cross-sections A A' and C C' taken on the axes of the second and third curves, illustrate the amount of erosion on the convex banks in the stabilized areas. Compared to the cross-sections of the Pilot Test, taken at the same location, little or no channel deepening was evident.

Cross-section B B' taken at the point of inflection of the second and third curve, shows the increase in bottom elevation due to the deposition of eroded material from upstream convex bank.

Changes in the Final Thalweg Profile (Plate 54)

The thalweg profile resulting from Bank Stabilization Test No. 7 was slightly lower than the final thalweg profile resulting from Tests 5 and 6 with spur dykes at 90° and 45° downstream, respectively. However, as a result of the concentrated erosion in the stabilized zones, the jagged profile common to Test No. 5 and 6 was still apparent. When compared to the Pilot Test, the overall effect of spur dykes placed at 45° upstream caused some lowering of the thalweg profile.

The location of the thalweg is shifted from the centreline of the initial channel.

Variations in Flow Stage During the Test (Plate 27)

The spur dykes set at this upstream angle caused the initial relative roughness of the channel to be the largest in all the tests considered. Extensive movement of material during the test rapidly increased the relative roughness of the channel, and therefore, the rate of increase in stage. Equilibrium appeared to develop just at the end of the four hour test period.

THE UNSTABILIZED CURVE

The farthest downstream curve of the test channel was purposely left unstabilized in order to study what effects might occur as a result of stabilization upstream. However, due to the variations in initial relative roughness induced by different stabilizing measures and their angular positions, the erosion and deposition patterns in the unstabilized curve were greatly effected. For example, when a particular stabilizing measure such as spur-dykes at 90° caused the initial relative roughness (and therefore, the stage) to increase, the velocities in the unstabilized curve were too low to cause any appreciable material movement. On the other hand, when revetments were used, the initial relative roughness was low causing a shallower depth of flow and therefore higher velocities which severely eroded the unstabilized curve.

CHAPTER VIII

CONCLUSIONS

From the analysis of the results obtained in Part I and II of this thesis, the following conclusions are made:

1. Helical flow will develop naturally in a small scale sinuous channel.
2. The transverse slope (super elevation) of the free surface and the angular deviation of bottom velocities that occur as a consequence of helical flow, can be accurately measured. The measured magnitudes are in general, in agreement with those calculated from equations derived by previous investigators. However, the variations of the measured values along the channel do not agree with calculated values.
3. It is apparent from these results, that the location of maximum transverse slope (super elevation) of the free surface cannot be generally specified to occur at the apex of the curve. The locations of maximum super elevation vary with the discharge, the length of curve and the approach conditions to the curve.
4. The angular deviation of bottom velocities depends on the flow properties of the channel (that is, Reynolds Number, discharge and wetted perimeter).
5. The development of the angular deviation of bottom velocities begins after the initial development of the transverse slope.
6. The changes of flow direction due to the geometry of the sinuous channel follow the Harbrecht Reflection Theory[5]. From the results of this study it appears that helical flow and its associated phenomena (transverse slope, etc.) occur as a consequence of reflected flow.

7. Protruding types of stabilizing measures (spur dykes and jetties) obstruct the development of helical flow. Parallel forms of stabilization (as revetments) allow helical flow to occur naturally.

8. Because of extensive flow deflection, spur dykes as a form of bank stabilization appear to generally increase the bottom elevation and decrease the flow capacity of the channel. The alignment of the initial channel is not maintained.

9. It is apparent from these results that jetties cause channel deepening in the stabilized bends and points of inflection. The flow carrying capacity is increased, and at constant discharge, equilibrium occurs early.

10. The results of the revetment study are similar to the results of the Friedken study. The revetments cause general deepening around the stabilized bends but cause little or no change to points of inflection. Due to extensive deposition at the points of inflection, the overall flow capacity of the channel decreases rapidly just prior to equilibrium.

Suggestion for Future Studies

An optimum type of stabilization cannot be obtained from the results of this study, as only a constant discharge was considered. Any future work in this regard should consider varying discharges as well as induced sediment loads.

BIBLIOGRAPHY

1. Friedken, J.F., A Laboratory Study of the Meandering of Alluvial Rivers. War Department Corps of Engineers, U.S. Army, Mississippi River Commission.

2. Leliavsky, Serge, An Introduction to Fluvial Hydraulics.

3. Leopold, L.B. and Wolman, M.G., River Meanders, Bulletin of the Geological Society of America, Vol. 71, pp. 769-794, 1960.

4. Muller, M., Investigations of Vertical and Transverse Motion of Flowing Water. Hydraulic Laboratory Practice. Die Wasserbaulaboratorien Europas, 1929. American Society of Mechanical Engineers.

5. Kondratev, N.E., River Flow and Channel Formation, Published for the National Science Foundation, Washington, D.C. and the Department of the Interior by the Israel Program for Scientific Translations.

<u>ADDITIONAL REFERENCES:</u>

1. Kuiper, E., Water Resources Development, University of Manitoba, 1963.

2. Parsons, D.A., Effects of Flood Flow on Channel Boundaries, A.S.C.E. Trans. #3115, Vol. 126, 1961.

3. Bush, J.L., Channel Stabilization of the Arkansas River, A.S.C.E., Waterways and Harbour Division.

4. Neill, C.R., Alluvial Processes and River Channel Regime, E.I.C., Trans., Vol. 7, 1964.

APPENDICES

APPENDIX A

LABORATORY APPARATUS

TESTING AREA

Parts I and II of this study were conducted in an abandoned hydraulic model. The sump, supply reservoir, pump and motor were all intact. The inlet conditions, test area and outlet were modified to satisfy the needs of this study. Figure 9 , page 80 , shows the final layout as used in Parts I and II. The overall dimensions of the testing area may be obtained from the scale drawing, Figure 9 .

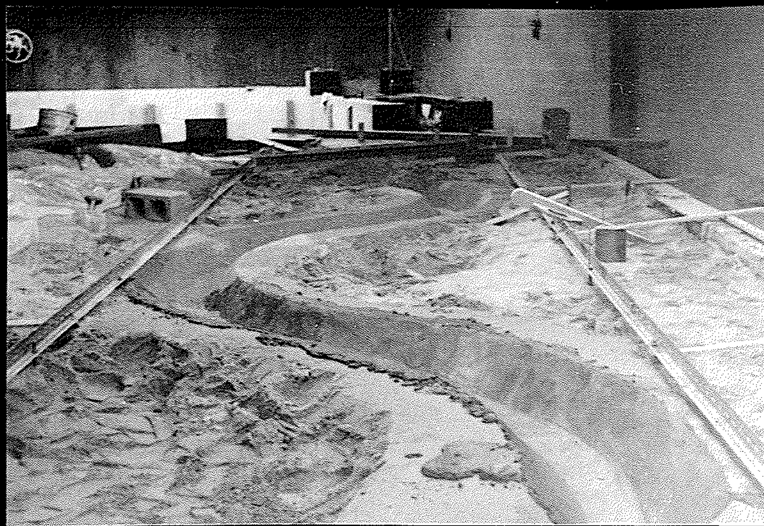
Construction

The two sets of rails, (one set was sloped at 0.0006 and the other set was level) used to carry the travelling electric point gauge and velocity instrument were mounted on 1/2" stud bolts spaced at four feet and anchored to the concrete floor. Both sets of rails were precisely levelled and rechecked from time to time during the investigation.

The model area was filled with coarse mortar sand. The grain size of this material is of no importance as this material was used as a bed for the test channel in Part I. In Part II, this material was replaced with a silty sand mixture.

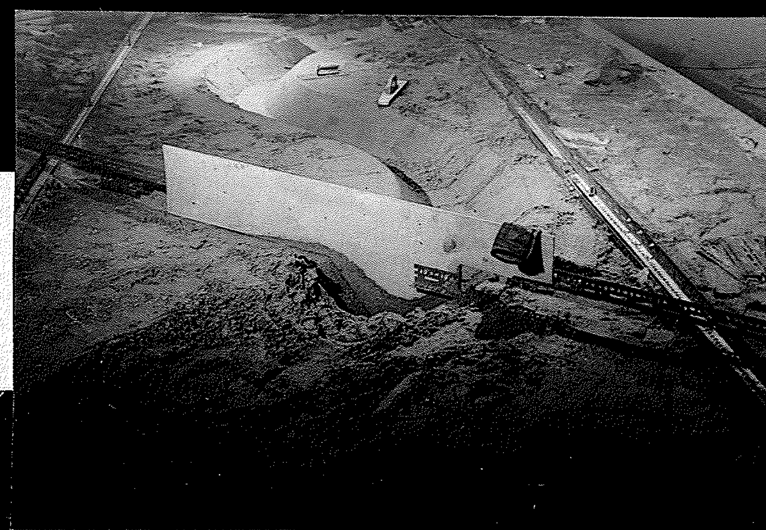
CONSTRUCTION OF THE FIXED CHANNEL - PART I

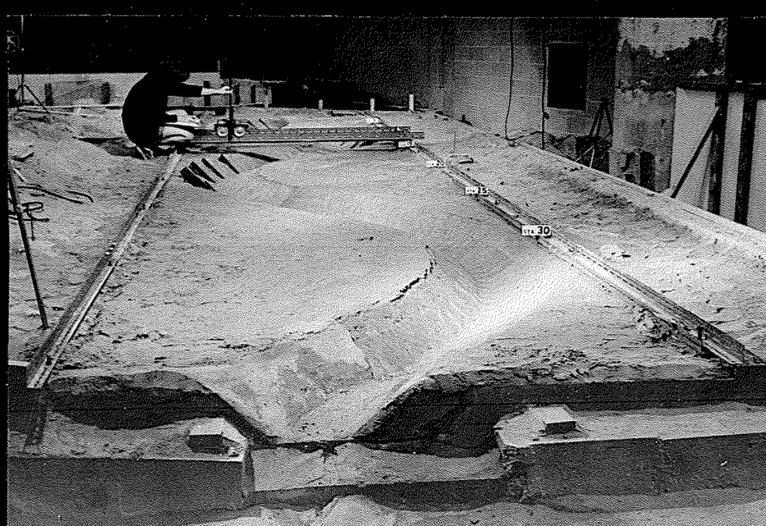
Steel rods anchored in the concrete floor marked the centre of curvature for each curve in the test channel. A trapezoidal "male" template pivoting on the centre was used to produce the channel outline. The slope of the channel was obtained by sliding the template on the sloping rails while pivoting on the centre rods. (See Figure 7, page 75). After



PHOTOGRAPH 1 : The channel in Part I was first formed in sand, then "fixed" with a layer of mortar.

PHOTOGRAPH 2 : The initial channel for each test in Part II was formed by pivoting a "male" template on the rods which marked the centre of each curve.





PHOTOGRAPH 3 : Taking cross-sections at the end of a Bank Stabilization Test.

FIGURE 7 : CONSTRUCTION OF THE CHANNEL

the channel was formed in wet coarse mortar sand, a layer of fine mortar 1/2 inch in thickness was used to line the channel. When the mortar had set, the centreline was marked and sub-divided into one foot intervals beginning at the extreme upstream end. Each foot located an observation station. The locations of required velocity readings across the channel were also marked at the observation stations.

CONSTRUCTION OF THE CHANNEL - PART II

A. Effects of Stabilizing Measures on Bed Material

The channel used in Part I was used again in this phase. Silica sand, (passing a #60 sieve and retained on a #100 sieve) spread at a depth of 0.05' throughout the length of the channel was used to simulate the bed material.

B. Bank Stabilization Tests

Although several preliminary tests were conducted on different mixtures of sand, the material finally used to form the initial test channels was patterned after that used by Friedken[1] in one of his studies. The grain size analysis of the material used in the Bank Stabilizatoion Tests is shown on page 81, Appendix B.

The initial test channels had the same sinuosity as the "fixed" channel in Part I. For each Bank Stabilization Test, the initial channel was formed in the same manner as described above. That is, pivoting the male (trapezoid) template on the curve centres and simultaneously sliding the template on the sloping rails. (See Figure 7, page 75). After the initial channel was formed, the stabilizing measures to be tested were installed.

STABILIZING MEASURES

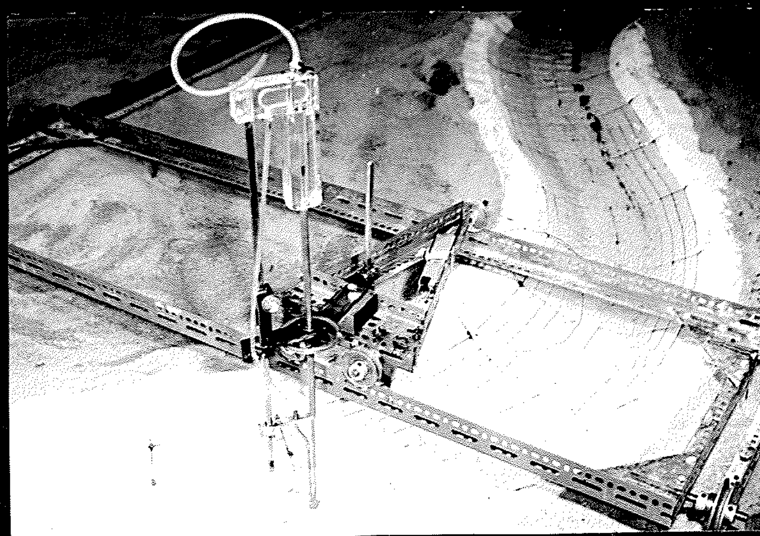
Jetties were simulated by expanded metal which had a 90% void area. Perforated metal (15% void area), was used to simulate the spur dykes.

INSTRUMENTATION

(a) The Velocity Instrument

Construction: A Bentzel Tube, (a form of pitot tube) was used in measuring velocity magnitudes. In obtaining velocity directions, a discarded transit vertical circle (with verniers), was modified and accurately installed on the vertical axis of the Bentzel Tube to form a graduated horizontal plate. The instrument was attached to the rack and pinion assembly of a standard point gauge, which in turn fastened to the rail mounted carriage. As illustration of the velocity instrument is seen on Figure 8, page 78.

Operation: A theodolite was set over the centre of the curve on which a series of velocity readings were to be taken. The theodolite was then sighted on an observation station. The velocity instrument was moved into position, and lowered, by the rack and pinion mechanism, to the required depth of the reading. By turning the velocity instrument on its vertical axis, the zero point on one of the two verniers was made to coincide with the line of sight of the theodolite. (In the construction of the velocity instrument, the line joining the two zero points of the vernier was made perpendicular to the line of velocity measurement of the Bentzel Tube). When one of the zero points of the vernier was lined in, the velocity instrument was then tangent to the curve at this point. The reading on the horizontal plate was then recorded and a



PHOTOGRAPH 1 : The Velocity Instrument. Note the graduated horizontal plate attached to the vertical axis of the Bentzel Tube.

PHOTOGRAPH 2 : The Electric Point Gauge.

FIGURE 8 : INSTRUMENTATION

tangential velocity was obtained. In obtaining the resultant velocity and its angle from tangency, the instrument was slowly rotated until a maximum velocity was observed. At this point, the resultant velocity and the angle on the horizontal plate were recorded. The angular deviation of the resultant velocity from tangency was obtained by subtracting the angle recorded when the instrument was initially placed tangent to the curve and the final angle read when the resultant velocity was observed.

(b) Electric Point Gauge

Construction: To ensure greater accuracy in obtaining water surface readings, an electric point gauge was used. A standard rack and pinion gauge assembly was slightly modified by soldering a steel needle to the normal point of the gauge. This was done in order to eliminate as much surface tension as possible. A wire attached to the rack of the gauge connected a very low voltage neon light bulb in series to the positive terminal of a nine volt dry-cell battery. From the negative terminal, a copper wire trailed in the water. (See Figure 8, page 78, Volume I).

Operation: At the time of a water surface reading, the needle was lowered by the pinion mechanism. When the needle barely made contact with the water, the electric circuit was completed and the neon bulb was illuminated. At this point, the reading was recorded.

(c) Standard Equipment

In addition to the aforementioned apparatus, hook gauges were installed to measure tailwater levels and discharges through the 90° V-notch weir. (See Figure 9, page 80, Volume I).

PLAN OF TESTING AREA AND LOCATION OF APPURTENANCES.

SCALE: 1" = 4 FT.

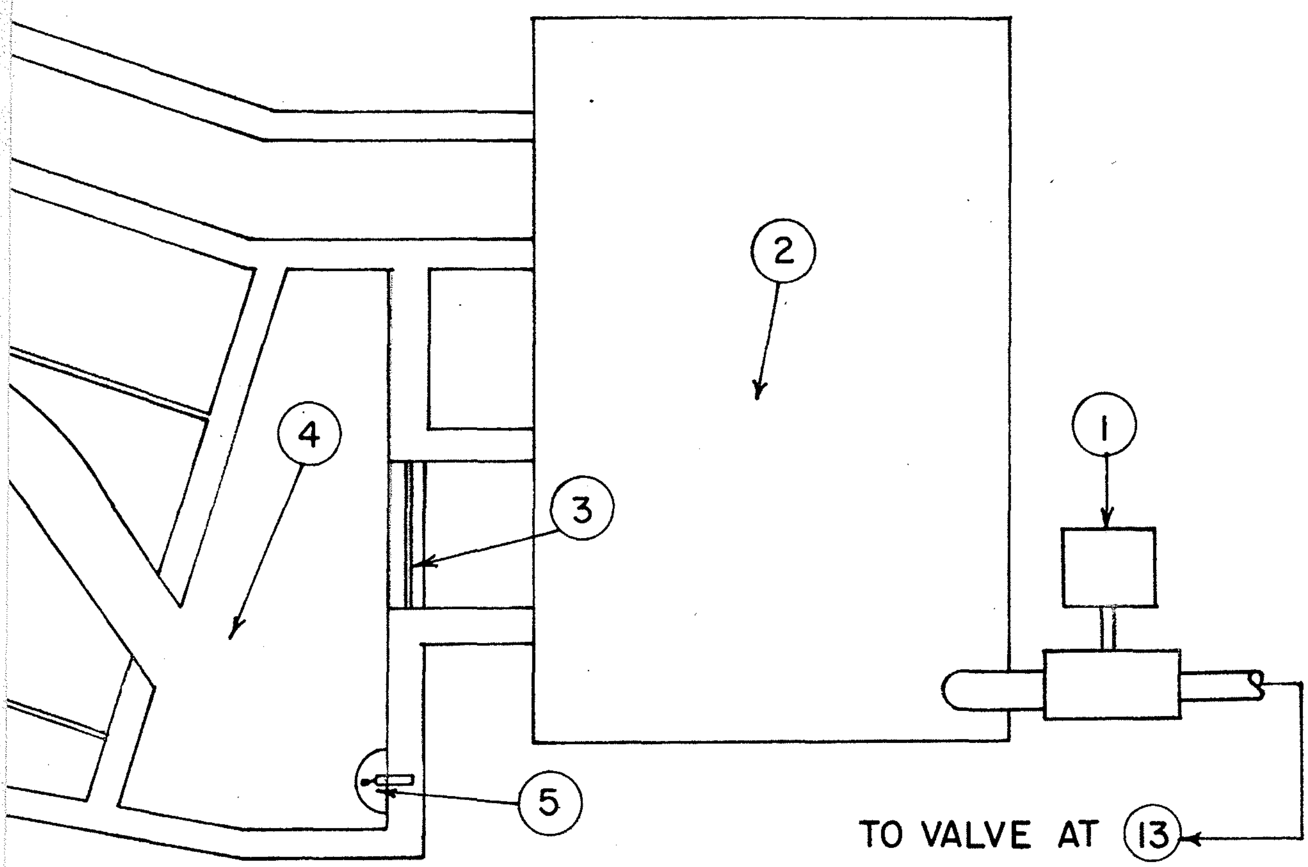
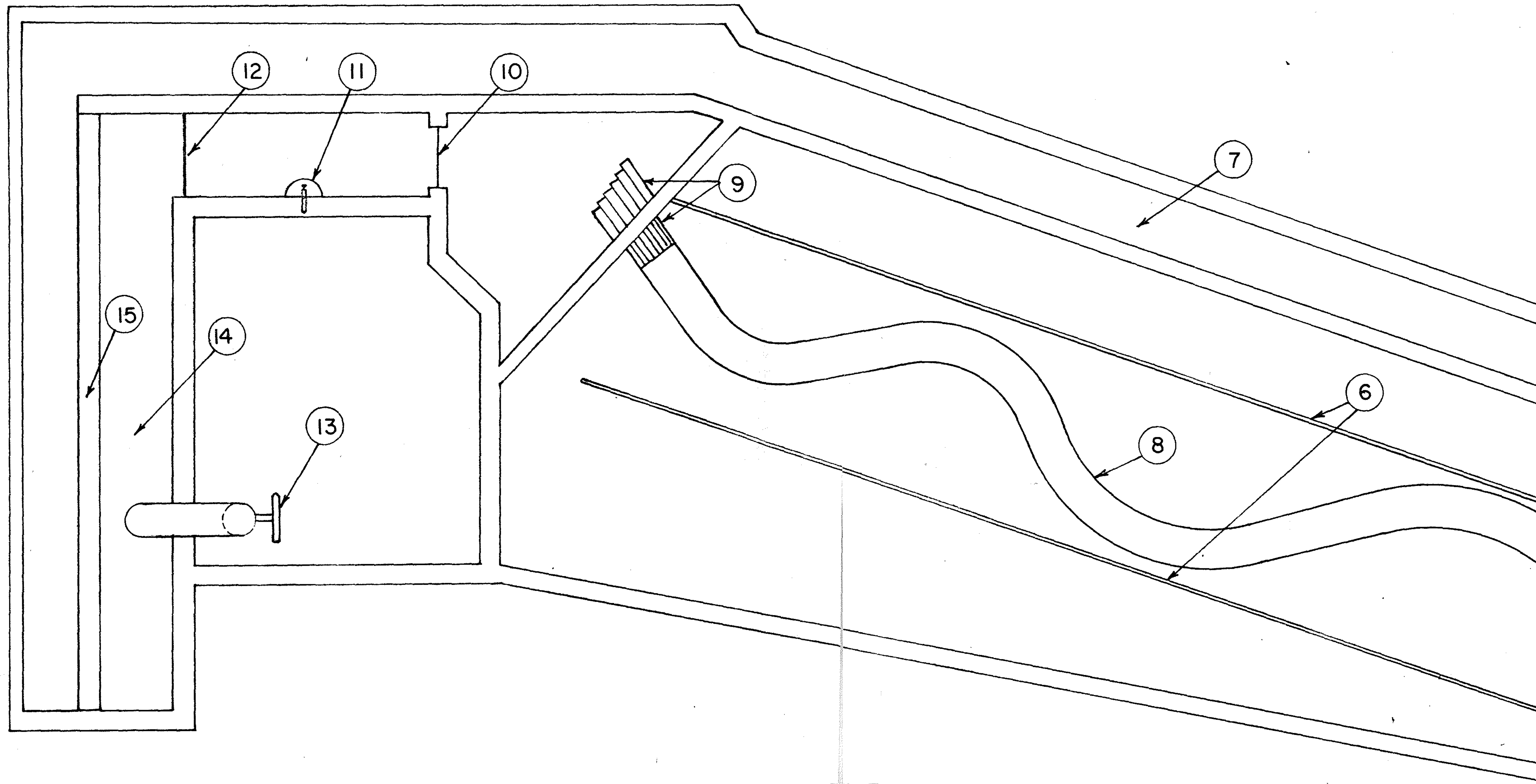
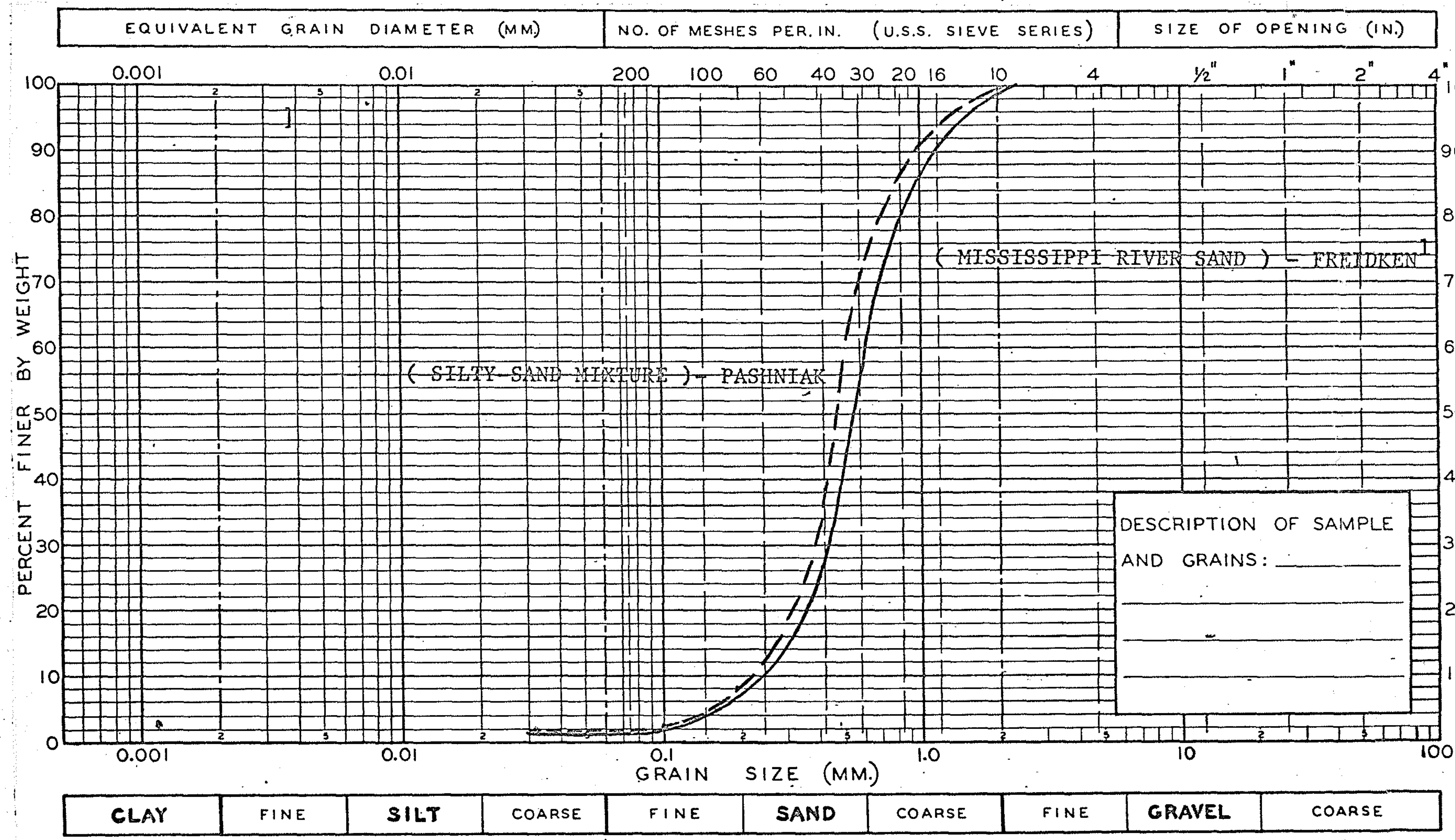


FIGURE 9



1. PUMP & MOTOR
2. SUMP
3. TAILWATER GATES
4. TAILWATER STILLING BASIN
5. TAILWATER HOOK GAUGE
6. RAILS FOR TRAVELLING GAUSE
7. OVERFLOW RETURN CHANNEL
8. TEST CHANNEL
9. FLOW STRAIGHTENERS
10. 90° V-NOTCH WEIR
11. HEADWATER HOOK GAUGE
12. SUPPLY RESERVOIR GATE
13. SUPPLY RESERVOIR VALVE
14. SUPPLY RESERVOIR
15. OVERFLOW CREST

APPENDIX B



MECHANICAL GRAIN SIZE ANALYSIS OF SILTY-SAND - PART II

A LABORATORY STUDY OF FLOW AROUND BENDS AND BANK STABILIZATION

Vol. II

A Thesis

Presented to

The Faculty of Engineering

The University of Manitoba

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Civil Engineering

---

by

David A. Pashniak

March, 1966.

TABLE OF CONTENTS

VOLUME II

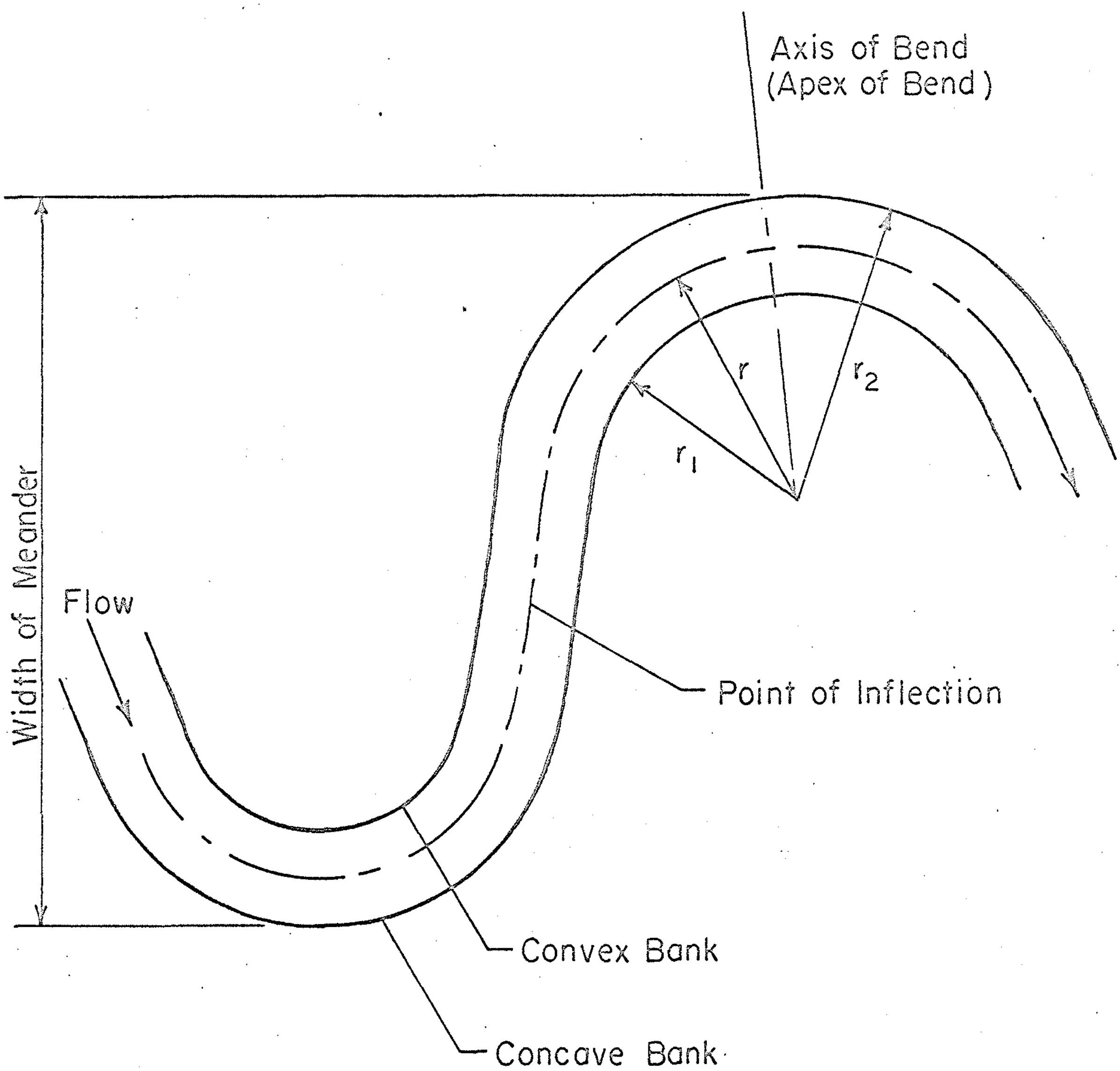
PART I

PART II

PART II (Cont'd)

PART II (Cont'd)

TYPICAL MEANDER BEND



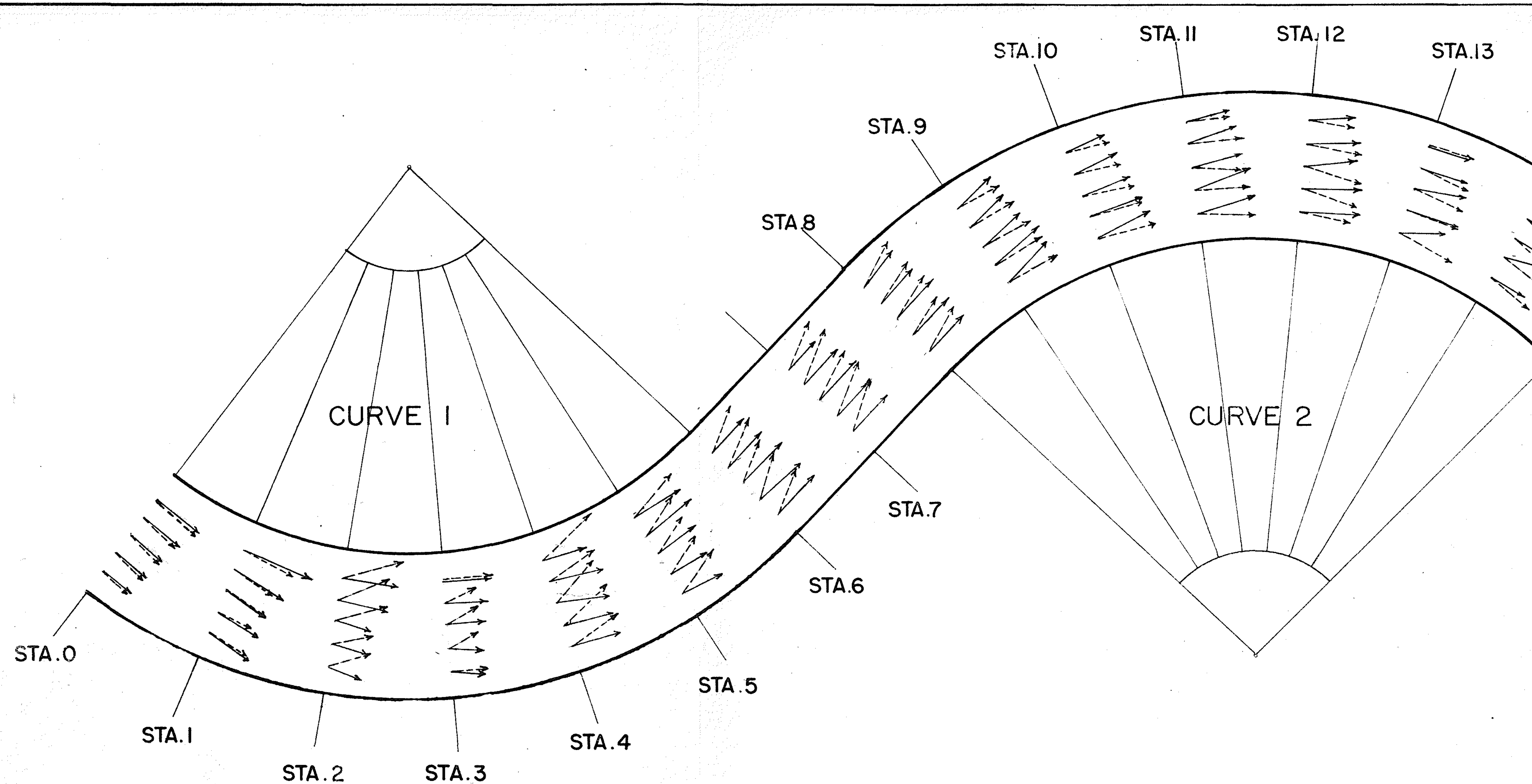
Sinuosity = Centreline distance divided by airline distance.

r = Radius of channel centreline

r_1 = Radius of inside bank

r_2 = Radius of outside bank.

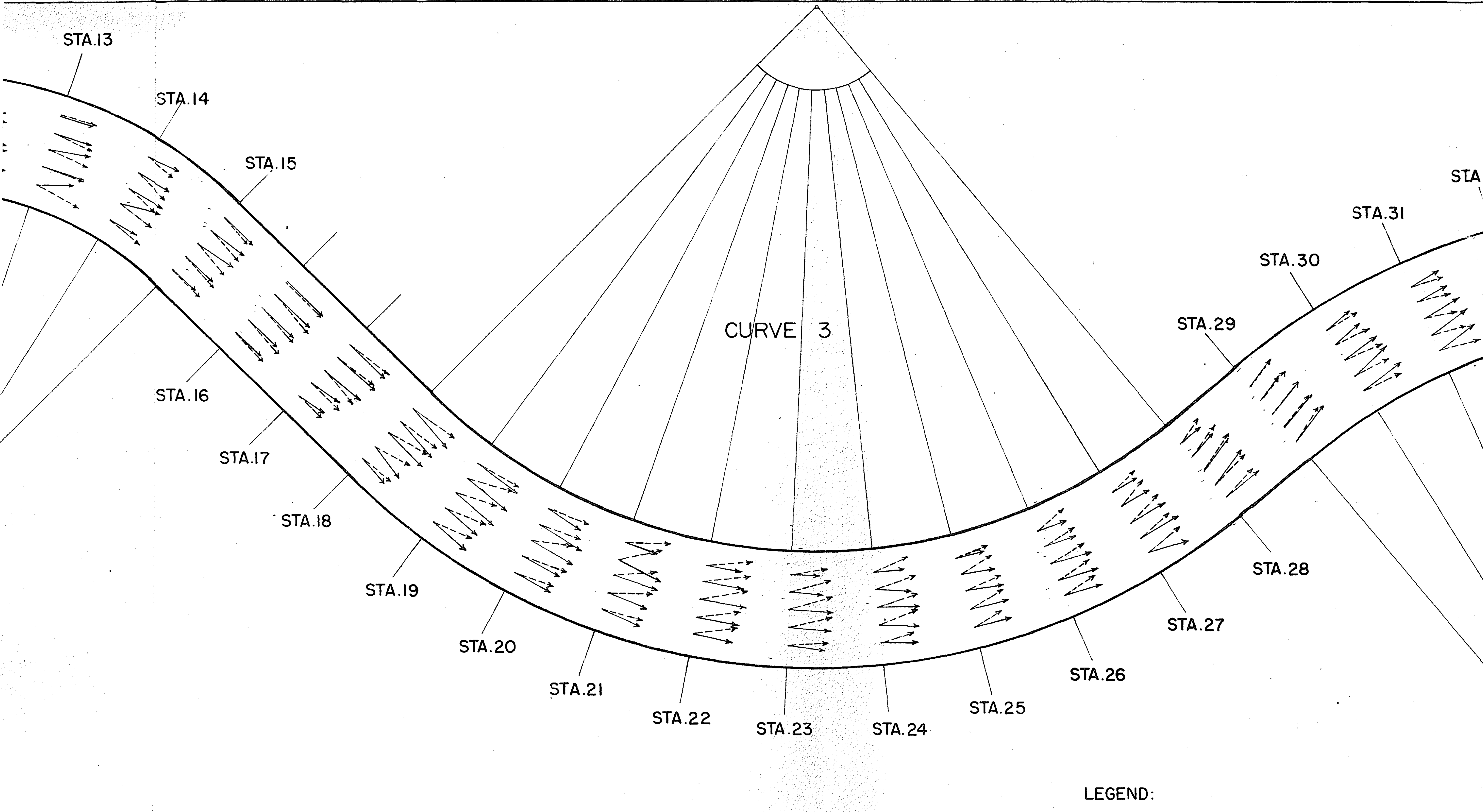
PLATE I



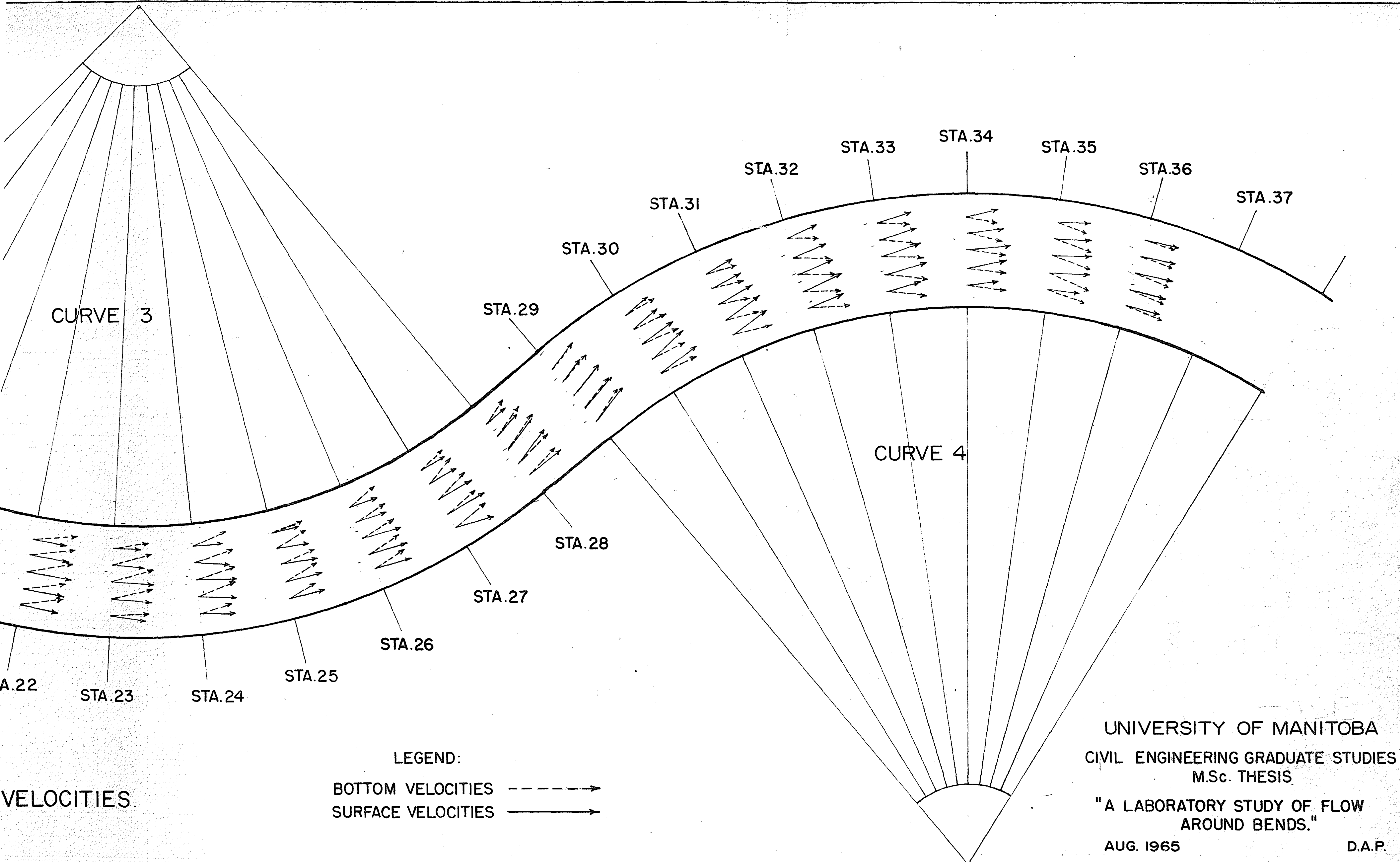
VELOCITY SCALE — 1" = 2 FT./SEC.
SPACE SCALE — 1" = 12"

DIRECTION OF FLOW

MAGNITUDE



MAGNITUDE & DIRECTION OF SURFACE AND BOTTOM VELOCITIES.



UNIVERSITY OF MANITOBA

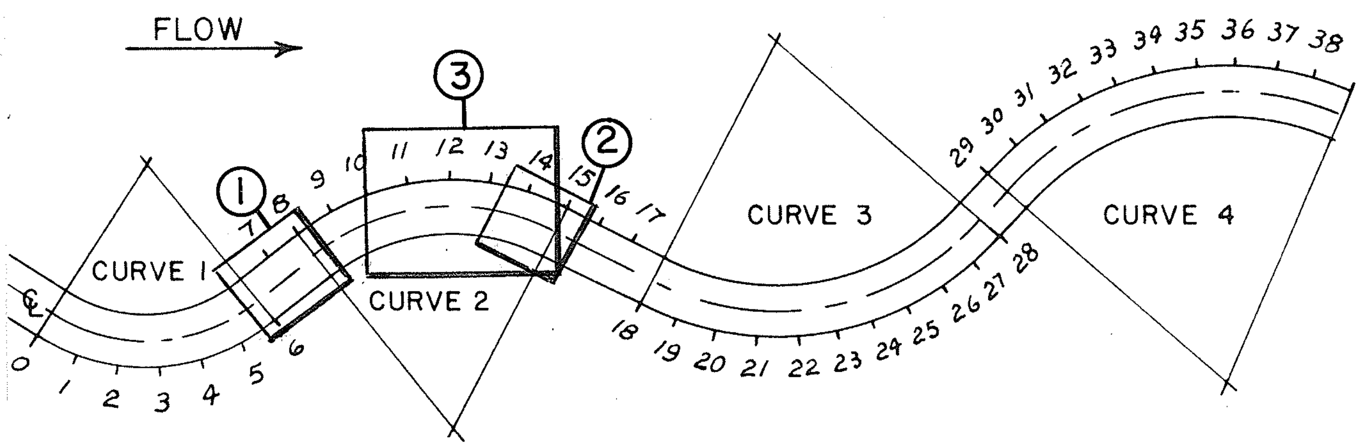
CIVIL ENGINEERING GRADUATE STUDIES
M.Sc. THESIS

"A LABORATORY STUDY OF FLOW AROUND BENDS."

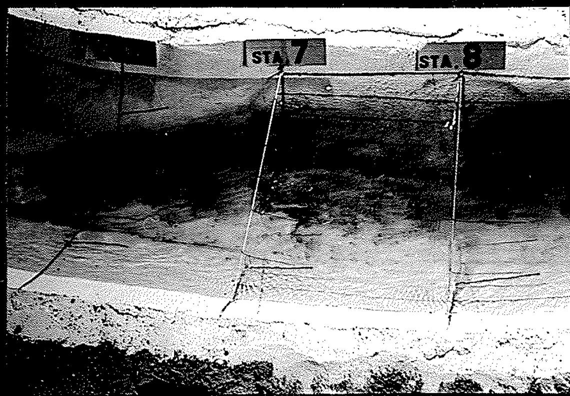
AUG. 1965 D.A.P.

PLATE 2

PHOTOGRAPH LOCATIONS

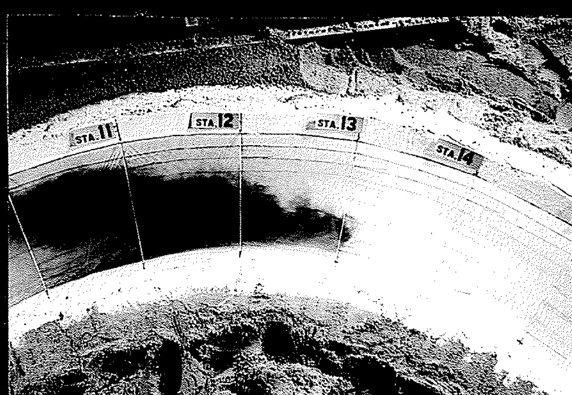


CHANNEL



PHOTOGRAPH 1 : Partial emergence of dye streaks on the convex side, downstream of the axis of Curve 1.

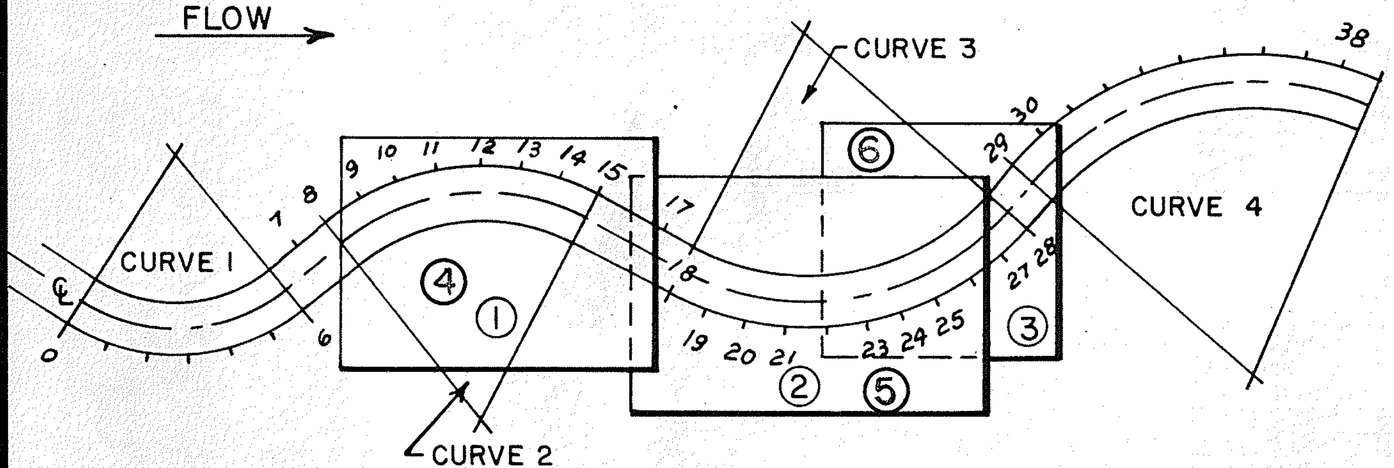
PHOTOGRAPH 2 : Partial cross over of dye streaks, when dye crystals are placed on the concave bank.



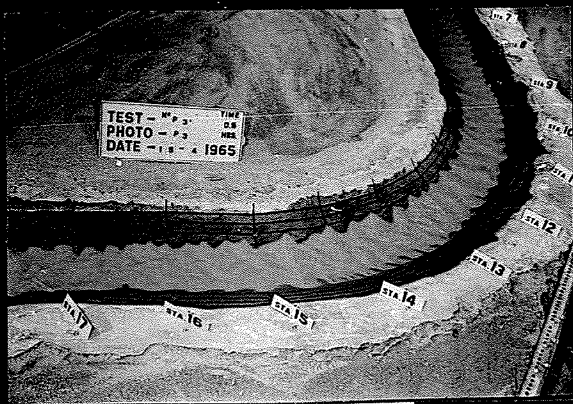
PHOTOGRAPH 3 : High velocities tend to favour the convex side.

PLATE 3
DYE STREAKS SHOWING HELICAL FLOW

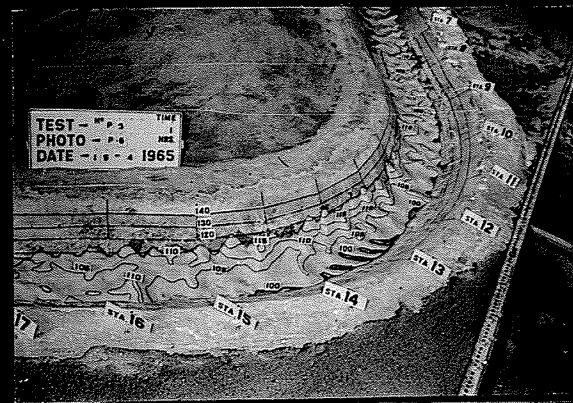
PHOTOGRAPH LOCATIONS



CHANNEL



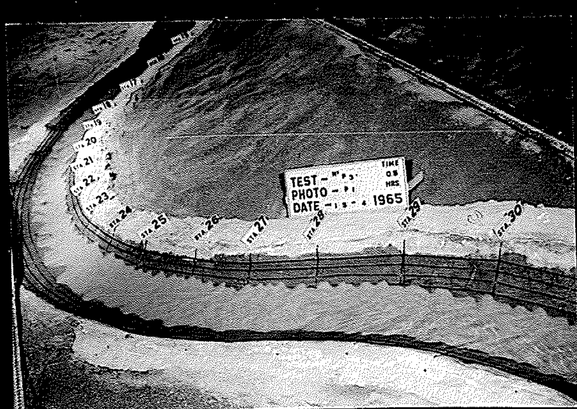
PHOTOGRAPH 1



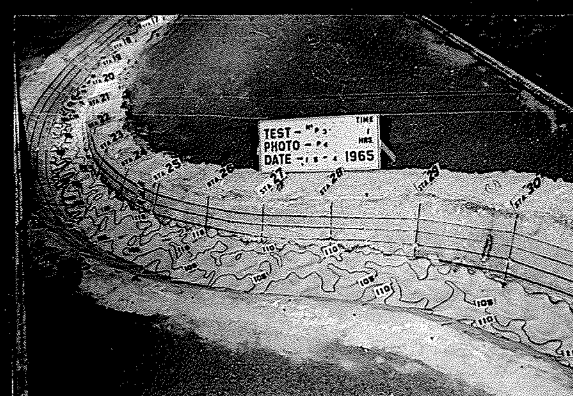
PHOTOGRAPH 4

PHOTOGRAPH 2

PHOTOGRAPH 5



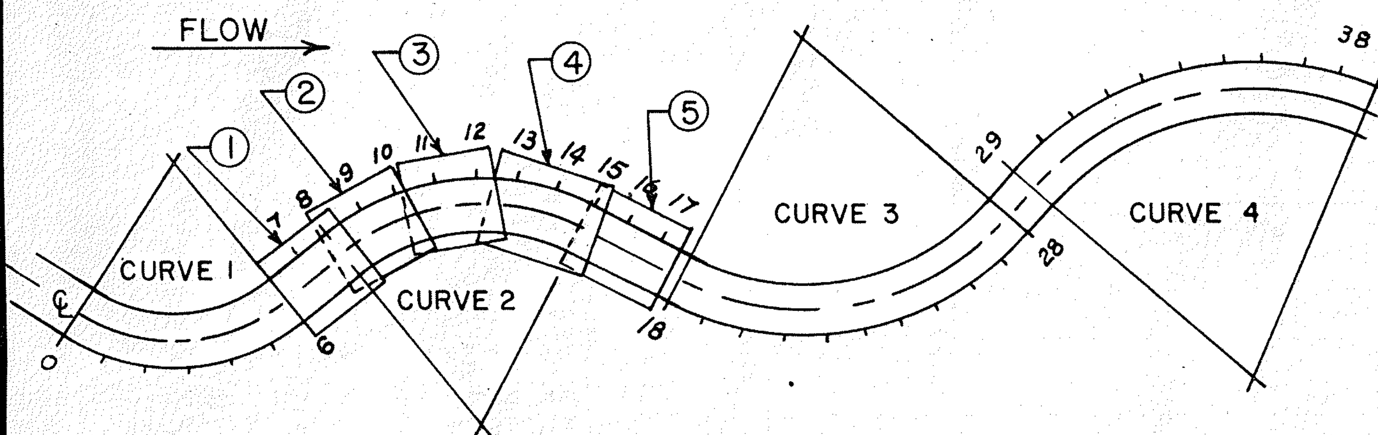
PHOTOGRAPH 3



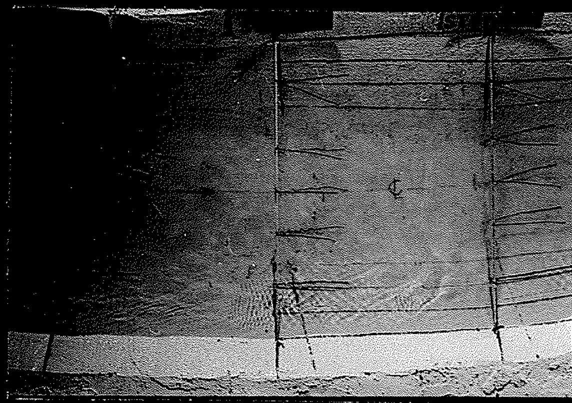
PHOTOGRAPH 6

PLATE 4
THE EFFECT OF HELICAL FLOW ON BED MATERIAL

PHOTOGRAPH LOCATIONS

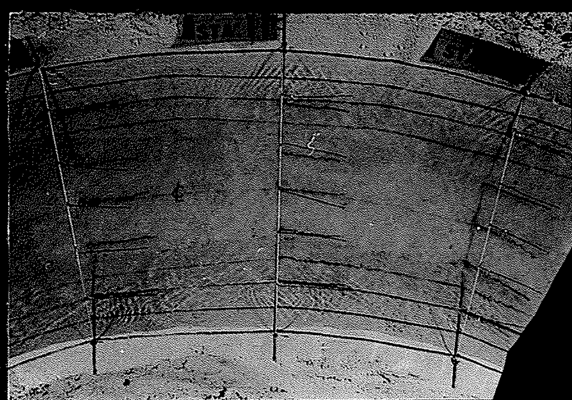


CHANNEL

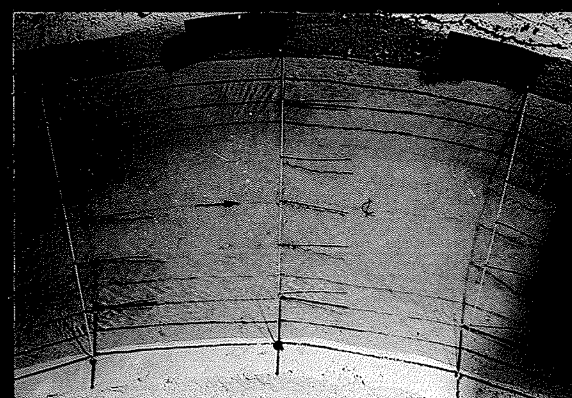


PHOTOGRAPH 1

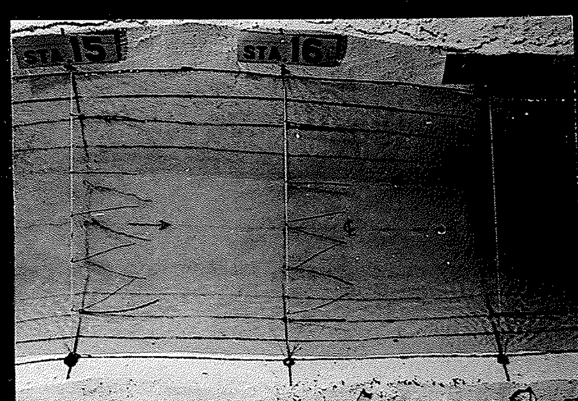
PHOTOGRAPH 2



PHOTOGRAPH 3



PHOTOGRAPH 4



PHOTOGRAPH 5

PLATE 5
FLOW AROUND BENDS ILLUSTRATED BY SUSPENDED THREADS

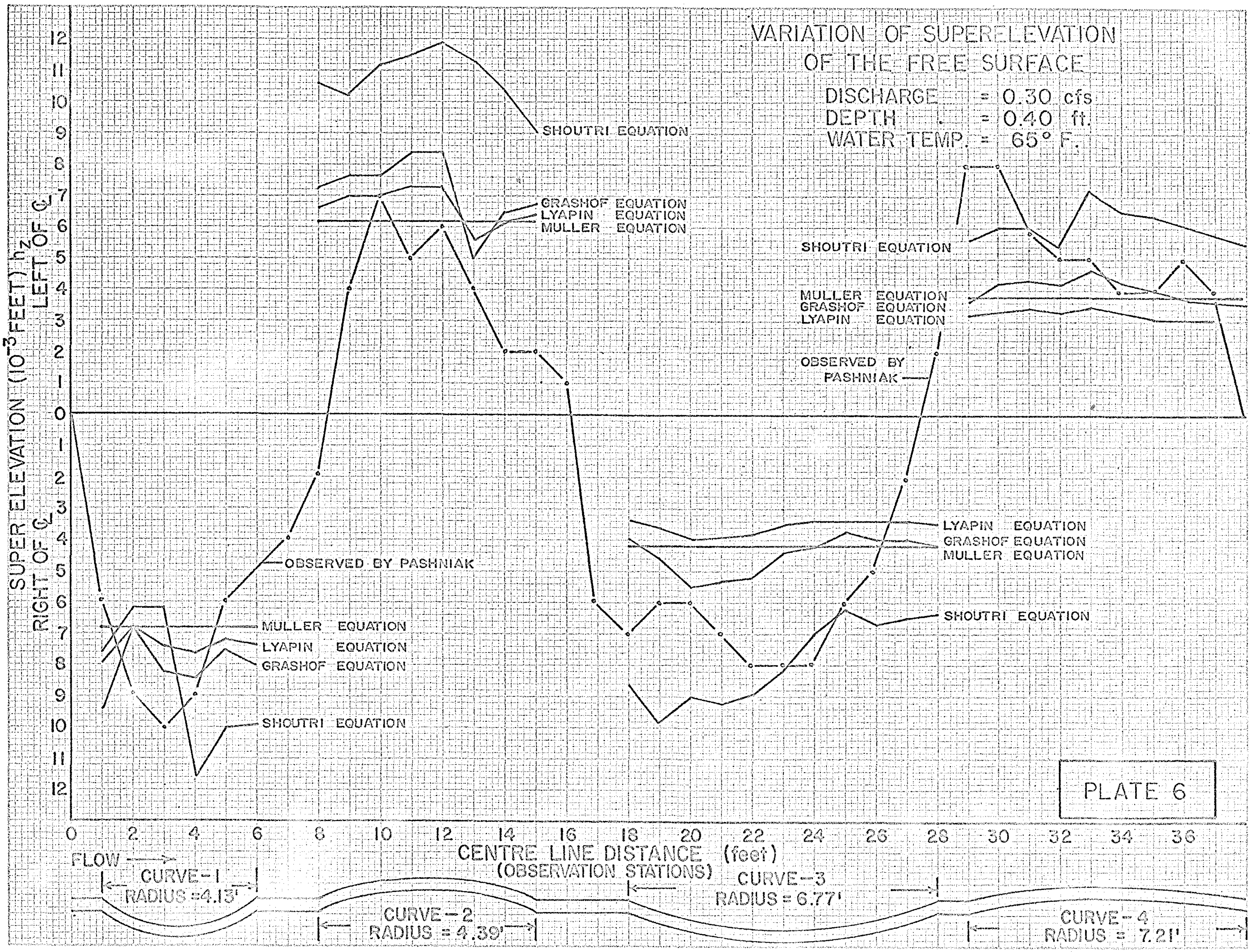
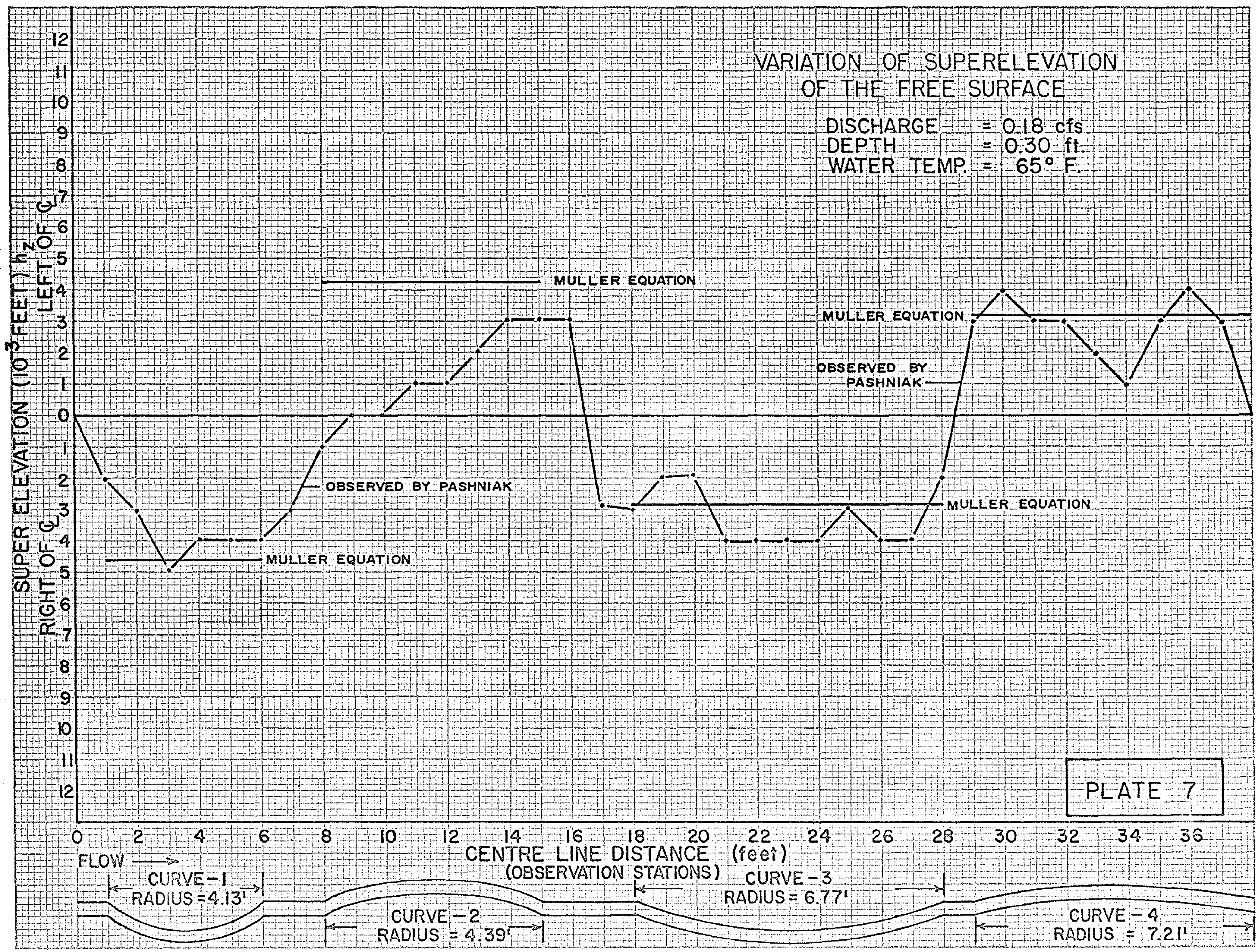
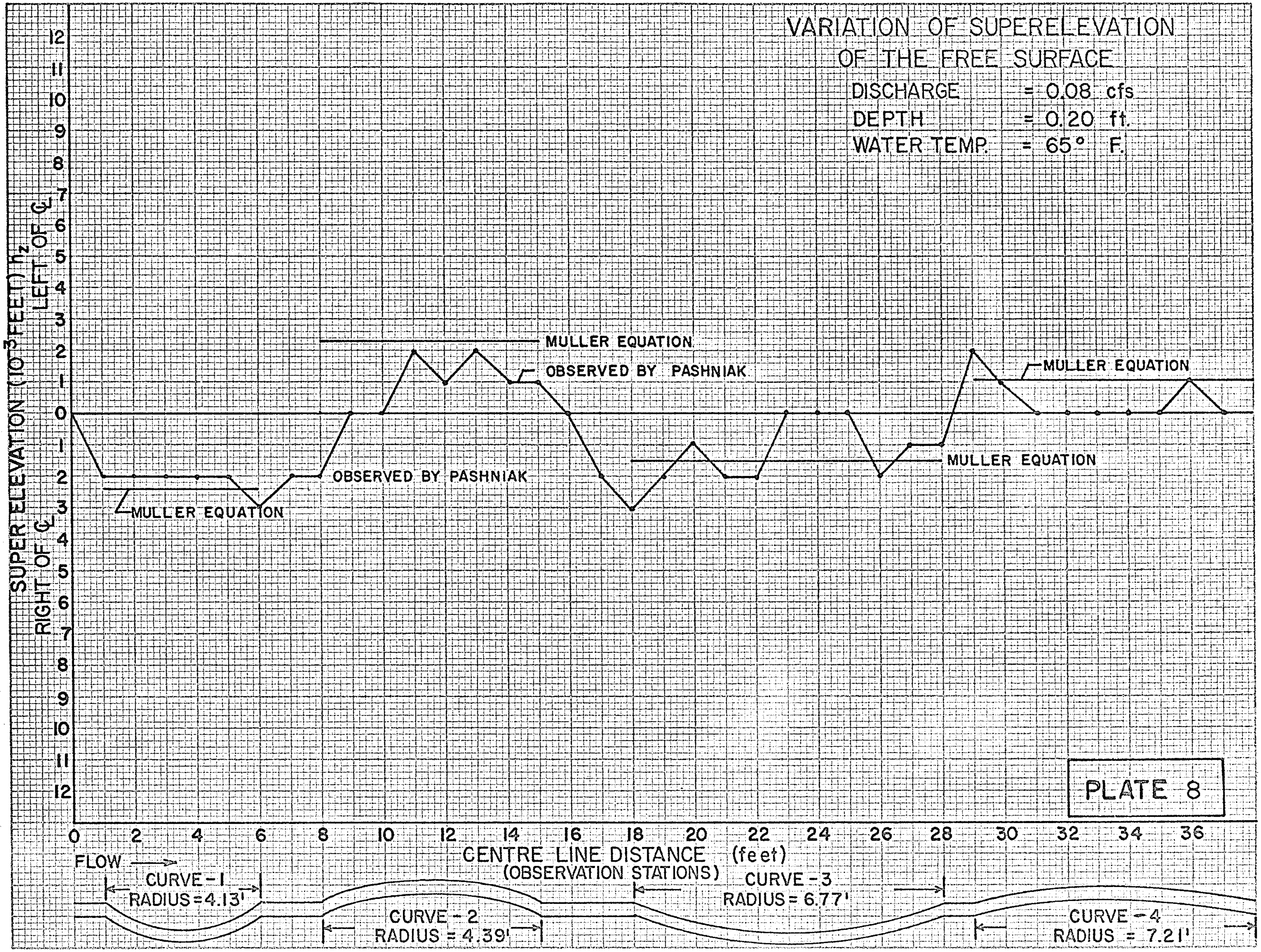


PLATE 6

D.A.P. 1965

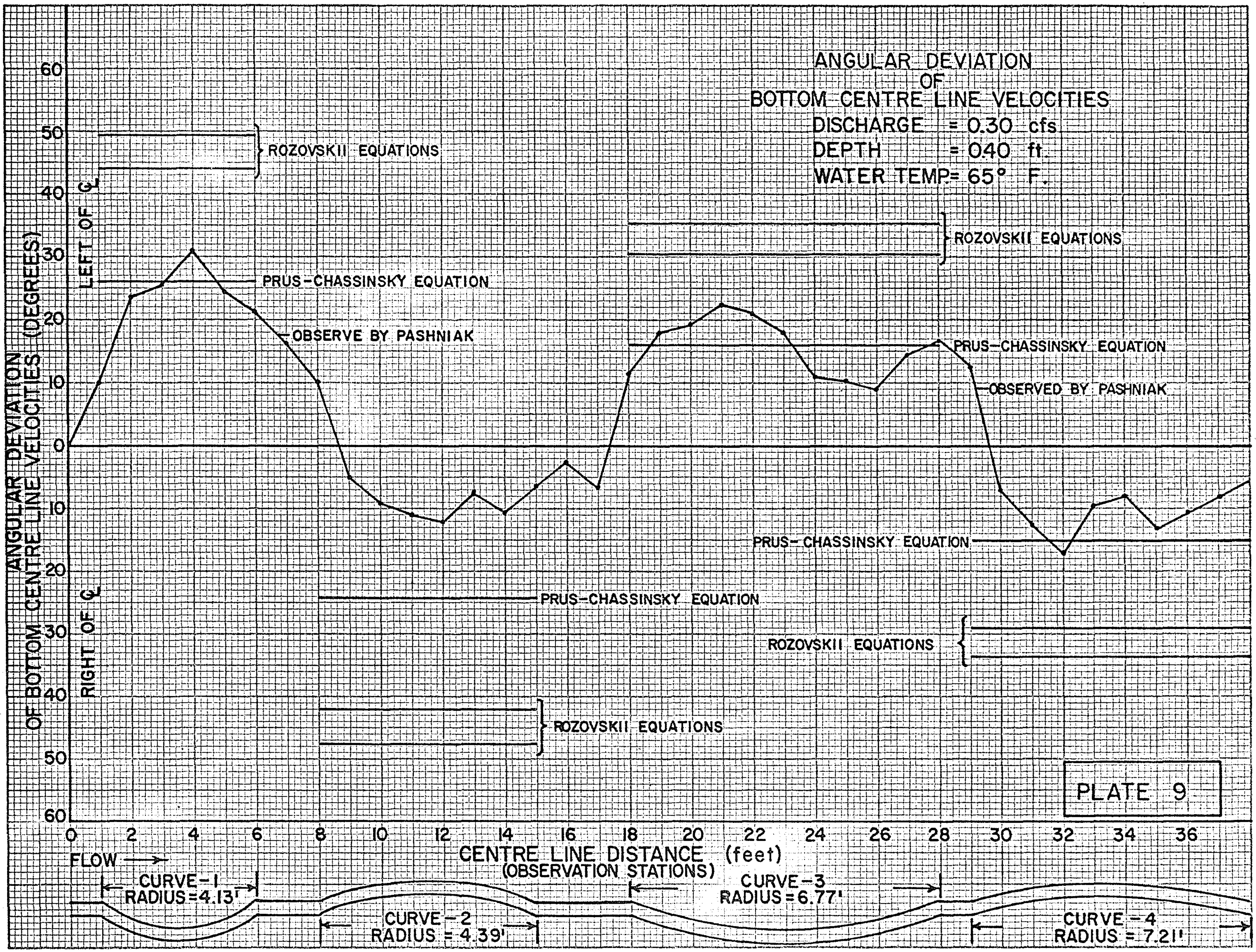

VARIATION OF SUPERELEVATION
OF THE FREE SURFACE
DISCHARGE = 0.18 cfs
DEPTH = 0.30 ft.
WATER TEMP. = 65° F.
MULLER EQUATION
OBSERVED BY PASHNIAK
MULLER EQUATION
MULLER EQUATION
OBSERVED BY PASHNIAK
MULLER EQUATION
SUPER ELEVATION (10⁻³ FEET) hz
LEFT OF ℄
RIGHT OF ℄
CENTRE LINE DISTANCE (feet)
(OBSERVATION STATIONS)
FLOW
CURVE - 1 RADIUS = 4.13'
CURVE - 2 RADIUS = 4.39'
CURVE - 3 RADIUS = 6.77'
CURVE - 4 RADIUS = 7.21'
PLATE 7

D.A.P. 1965



VARIATION OF SUPERELEVATION
OF THE FREE SURFACE
DISCHARGE = 0.08 cfs
DEPTH = 0.20 ft.
WATER TEMP. = 65° F.
SUPER ELEVATION (10^{-3} FEET) h_z
LEFT OF ℄
RIGHT OF ℄
MULLER EQUATION
OBSERVED BY PASHNIAK
MULLER EQUATION
OBSERVED BY PASHNIAK
MULLER EQUATION
MULLER EQUATION
MULLER EQUATION
CENTRE LINE DISTANCE (feet)
(OBSERVATION STATIONS)
FLOW
CURVE - 1
RADIUS = 4.13'
CURVE - 2
RADIUS = 4.39'
CURVE - 3
RADIUS = 6.77'
CURVE - 4
RADIUS = 7.21'
PLATE 8

D.A.P. 1965


ANGULAR DEVIATION
OF
BOTTOM CENTRE LINE VELOCITIES
DISCHARGE = 0.30 cfs
DEPTH = 0.40 ft.
WATER TEMP = 65° F.
ANGULAR DEVIATION
OF BOTTOM CENTRE LINE VELOCITIES (DEGREES)
LEFT OF ℄
RIGHT OF ℄
ROZOVSKII EQUATIONS
PRUS-CHASSINSKY EQUATION
OBSERVE BY PASHNIAK
OBSERVED BY PASHNIAK
CENTRE LINE DISTANCE (feet)
(OBSERVATION STATIONS)
FLOW
CURVE-1
RADIUS = 4.13'
CURVE-2
RADIUS = 4.39'
CURVE-3
RADIUS = 6.77'
CURVE-4
RADIUS = 7.21'
PLATE 9

D.A.P. 1965

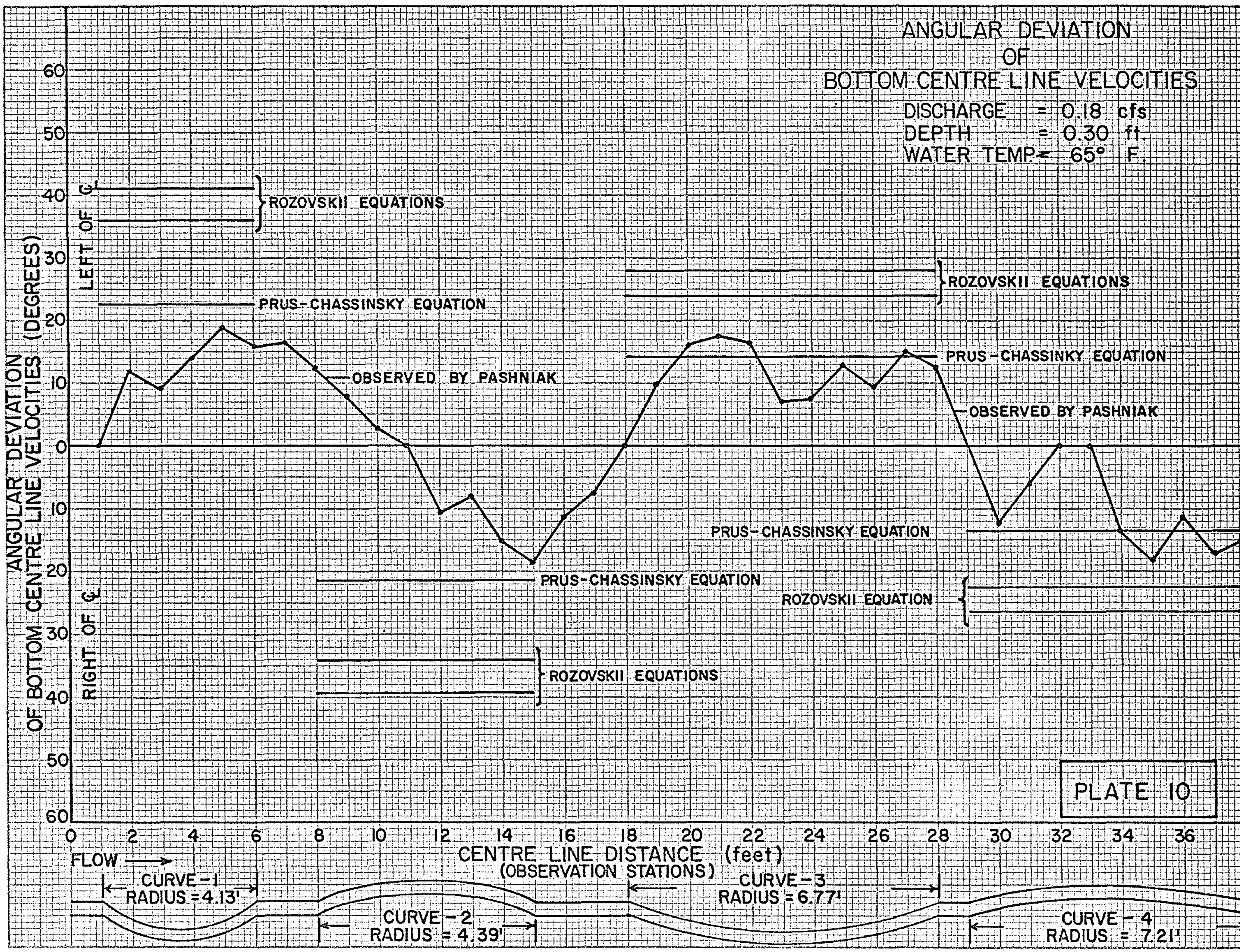


PLATE 10

D.A.P. 1965

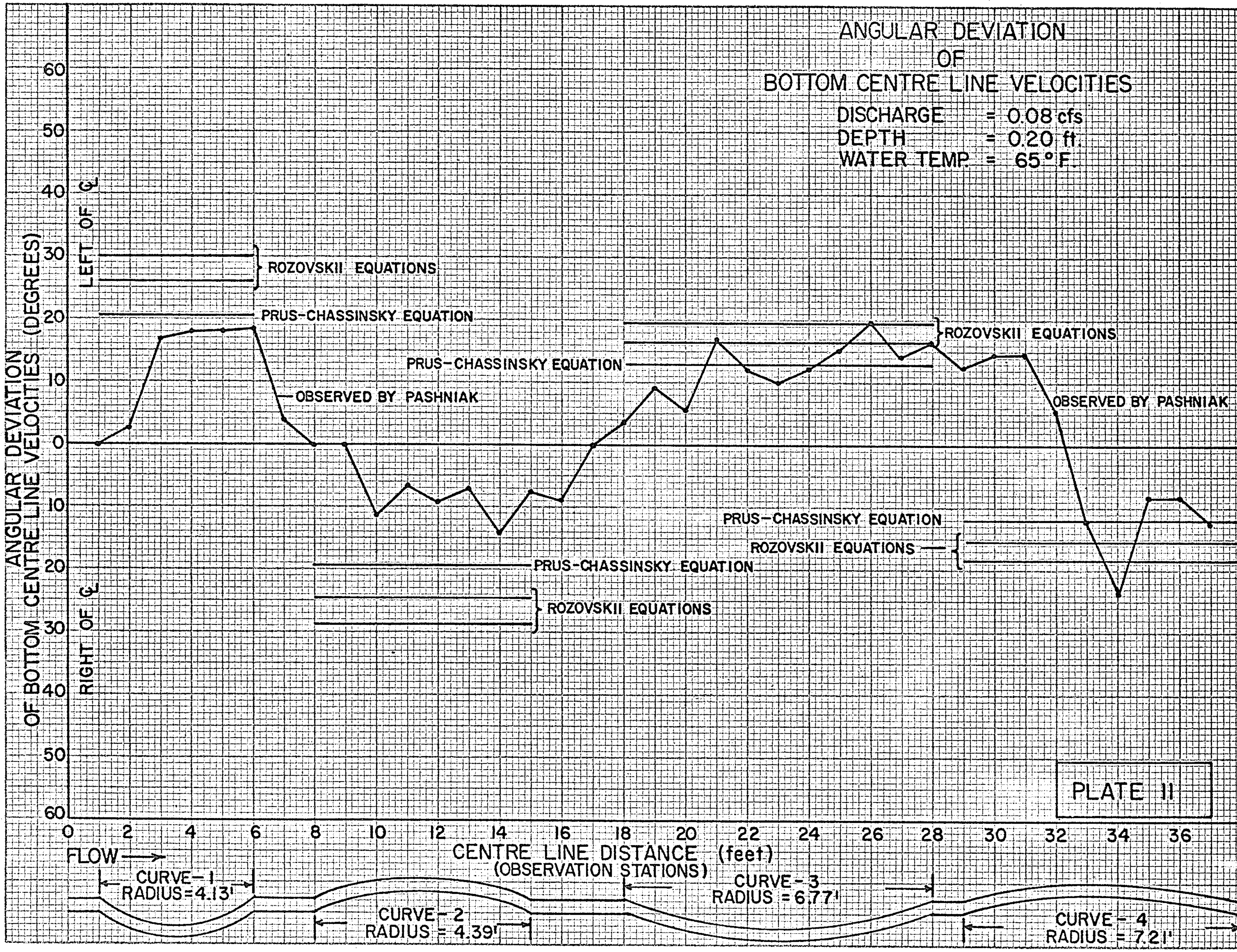
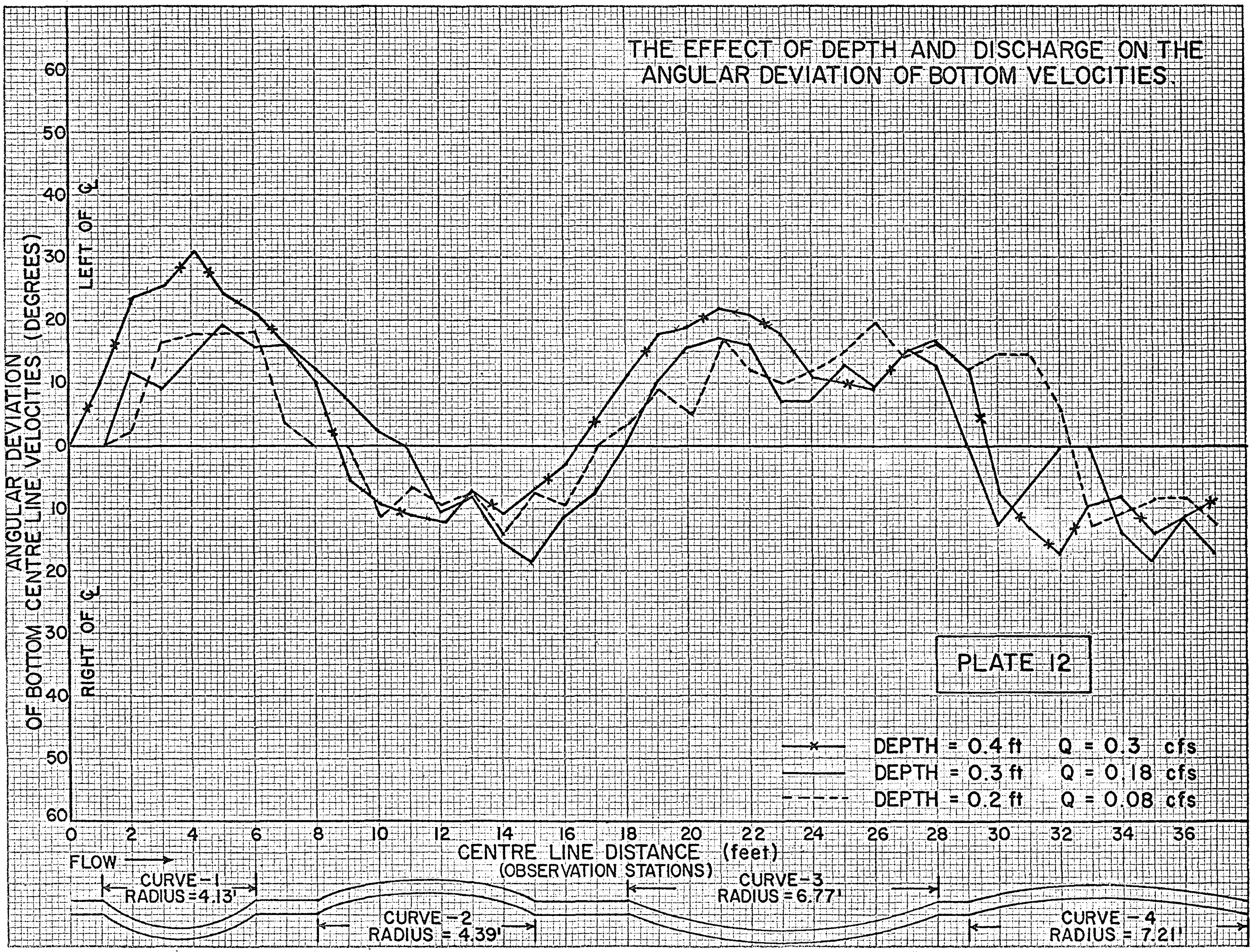
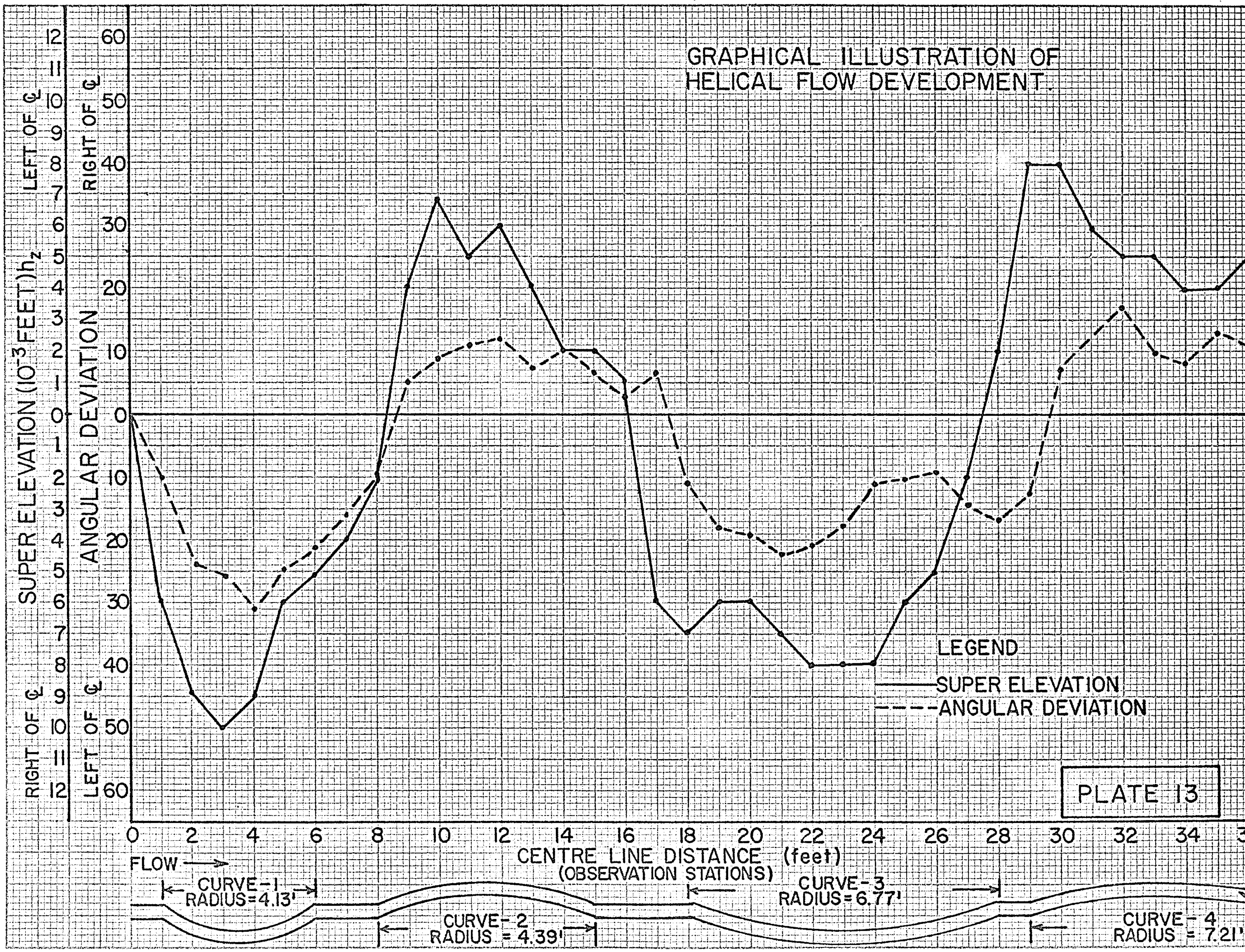


PLATE II

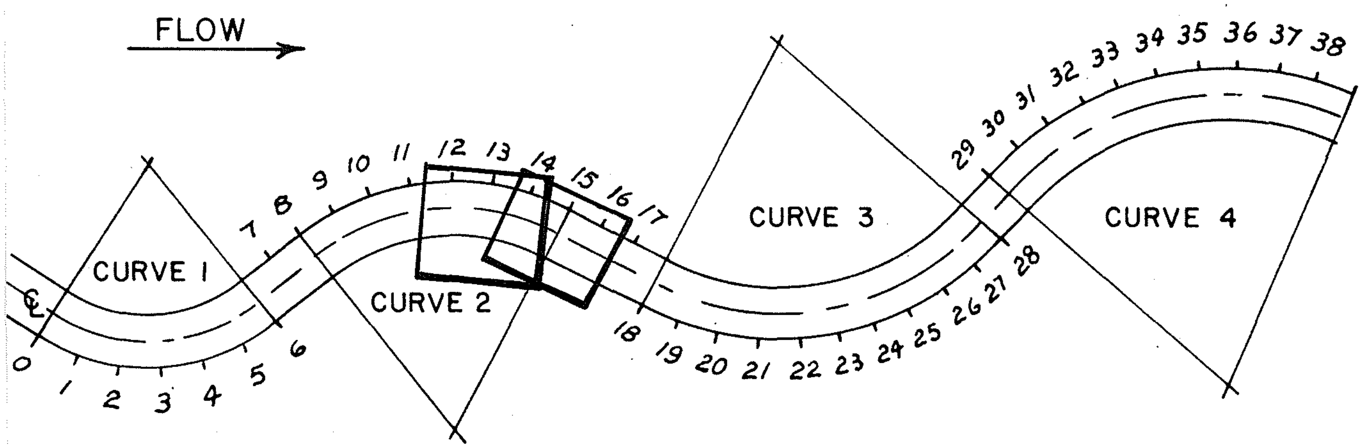
D.A.P. 1965


THE EFFECT OF DEPTH AND DISCHARGE ON THE ANGULAR DEVIATION OF BOTTOM VELOCITIES.
ANGULAR DEVIATION OF BOTTOM CENTRE LINE VELOCITIES (DEGREES)
LEFT OF ℄
RIGHT OF ℄
60
50
40
30
20
10
0
10
20
30
40
50
60
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
CENTRE LINE DISTANCE (feet)
(OBSERVATION STATIONS)
FLOW
CURVE-1
RADIUS = 4.13'
CURVE-2
RADIUS = 4.39'
CURVE-3
RADIUS = 6.77'
CURVE-4
RADIUS = 7.21'
PLATE 12
DEPTH = 0.4 ft Q = 0.3 cfs
DEPTH = 0.3 ft Q = 0.18 cfs
DEPTH = 0.2 ft Q = 0.08 cfs
D.A.P. 1965

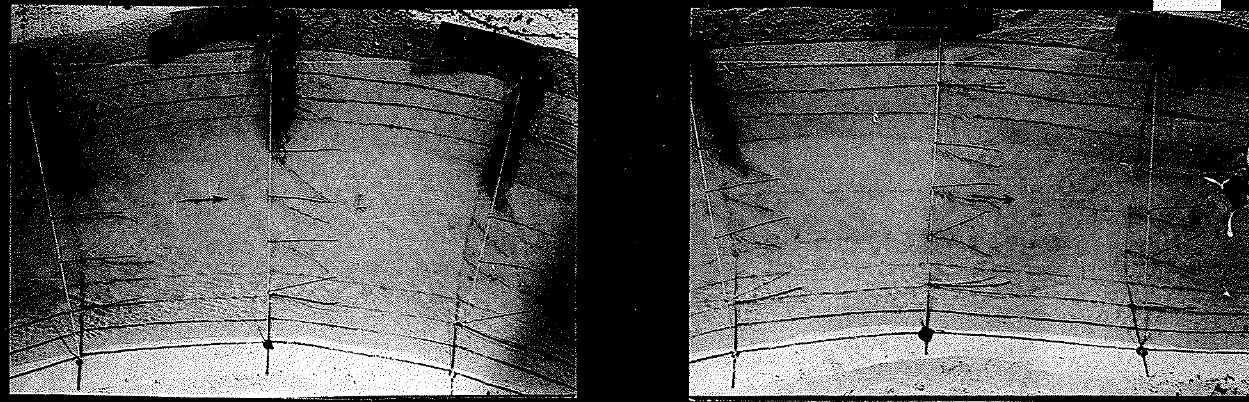


GRAPHICAL ILLUSTRATION OF HELICAL FLOW DEVELOPMENT.
SUPER ELEVATION (10^-3 FEET) h_z
LEFT OF ℄
RIGHT OF ℄
ANGULAR DEVIATION
RIGHT OF ℄
LEFT OF ℄
CENTRE LINE DISTANCE (feet)
(OBSERVATION STATIONS)
FLOW
CURVE-1 RADIUS=4.13'
CURVE-2 RADIUS = 4.39'
CURVE-3 RADIUS=6.77'
CURVE-4 RADIUS = 7.21'
LEGEND
SUPER ELEVATION
ANGULAR DEVIATION
PLATE 13
D.A.P. 1965

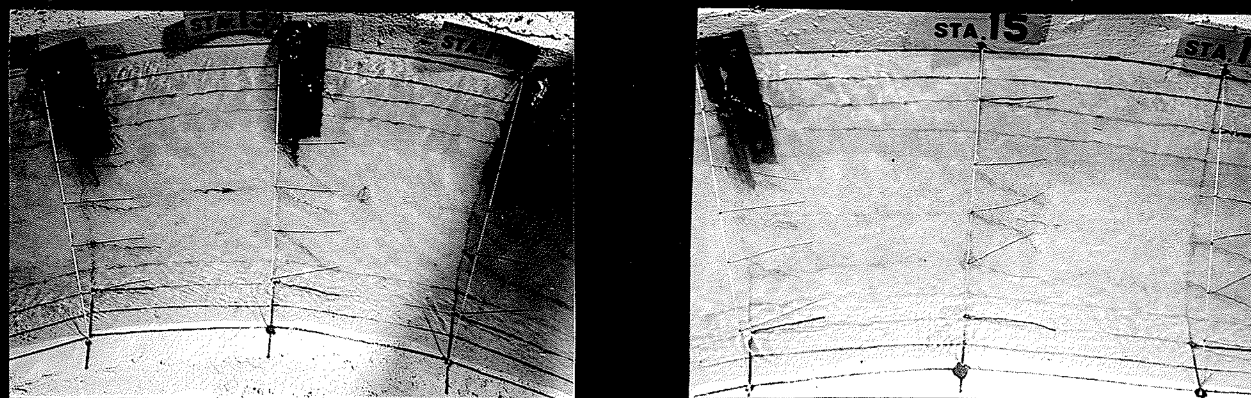
PHOTOGRAPH LOCATIONS



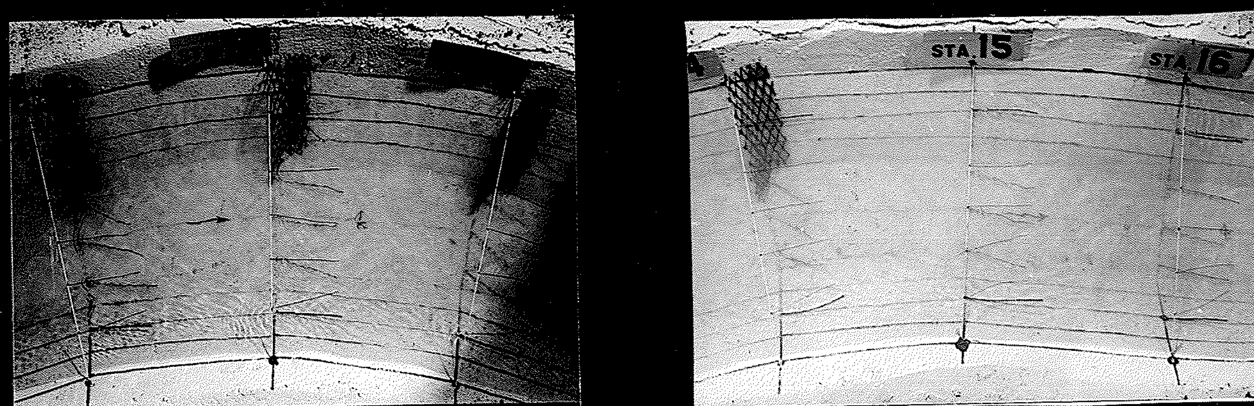
CHANNEL



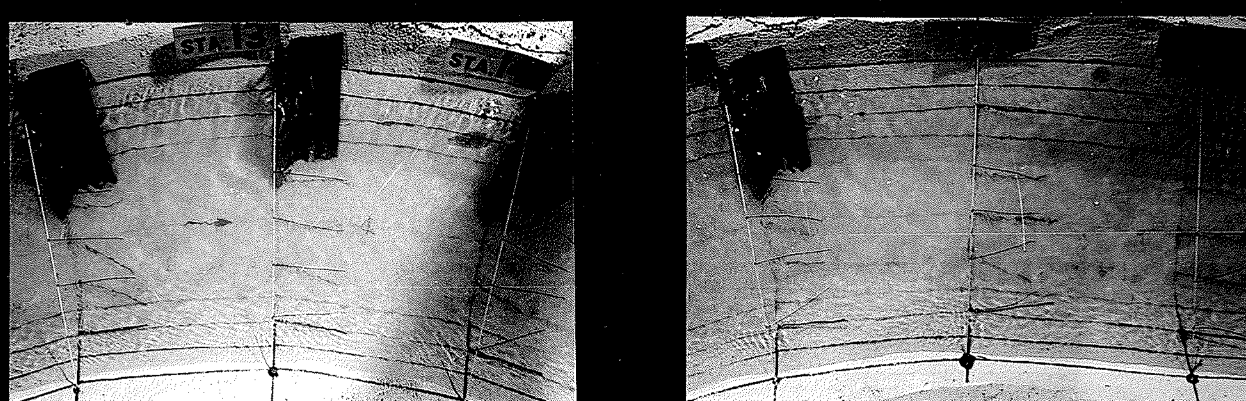
JETTIES AT 45° TO THE CENTRELINE DOWNSTREAM



SPUR DYKES AT 45° TO THE CENTRELINE DOWNSTREAM



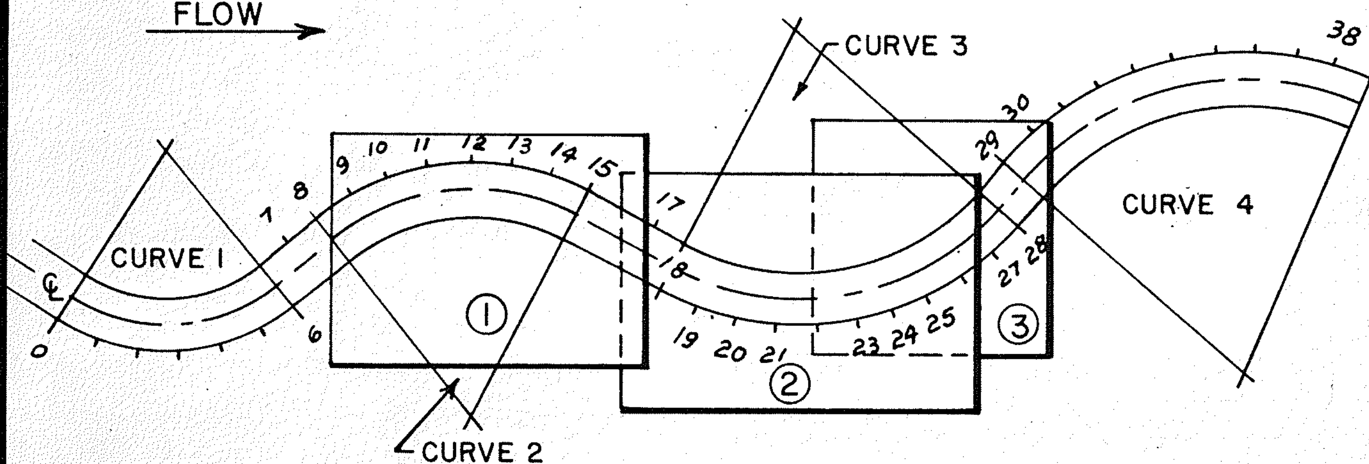
JETTIES AT 45° TO THE CENTRELINE UPSTREAM



SPUR DYKES AT 45° TO THE CENTRELINE UPSTREAM

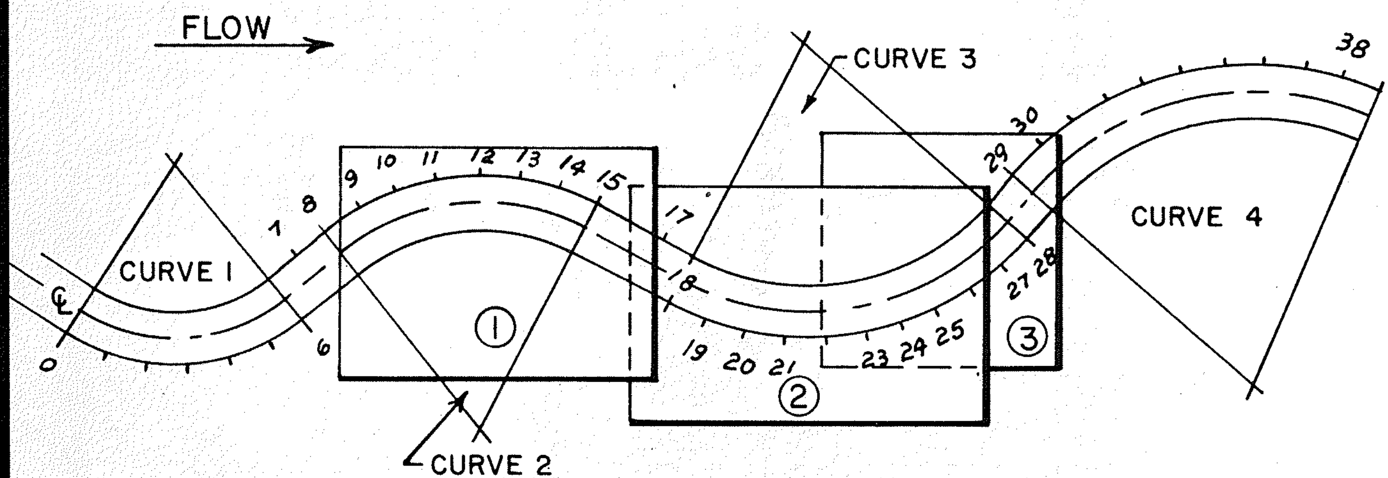
PLATE 14
THE EFFECT OF STABILIZING MEASURES ON HELICAL FLOW
USING SUSPENDED THREADS

PHOTOGRAPH LOCATIONS

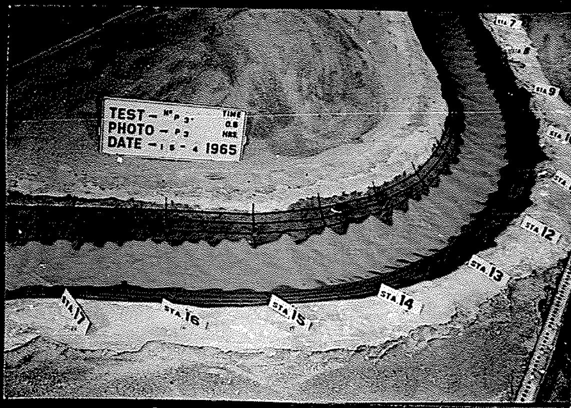


CHANNEL

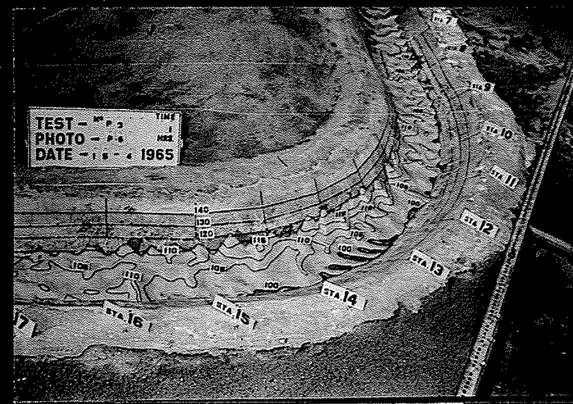
PHOTOGRAPH LOCATIONS



CHANNEL

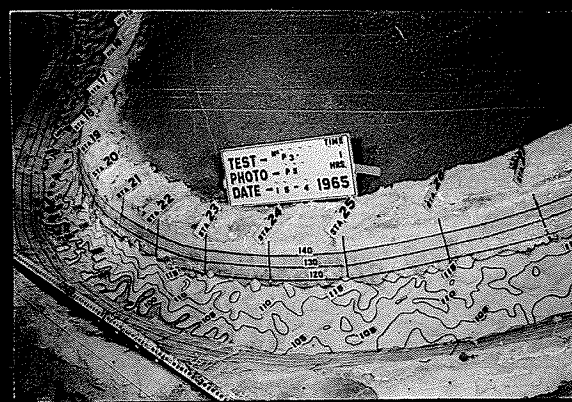


PHOTOGRAPH 1A



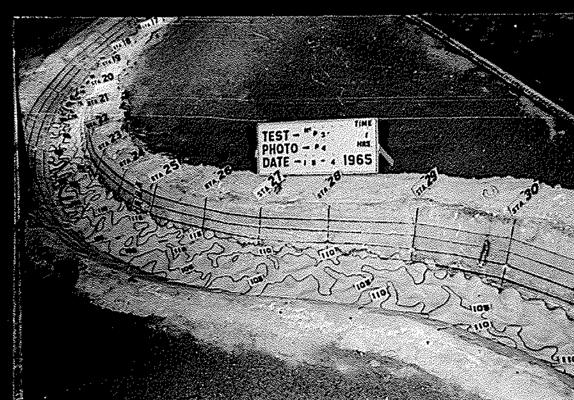
PHOTOGRAPH 1B

PHOTOGRAPH 2A



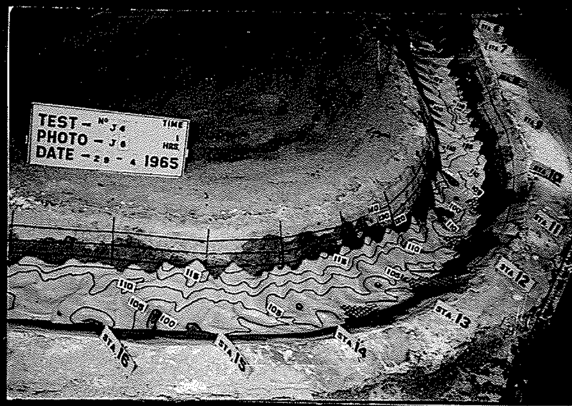
PHOTOGRAPH 2B

PHOTOGRAPH 3A

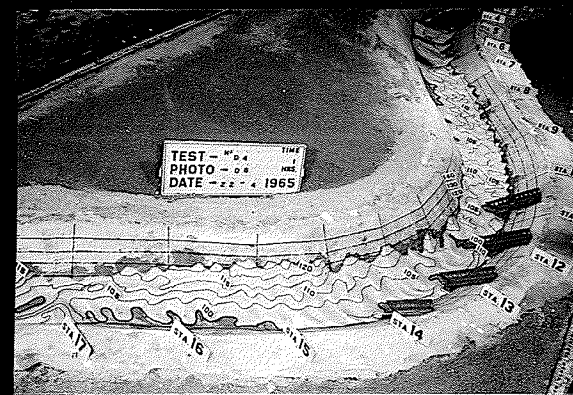


PHOTOGRAPH 3B

PLATE 15
PILOT TEST - CONTOURS OF BED EROSION WITH NO STABILIZATION

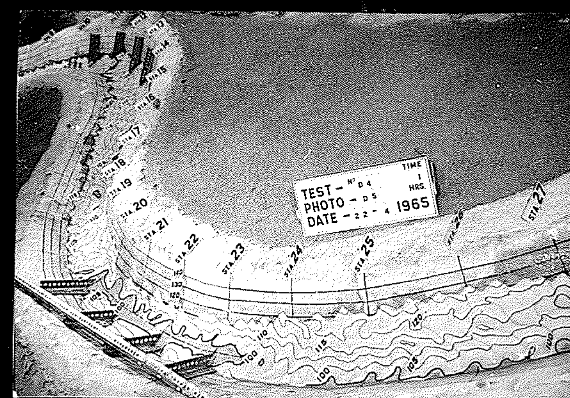


PHOTOGRAPH 1A



PHOTOGRAPH 1B

PHOTOGRAPH 2A



PHOTOGRAPH 2B

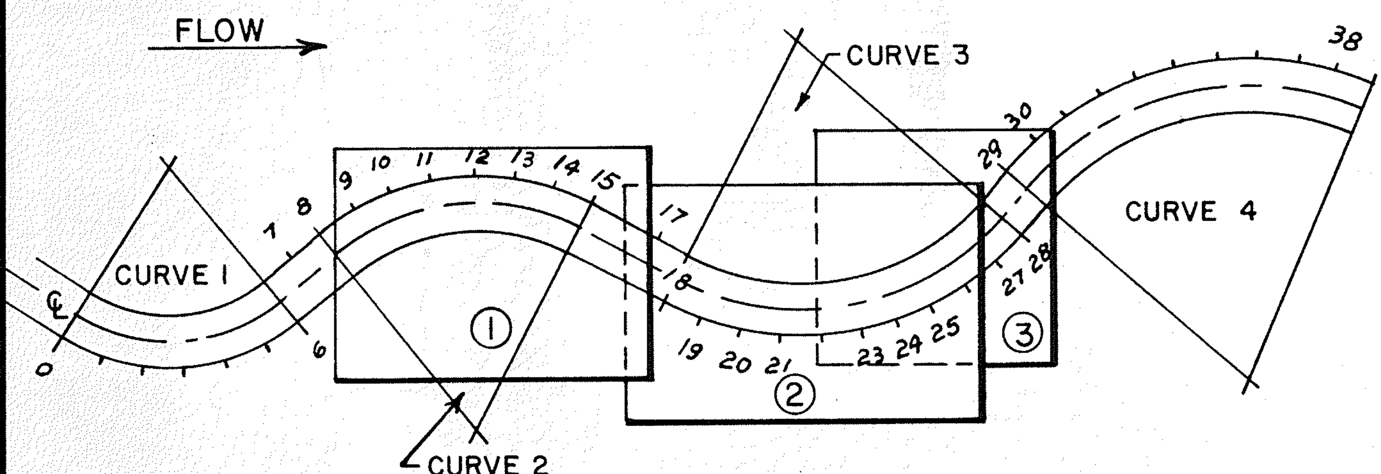
PHOTOGRAPH 3A

PHOTOGRAPH 3B

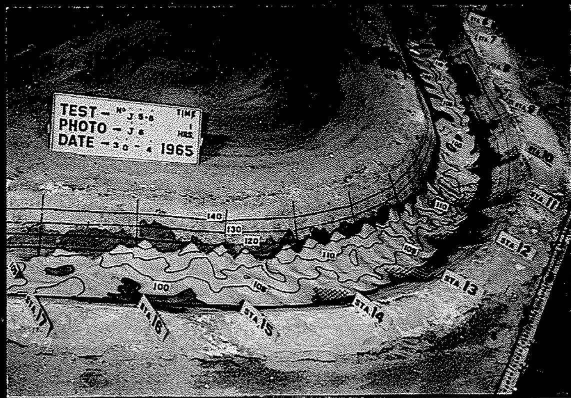
PLATE 16

SPUR DYKES AND JETTIES AT 90° TO THE CENTRELINE
FOUR STABILIZING MEASURES ON CURVES 2 AND 3.

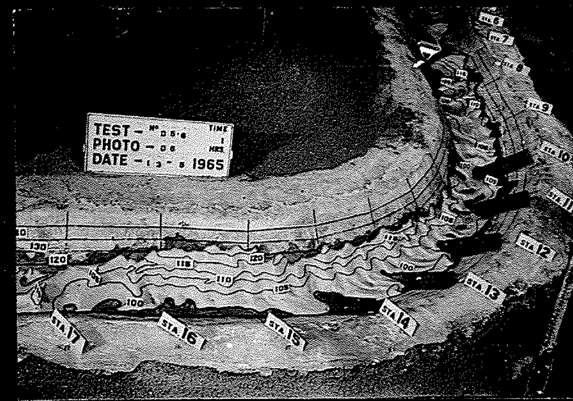
PHOTOGRAPH LOCATIONS



CHANNEL

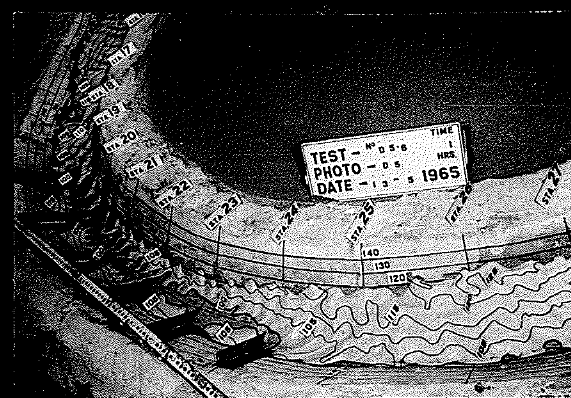


PHOTOGRAPH 1A



PHOTOGRAPH 1B

PHOTOGRAPH 2A



PHOTOGRAPH 2B

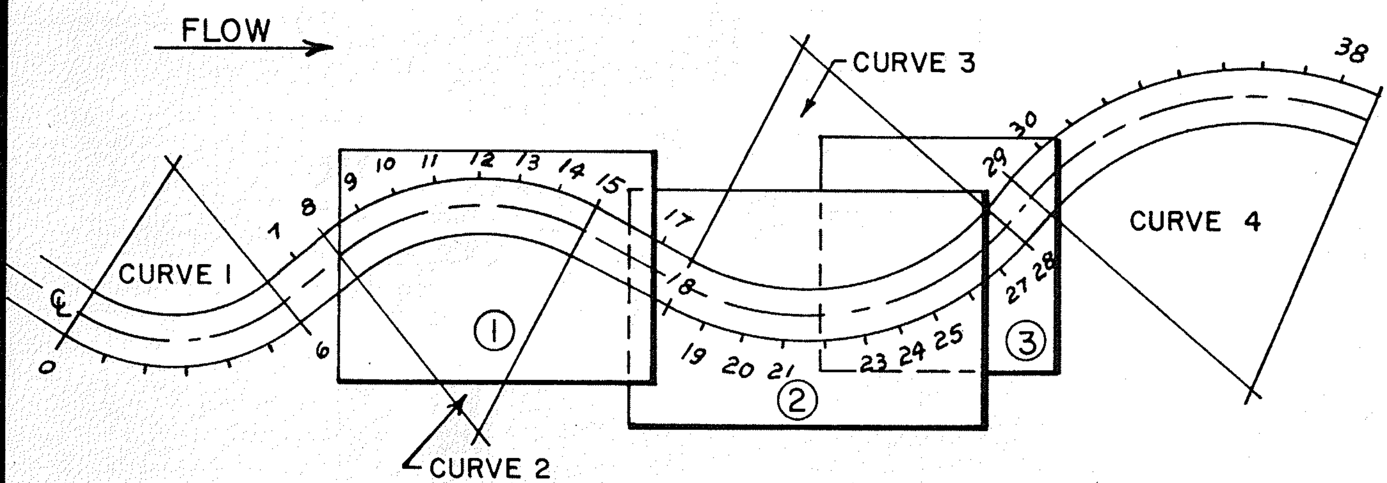
PHOTOGRAPH 3A

PHOTOGRAPH 3B

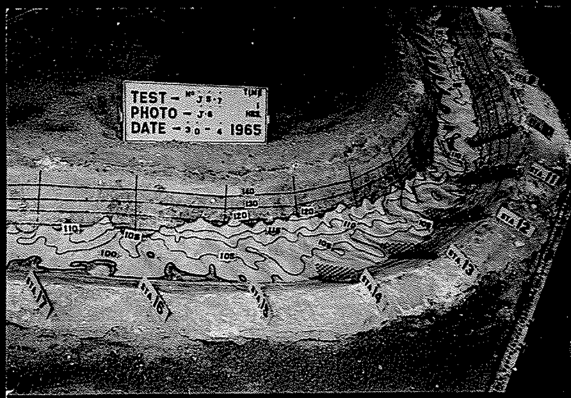
PLATE 17

SPUR DYKES AND JETTIES AT 90° TO THE CENTRELINE
FIVE STABILIZING MEASURES ON CURVE 2
SIX STABILIZING MEASURES ON CURVE 3

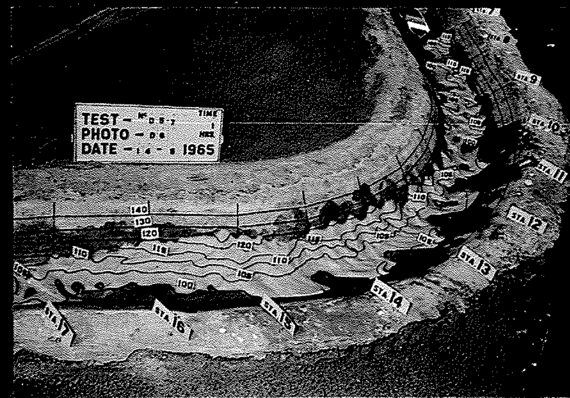
PHOTOGRAPH LOCATIONS



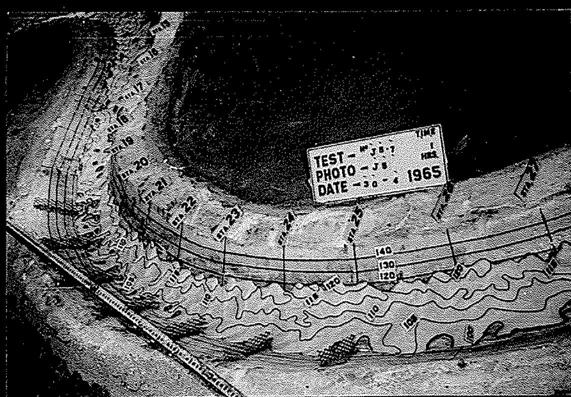
CHANNEL



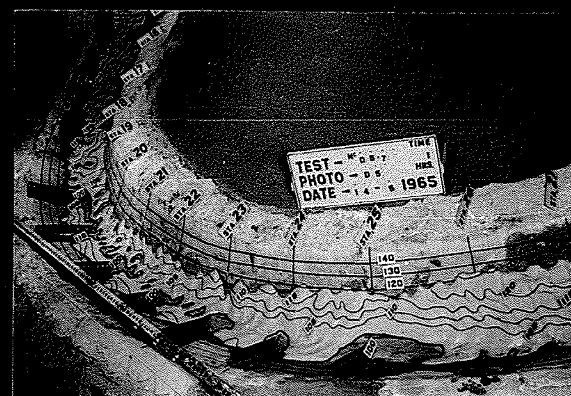
PHOTOGRAPH 1A



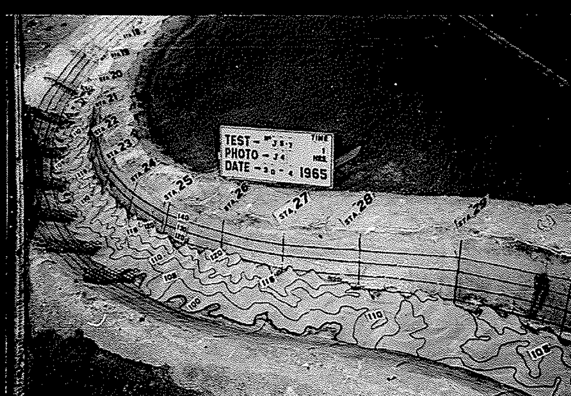
PHOTOGRAPH 1B



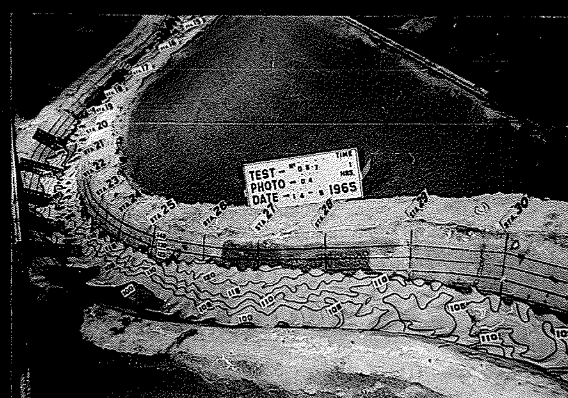
PHOTOGRAPH 2A



PHOTOGRAPH 2B



PHOTOGRAPH 3A

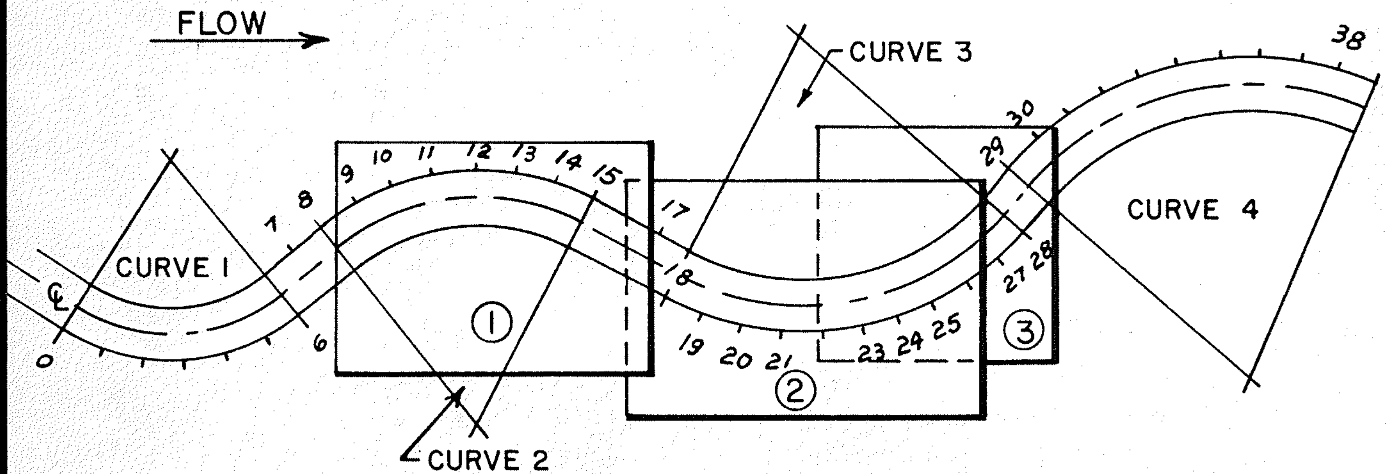


PHOTOGRAPH 3B

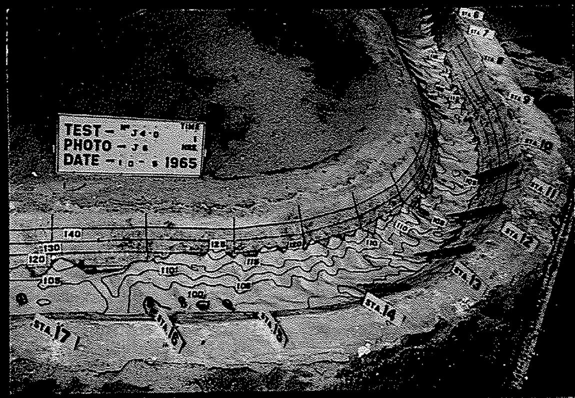
PLATE 18

SPUR DYKES AND JETTIES AT 90° TO THE CENTRELINE
FIVE STABILIZING MEASURES ON CURVE 2
SEVEN STABILIZING MEASURES ON CURVE 3

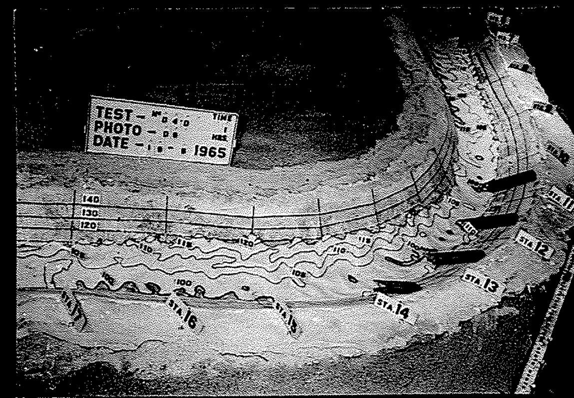
PHOTOGRAPH LOCATIONS



CHANNEL

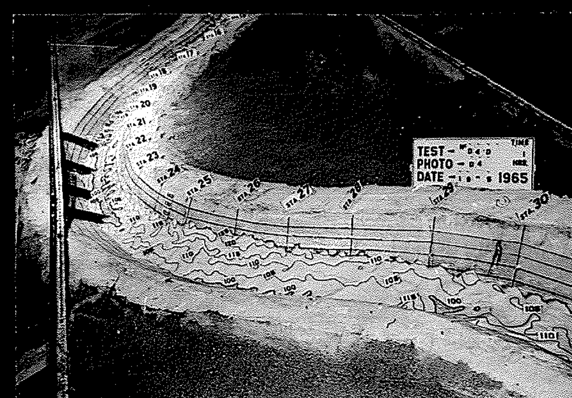


PHOTOGRAPH 1A

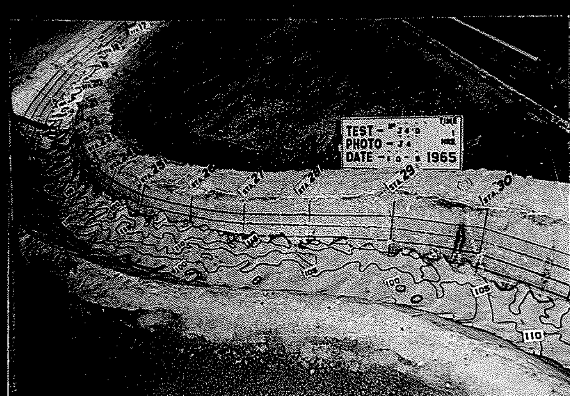


PHOTOGRAPH 1B

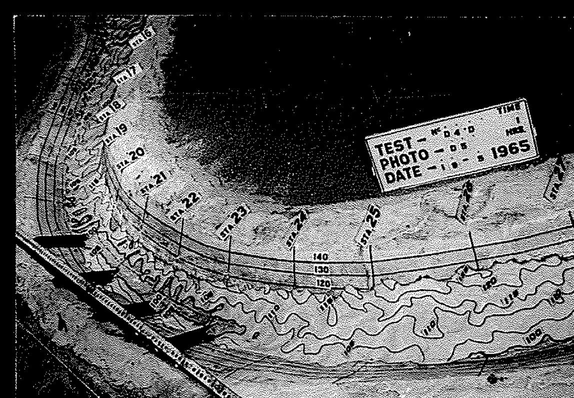
PHOTOGRAPH 2A



PHOTOGRAPH 2B



PHOTOGRAPH 3A

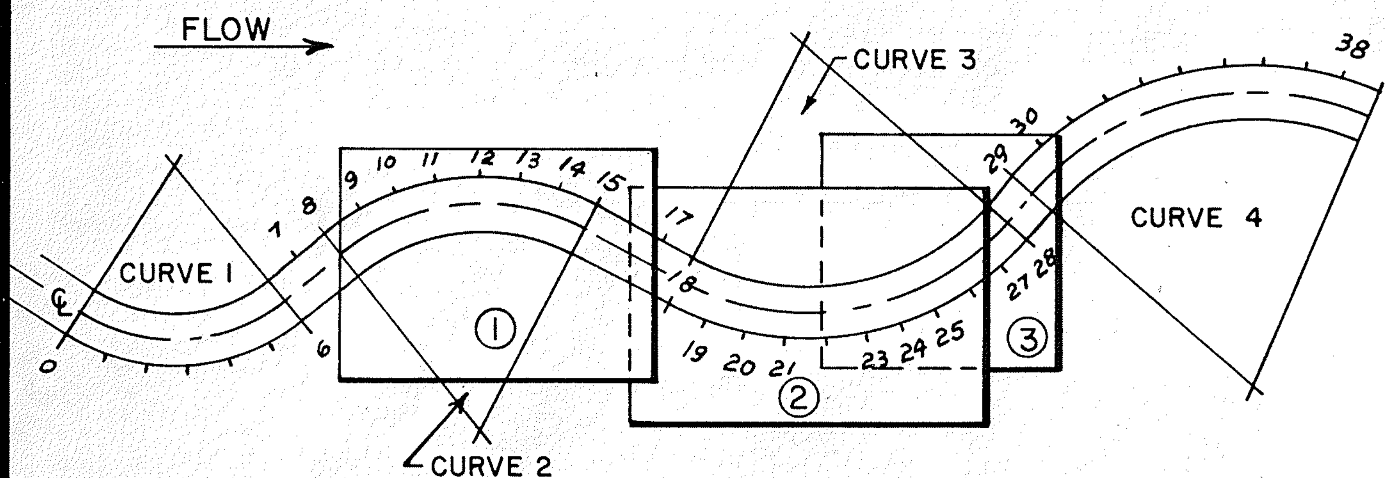


PHOTOGRAPH 3B

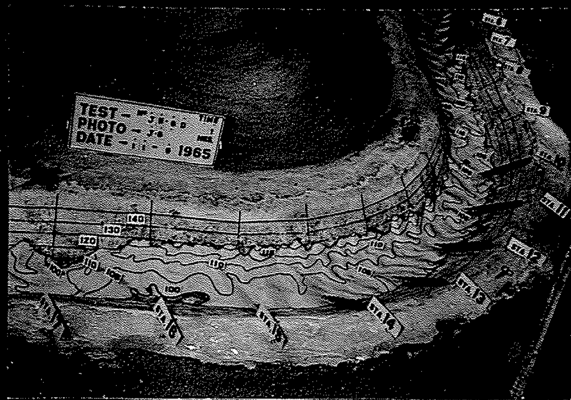
PLATE 19

SPUR DYKES AND JETTIES AT 45° TO THE CENTRELINE DOWNSTREAM
FOUR STABILIZING MEASURES ON CURVES 2 AND 3

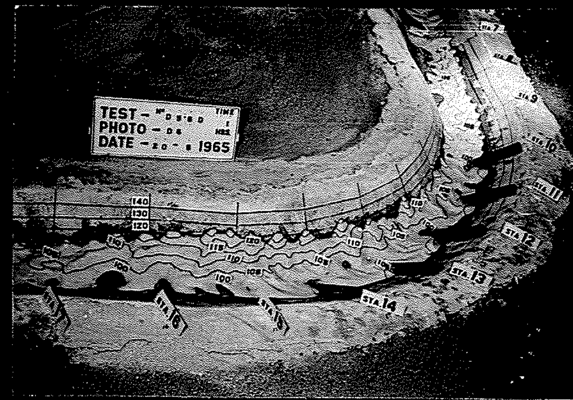
PHOTOGRAPH LOCATIONS



CHANNEL

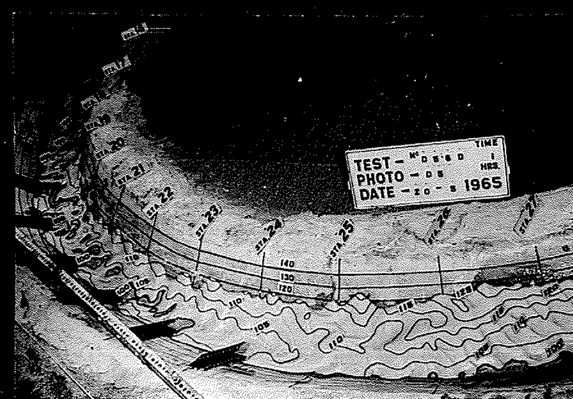


PHOTOGRAPH 1A

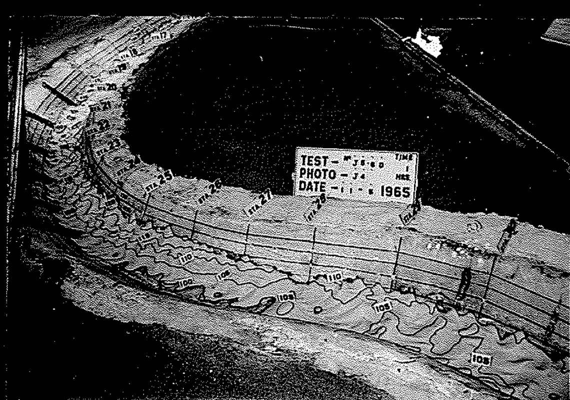


PHOTOGRAPH 1B

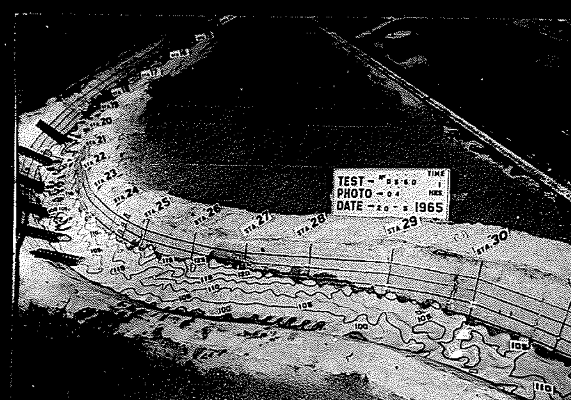
PHOTOGRAPH 2A



PHOTOGRAPH 2B



PHOTOGRAPH 3A

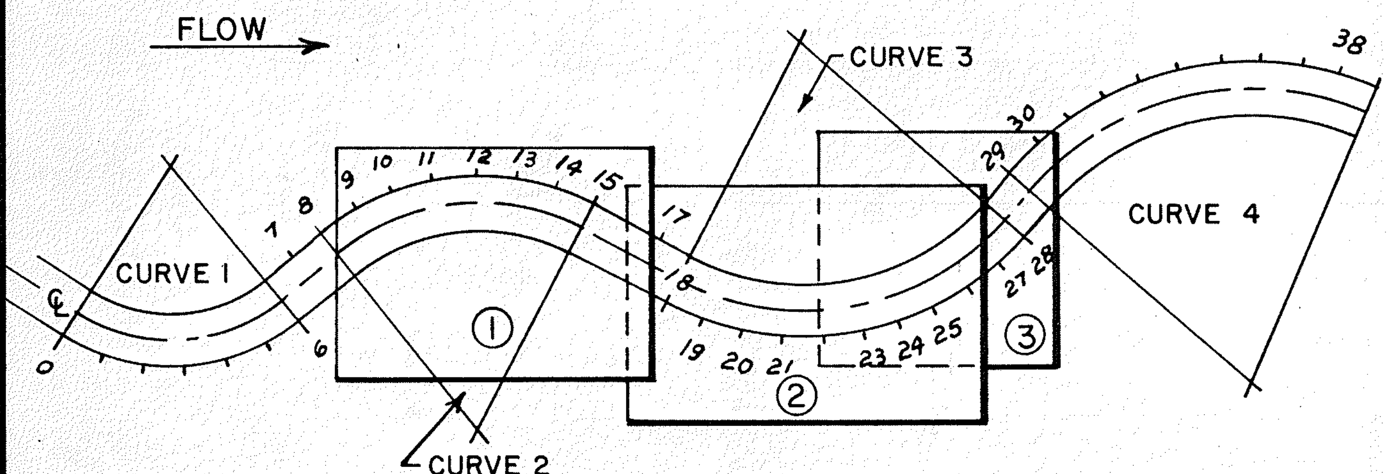


PHOTOGRAPH 3B

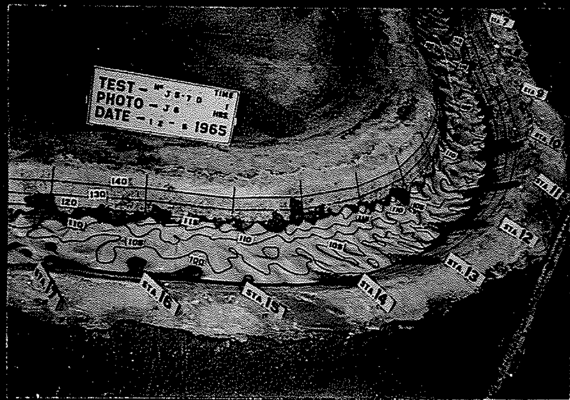
PLATE 20

SPUR DYKES AND JETTIES AT 45° TO THE CENTRELINE DOWNSTREAM
FIVE STABILIZING MEASURES ON CURVE 2
SIX STABILIZING MEASURES ON CURVE 3

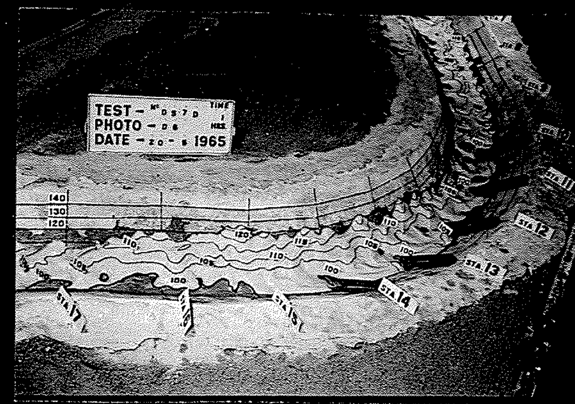
PHOTOGRAPH LOCATIONS



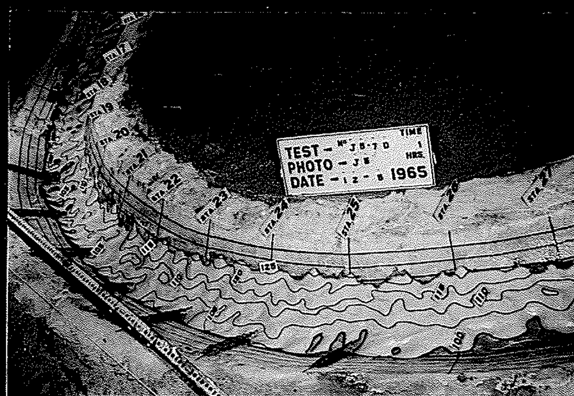
CHANNEL



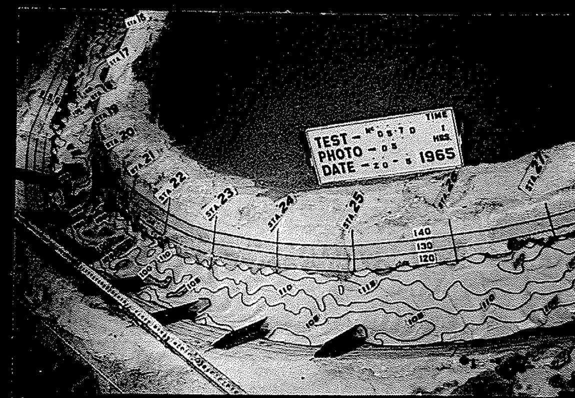
PHOTOGRAPH 1A



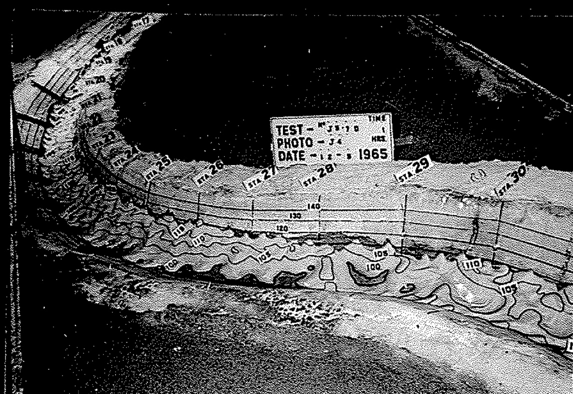
PHOTOGRAPH 1B



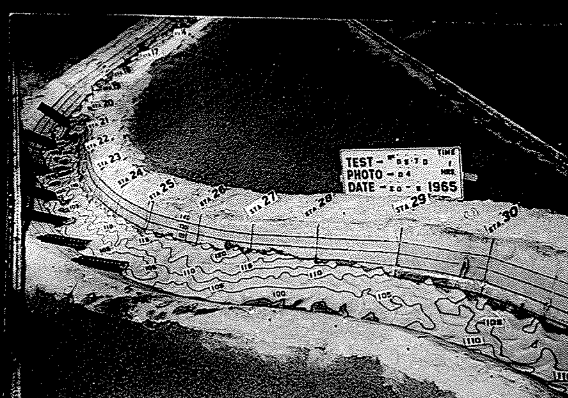
PHOTOGRAPH 2A



PHOTOGRAPH 2B



PHOTOGRAPH 3A

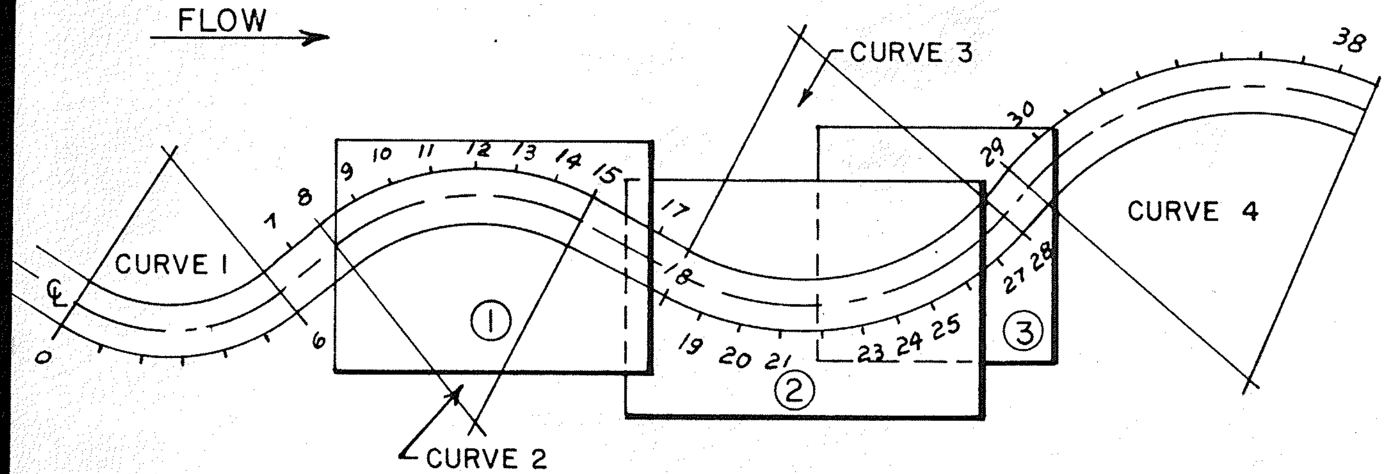


PHOTOGRAPH 3B

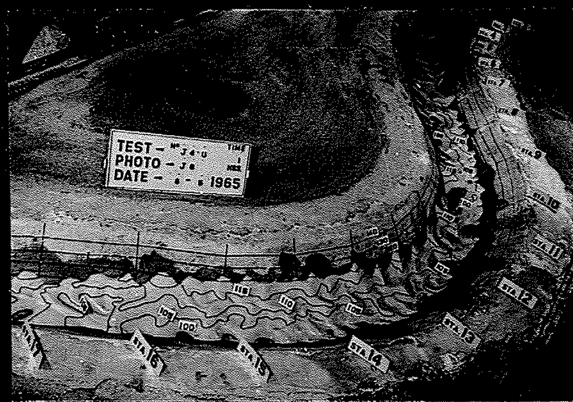
PLATE 21

SPUR DYKES AND JETTIES AT 45° TO THE CENTRELINE DOWNSTREAM
FIVE STABILIZING MEASURES ON CURVE 2
SEVEN STABILIZING MEASURES ON CURVE 3

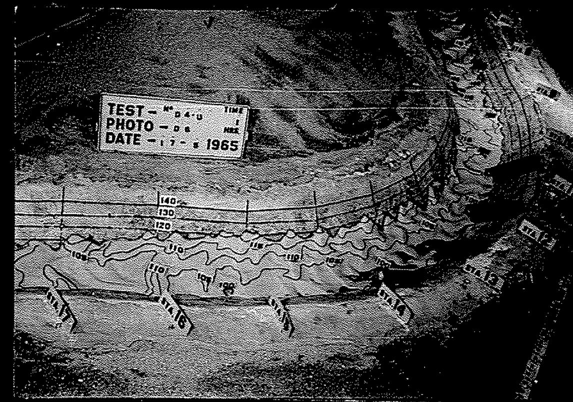
PHOTOGRAPH LOCATIONS



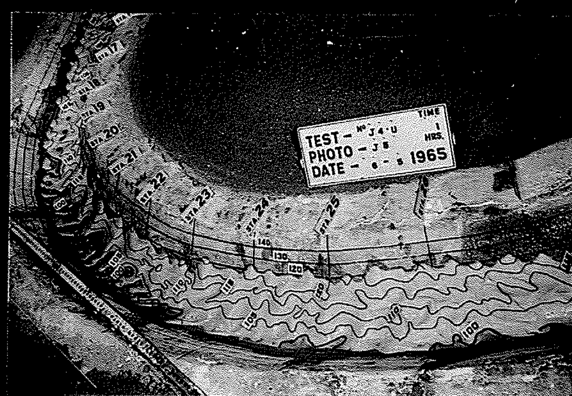
CHANNEL



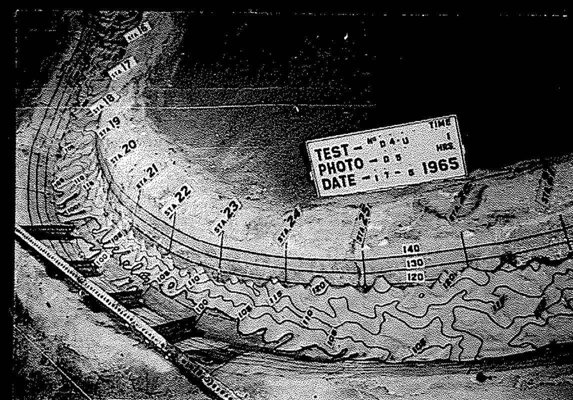
PHOTOGRAPH 1A



PHOTOGRAPH 1B

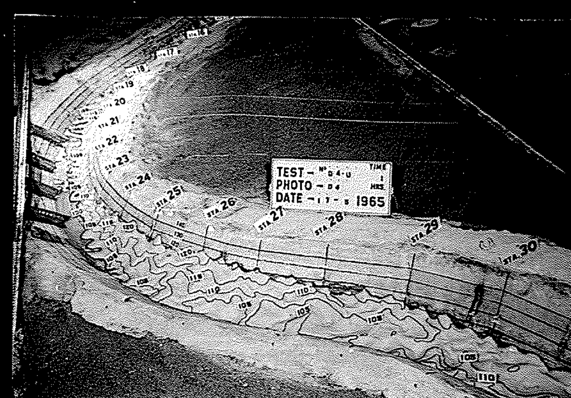


PHOTOGRAPH 2A



PHOTOGRAPH 2B

PHOTOGRAPH 3A

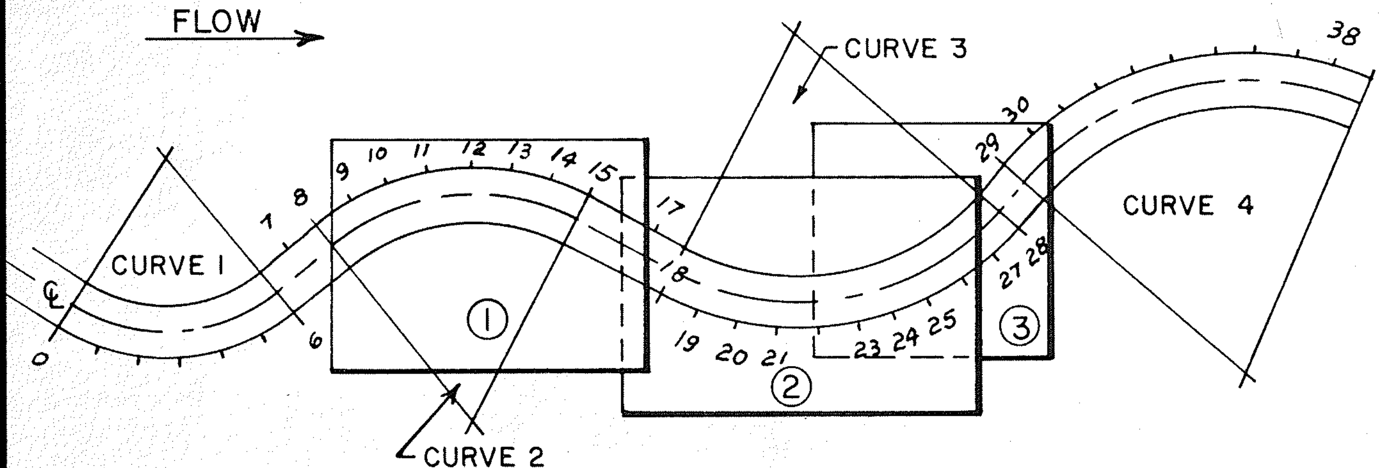


PHOTOGRAPH 3B

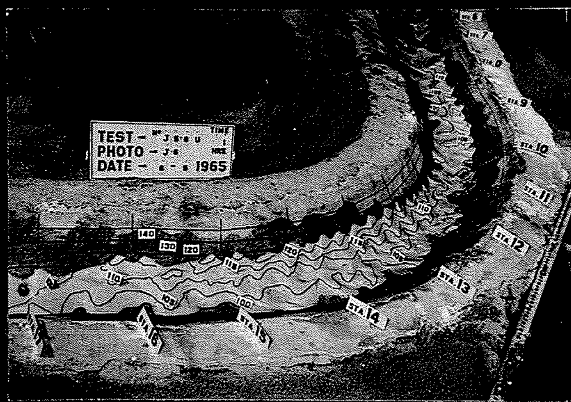
PLATE 22

SPUR DYKES AND JETTIES AT 45° TO THE CENTRELINE UPSTREAM
FOUR STABILIZING MEASURES ON CURVES 2 AND 3

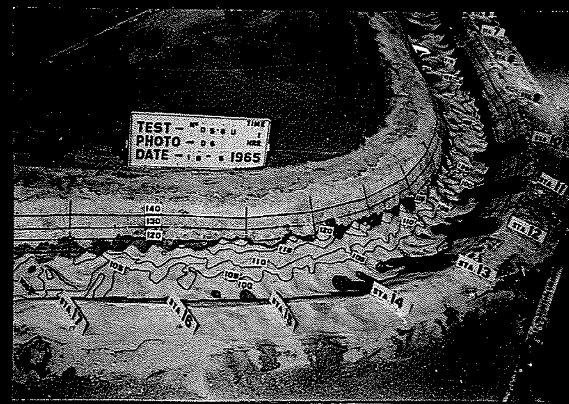
PHOTOGRAPH LOCATIONS



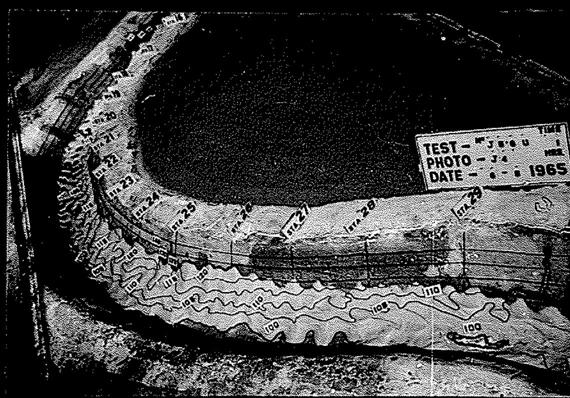
CHANNEL



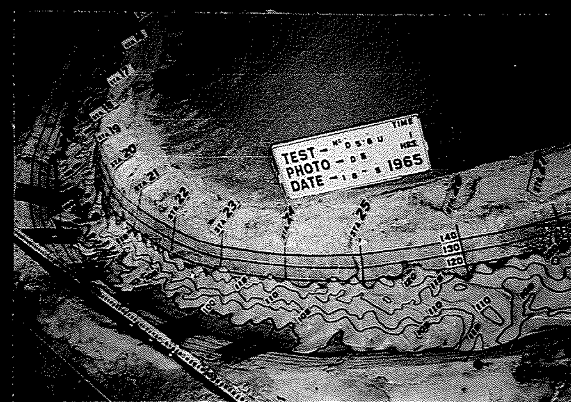
PHOTOGRAPH 1A



PHOTOGRAPH 1B



PHOTOGRAPH 2A



PHOTOGRAPH 2B

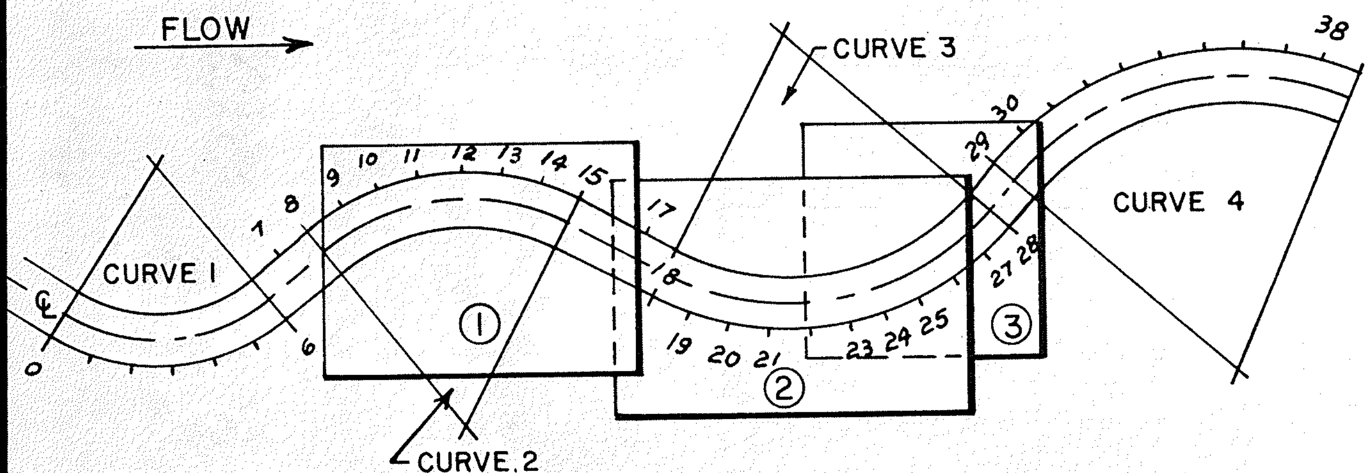
PHOTOGRAPH 3A

PHOTOGRAPH 3B

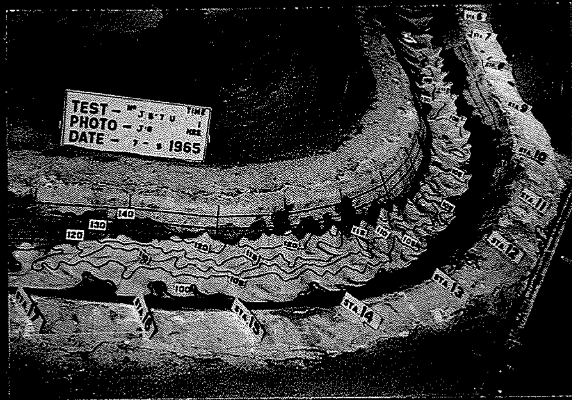
PLATE 23

SPUR DYKES AND JETTIES AT 45° TO THE CENTRELINE UPSTREAM
FIVE STABILIZING MEASURES ON CURVE 2
SIX STABILIZING MEASURES ON CURVE 3

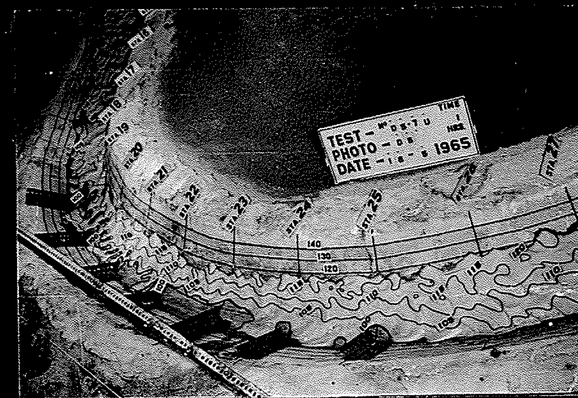
PHOTOGRAPH LOCATIONS



CHANNEL

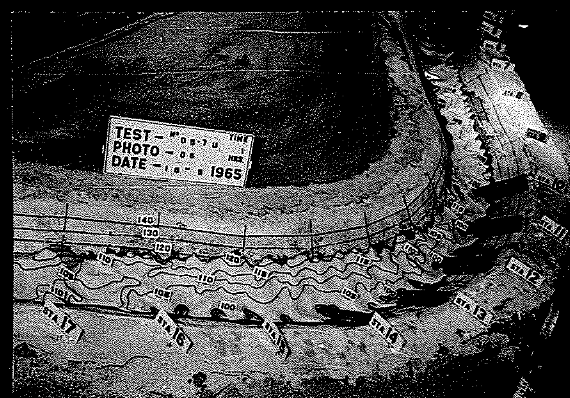


PHOTOGRAPH 1A

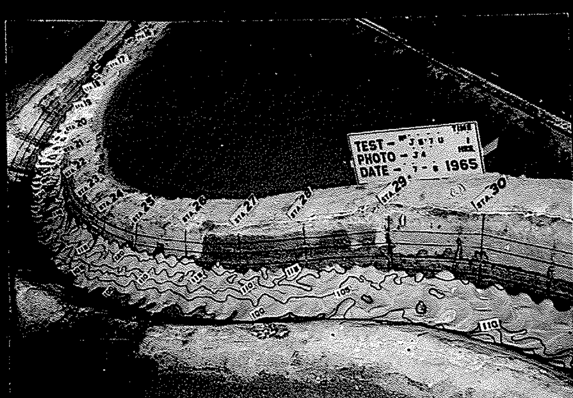


PHOTOGRAPH 1B

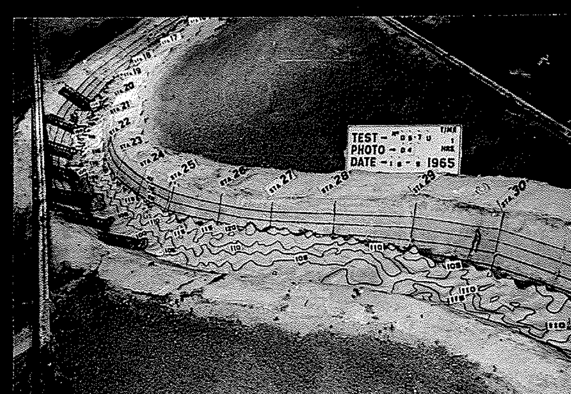
PHOTOGRAPH 2A



PHOTOGRAPH 2B



PHOTOGRAPH 3A

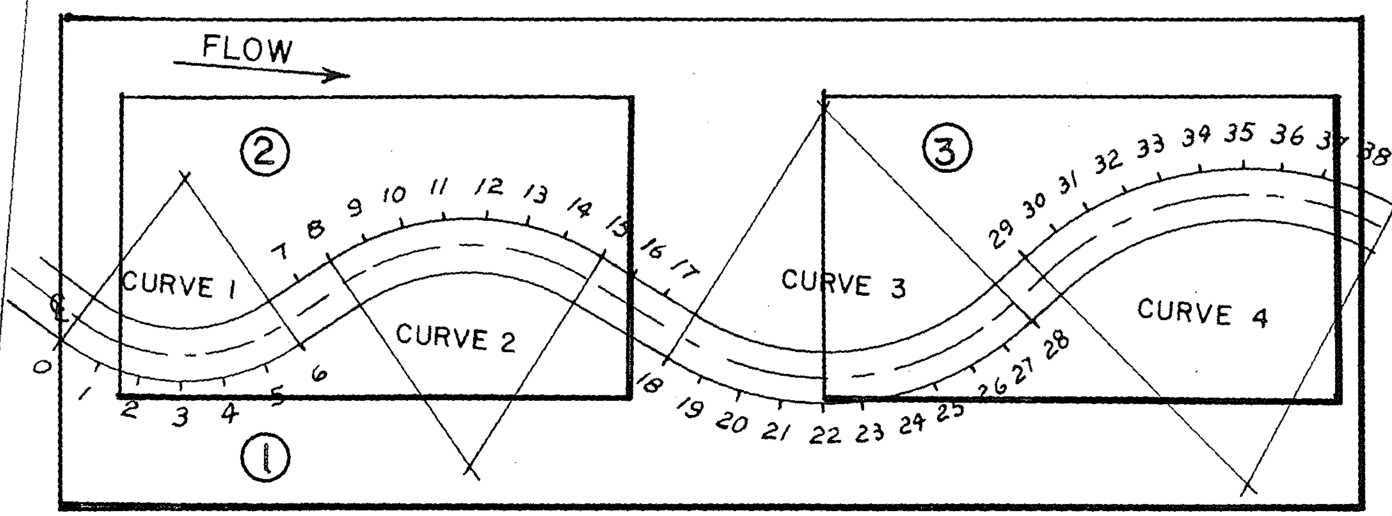


PHOTOGRAPH 3B

PLATE 24

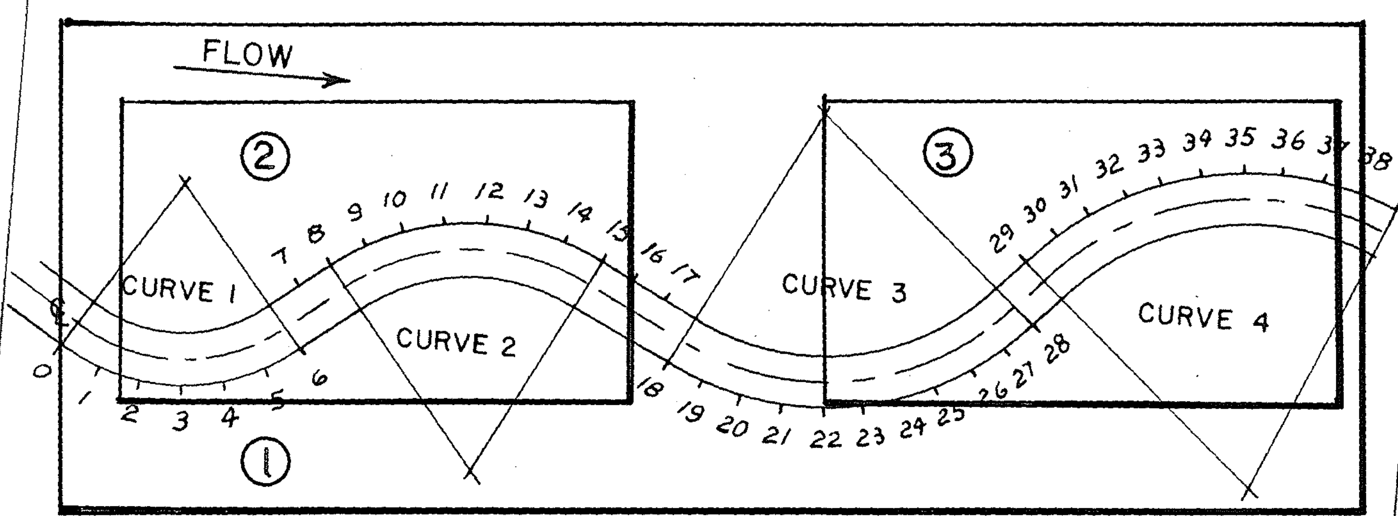
SPUR DYKES AND JETTIES AT 45° TO THE CENTRELINE UPSTREAM
FIVE STABILIZING MEASURES ON CURVE 2
SEVEN STABILIZING MEASURES ON CURVE 3

PHOTOGRAPH LOCATIONS



CHANNEL

PHOTOGRAPH LOCATIONS



CHANNEL

BANK STABILIZATION TESTS

PILOT TEST (NO STABILIZATION)

PHOTOGRAPH 1

PHOTOGRAPH 2

PHOTOGRAPH 3

PLATE 25

PHOTOGRAPHS - PILOT TEST (NO STABILIZATION)

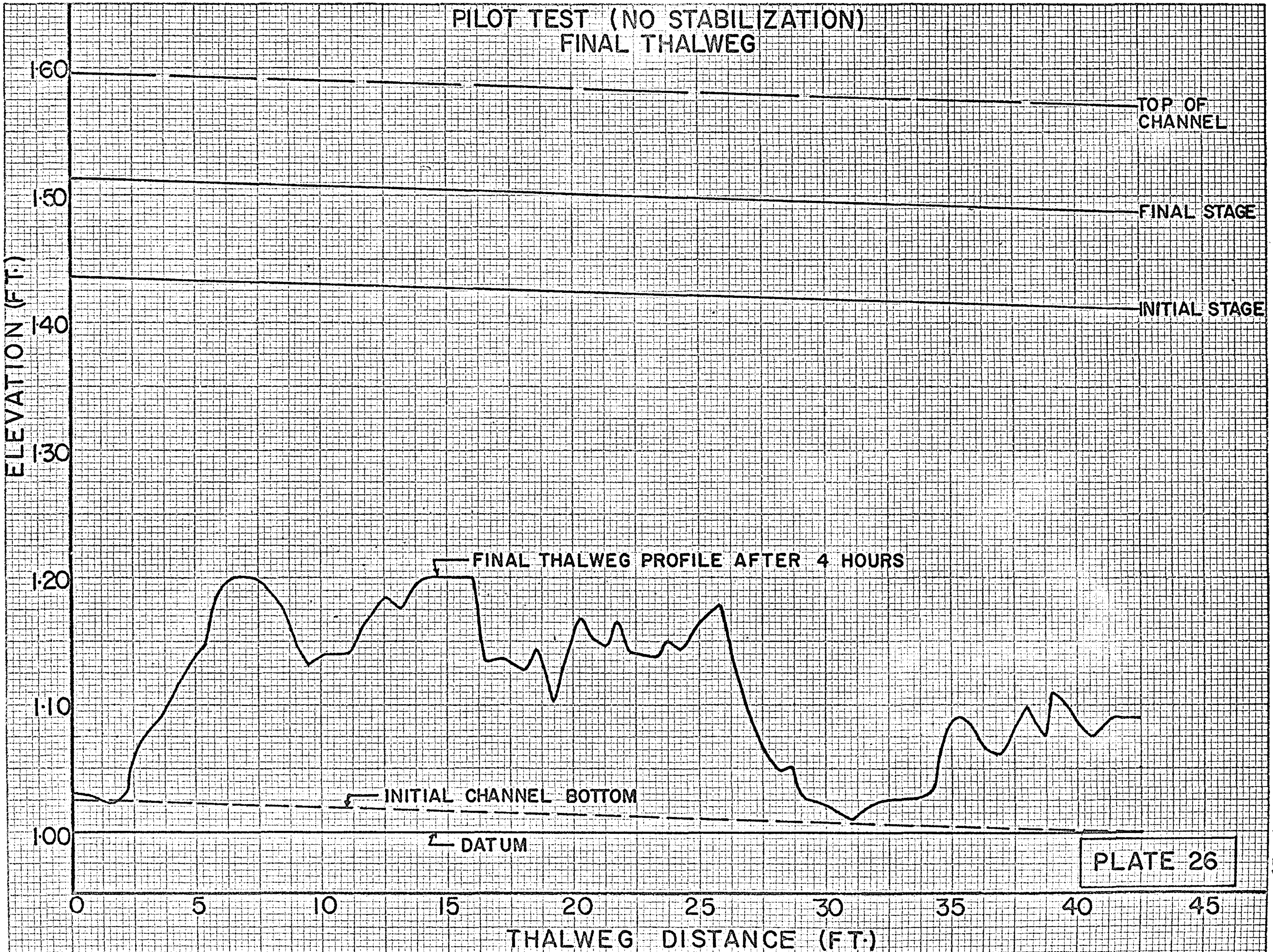

PILOT TEST (NO STABILIZATION)
FINAL THALWEG
TOP OF CHANNEL
FINAL STAGE
INITIAL STAGE
FINAL THALWEG PROFILE AFTER 4 HOURS
INITIAL CHANNEL BOTTOM
DATUM
ELEVATION (FT.)
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0
5
10
15
20
25
30
35
40
45
THALWEG DISTANCE (FT.)

PLATE 26

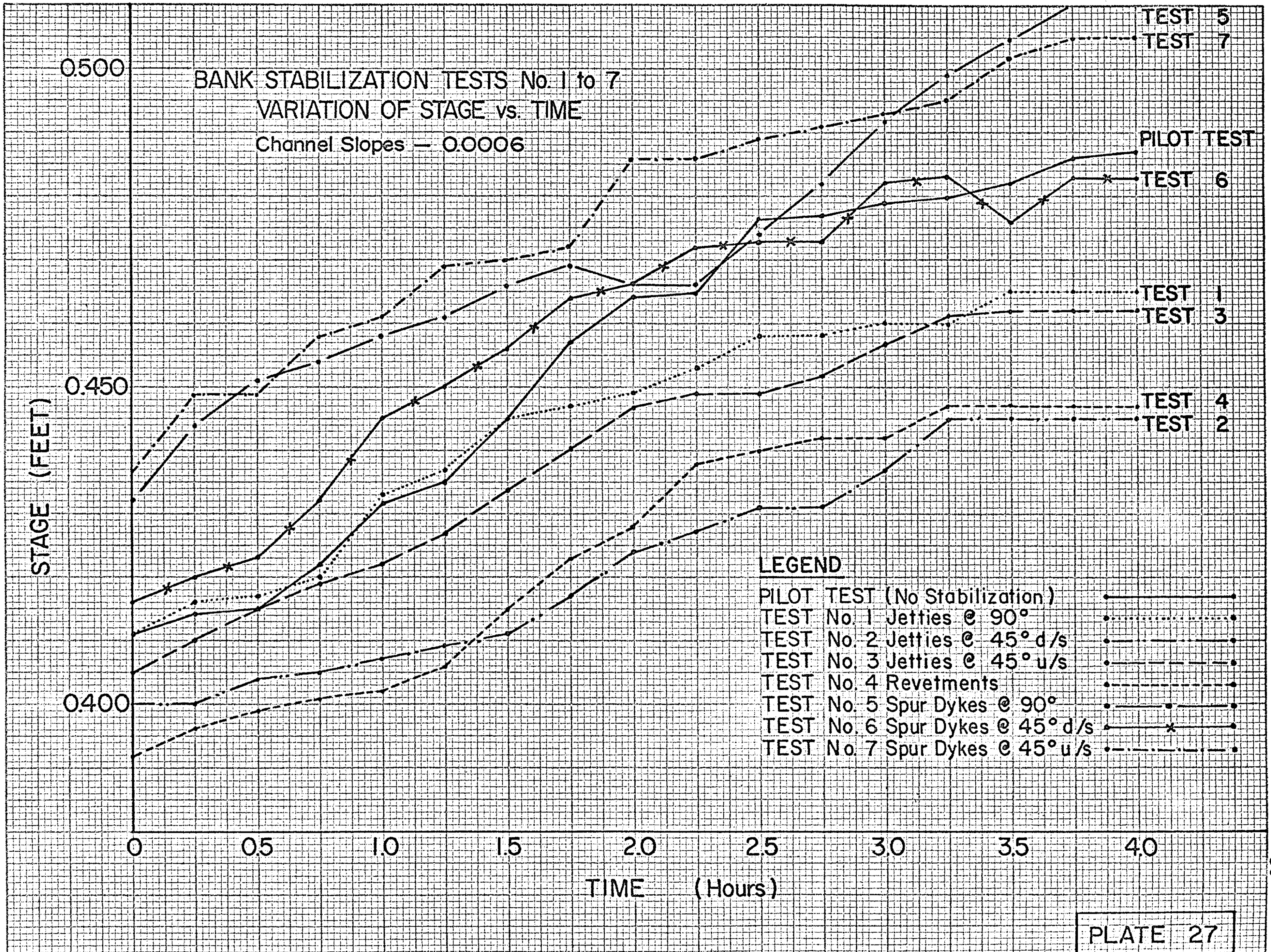
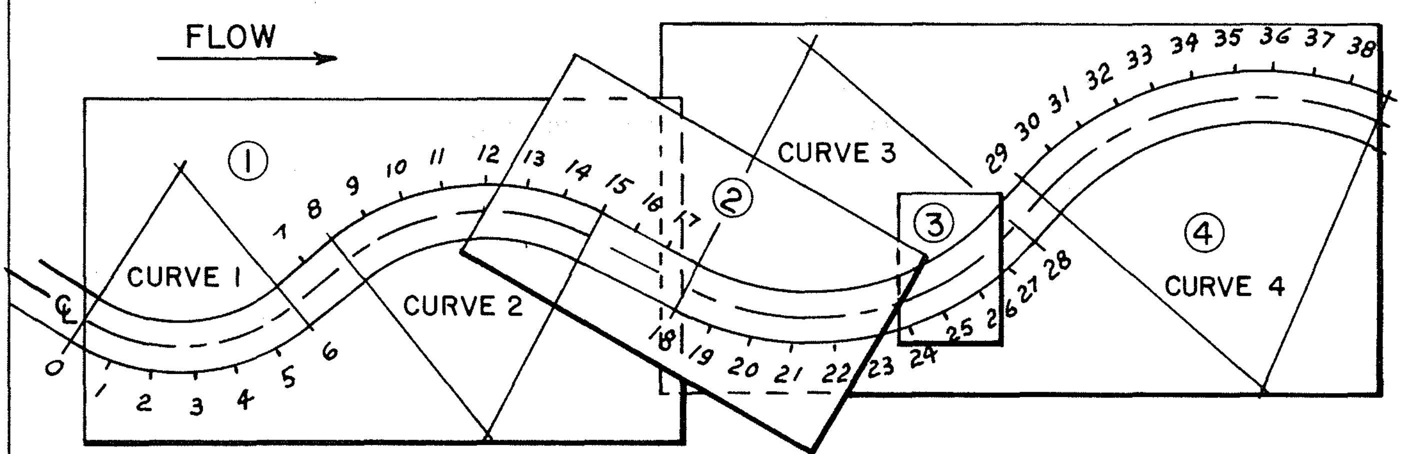

BANK STABILIZATION TESTS No. 1 to 7
VARIATION OF STAGE vs. TIME
Channel Slopes — 0.0006
STAGE (FEET)
0.500
0.450
0.400
TIME (Hours)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
TEST 5
TEST 7
PILOT TEST
TEST 6
TEST 1
TEST 3
TEST 4
TEST 2
LEGEND
PILOT TEST (No Stabilization)
TEST No. 1 Jetties @ 90°
TEST No. 2 Jetties @ 45° d/s
TEST No. 3 Jetties @ 45° u/s
TEST No. 4 Revetments
TEST No. 5 Spur Dykes @ 90°
TEST No. 6 Spur Dykes @ 45° d/s
TEST No. 7 Spur Dykes @ 45° u/s

PLATE 27

PHOTOGRAPH LOCATIONS



CHANNEL

BANK STABILIZATION TEST NO. 1

PHOTOGRAPH 1

PHOTOGRAPH 2

PHOTOGRAPH 3

PHOTOGRAPH 4

PLATE 28

PHOTOGRAPHS - BANK STABILIZATION TEST NO. 1

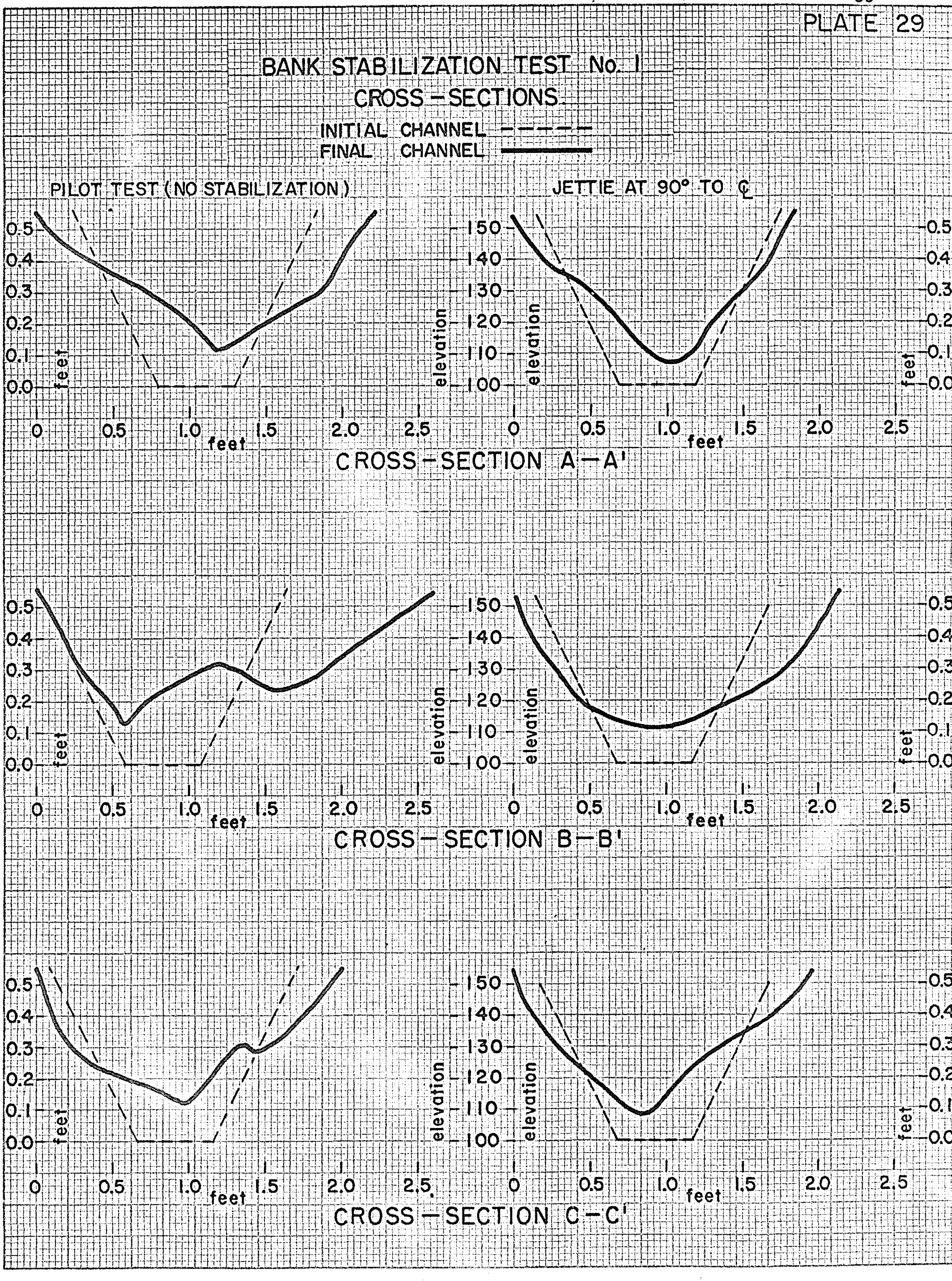


PLATE 29
BANK STABILIZATION TEST No. 1
CROSS-SECTIONS
INITIAL CHANNEL
FINAL CHANNEL
PILOT TEST (NO STABILIZATION)
JETTIE AT 90° TO ℄
feet
elevation
CROSS-SECTION A-A'
CROSS-SECTION B-B'
CROSS-SECTION C-C'
0.0
0.1
0.2
0.3
0.4
0.5
100
110
120
130
140
150
0
0.5
1.0
1.5
2.0
2.5

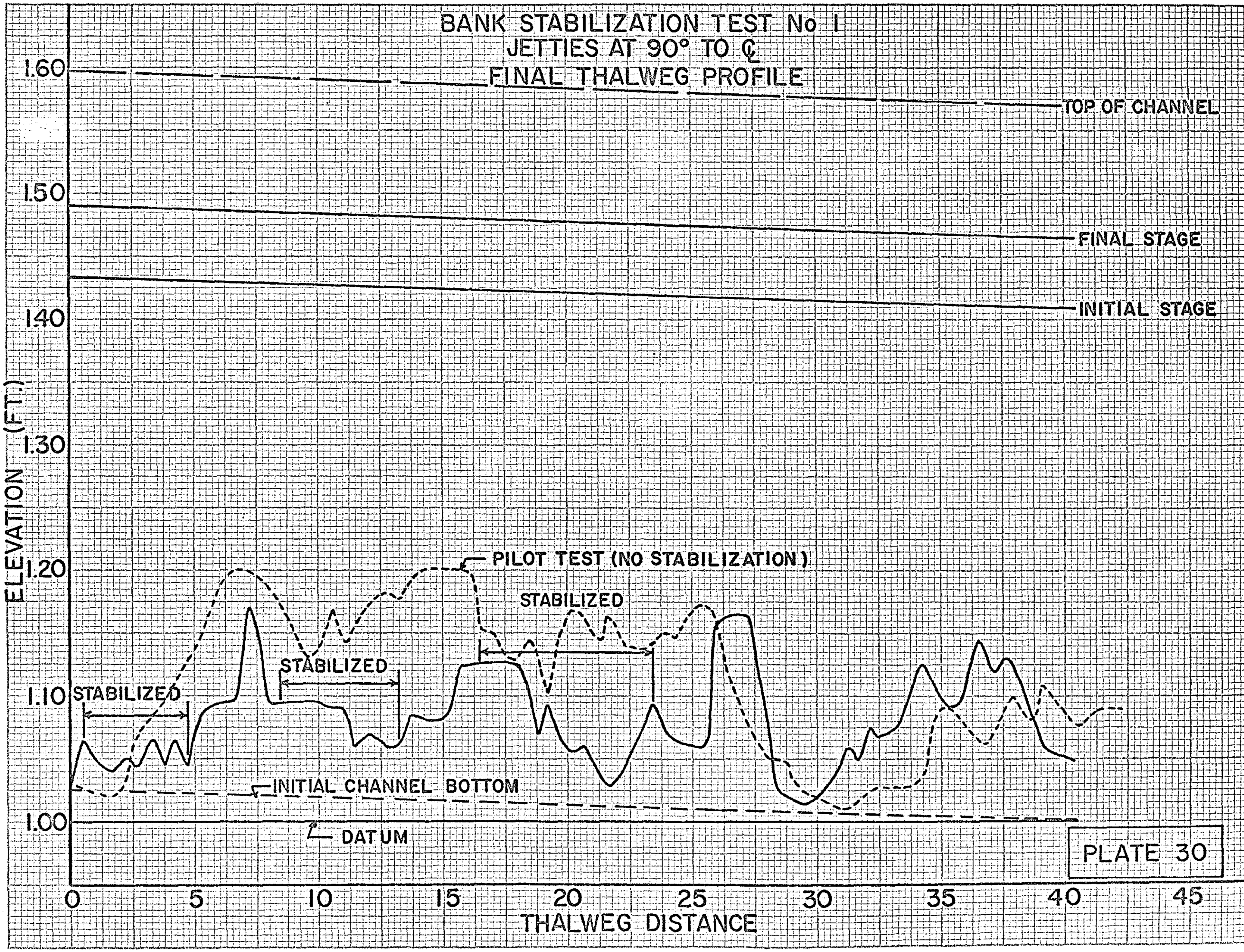
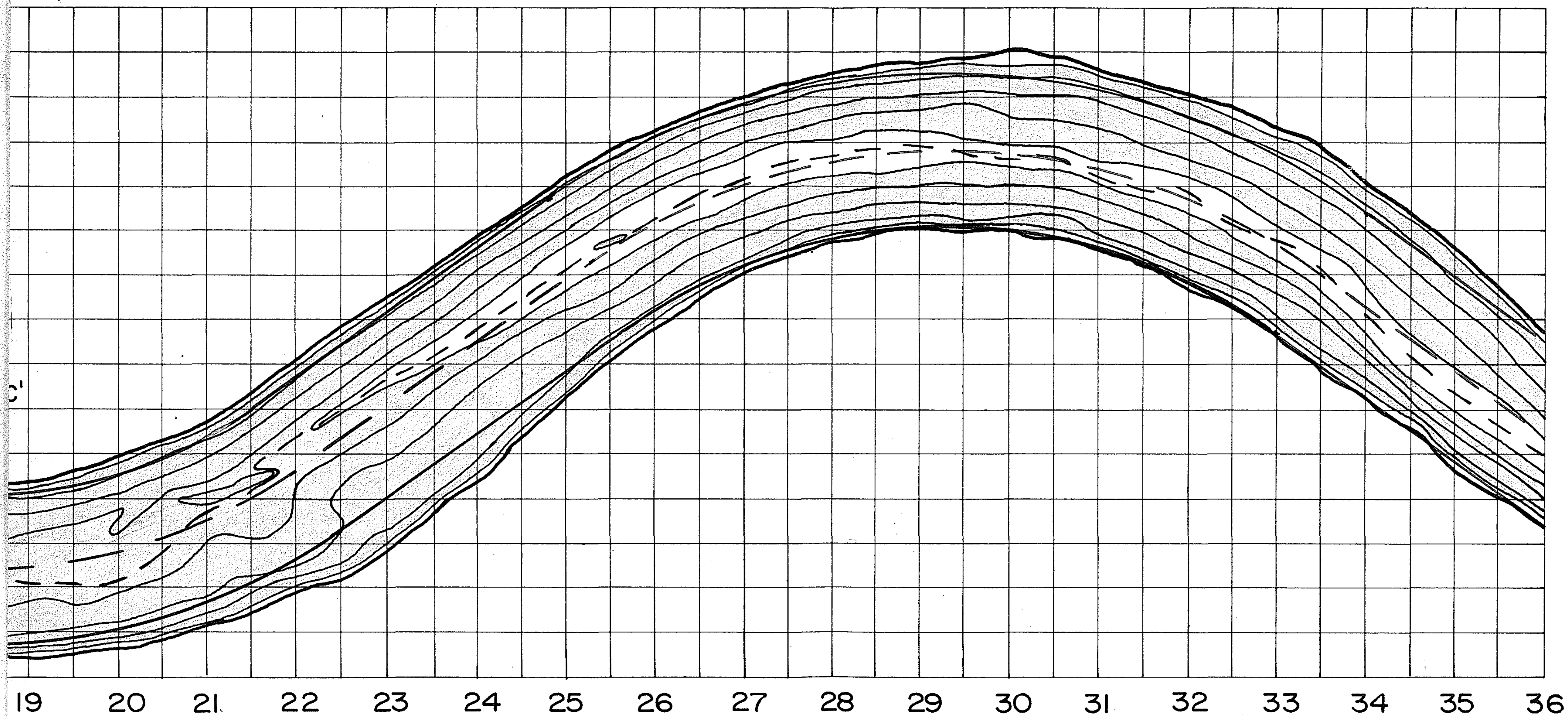

BANK STABILIZATION TEST No 1
JETTIES AT 90° TO ℄
FINAL THALWEG PROFILE
TOP OF CHANNEL
FINAL STAGE
INITIAL STAGE
PILOT TEST (NO STABILIZATION)
STABILIZED
STABILIZED
STABILIZED
INITIAL CHANNEL BOTTOM
DATUM
ELEVATION (FT.)
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0
5
10
15
20
25
30
35
40
45
THALWEG DISTANCE

PLATE 30

CHANNELS.
EST No. I.

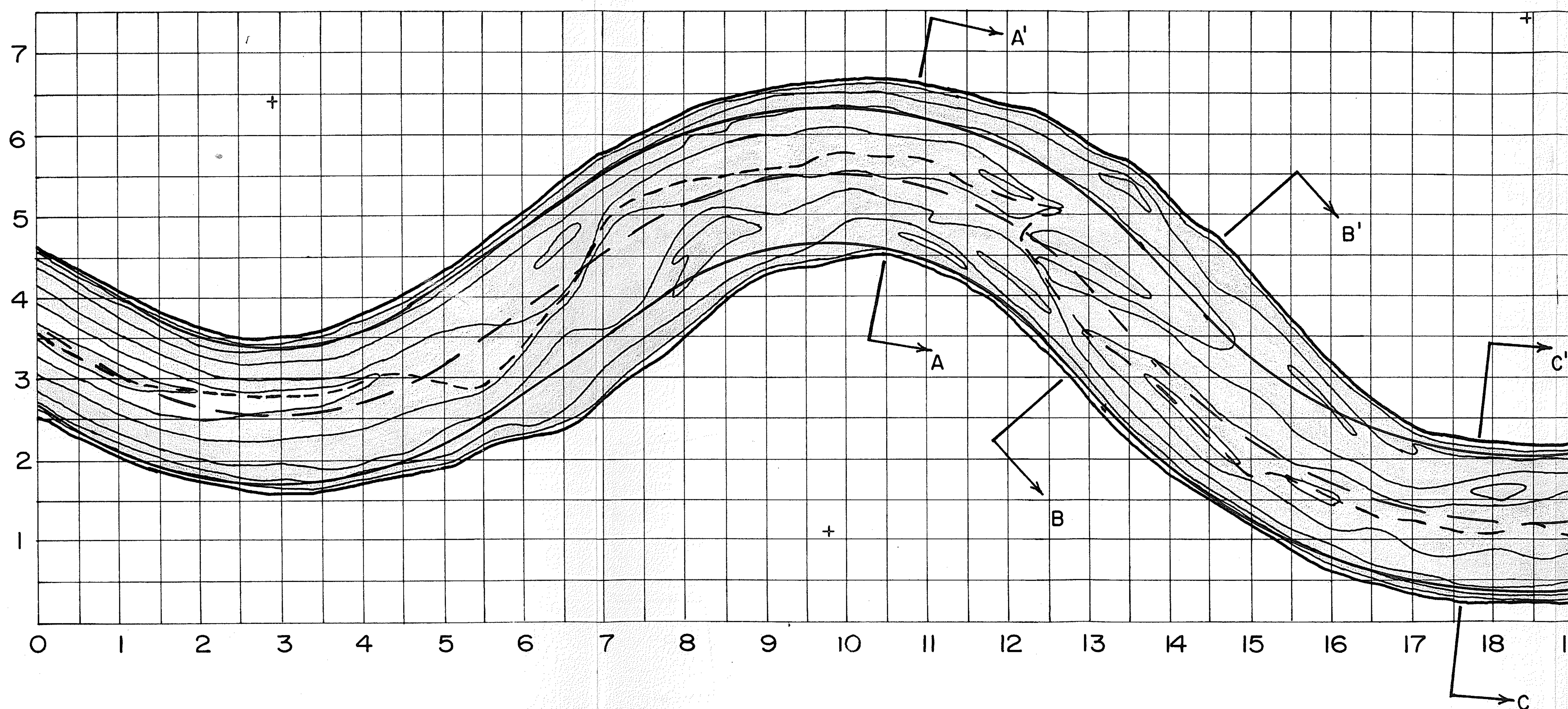


TABILIZATION

HOURS.

F

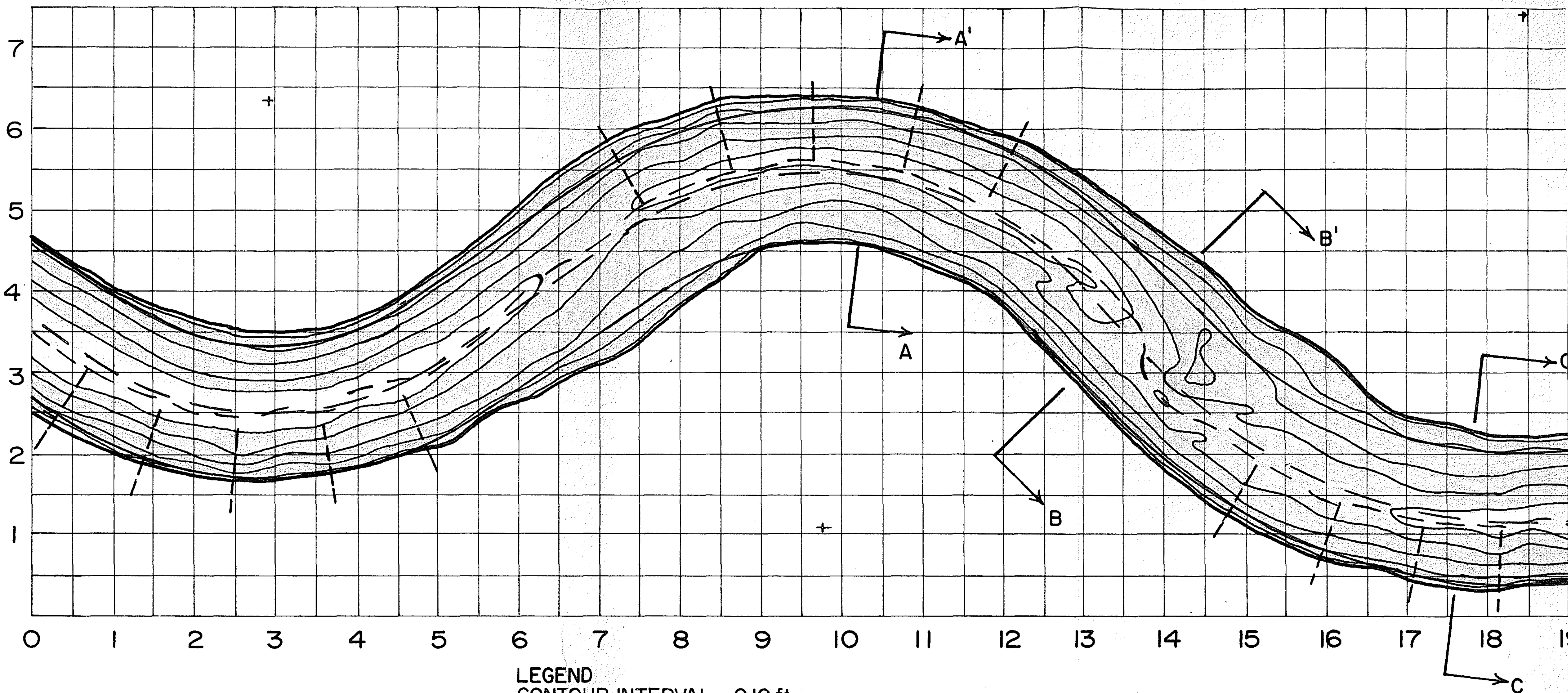
HYDROGRAPHIC MAPS OF (
BANK STABILIZATION TE



PILOT TEST — NO ST

TEST DURATION 4

DIRECTION OF
FLOW



LEGEND

CONTOUR INTERVAL - 0.10 ft

.90 - 1.00
1.00 - 1.10
1.10 - 1.20
1.20 - 1.30
1.30 - 1.40
1.40 - 1.50
1.50 - TOP OF CHANNEL

CONTOURS FROM 1.00 DATUM AT DOWNSTREAM END OF INITIAL CHANNEL BOTTOM

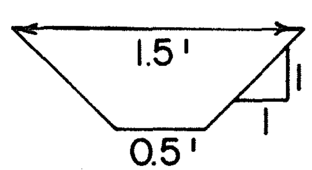
BLACK DASHED LINE - FINAL THALWEG

RED DASHED LINE — INITIAL CENTRE LINE.

JETTIES - /

TEST DATA

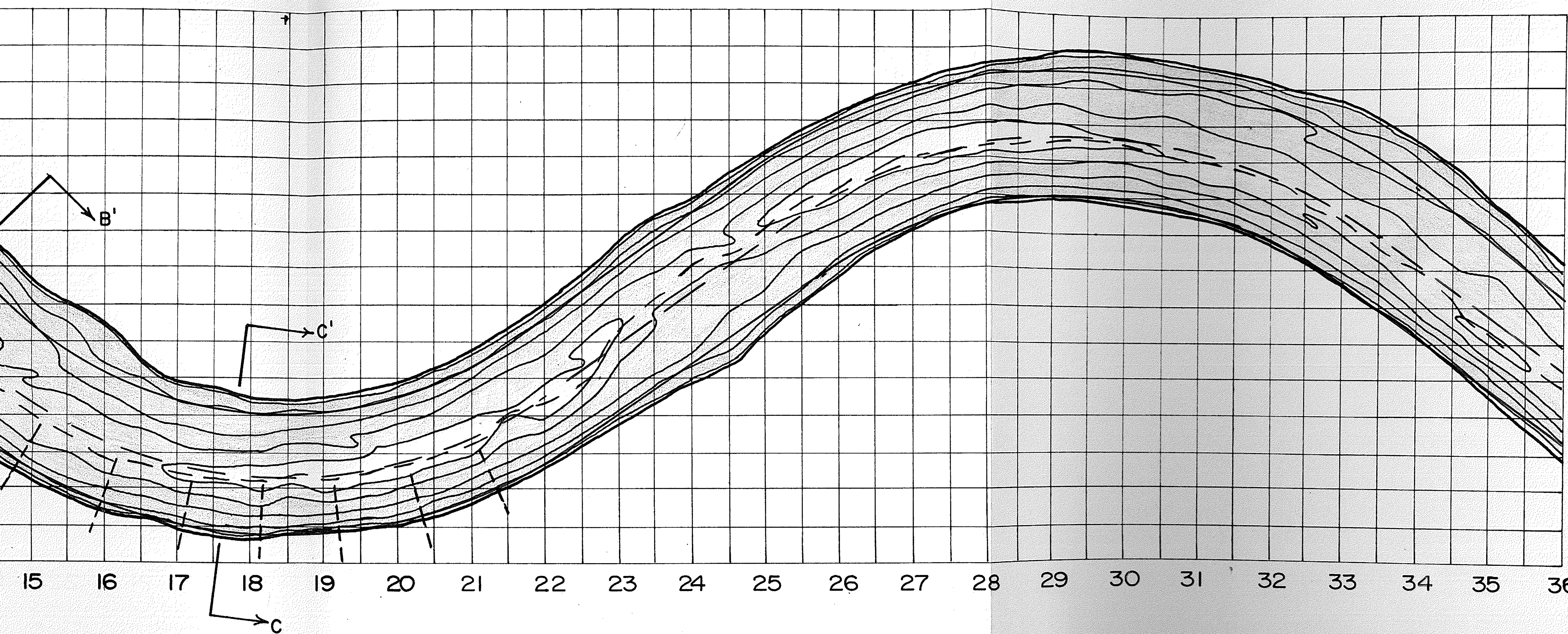
MATERIAL	93 %	BRICK SAND
	7 %	SILT
DISCHARGE	0.3	CFS (CONSTANT)
VALLEY SLOPE	0.0006	



INITIAL CHANNEL

JETTIES PLACED @ 90°

TEST DURATION 4



JETTIES PLACED @ 90° TO CENTRE LINE

TEST DURATION 4 HOURS

UNIVERSITY OF MANITOBA

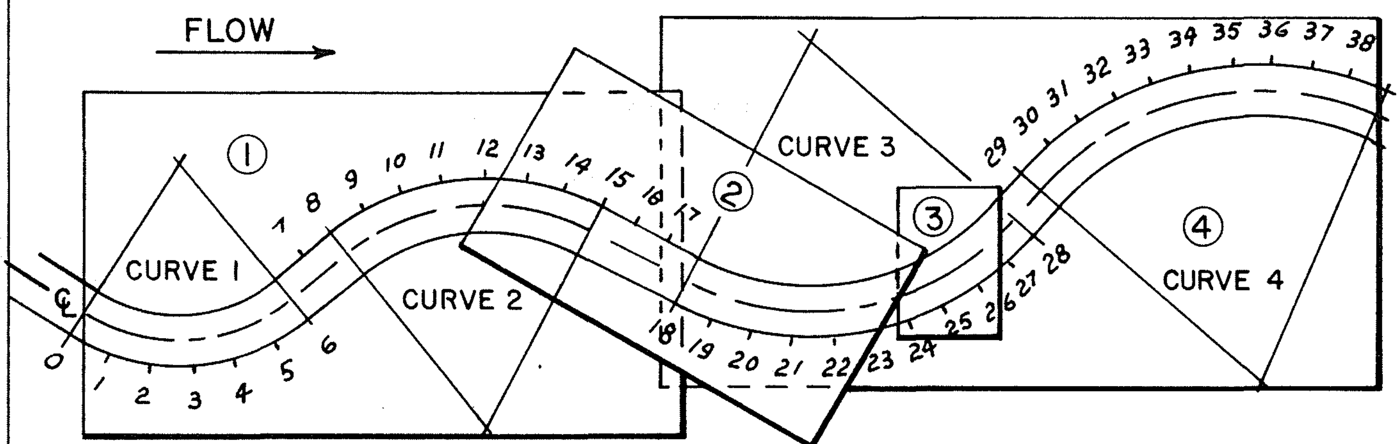
CIVIL ENGINEERING GRADUATE STUDIES
M.Sc. THESIS

"EFFECT OF STABILIZING METHODS ON BED AND BANK MATERIALS."

AUG. 1965, SCALE: 3/4" = 1', D.A.P.

PLATE 31

PHOTOGRAPH LOCATIONS



CHANNEL

PHOTOGRAPH 1

PHOTOGRAPH 2

PHOTOGRAPH 3

PLATE 32

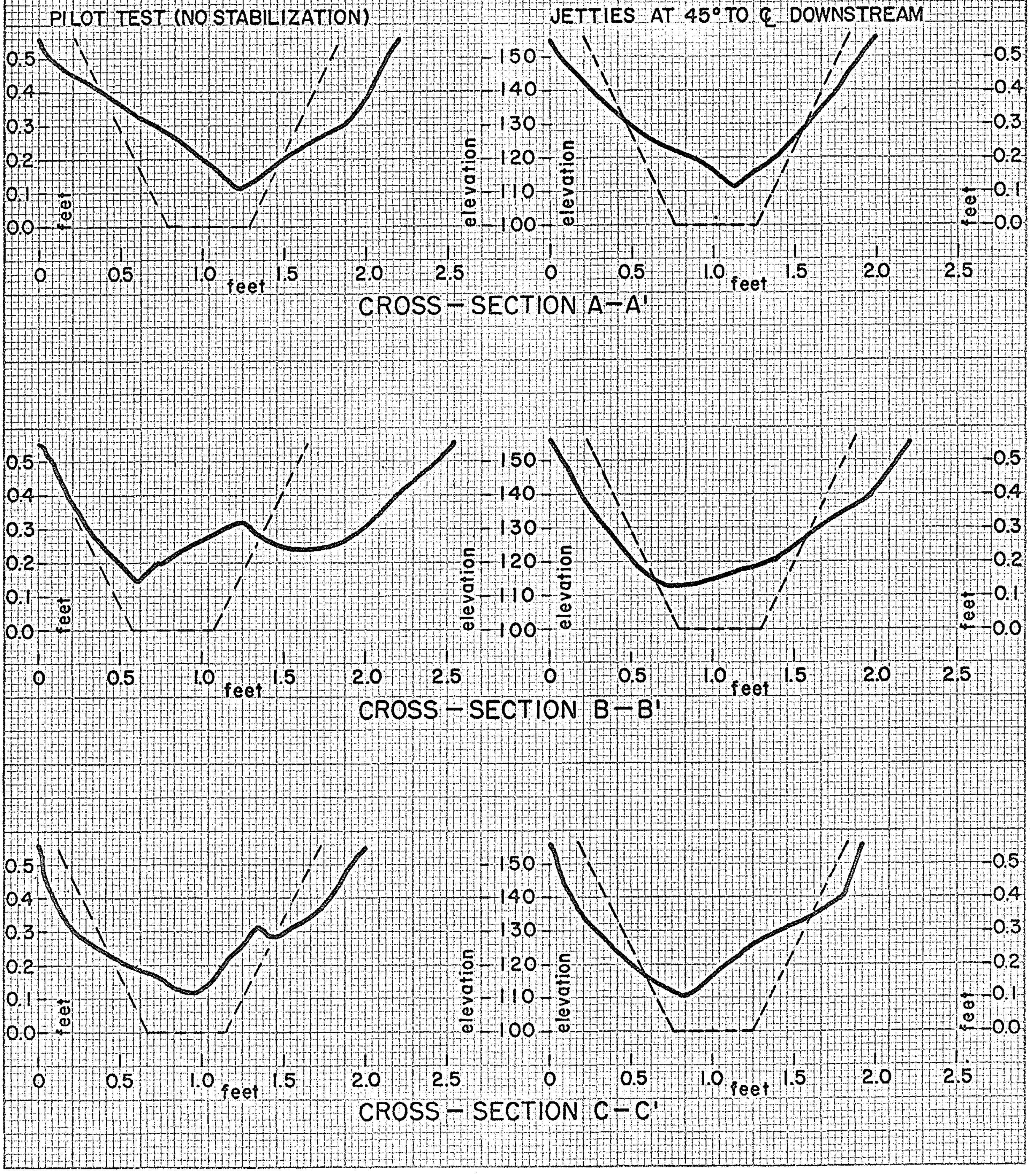
PHOTOGRAPHS - BANK STABILIZATION TEST NO. 2

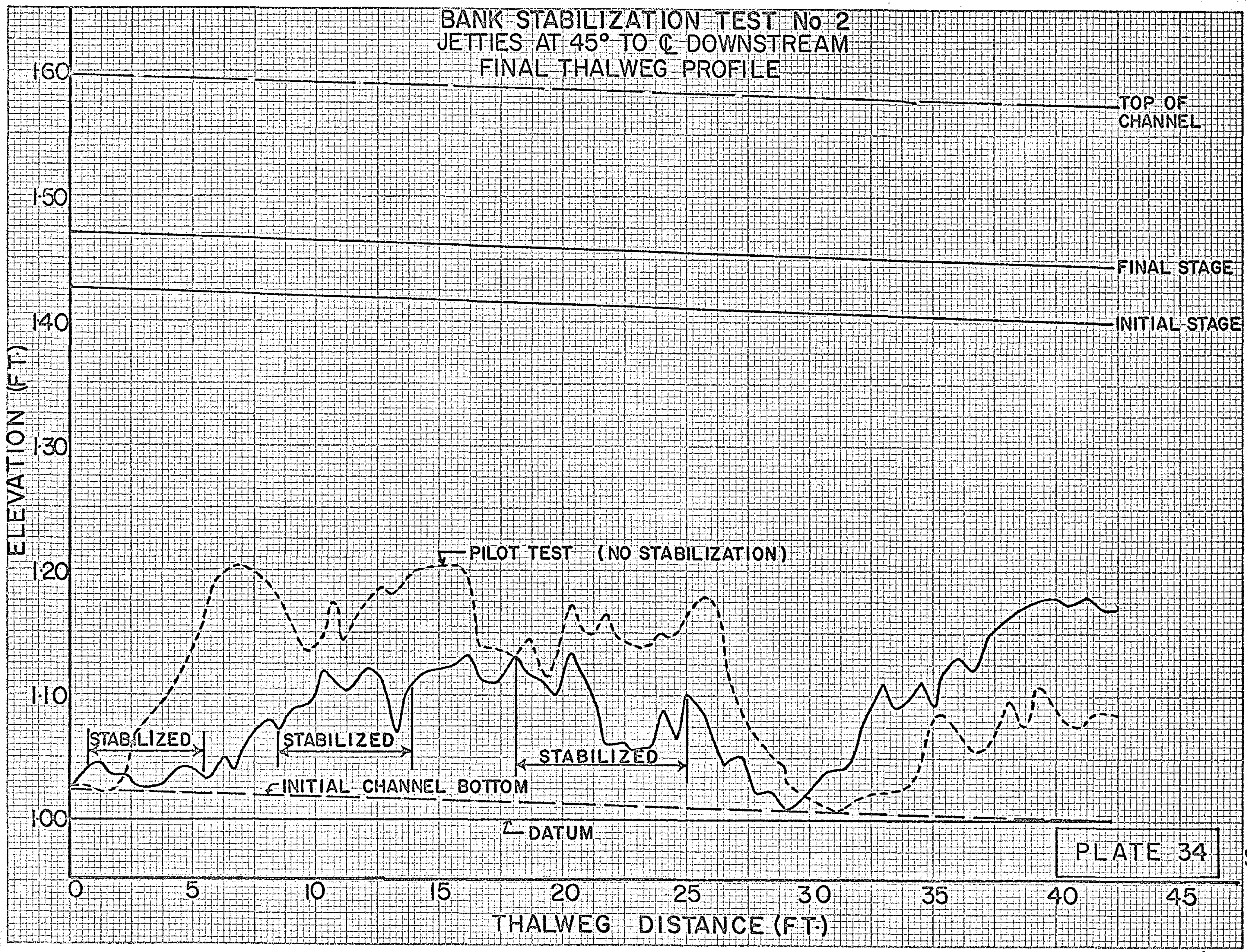
PLATE 33

BANK STABILIZATION TEST No. 2

CROSS-SECTIONS.

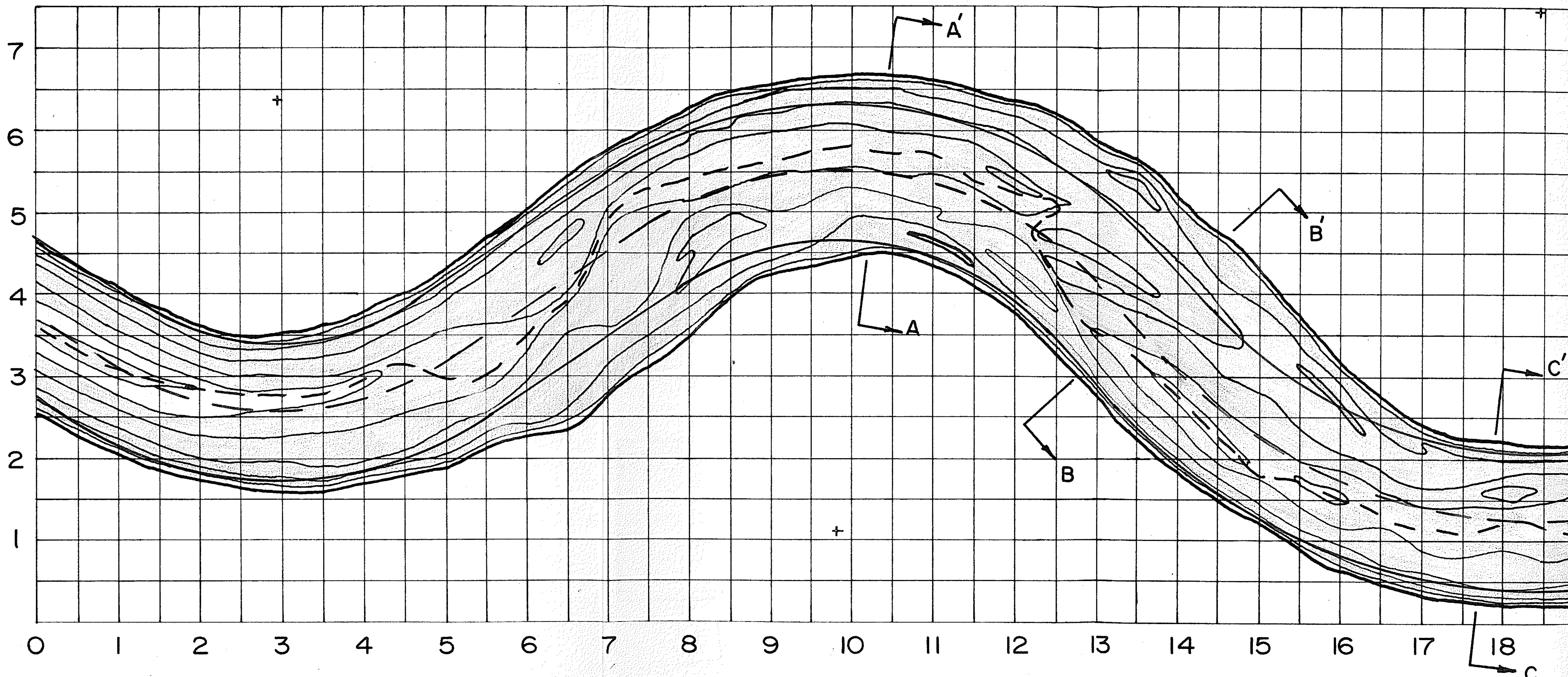
INITIAL CHANNEL ------
FINAL CHANNEL ——




BANK STABILIZATION TEST No 2
JETTIES AT 45° TO ℄ DOWNSTREAM
FINAL THALWEG PROFILE
TOP OF CHANNEL
FINAL STAGE
INITIAL STAGE
PILOT TEST (NO STABILIZATION)
STABILIZED
STABILIZED
STABILIZED
INITIAL CHANNEL BOTTOM
DATUM
ELEVATION (FT)
1·60
1·50
1·40
1·30
1·20
1·10
1·00
THALWEG DISTANCE (FT)
0
5
10
15
20
25
30
35
40
45
PLATE 34

HYDROGRAPHIC MAPS OF (

BANK STABILIZATION TE



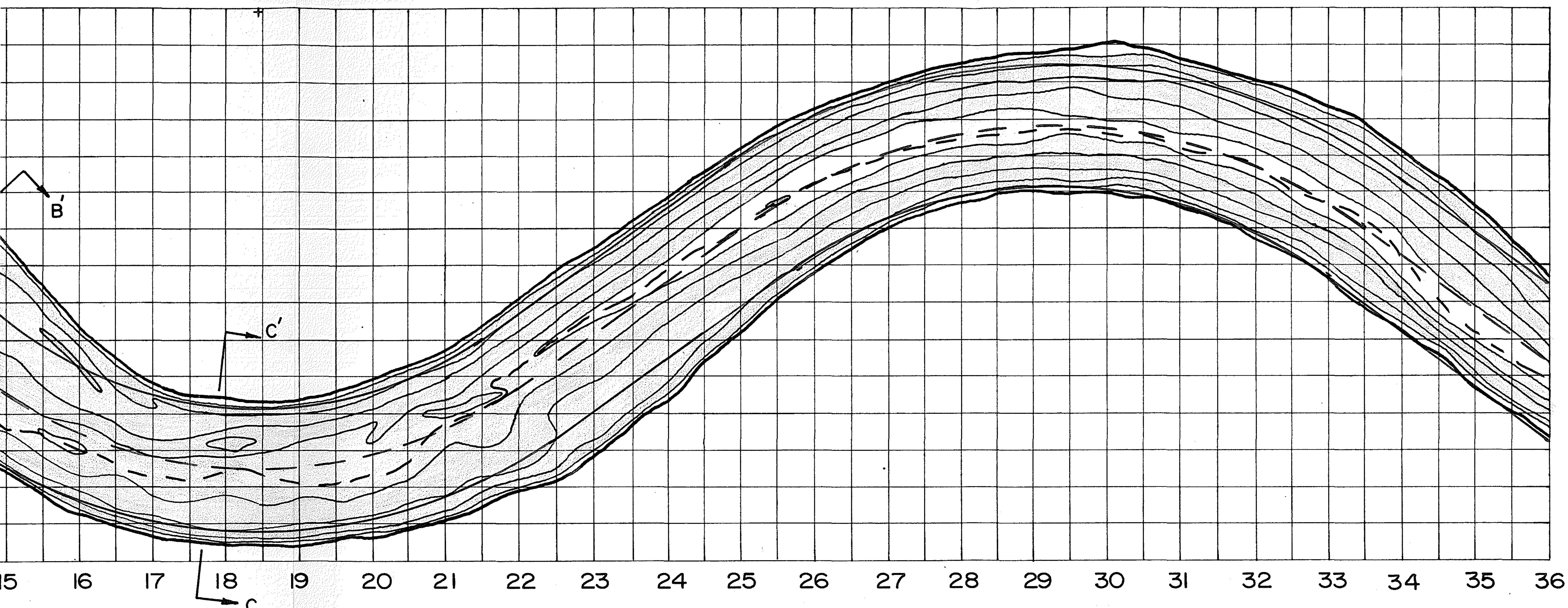
PILOT TEST — NO ST

TEST DURATION 4

DIRECTION OF

FLOW

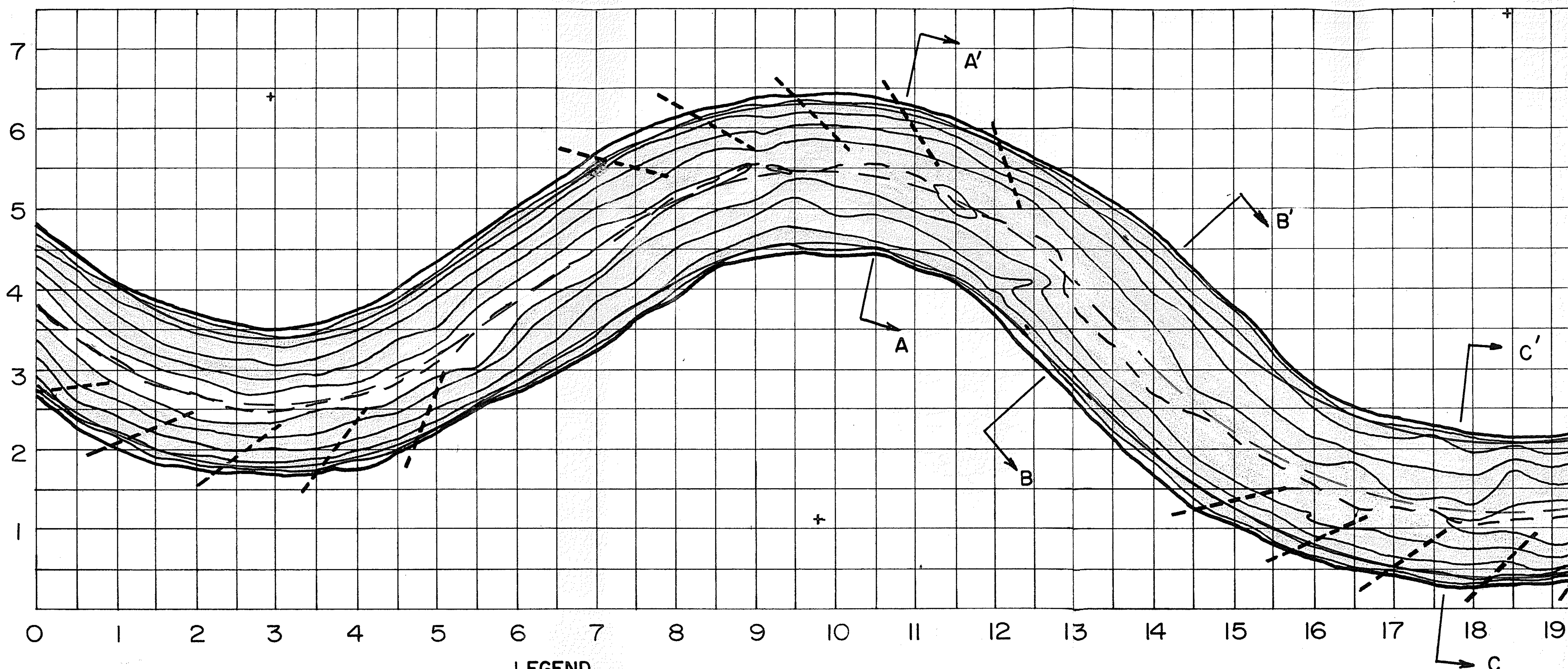
DROGRAPHIC MAPS OF CHANNELS.
BANK STABILIZATION TEST No. 2.



PILOT TEST — NO STABILIZATION

TEST DURATION 4 HOURS.

DIRECTION OF FLOW



JETTIES PLACED @ 45°

TEST DURATION 4 HO

LEGEND

CONTOUR INTERVAL – 0.10 ft.

- .90 – 1.00
- 1.00 – 1.10
- 1.10 – 1.20
- 1.20 – 1.30
- 1.30 – 1.40
- 1.40 – 1.50
- 1.50 – TOP OF CHANNEL

CONTOURS FROM 1.00 DATUM AT DOWNSTREAM END OF INITIAL CHANNEL BOTTOM

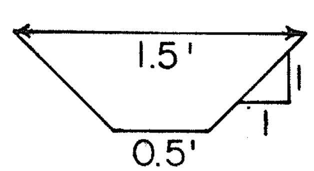
BLACK DASHED LINE – FINAL THALWEG

RED DASHED LINE – INITIAL CENTRE LINE.

JETTIES – /

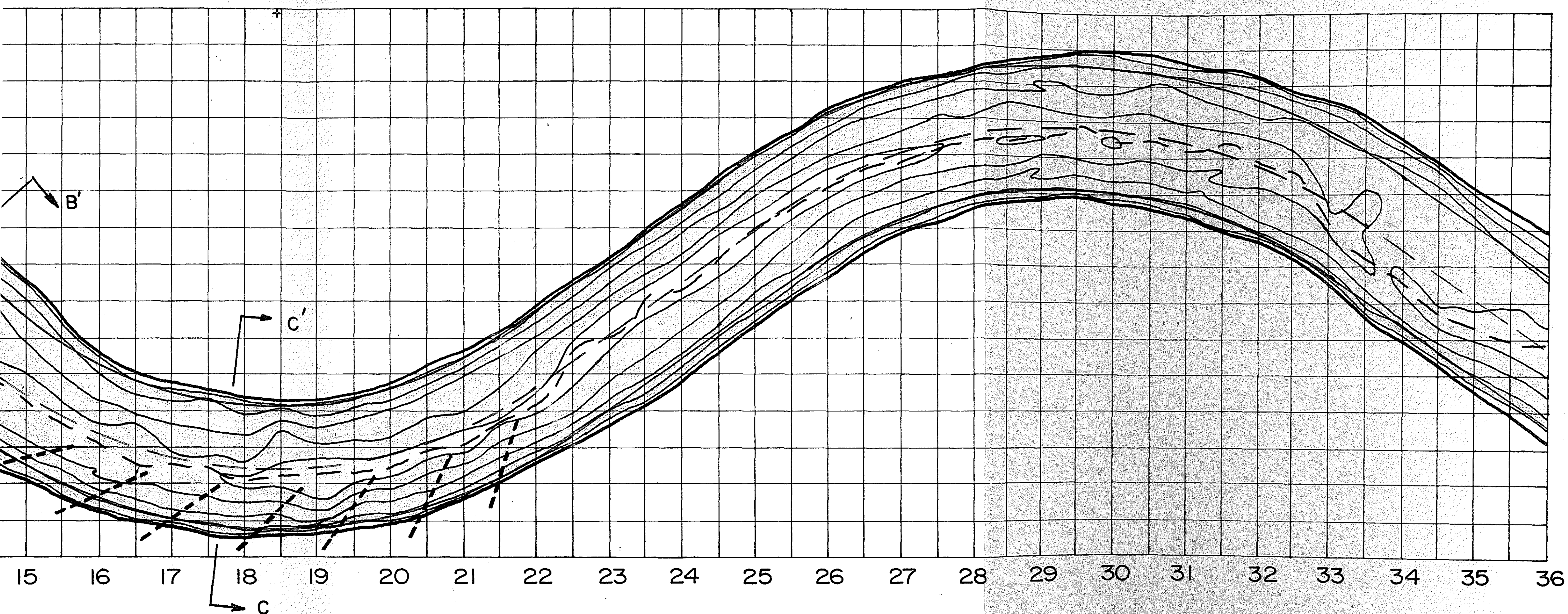
TEST DATA

MATERIAL	93 % BRICK SAND 7 % SILT
DISCHARGE	0.3 CFS (CONSTANT)
VALLEY SLOPE	0.0006



INITIAL CHANNEL

FLOW



JETTIES PLACED @ 45° TO ℄ DOWNSTREAM.

TEST DURATION 4 HOURS

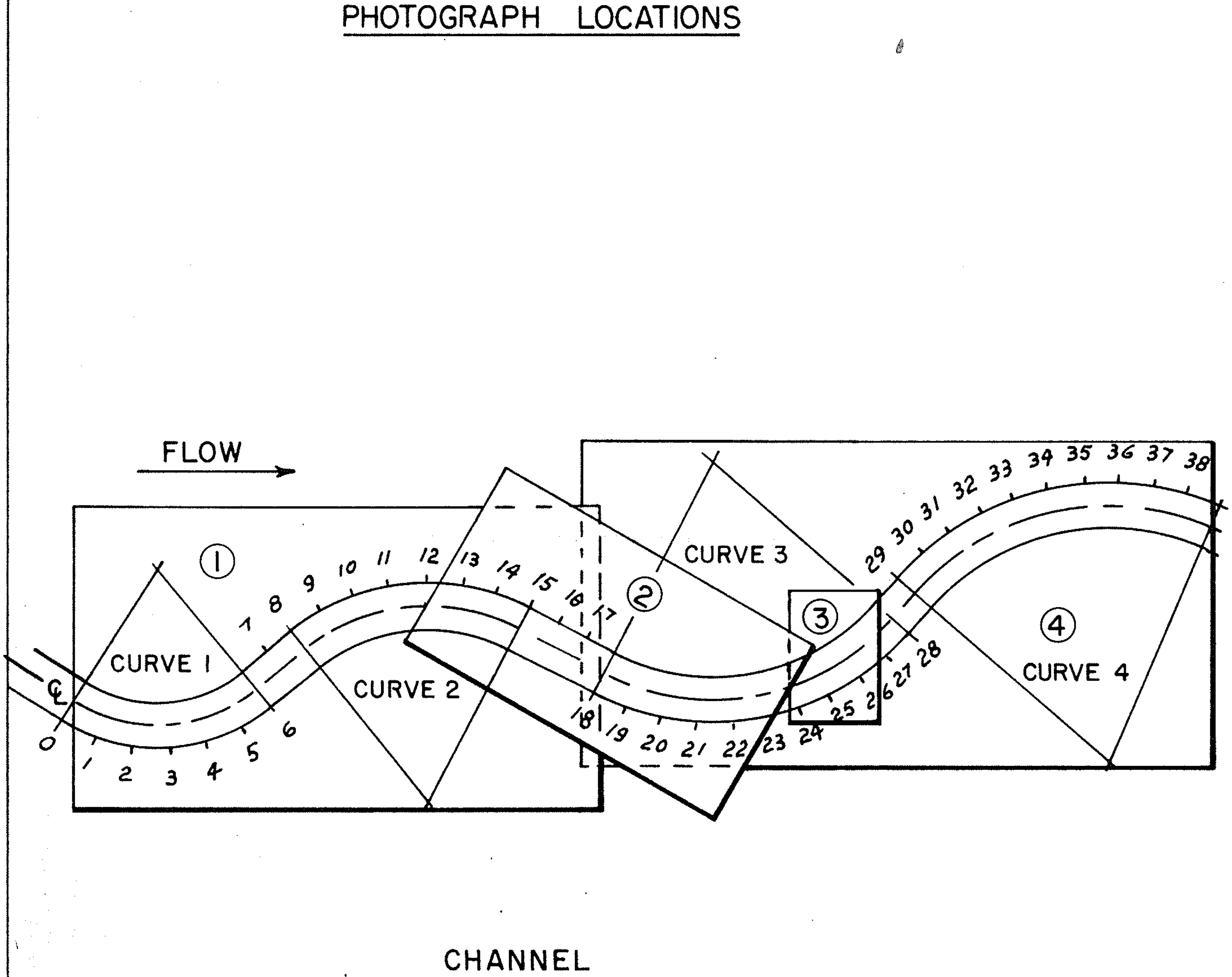
UNIVERSITY OF MANITOBA

CIVIL ENGINEERING GRADUATE STUDIES
M.Sc. THESIS

"EFFECT OF STABILIZING METHODS ON BED AND BANK MATERIALS."

AUG. 1965, SCALE: 3/4" = 1', D.A.P.

PLATE 35


PHOTOGRAPH LOCATIONS
FLOW
1
2
3
4
CURVE 1
CURVE 2
CURVE 3
CURVE 4
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
CHANNEL

BANK STABILIZATION TEST NO. 3

PHOTOGRAPH 1

PHOTOGRAPH 2

PHOTOGRAPH 3

PHOTOGRAPH 4

PLATE 36

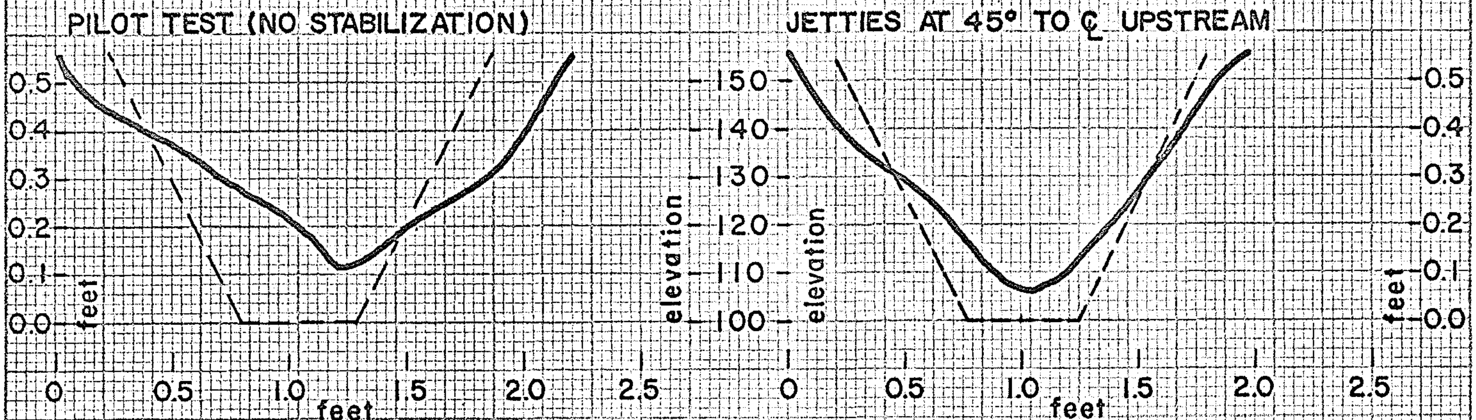
PHOTOGRAPHS - BANK STABILIZATION TEST NO. 3

PLATE 37

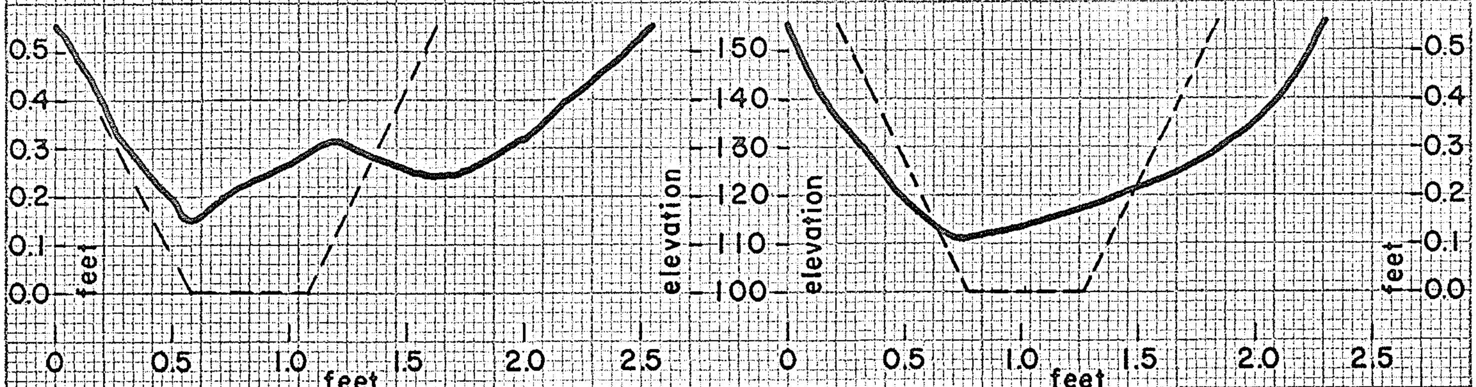
BANK STABILIZATION TEST No. 3

CROSS - SECTIONS.

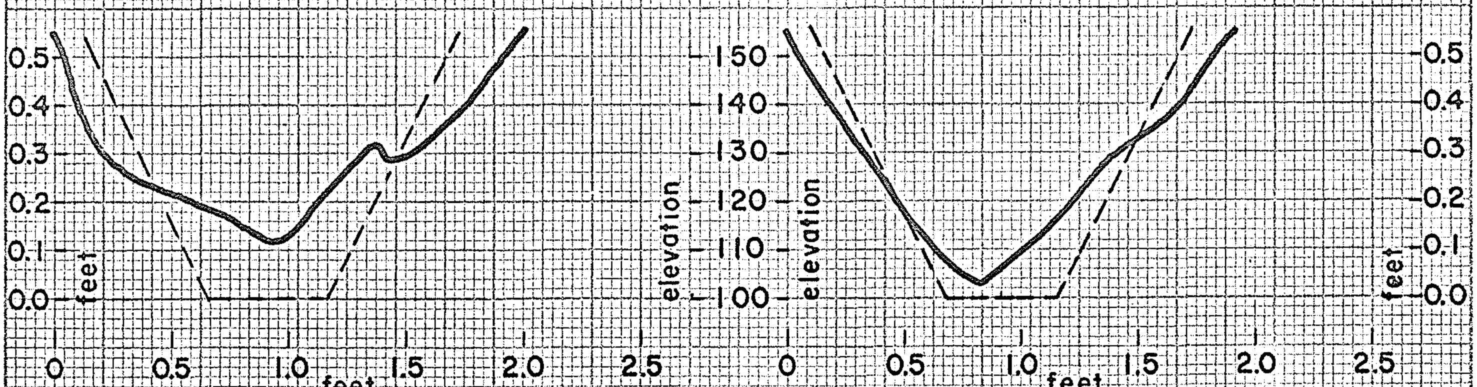
INITIAL CHANNEL - - - - -
FINAL CHANNEL ———



CROSS - SECTION A - A'



CROSS - SECTION B - B'



CROSS - SECTION C - C'

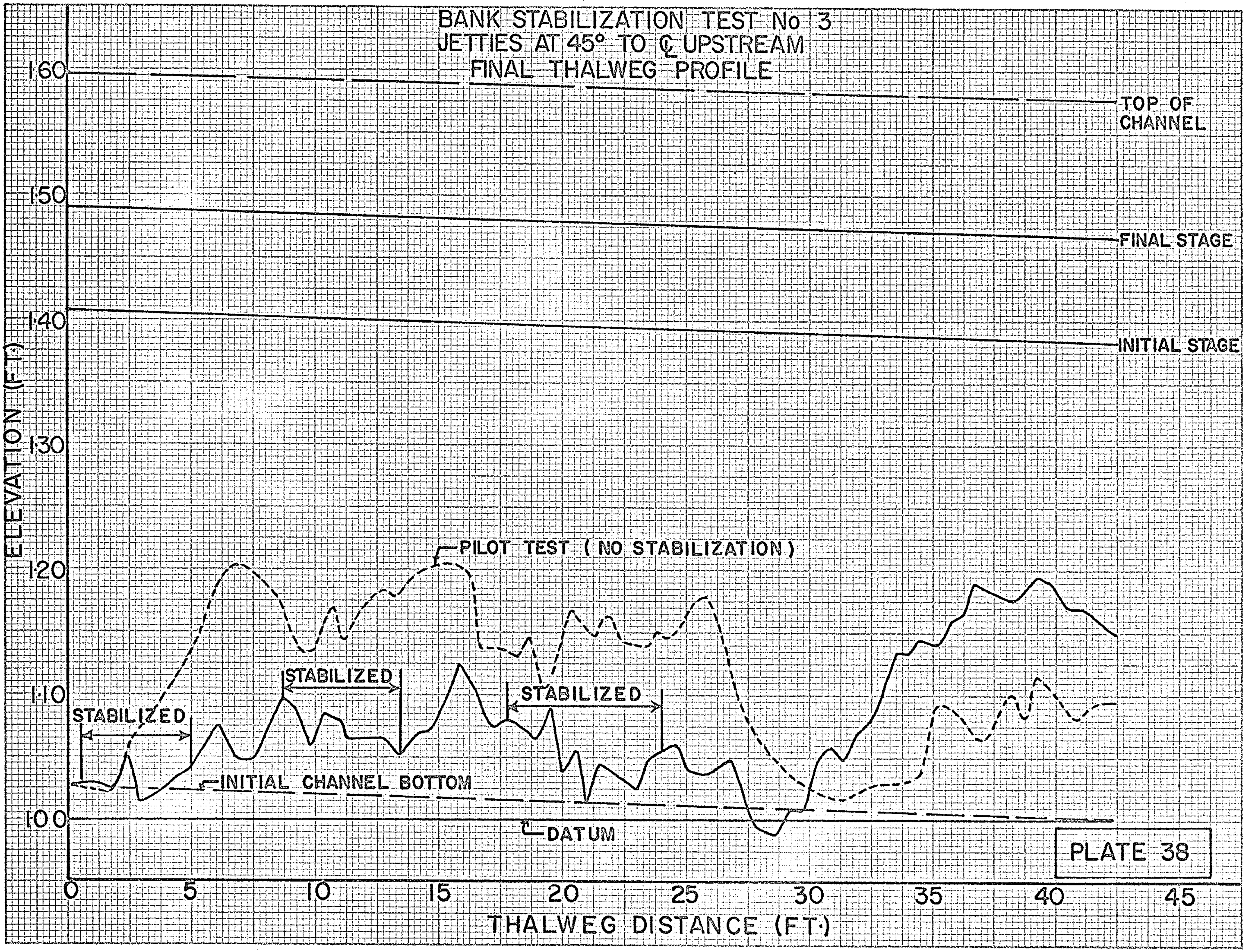
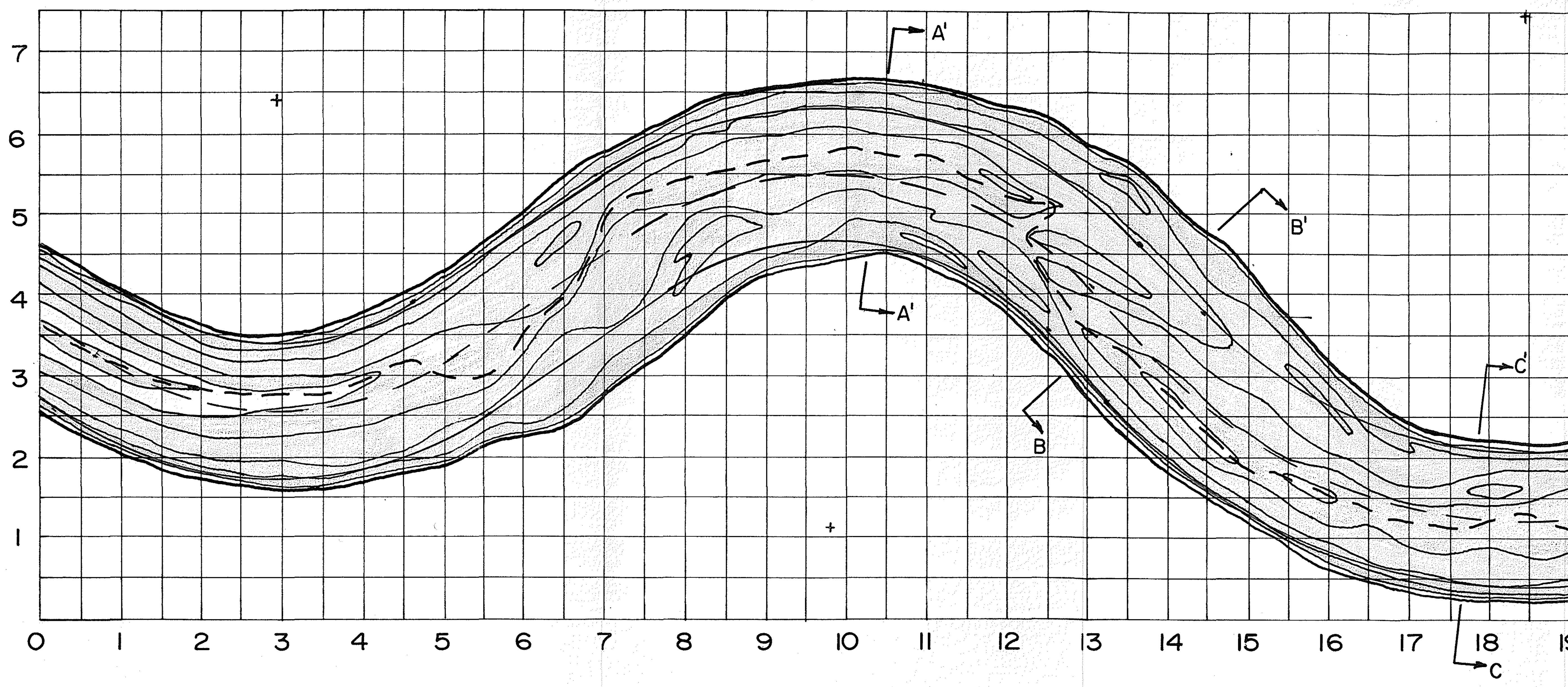

BANK STABILIZATION TEST No 3
JETTIES AT 45° TO ℄ UPSTREAM
FINAL THALWEG PROFILE
ELEVATION (FT)
1·60
1·50
1·40
1·30
1·20
1·10
1·00
TOP OF CHANNEL
FINAL STAGE
INITIAL STAGE
PILOT TEST (NO STABILIZATION)
STABILIZED
STABILIZED
STABILIZED
INITIAL CHANNEL BOTTOM
℄ DATUM
0
5
10
15
20
25
30
35
40
45
THALWEG DISTANCE (FT)

PLATE 38

HYDROGRAPHIC MAPS OF CH

BANK STABILIZATION TES

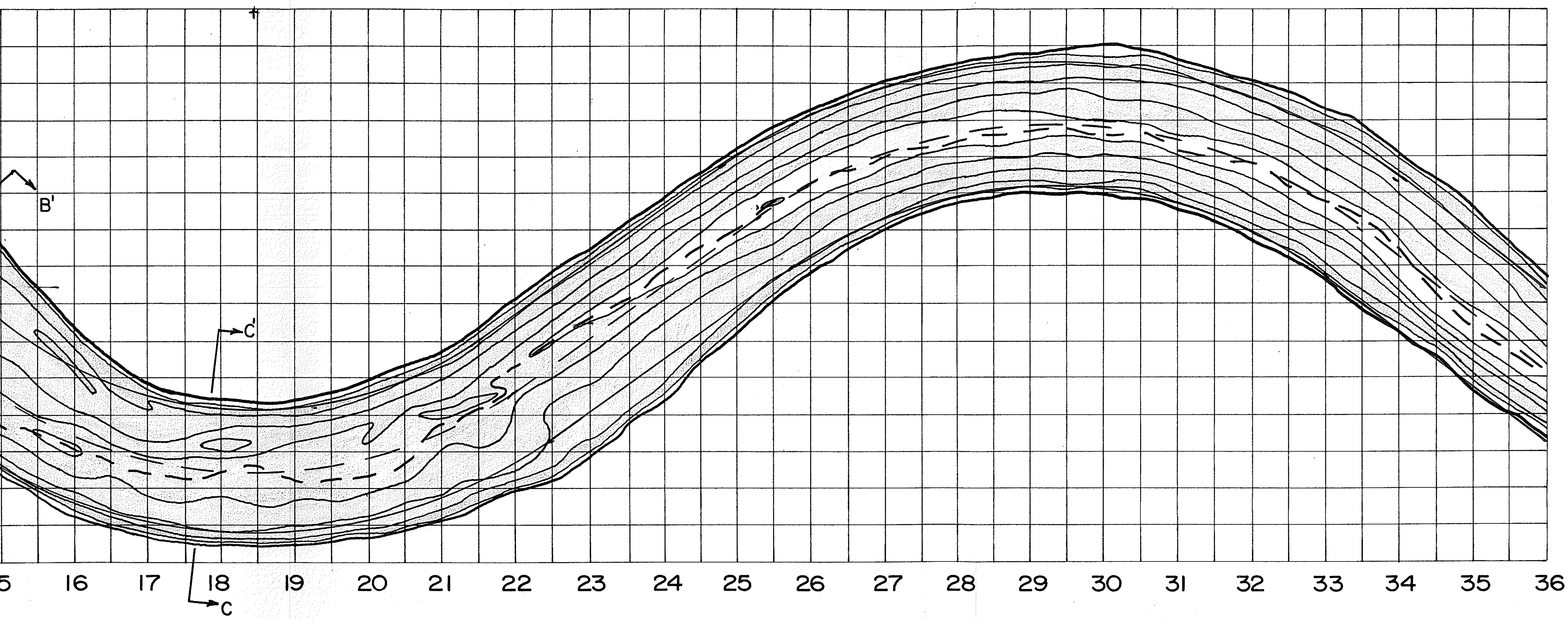


PILOT TEST — NO STA

TEST DURATION 4 HO

DIRECTION OF

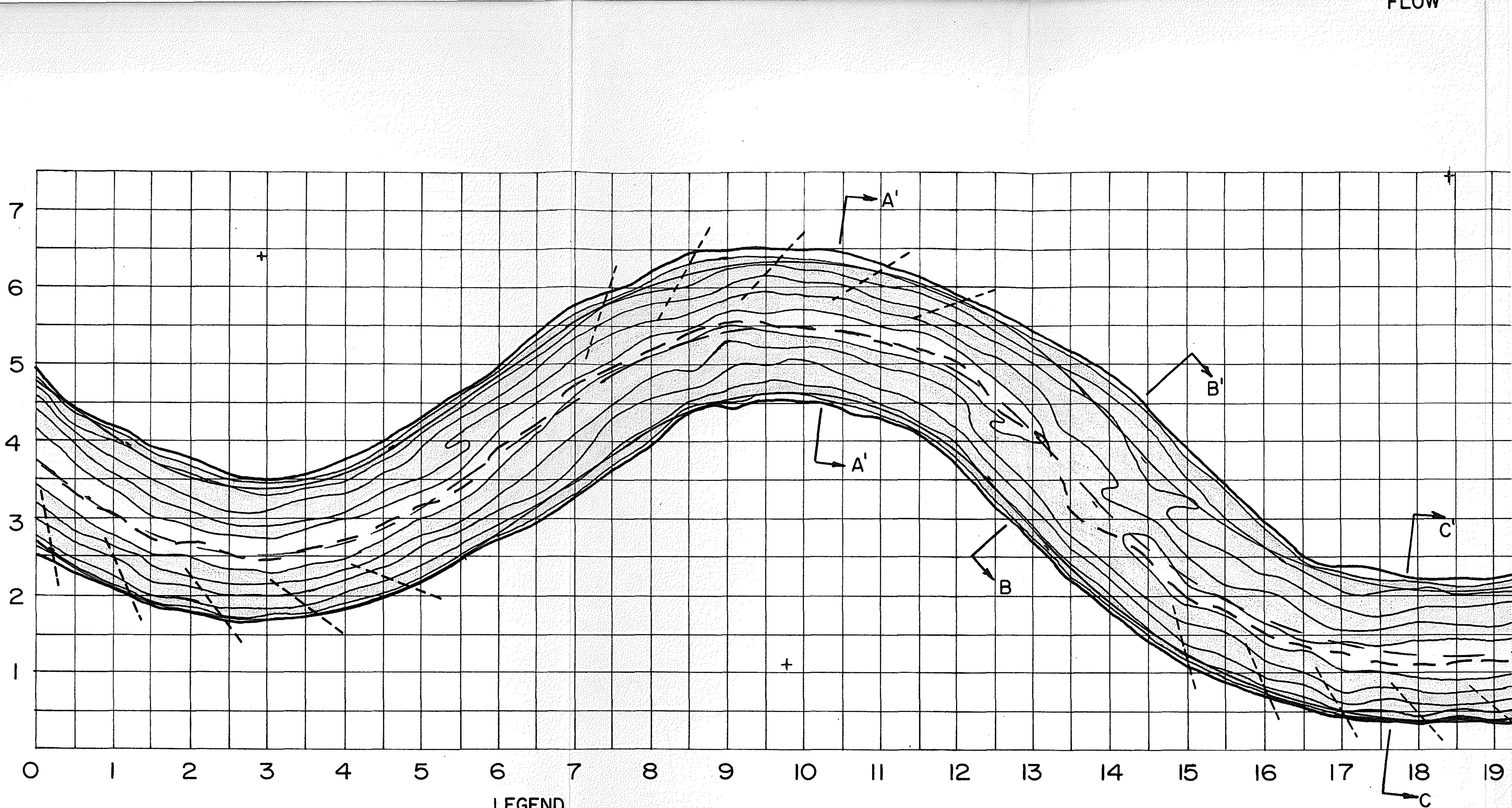
DROGRAPHIC MAPS OF CHANNELS.
BANK STABILIZATION TEST No. 3.



PILOT TEST — NO STABILIZATION

TEST DURATION 4 HOURS.

DIRECTION OF



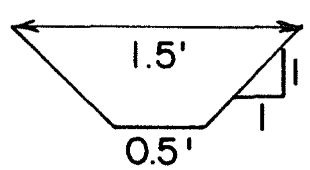
LEGEND
CONTOUR INTERVAL – 0.10 ft

.90 – 1.00
1.00 – 1.10
1.10 – 1.20
1.20 – 1.30
1.30 – 1.40
1.40 – 1.50
1.50 – TOP OF CHANNEL

CONTOURS FROM 1.00 DATUM AT DOWNSTREAM END OF INITIAL CHANNEL BOTTOM
BLACK DASHED LINE – FINAL THALWEG
RED DASHED LINE – INITIAL CENTRE LINE.
JETTIES – /

TEST DATA

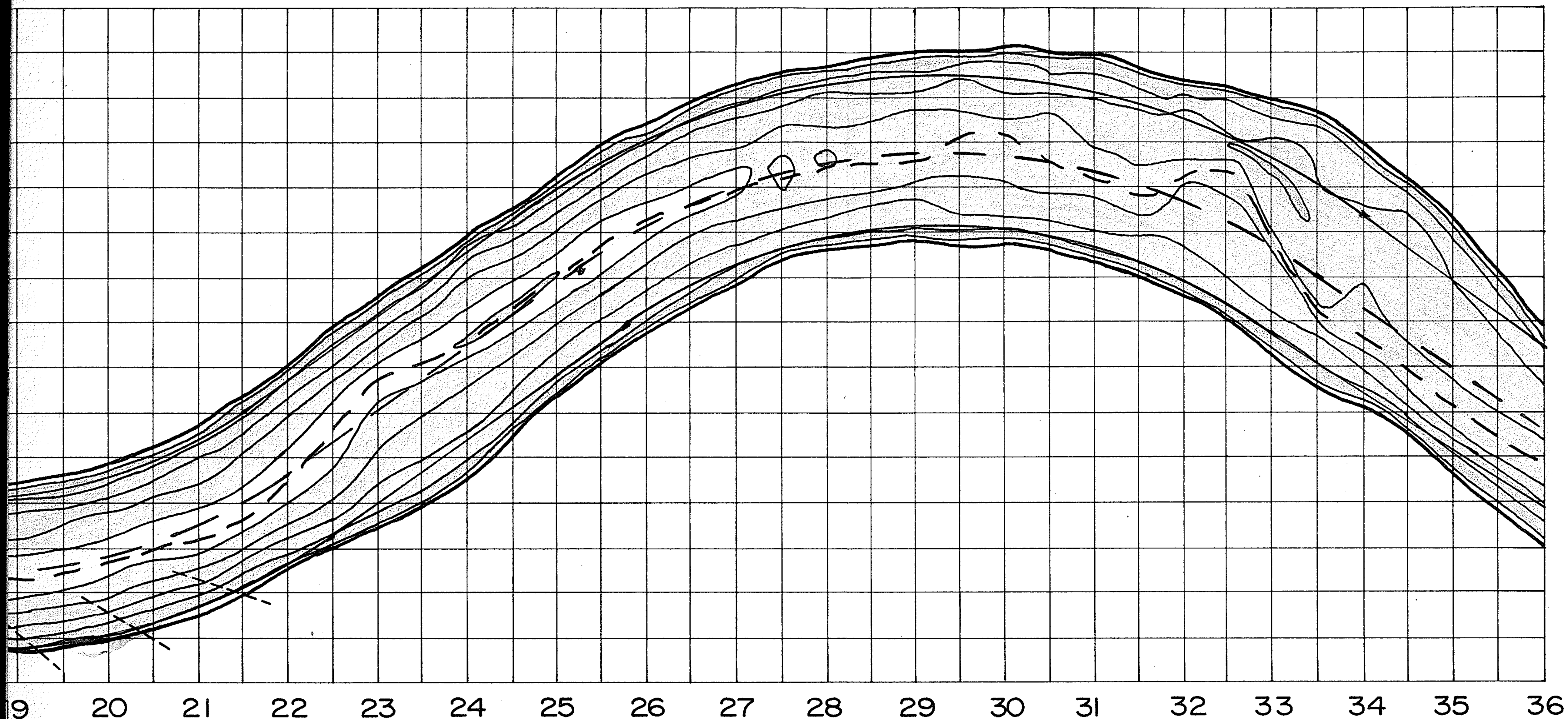
MATERIAL 93 % BRICK SAND
7 % SILT
DISCHARGE 0.3 CFS (CONSTANT)
VALLEY SLOPE 0.0006



INITIAL CHANNEL

JETTIES PLACED @ 45° T

TEST DURATION 4 HO



TO ℄ UPSTREAM.

HOURS

UNIVERSITY OF MANITOBA

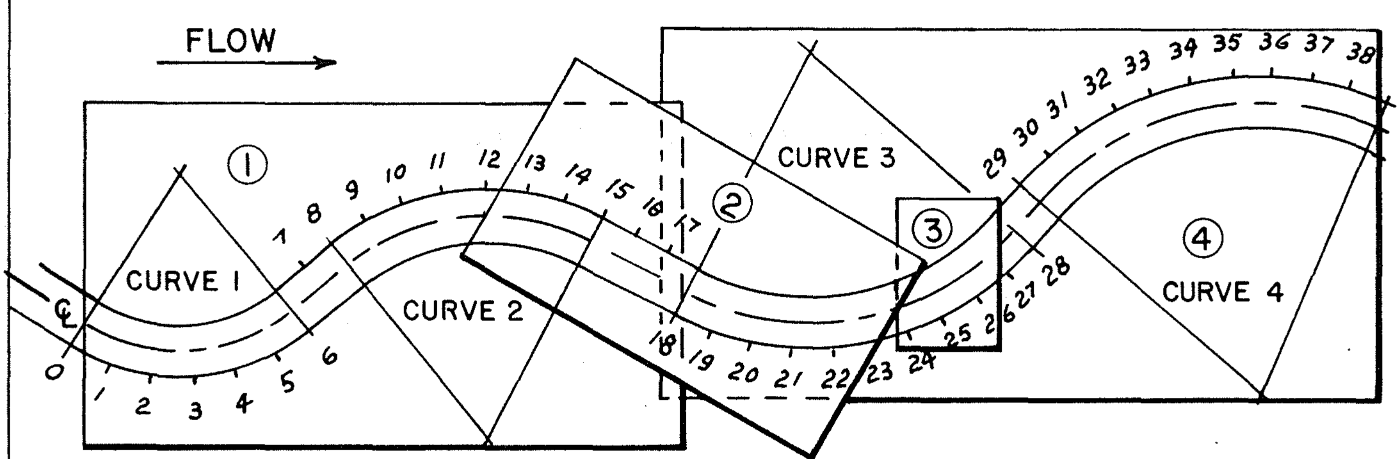
CIVIL ENGINEERING GRADUATE STUDIES
M.Sc. THESIS

"EFFECT OF STABILIZING METHODS
ON BED AND BANK MATERIALS."

AUG. 1965, SCALE: 3/4" = 1', D.A.P.

PLATE 39

PHOTOGRAPH LOCATIONS



CHANNEL

BANK STABILIZATION TEST NO. 4

PHOTOGRAPH 2

PHOTOGRAPH 2

PHOTOGRAPH 3

PHOTOGRAPH 4

PLATE 40

PHOTOGRAPHS - BANK STABILIZATION TEST NO. 4

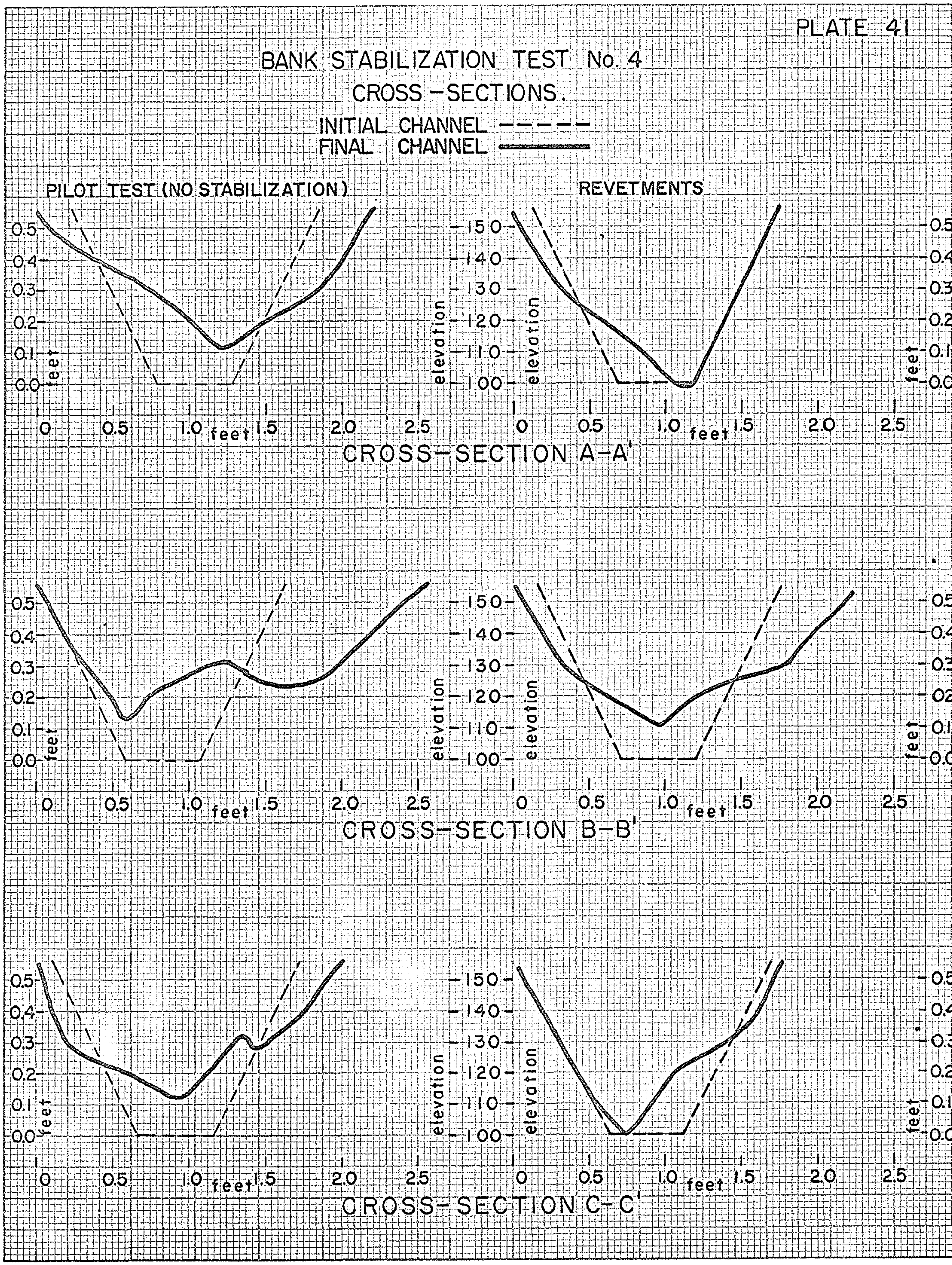


PLATE 41
BANK STABILIZATION TEST No. 4
CROSS-SECTIONS.
INITIAL CHANNEL - - - - -
FINAL CHANNEL ———
PILOT TEST (NO STABILIZATION)
REVETMENTS
0.5
0.4
0.3
0.2
0.1
0.0
feet
150
140
130
120
110
100
elevation
0
0.5
1.0
1.5
2.0
2.5
feet
CROSS-SECTION A-A'
CROSS-SECTION B-B'
CROSS-SECTION C-C'

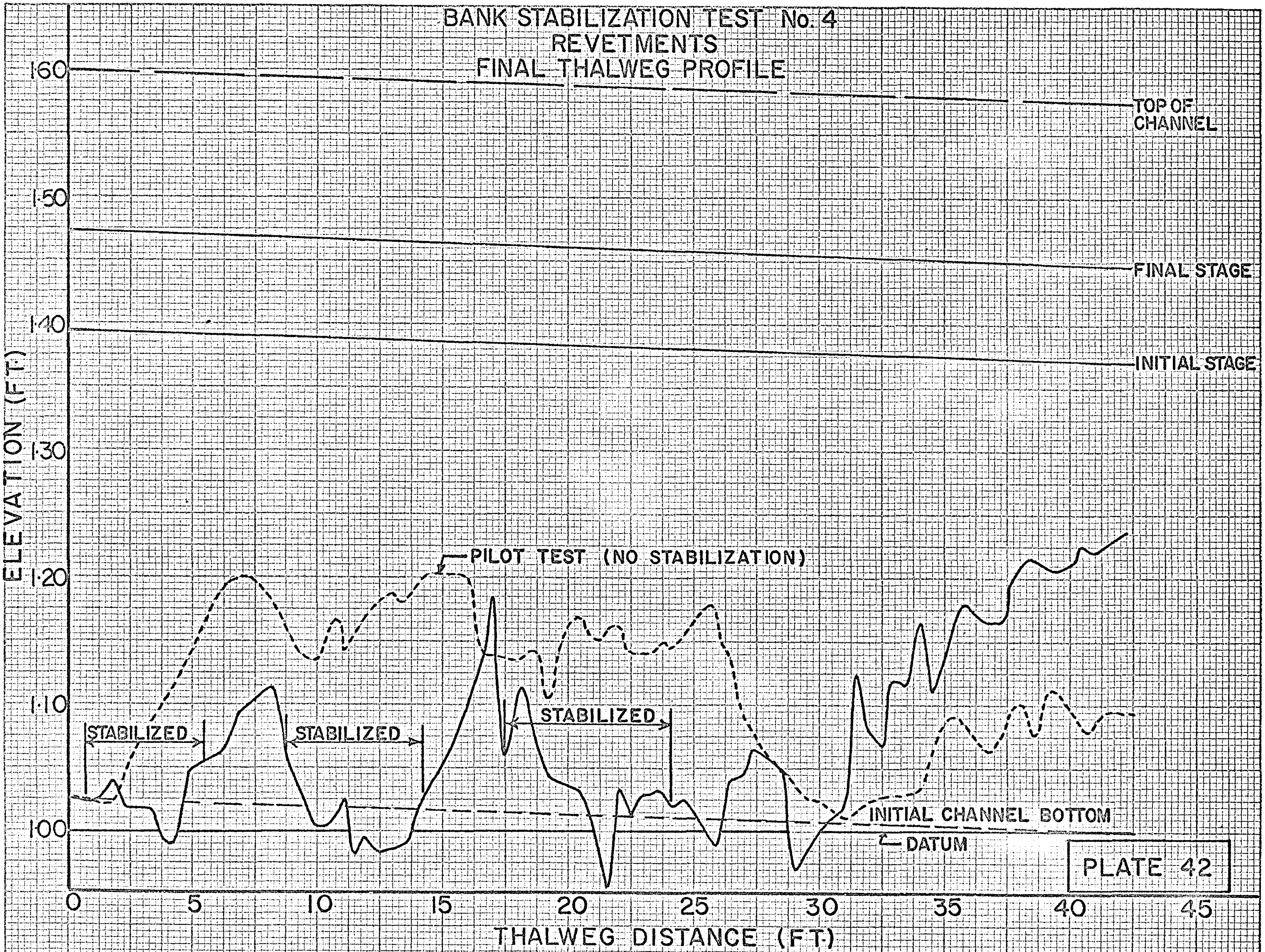
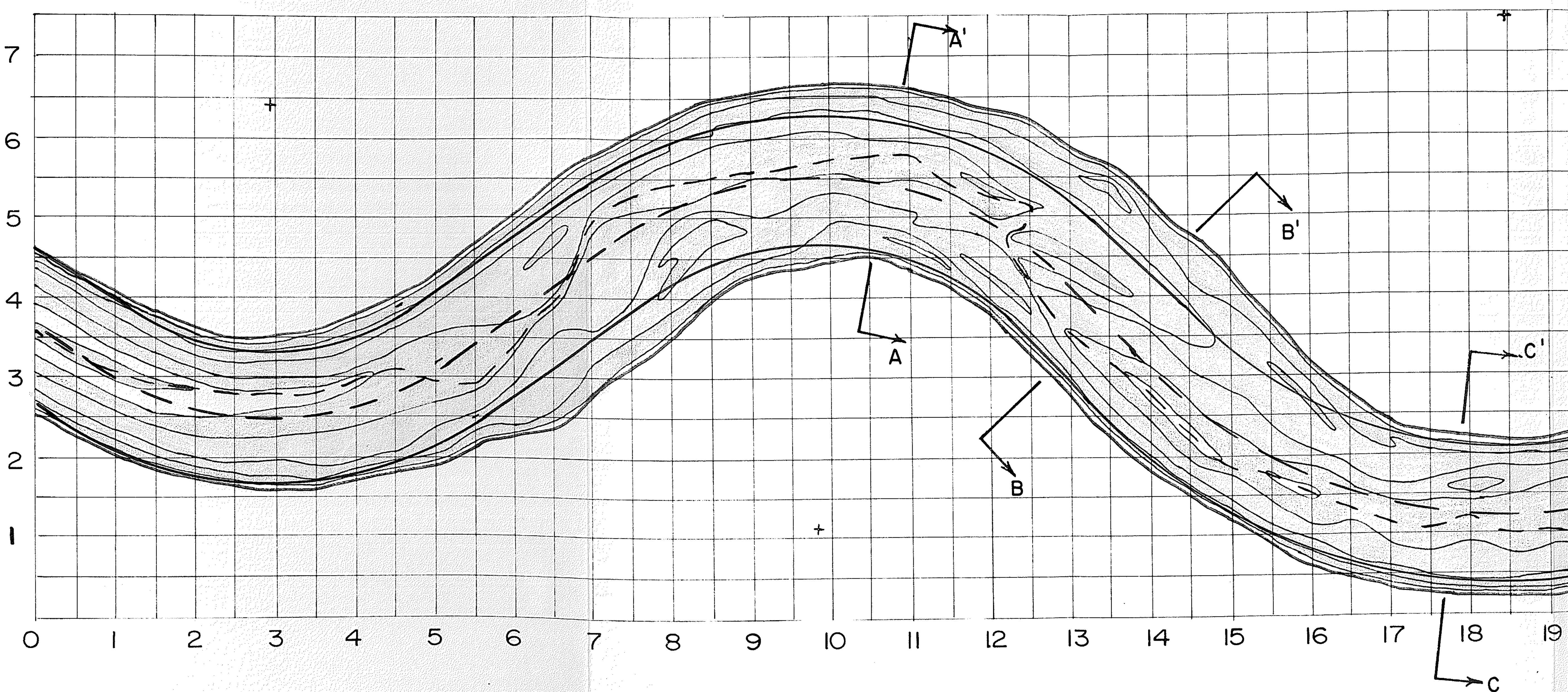

BANK STABILIZATION TEST No. 4
REVETMENTS
FINAL THALWEG PROFILE
TOP OF CHANNEL
FINAL STAGE
INITIAL STAGE
PILOT TEST (NO STABILIZATION)
STABILIZED
STABILIZED
STABILIZED
INITIAL CHANNEL BOTTOM
DATUM
ELEVATION (FT)
1·60
1·50
1·40
1·30
1·20
1·10
1·00
0
5
10
15
20
25
30
35
40
45
THALWEG DISTANCE (FT)

PLATE 42

HYDROGRAPHIC MAPS OF CH

BANK STABILIZATION TES

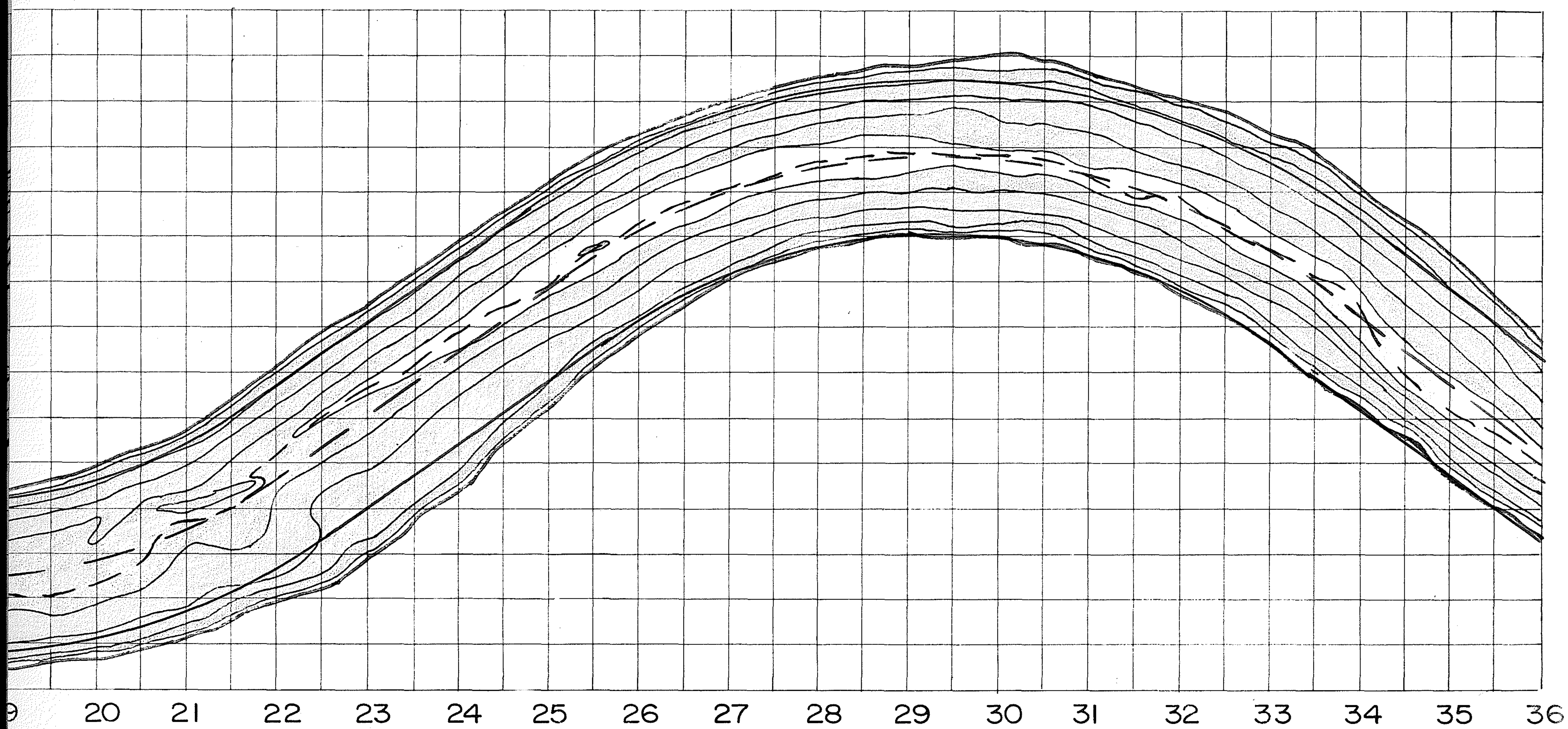


PILOT TEST – NO STA

TEST DURATION 4 HO

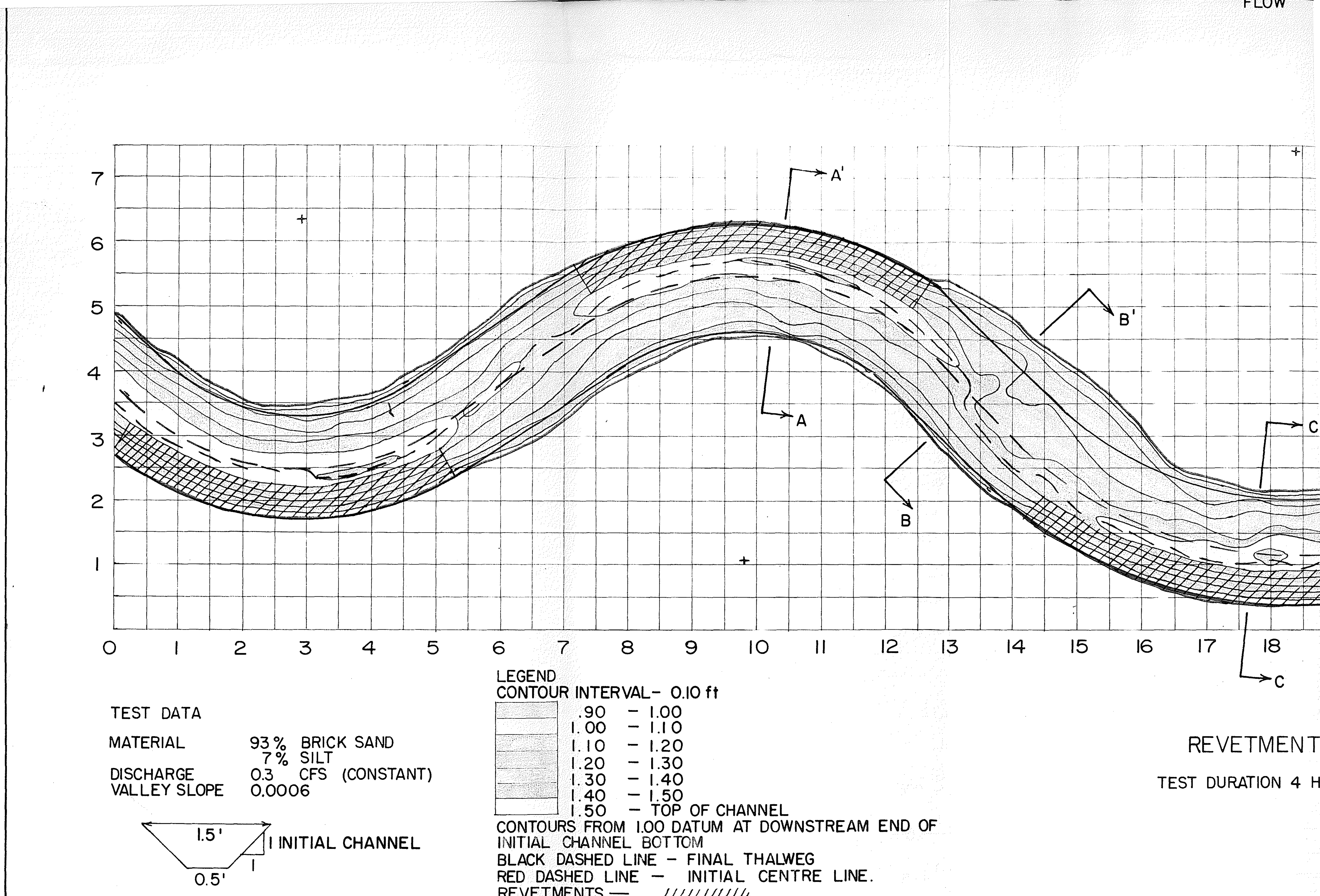
DIRECTION OF

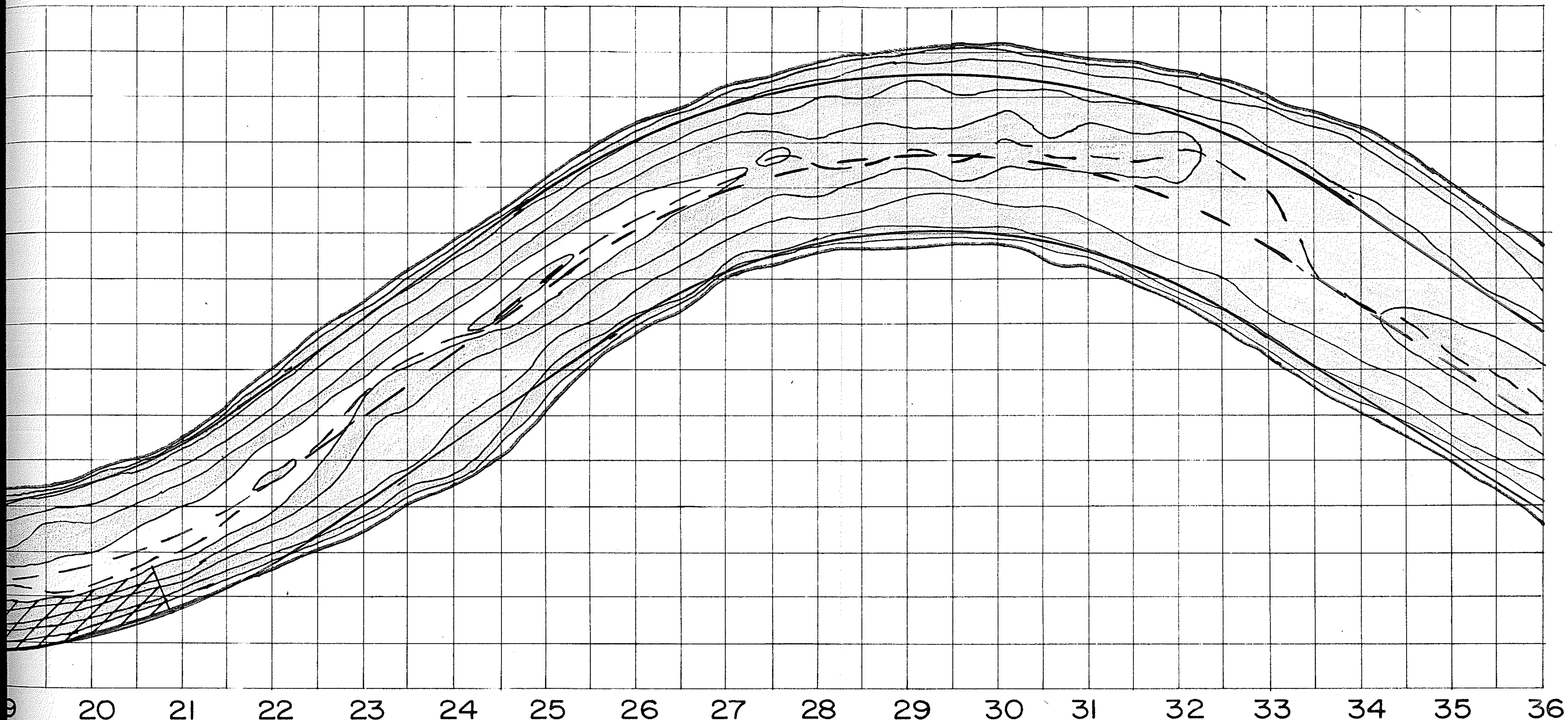
CHANNELS.
ST No. 4.



ABILIZATION

HOURS.


FLOW
A'
A
B'
B
C
C
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
1 2 3 4 5 6 7
TEST DATA
MATERIAL 93 % BRICK SAND
7 % SILT
DISCHARGE 0.3 CFS (CONSTANT)
VALLEY SLOPE 0.0006
1.5'
1 INITIAL CHANNEL
1
0.5'
LEGEND
CONTOUR INTERVAL- 0.10 ft
.90 - 1.00
1.00 - 1.10
1.10 - 1.20
1.20 - 1.30
1.30 - 1.40
1.40 - 1.50
1.50 - TOP OF CHANNEL
CONTOURS FROM 1.00 DATUM AT DOWNSTREAM END OF
INITIAL CHANNEL BOTTOM
BLACK DASHED LINE - FINAL THALWEG
RED DASHED LINE - INITIAL CENTRE LINE.
REVETMENTS —
REVETMENT
TEST DURATION 4 H



URS

UNIVERSITY OF MANITOBA

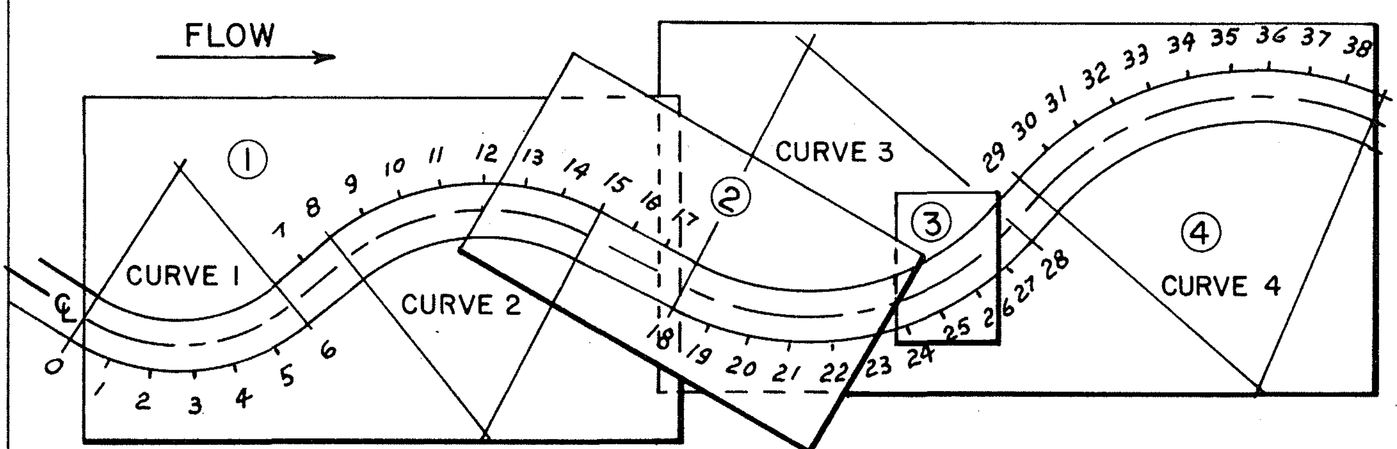
CIVIL ENGINEERING GRADUATE STUDIES
M.Sc. THESIS

"EFFECT OF STABILIZING METHODS
ON BED AND BANK MATERIALS."

AUG. 1965, SCALE: 3/4" = 1', D.A.P.

PLATE 43

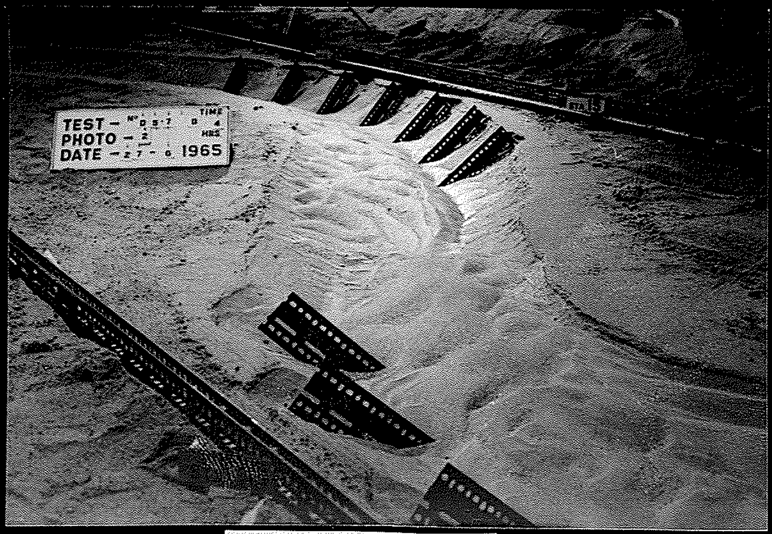
PHOTOGRAPH LOCATIONS



CHANNEL

BANK STABILIZATION TEST NO. 5

PHOTOGRAPH 1



PHOTOGRAPH 2

PHOTOGRAPH 3

PHOTOGRAPH 4

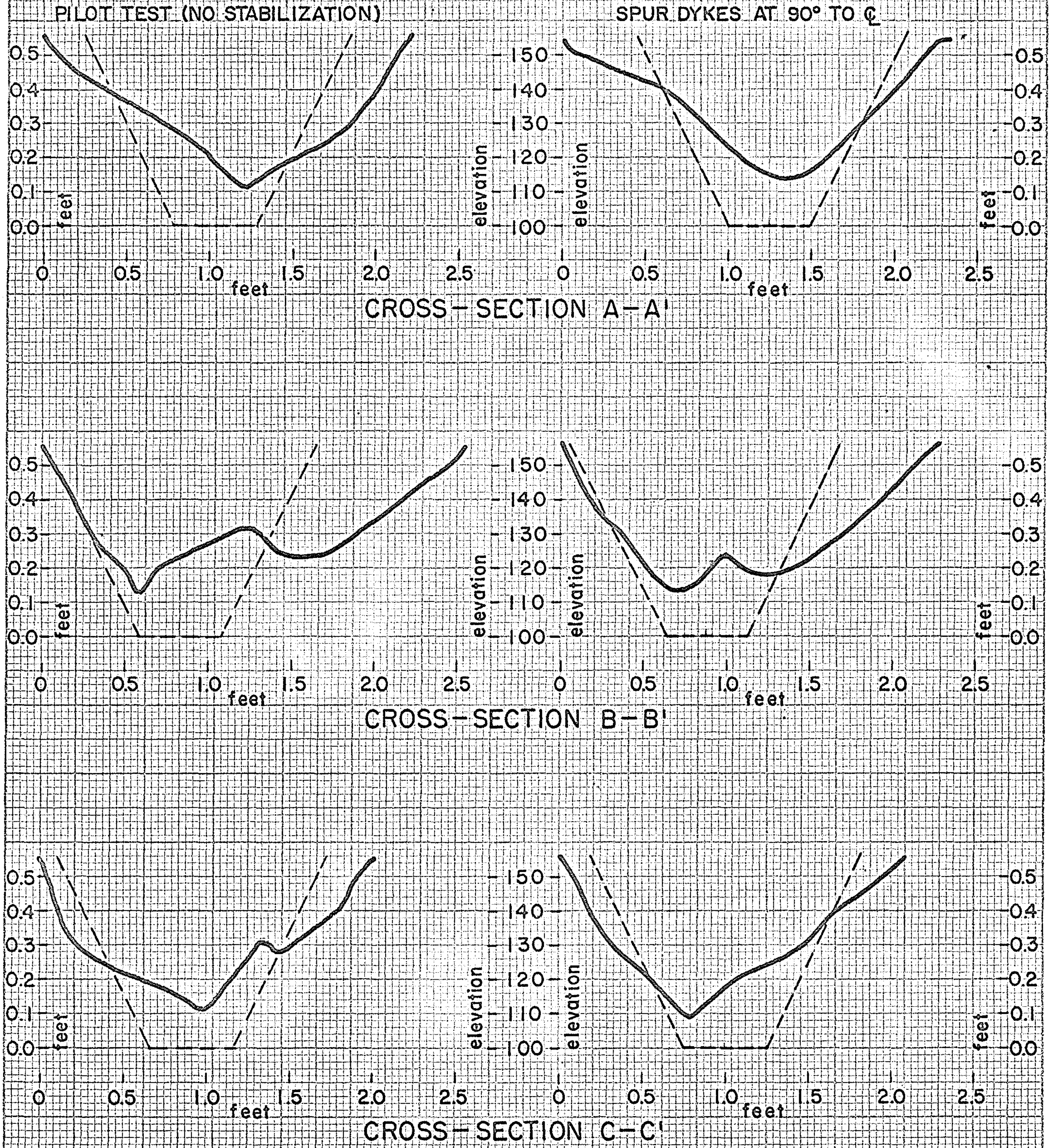
PLATE 44

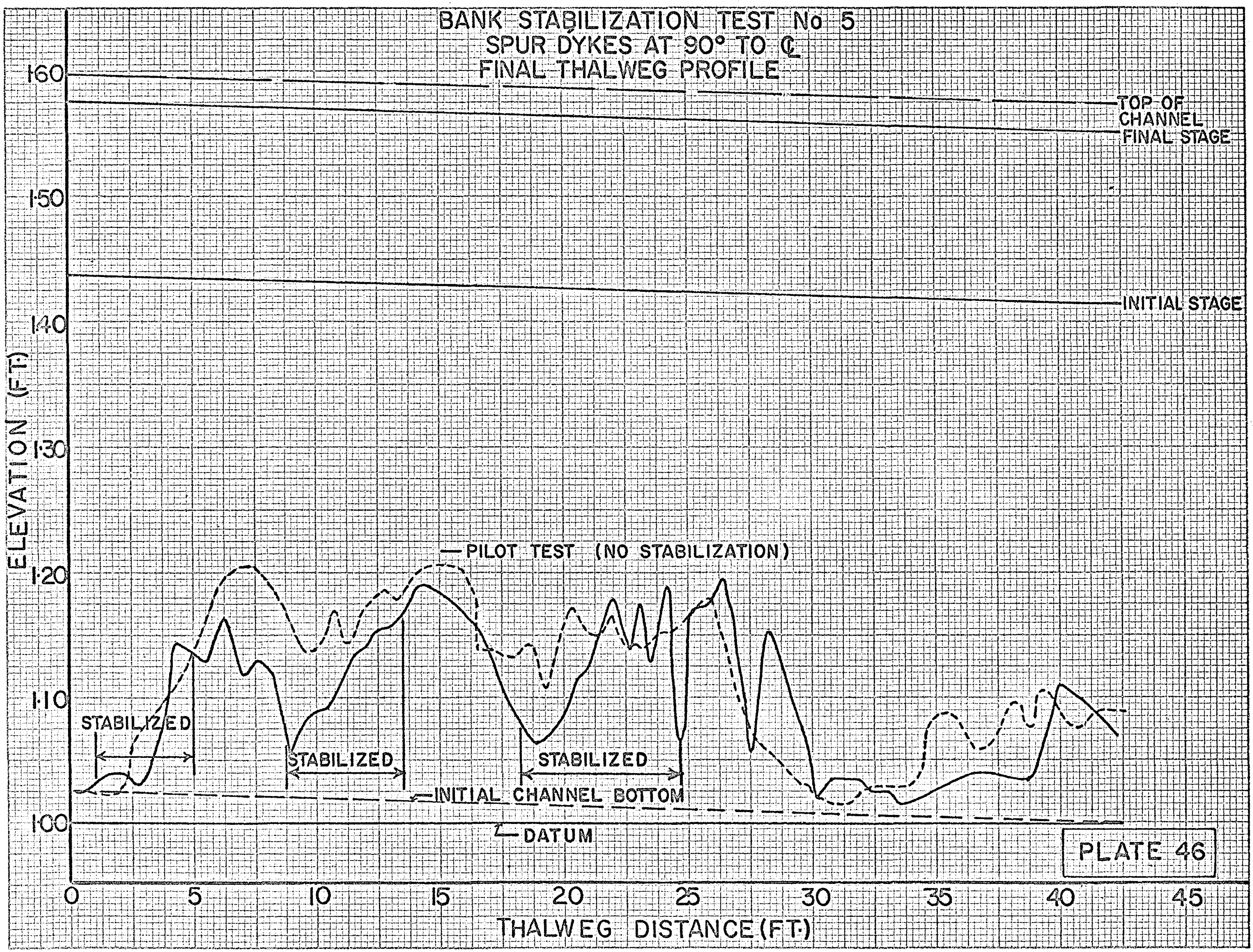
PHOTOGRAPHS - BANK STABILIZATION TEST NO. 5

PLATE 45

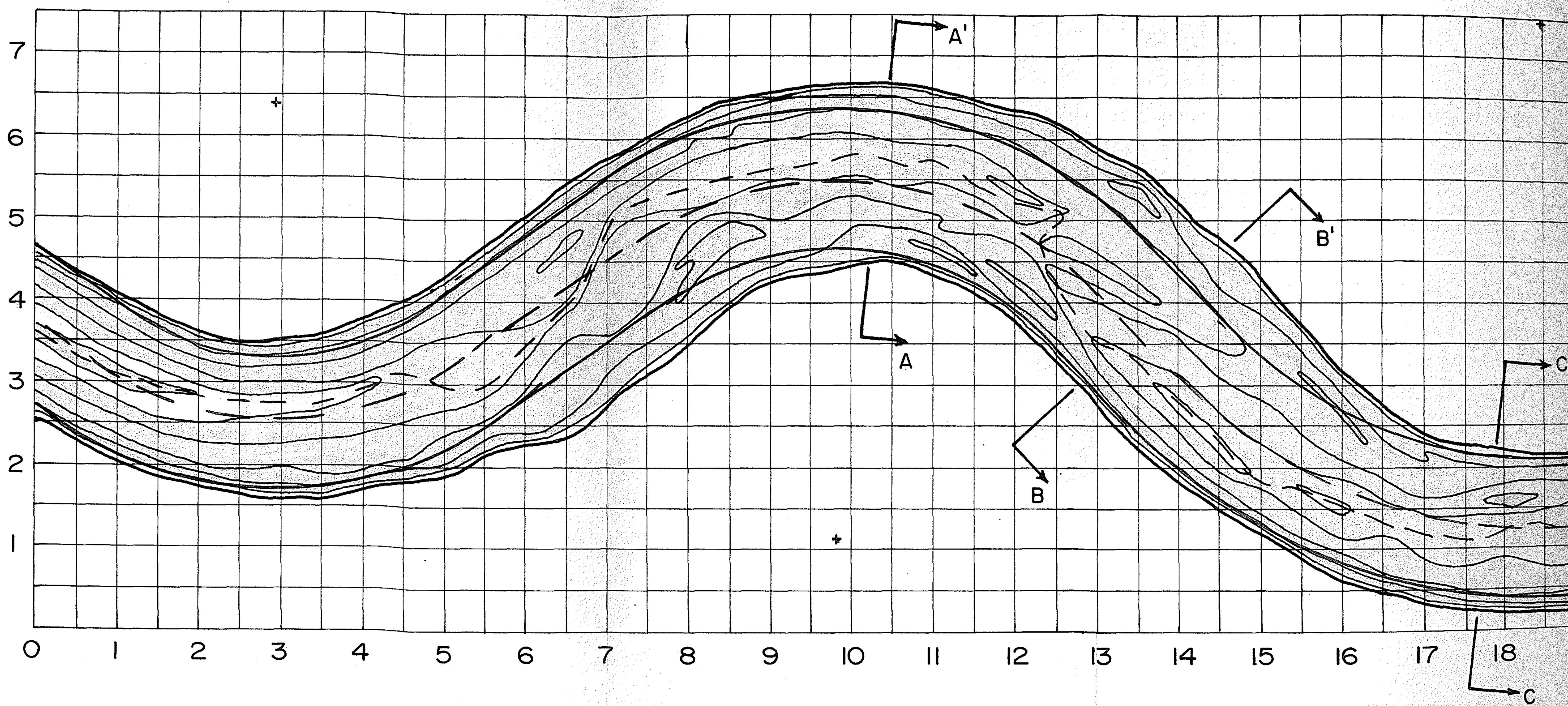
BANK STABILIZATION TEST No. 5
CROSS - SECTIONS.

INITIAL CHANNEL - - - - -
FINAL CHANNEL ———




BANK STABILIZATION TEST No 5
SPUR DYKES AT 90° TO ℄
FINAL THALWEG PROFILE
TOP OF CHANNEL
FINAL STAGE
INITIAL STAGE
PILOT TEST (NO STABILIZATION)
STABILIZED
STABILIZED
STABILIZED
INITIAL CHANNEL BOTTOM
DATUM
ELEVATION (FT.)
1·60
1·50
1·40
1·30
1·20
1·10
1·00
0
5
10
15
20
25
30
35
40
45
THALWEG DISTANCE (FT.)
PLATE 46

HYDROGRAPHIC MAPS OF (
BANK STABILIZATION TE

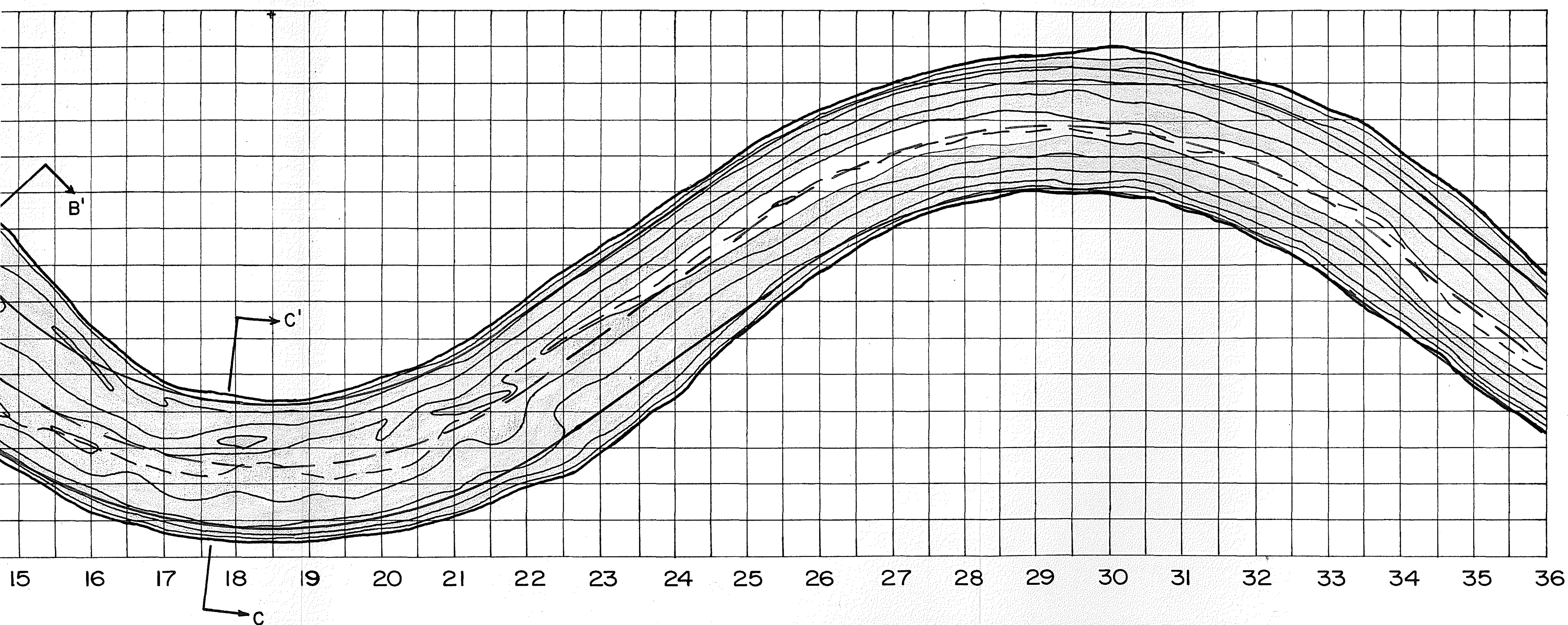


PILOT TEST — NO ST

TEST DURATION 4

DIRECTION OF

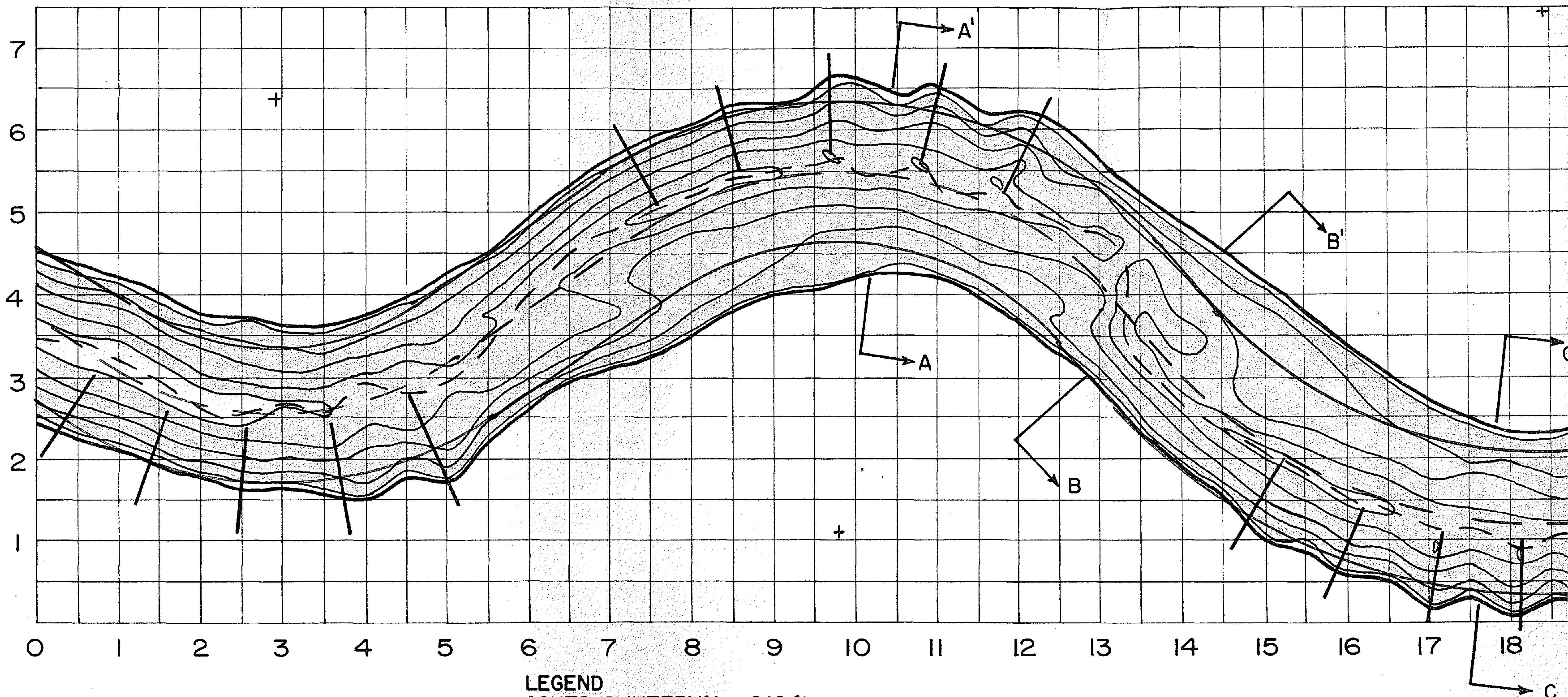
YDROGRAPHIC MAPS OF CHANNELS.
BANK STABILIZATION TEST No. 5.



PILOT TEST – NO STABILIZATION

TEST DURATION 4 HOURS.

DIRECTION OF



LEGEND

CONTOUR INTERVAL—0.10 ft

- .90 – 1.00
- 1.00 – 1.10
- 1.10 – 1.20
- 1.20 – 1.30
- 1.30 – 1.40
- 1.40 – 1.50
- 1.50 – TOP OF CHANNEL

CONTOURS FROM 1.00 DATUM AT DOWNSTREAM END OF INITIAL CHANNEL BOTTOM

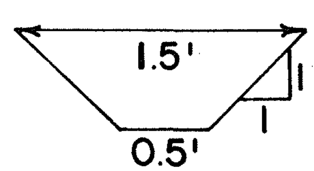
BLACK DASHED LINE – FINAL THALWEG

RED DASHED LINE — INITIAL CENTRE LINE.

SPUR DYKES — /

TEST DATA

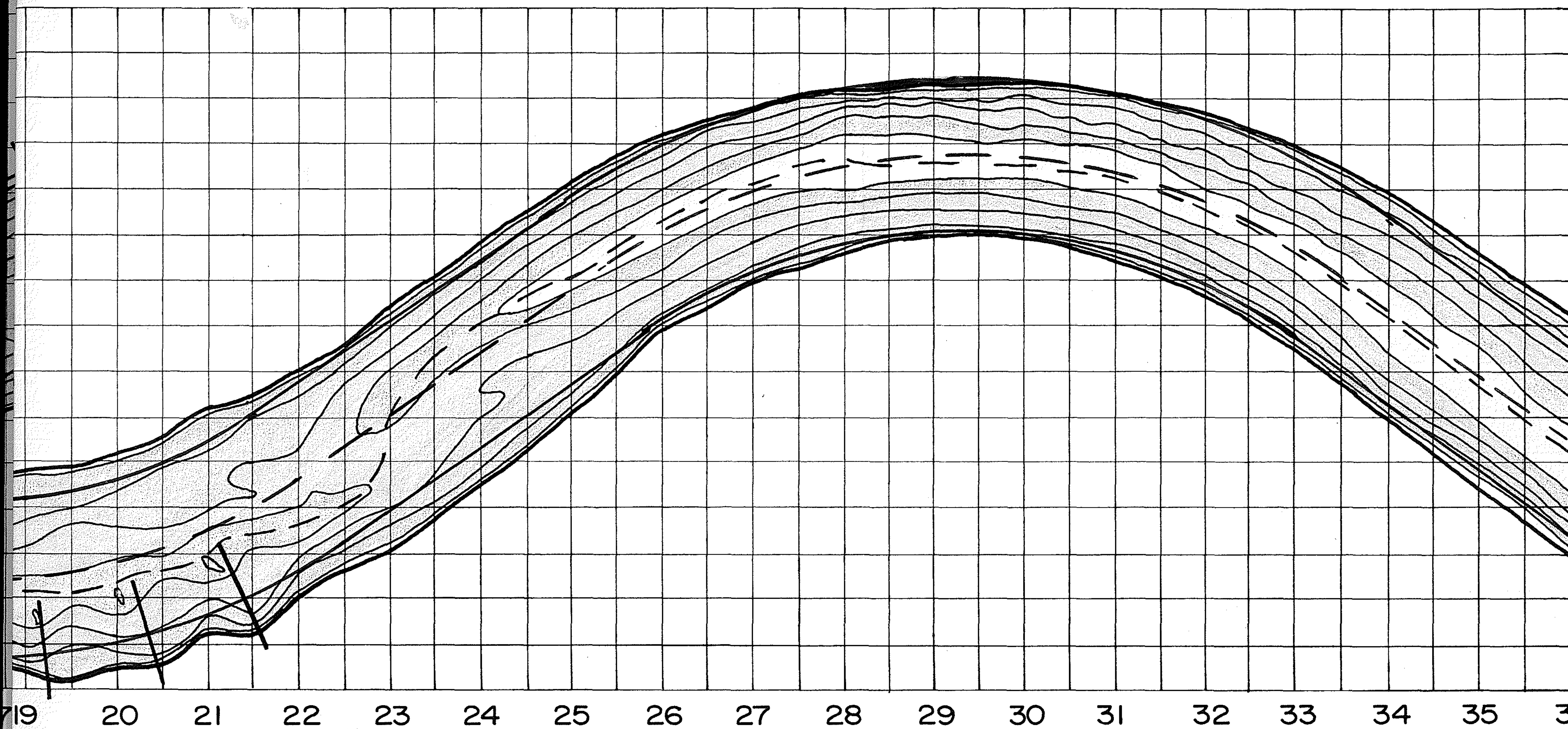
MATERIAL	93 % BRICK SAND
	7 % SILT
DISCHARGE	0.3 CFS (CONSTANT)
VALLEY SLOPE	0.0006



INITIAL CHANNEL

SPUR DYKES PLACED @ 9

TEST DURATION 4



° TO CENTRE LINE.

HOURS

UNIVERSITY OF MANITOBA

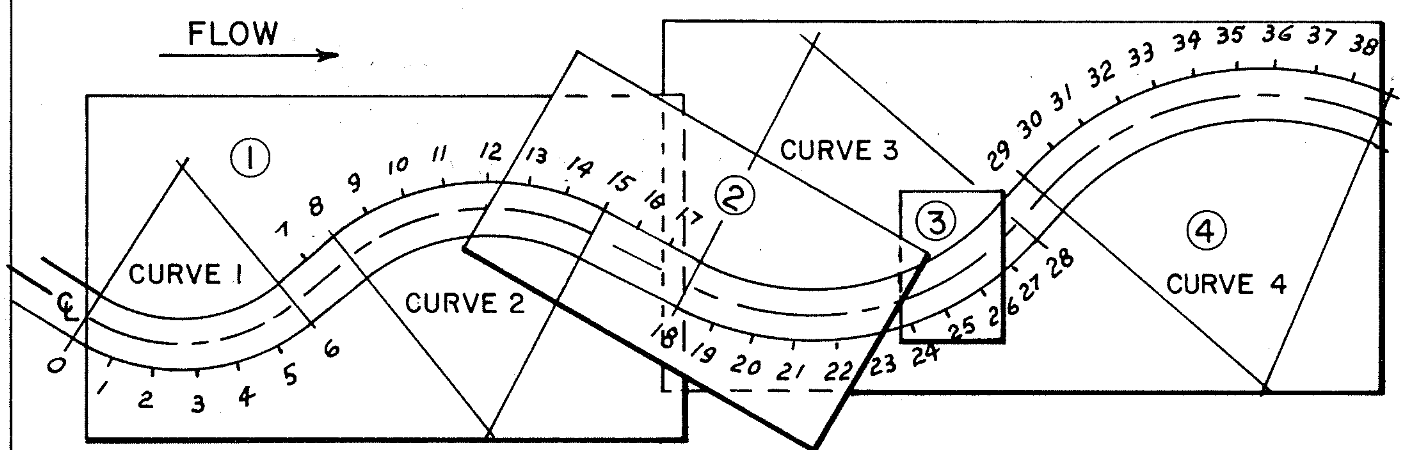
CIVIL ENGINEERING GRADUATE STUDIES
M.Sc. THESIS

"EFFECT OF STABILIZING METHODS
ON BED AND BANK MATERIALS."

AUG. 1965, SCALE: 3/4" = 1', D.A.P.

PLATE 47

PHOTOGRAPH LOCATIONS



CHANNEL

BANK STABILIZATION TEST NO. 6

PHOTOGRAPH 1

PHOTOGRAPH 2

PHOTOGRAPH 3

PHOTOGRAPH 4

PLATE 48

PHOTOGRAPHS - BANK STABILIZATION TEST NO. 6

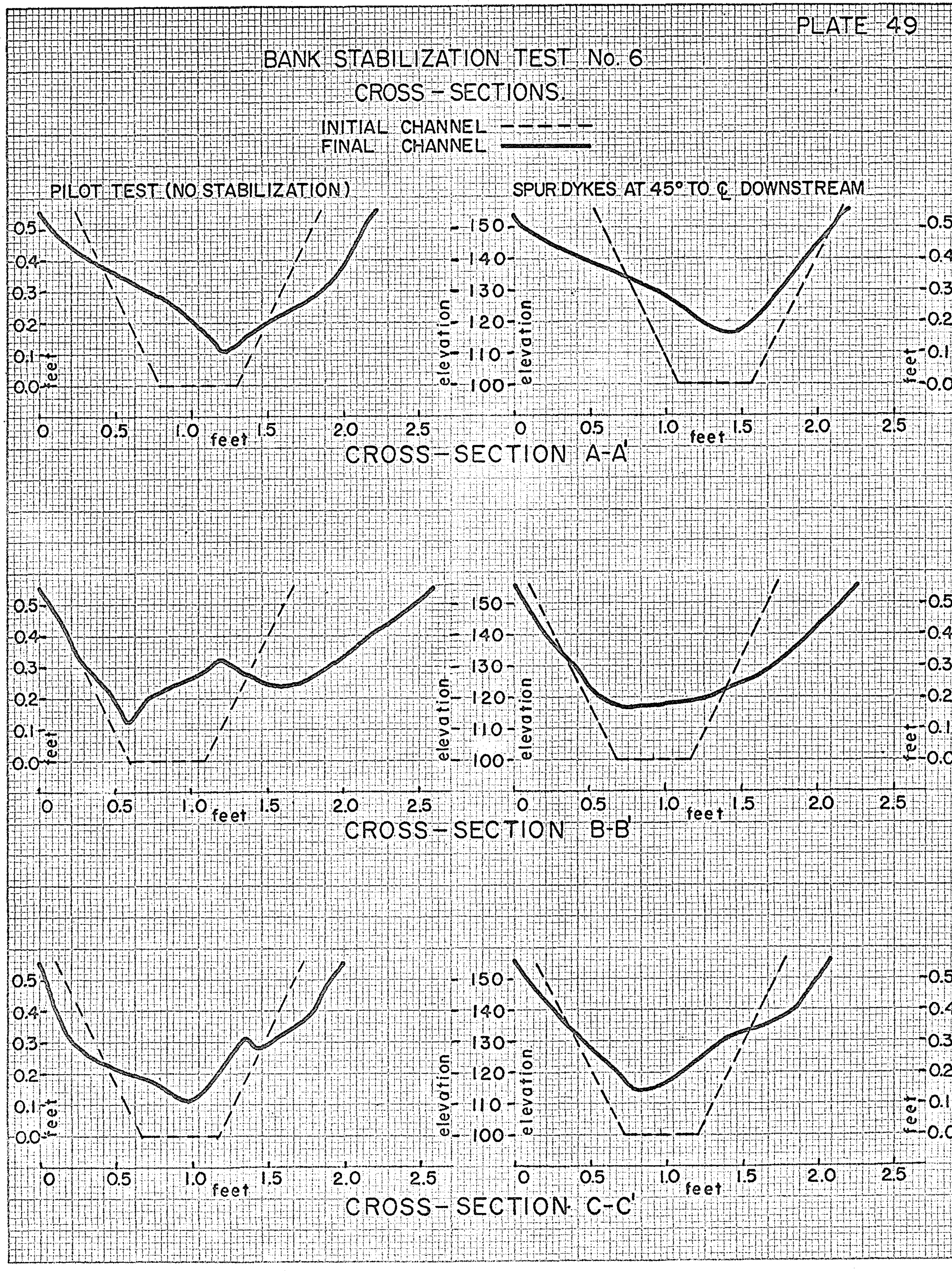


PLATE 49
BANK STABILIZATION TEST No. 6
CROSS-SECTIONS.
INITIAL CHANNEL
FINAL CHANNEL
PILOT TEST (NO STABILIZATION)
SPUR DYKES AT 45° TO ℄ DOWNSTREAM
feet
elevation
CROSS-SECTION A-A'
CROSS-SECTION B-B'
CROSS-SECTION C-C'

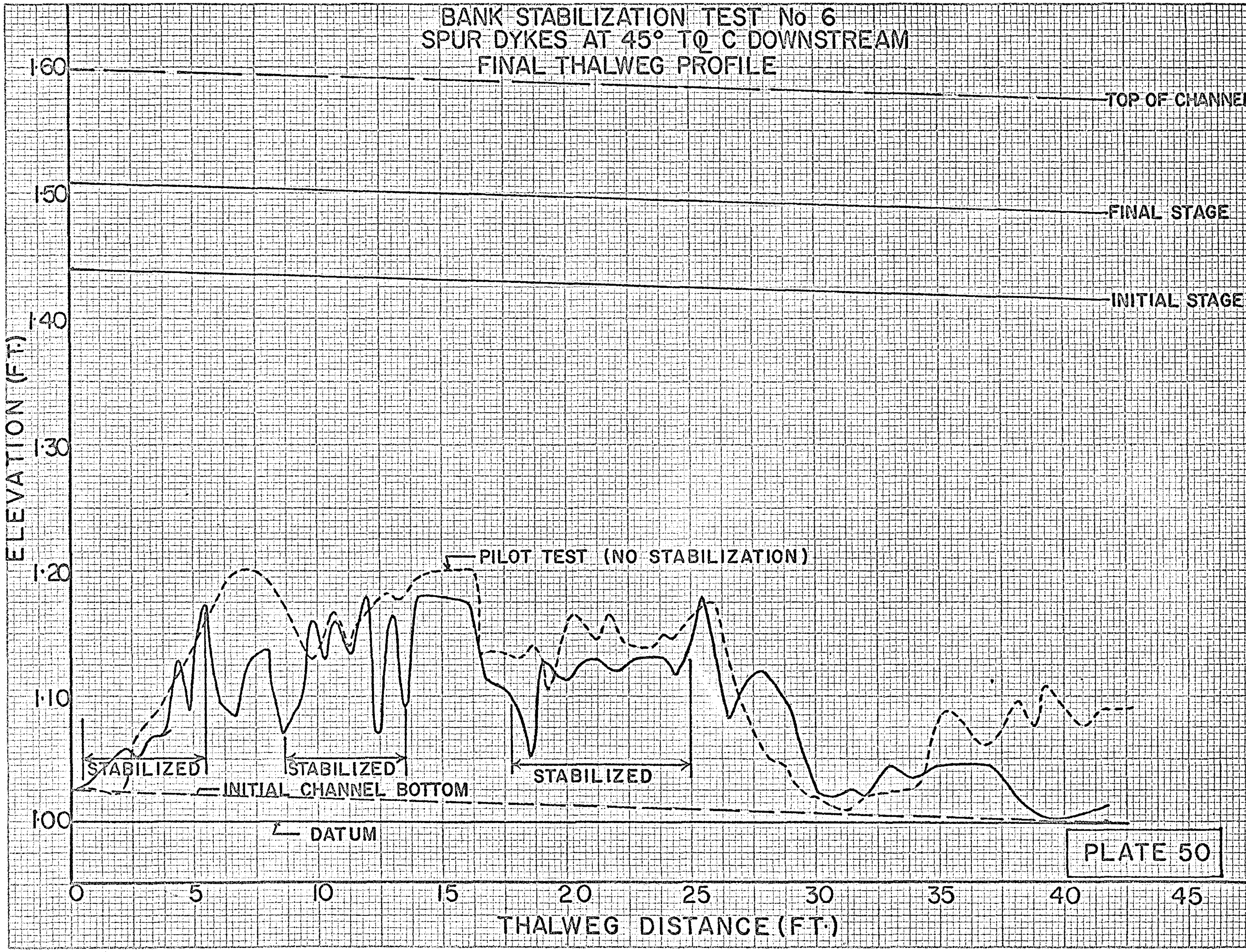
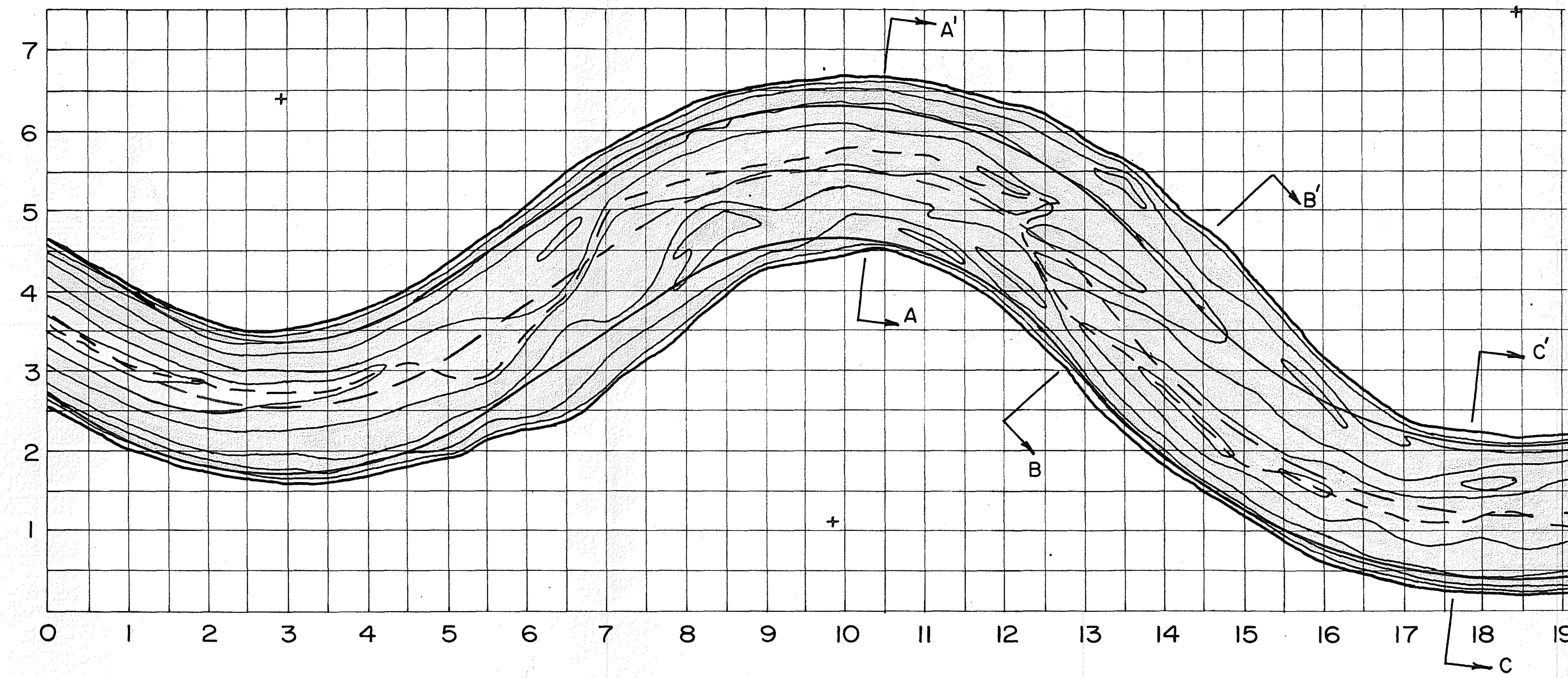

BANK STABILIZATION TEST No 6
SPUR DYKES AT 45° TO C DOWNSTREAM
FINAL THALWEG PROFILE
TOP OF CHANNEL
FINAL STAGE
INITIAL STAGE
PILOT TEST (NO STABILIZATION)
STABILIZED
STABILIZED
STABILIZED
INITIAL CHANNEL BOTTOM
DATUM
ELEVATION (FT.)
1·60
1·50
1·40
1·30
1·20
1·10
1·00
0
5
10
15
20
25
30
35
40
45
THALWEG DISTANCE (FT.)

PLATE 50

HYDROGRAPHIC MAPS OF C
BANK STABILIZATION TE



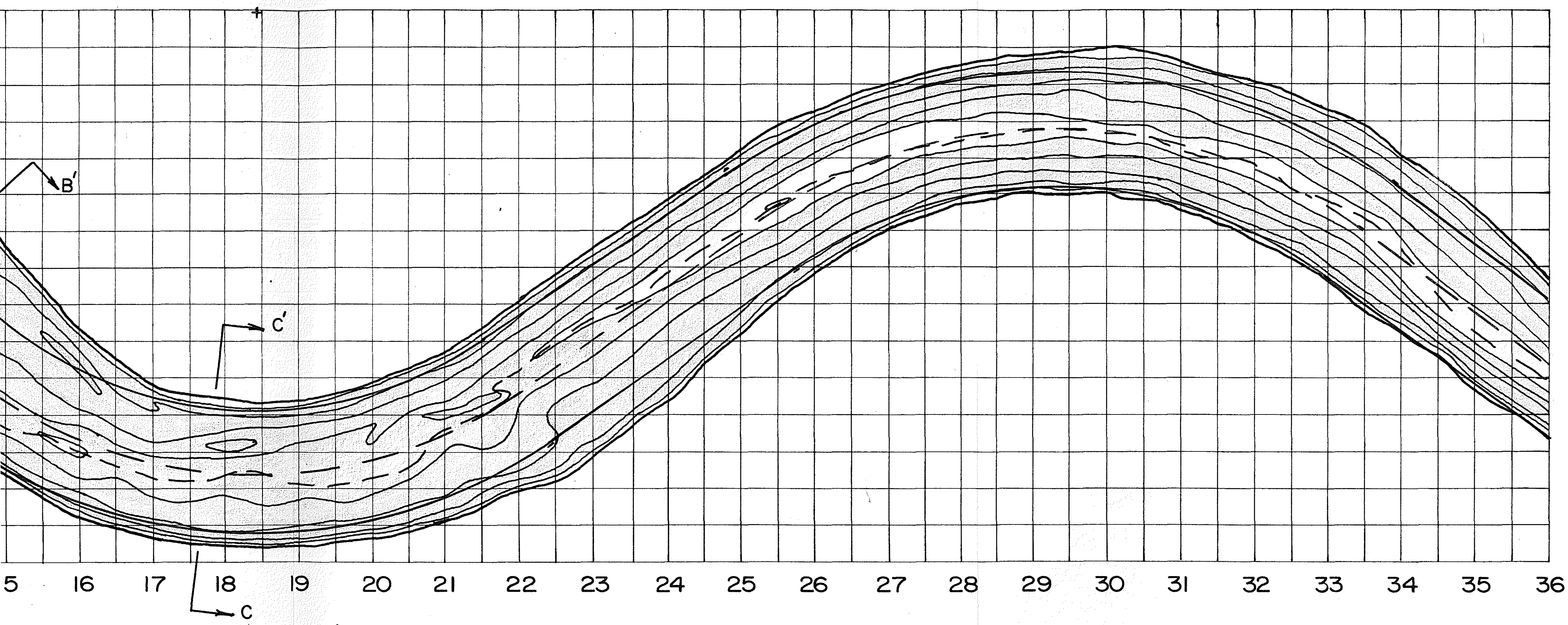
PILOT TEST — NO STA

TEST DURATION 4 H

DIRECTION OF
FLOW

DROGRAPHIC MAPS OF CHANNELS.

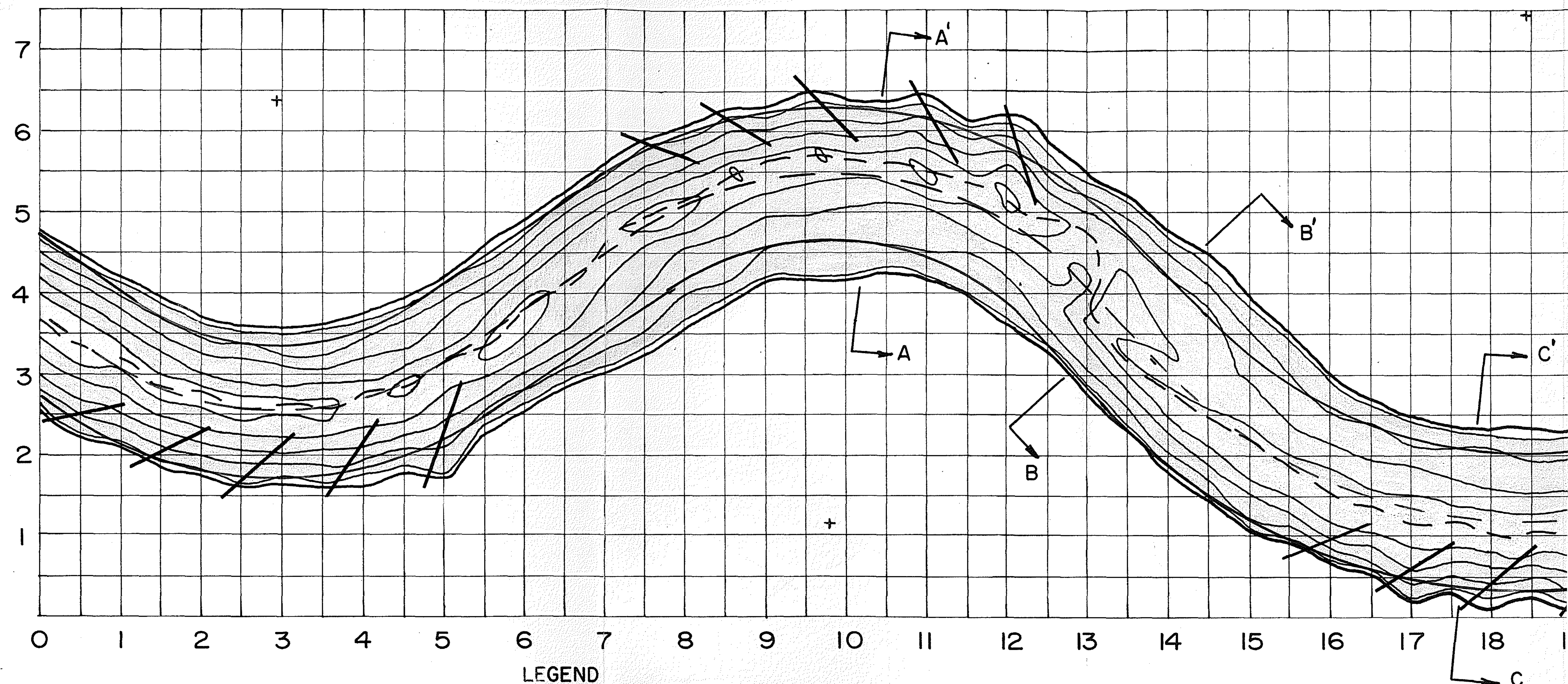
BANK STABILIZATION TEST No. 6.



PILOT TEST — NO STABILIZATION

TEST DURATION 4 HOURS.

DIRECTION OF



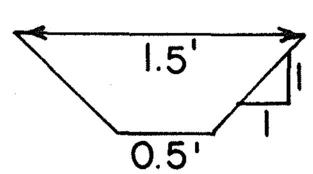
LEGEND
CONTOUR INTERVAL—0.10 ft

	.900 — 1.00
	1.00 — 1.10
	1.10 — 1.20
	1.20 — 1.30
	1.30 — 1.40
	1.40 — 1.50
	1.50 — TOP OF CHANNEL

CONTOURS FROM 1.00 DATUM AT DOWNSTREAM END OF INITIAL CHANNEL BOTTOM
BLACK DASHED LINE – FINAL THALWEG
RED DASHED LINE — INITIAL CENTRE LINE.
SPUR DYKES — /

TEST DATA

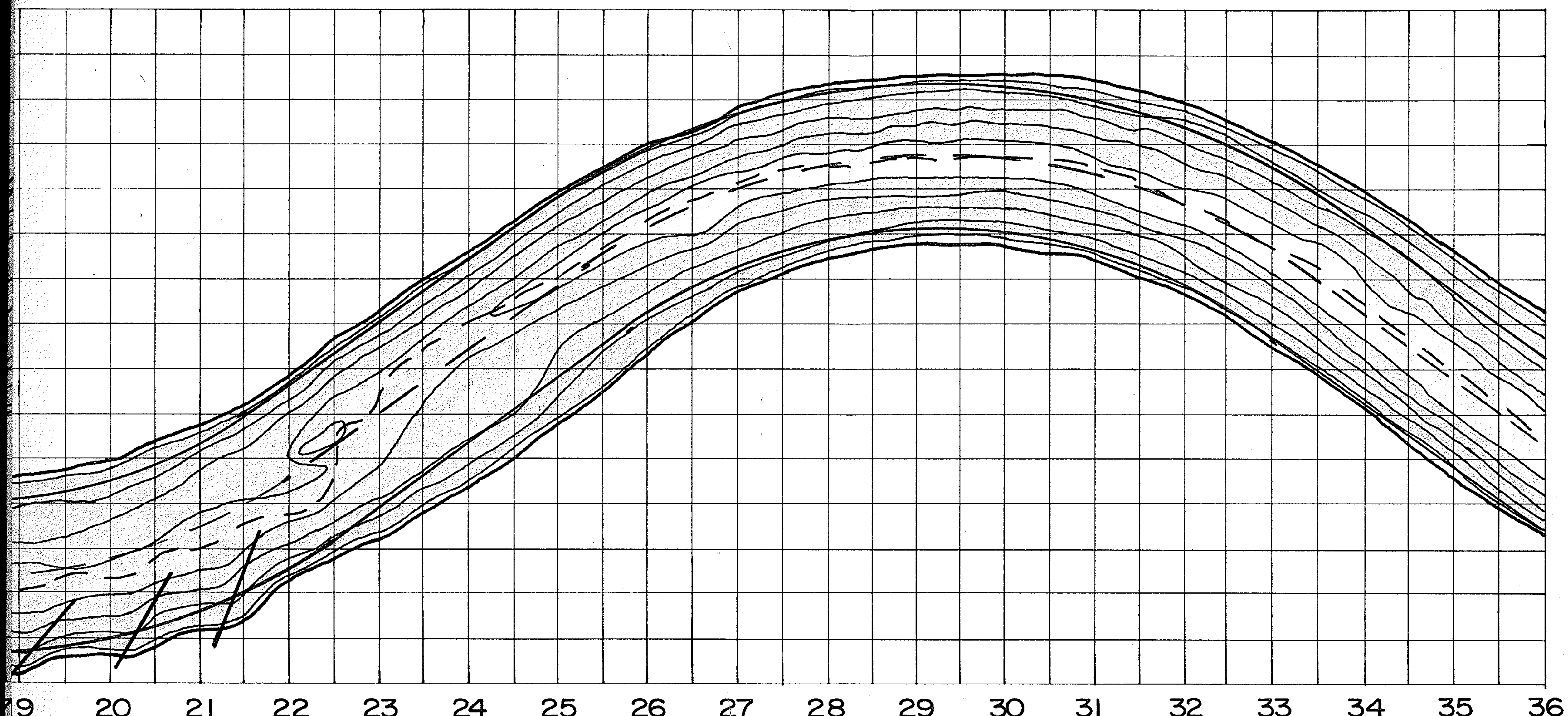
MATERIAL	93 % BRICK SAND
	7 % SILT
DISCHARGE	0.3 CFS (CONSTANT)
VALLEY SLOPE	0.0006



INITIAL CHANNEL

SPUR DYKES PLACED @ 45° T

TEST DURATION 4



O ℄ DOWNSTREAM

HOURS

UNIVERSITY OF MANITOBA

CIVIL ENGINEERING GRADUATE STUDIES
M.Sc. THESIS

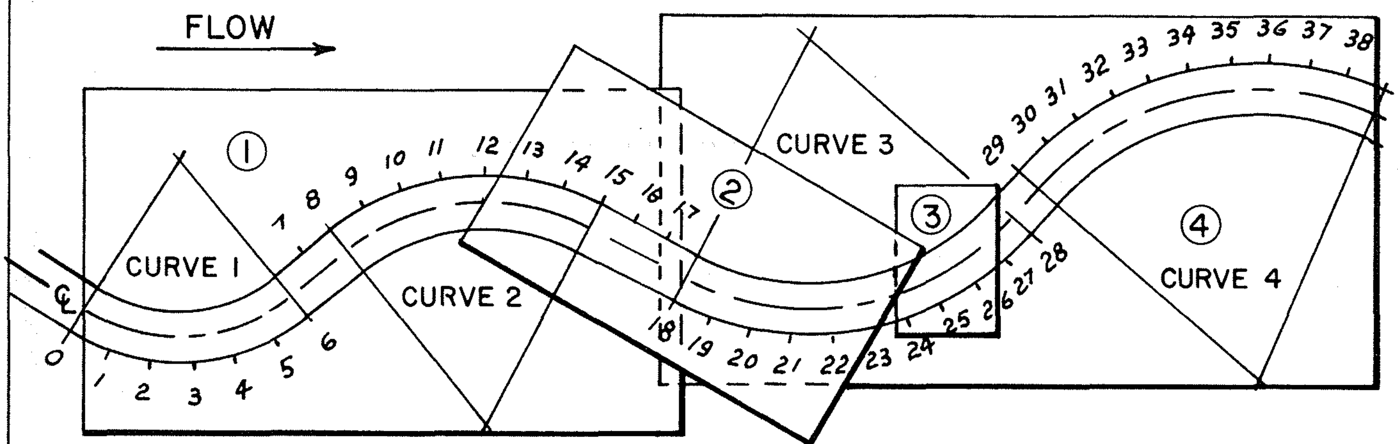
"EFFECT OF STABILIZING METHODS
ON BED AND BANK MATERIALS."

AUG. 1965, SCALE: 3/4" = 1', D.A.P.

PLATE 51

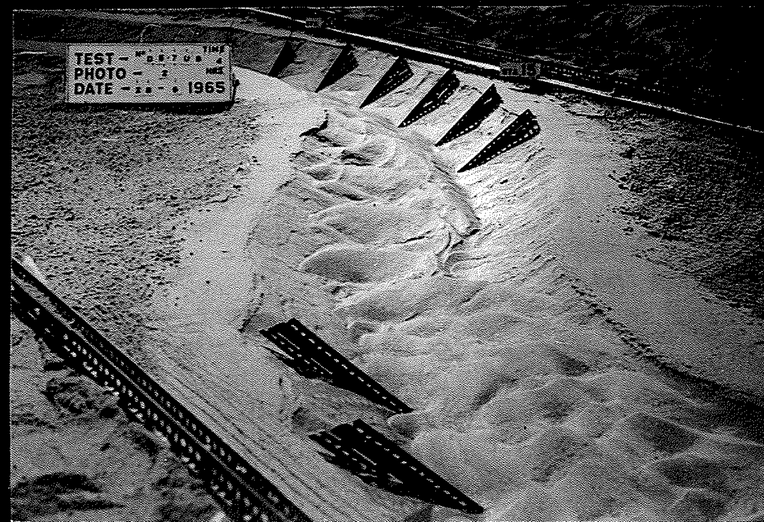
BANK STABILIZATION TEST NO. 7

PHOTOGRAPH LOCATIONS



CHANNEL

PHOTOGRAPH 1



PHOTOGRAPH 2

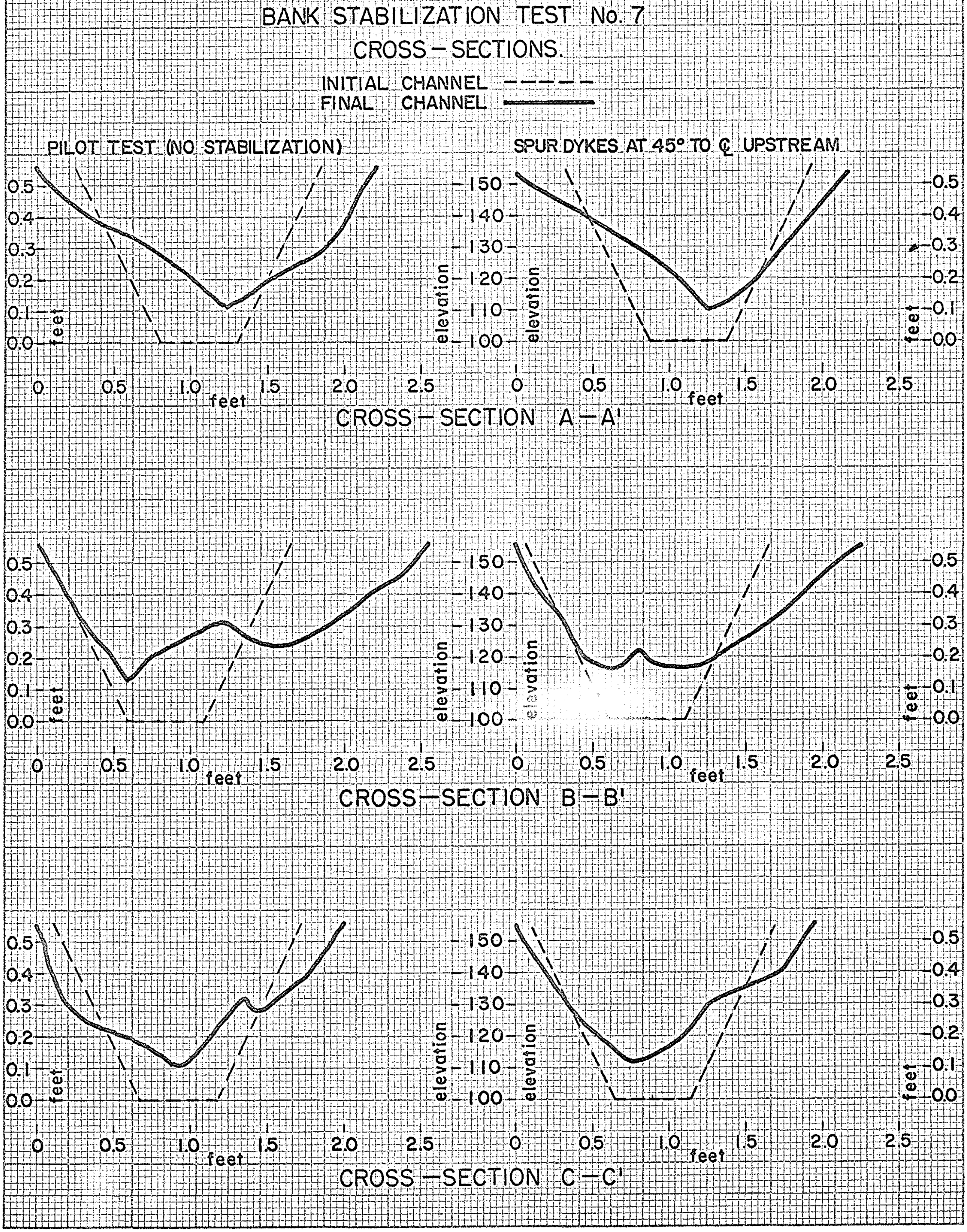
PHOTOGRAPH 3

PHOTOGRAPH 4

PLATE 52

PHOTOGRAPHS - BANK STABILIZATION TEST NO. 7

PLATE 53


BANK STABILIZATION TEST No. 7
CROSS-SECTIONS.
INITIAL CHANNEL
FINAL CHANNEL
PILOT TEST (NO STABILIZATION)
SPUR DYKES AT 45° TO ℄ UPSTREAM
0.5
0.4
0.3
0.2
0.1
0.0
feet
150
140
130
120
110
100
elevation
0
0.5
1.0
1.5
2.0
2.5
CROSS-SECTION A-A'
CROSS-SECTION B-B'
CROSS-SECTION C-C'

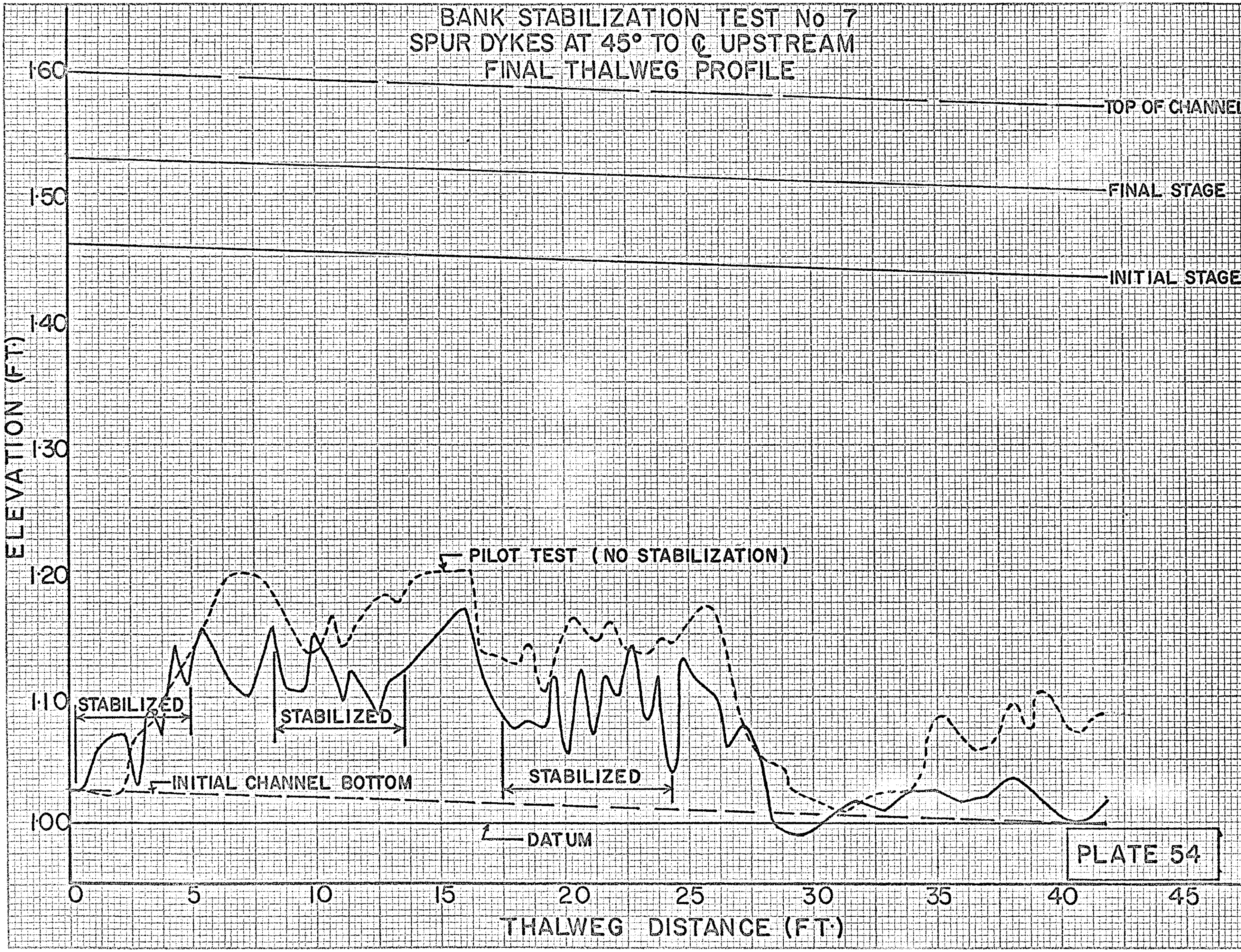
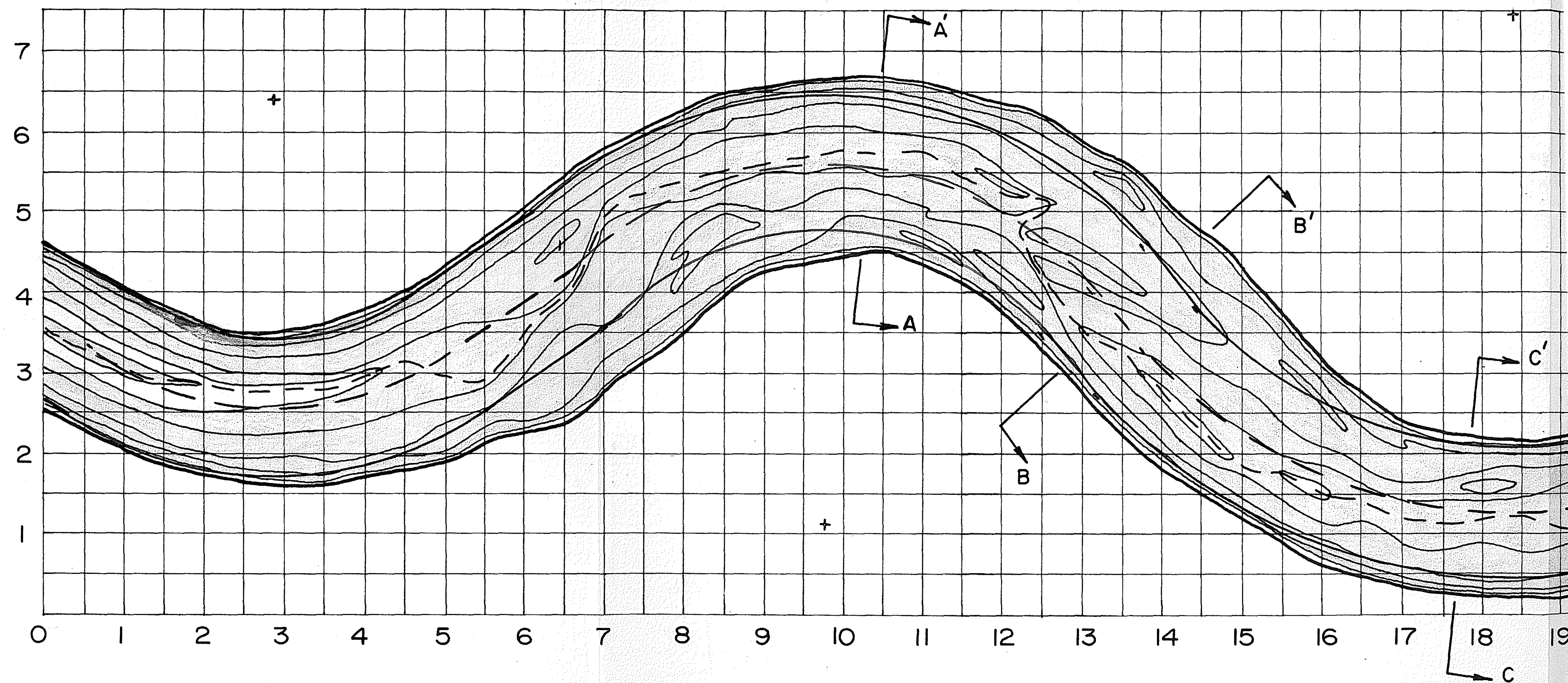

BANK STABILIZATION TEST No 7
SPUR DYKES AT 45° TO ℄ UPSTREAM
FINAL THALWEG PROFILE
TOP OF CHANNEL
FINAL STAGE
INITIAL STAGE
PILOT TEST (NO STABILIZATION)
STABILIZED
STABILIZED
STABILIZED
INITIAL CHANNEL BOTTOM
DATUM
ELEVATION (FT)
1·60
1·50
1·40
1·30
1·20
1·10
1·00
0
5
10
15
20
25
30
35
40
45
THALWEG DISTANCE (FT)

PLATE 54

HYDROGRAPHIC MAPS OF C
BANK STABILIZATION TE

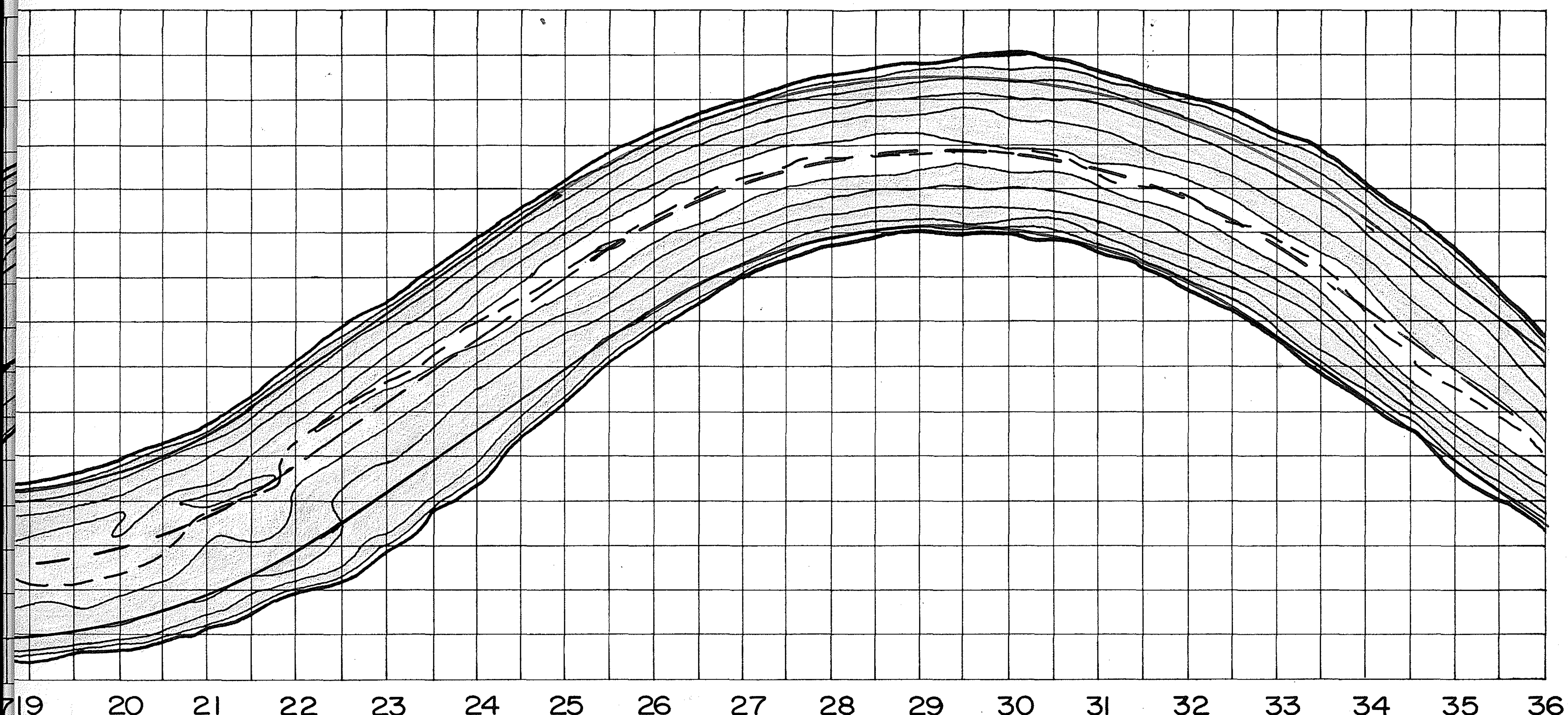


PILOT TEST – NO STA

TEST DURATION 4 H

DIRECTION OF

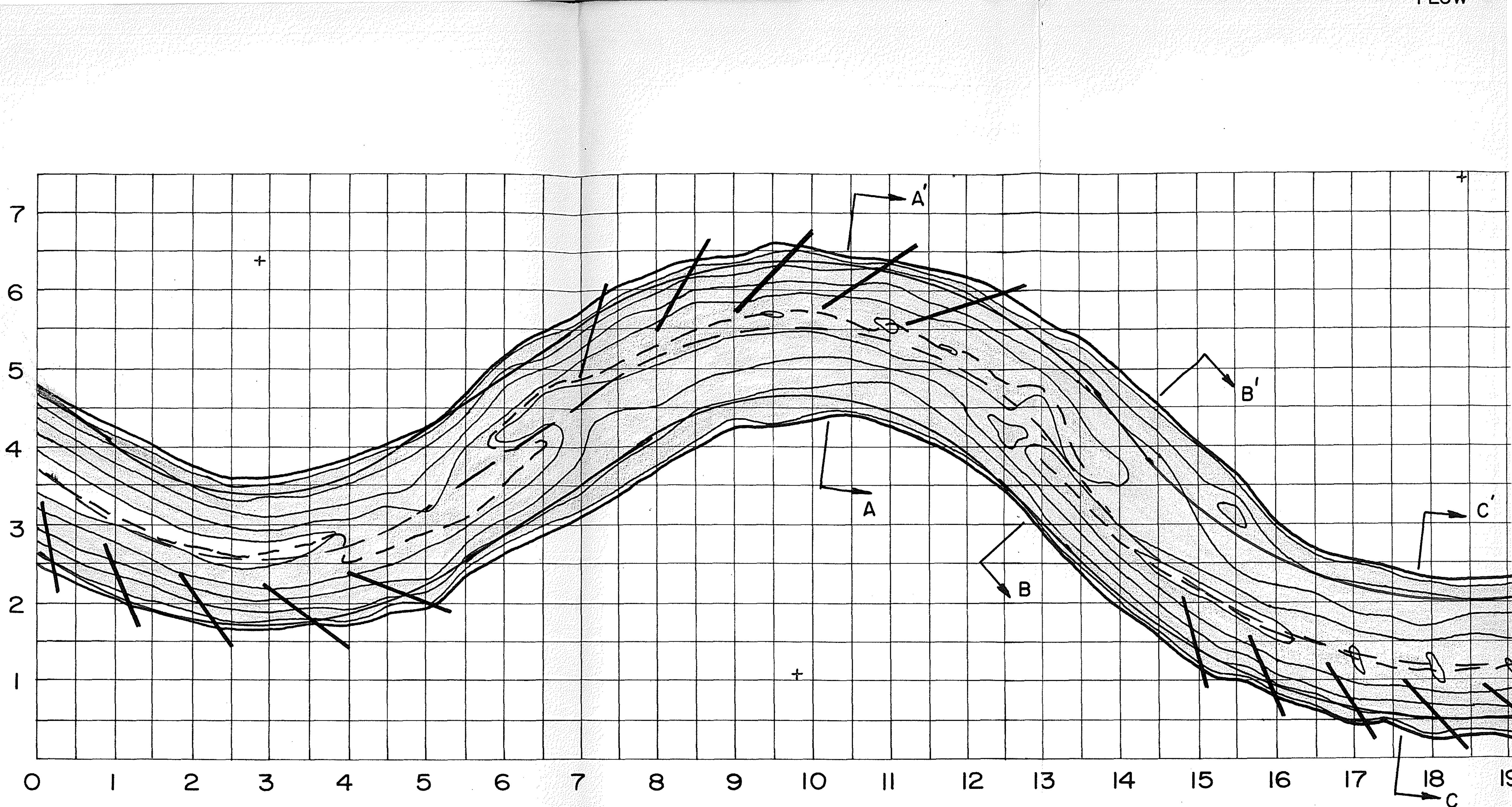
CHANNELS.
EST No. 7.



TABILIZATION

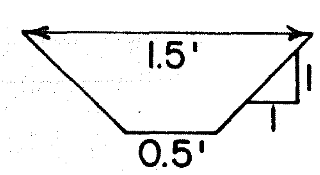
HOURS.

F



TEST DATA

MATERIAL	93 % BRICK SAND 7 % SILT
DISCHARGE	0.3 CFS (CONSTANT)
VALLEY SLOPE	0.0006



INITIAL CHANNEL

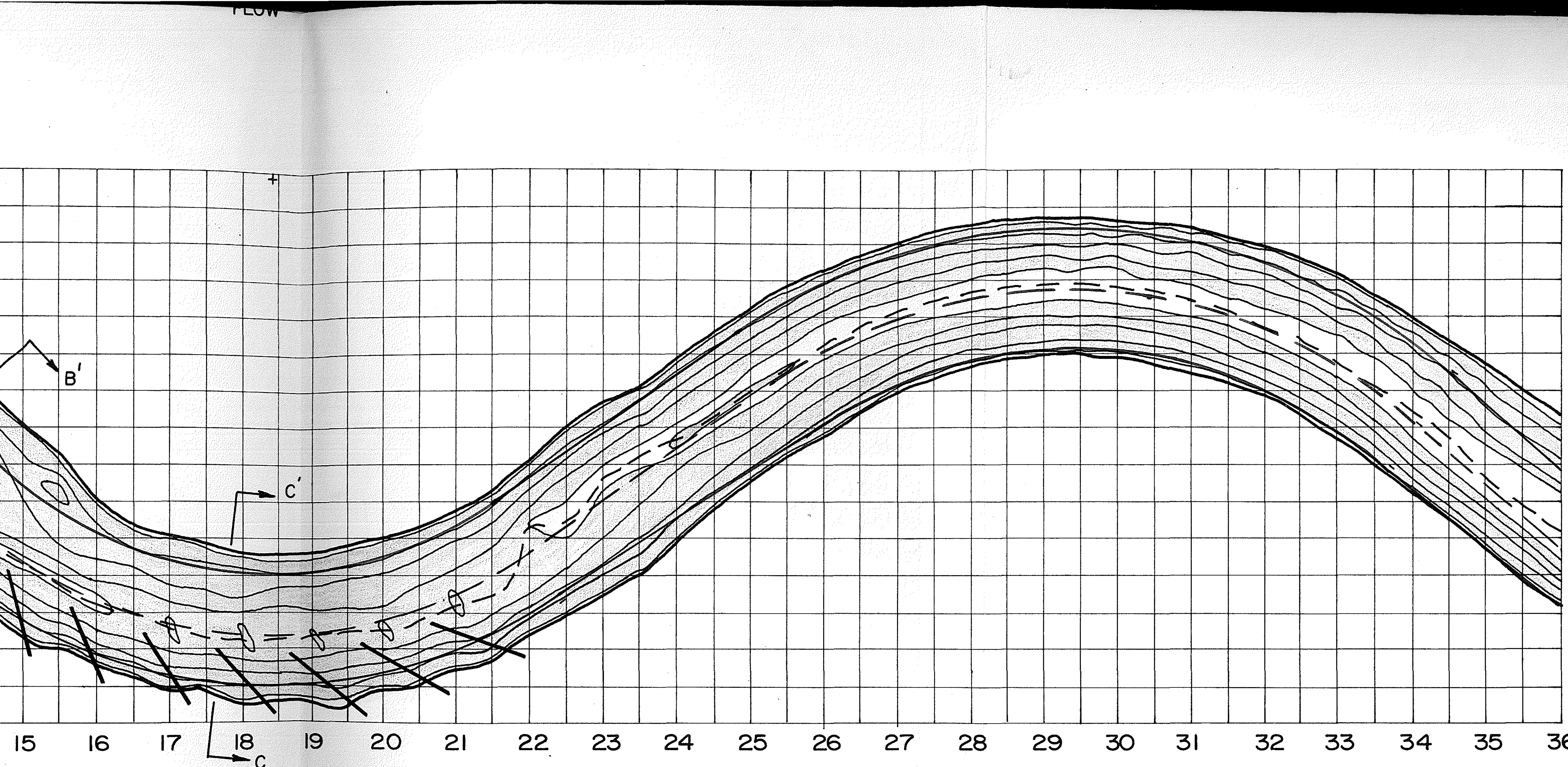
LEGEND
CONTOUR INTERVAL - 0.10 ft

.90 — 1.00
1.00 — 1.10
1.10 — 1.20
1.20 — 1.30
1.30 — 1.40
1.40 — 1.50
1.50 — TOP OF CHANNEL

CONTOURS FROM 1.00 DATUM AT DOWNSTREAM END OF INITIAL CHANNEL BOTTOM
BLACK DASHED LINE — FINAL THALWEG
RED DASHED LINE — INITIAL CENTRE LINE.
SPUR DYKES — /

SPUR DYKES PLACED @ 45°

TEST DURATION 4 H



R DYKES PLACED @ 45° TO ℄ UPSTREAM.

TEST DURATION 4 HOURS

UNIVERSITY OF MANITOBA

CIVIL ENGINEERING GRADUATE STUDIES
M.Sc. THESIS

"EFFECT OF STABILIZING METHODS ON BED AND BANK MATERIALS."

AUG. 1965, SCALE: 3/4" = 1', D.A.P.

PLATE 55