

LAUNCHING OF RIPRAP REVETMENTS

a

thesis

submitted to the

Faculty of Graduate Studies

in partial fulfillment of the requirements

for the degree of Master of Science in the

Department of Civil Engineering

University of Manitoba

Winnipeg

by

J. A. Redhead, B.Sc.

Calgary, Alberta

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ABSTRACT

A hydraulic model study was undertaken to investigate launching of riprap revetments placed on the bend of a trapezoidal laboratory channel and to assess the performance of the launched revetments vs a placed revetment. The launched revetment forms when a stockpile of stone on a river bank (embankment) or on top of a bank (embankment) rolls into and armours the side of a scour hole. A placed revetment is constructed on the bank to prevent additional loss of bank material.

The extent of scour and the depth of scour for each of the protection systems used are compared and related to the performance of each.

The launching of a revetment, while dumping with mechanical devices was in progress, was simulated in the model and the performance of this type of revetment was compared to revetments launched by displacement from a previously dumped collection of stones placed on a bench above high water. Findings show that less bank material is lost and a more regular revetment is obtained when using the latter system.

The loss of riprap to the flow should not endanger the stability of the revetment. The loss of riprap for each system was compared. The study indicated, that although the loss to the centre of the stream was greater for the launched revetments than the placed revetments, very effective protection is provided even with some loss of riprap material.

The material in the model (crushed walnut shell) represented a channel having banks and bed of sand. The performance of revetments having different gradations of stone were compared with respect to movement in the scour hole and the regularity of the final structure. Small pebbles were used to represent the riprap material in the model.

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1. INTRODUCTION

1.1 Statement of the Problem

During periods of high discharge the erosive forces within a river are increased. The typical materials making up the bed and banks of rivers are not always resistant enough to the attack to which they are subjected. Outward movement and sloughing of bank material, especially within bends, may cause the loss of potentially valuable land and may endanger important structures located near the banks of eroding rivers. To control the erosion and migration of banks, it is often necessary to construct river bank protection structures known as revetments.

1.2 Previous Work

Launching is the process whereby stones slide or roll from a higher elevation on a river bank or embankment to a lower elevation. A method of providing continuous protection using a launched revetment was first attempted in India as far back as the 1890's. From 1890 onwards, investigations into the launching of riprap have been undertaken by the U.S. Bureau of Public Roads, the U.S. Corps of Engineers, the California Highway Division and Research Stations in India. Many structures have been built in the United States and in India utilizing the launching of riprap as an alternative to the placed revetment for the protection of river banks.

1.3 Limit of Undertaking

This study was limited to the testing of a hydraulic model to observe, firstly, the launching of riprap (stone) on a 90 degree bend of a trapezoidal channel and secondly, to observe how the various revetment configurations affected the scour and erosion processes taking place within the bend. Observations were also made to develop guidelines concerning the placement of riprap structures and armour material on the face of endangered banks. Results will be discussed more from a qualitative than a quantitative point of view. No measurements of instantaneous velocities were possible because of the difficulty in taking instantaneous measurements near an erodible bed and because of the small scale of the model.

1.4 Justification of the Topic

Should the launching of revetments be effective in providing adequate bank protection, recommendations for further studies will be made and conclusions drawn as to the usefulness of this approach to bank protection. The launched riprap revetment could be an ideal alternative to the "placed" revetment in areas that may be difficult to work in, either for construction or maintenance reasons. It is necessary, therefore, to investigate the launching system to obtain information on the extent of the revetment, the placement of stones and the effectiveness of the structure.

1.5 Preview

A summary of the various types of riprap revetments and the various methods of placement will be presented. Two gradations of stone used for the revetments were tested to observe the effect of stone size on the performance of the revetments. The manner in which the location and extent of the revetment affects the loss of bank material and the stability of the revetments were investigated.

2. RIPRAP REVETMENTS FOR RIVER BANK PROTECTION

2.1 Introduction

The development of farms, towns and cities on the flood plains of rivers introduced the need for river bank protection devices. Stone and wood were used exclusively until the advent of concrete and metal. Wood, being less durable, has fallen out of the list of materials most suited to bank protection. Stone is considered to be one of the most suitable materials for bank protection.

Bank protection structures are required for four main reasons. These are:

1. To aid navigation on our rivers. Firstly, to provide adequate depth of water for ships and other floating craft by restricting the widening of rivers at suitable locations and thereby encouraging deepening and secondly, to protect cargo handling facilities;
2. To prevent the loss of valuable river property;
3. To protect major engineering works, e.g. roads, bridges and pipelines, etc.;
4. To prevent flooding. Increasing the river's capability for conveying water at higher velocities, helps to reduce the level to which flood waters rise at specific locations.

If protective measures are considered, there are three methods that may be used to obtain the necessary protection.

These are as follows:

1. The attacking water can be turned away by structures such as spurs;
2. The destructive force of the water can be reduced by using permeable jetties or retards which add additional roughness to the channel and retard the flow, thereby causing a reduction in velocity;
3. The endangered area can be armoured to withstand the full force of the attacking water. The armouring layer or structure is called a revetment.

The subject of this thesis is the riprap revetment.

A brief discussion of the various types of riprap revetments will be presented in the following sections.

2.2

Revetments

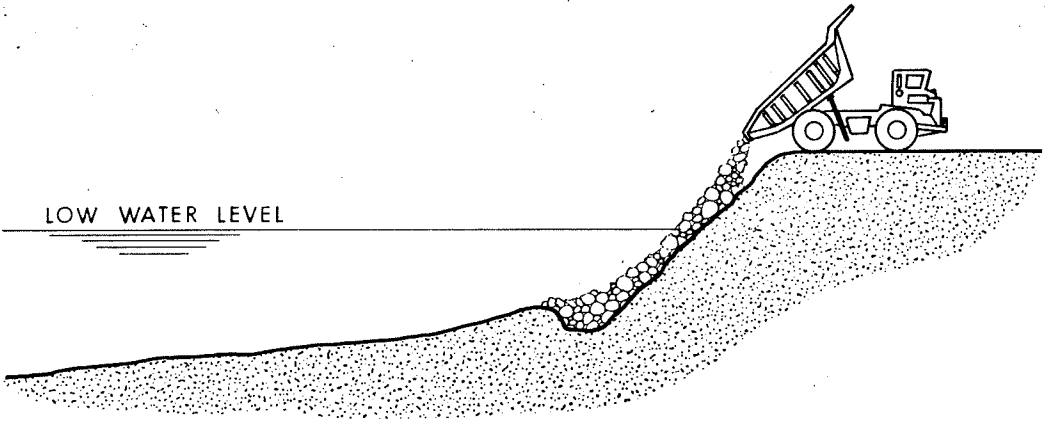
A revetment is a continuous artificial lining laid on a river bank to protect against the forces of erosion and scour. Revetments may be flexible or rigid depending on the materials used and are usually placed on the concave banks of rivers where the forces of erosion and scour are generally greatest. Revetments may be constructed of ordinary stone (called riprap), with wood in the form of a mattress, with wire cages (called gabions) holding stone and concrete either in sacks or in the form of blocks and/or cells. The three types of riprap revetments are dumped riprap, hand placed riprap and grouted riprap. The three types will be briefly discussed.

2.2.1 Dumped Riprap Revetment

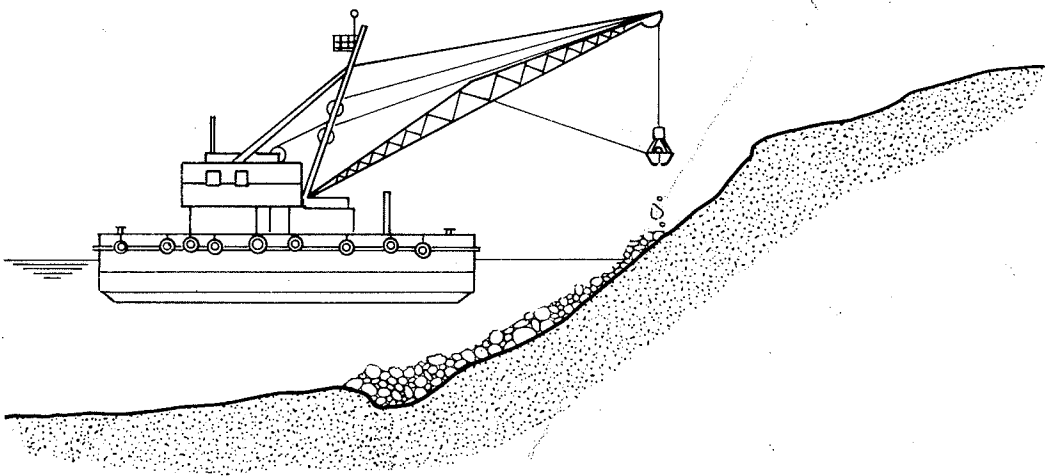
A dumped riprap revetment is formed by the dumping of large stones onto the bank of a river from trucks, barges or cranes, or by pushing the stones over the top of the bank with a bulldozer. The latter method is not recommended because of the possibility of damage to the stones, filter layer or the surface of the slope. The structure is flexible and can tolerate movement of individual stones and/or the foundation material. To improve the performance of the revetment the slope is trimmed to eliminate protruding tree stumps and rock or stone outcrops. A filter layer is added if loss of bank material is likely through the revetment. The filter is graded so that the material from the bank does not move through the filter and the material from the filter does not move through the riprap. To safeguard the revetment, an apron or mattress of resistant material is constructed at the toe of the revetment to ensure its stability. Figure 1 shows the various methods of placing a dumped riprap revetment.

2.2.2 Hand Placed Riprap Revetment

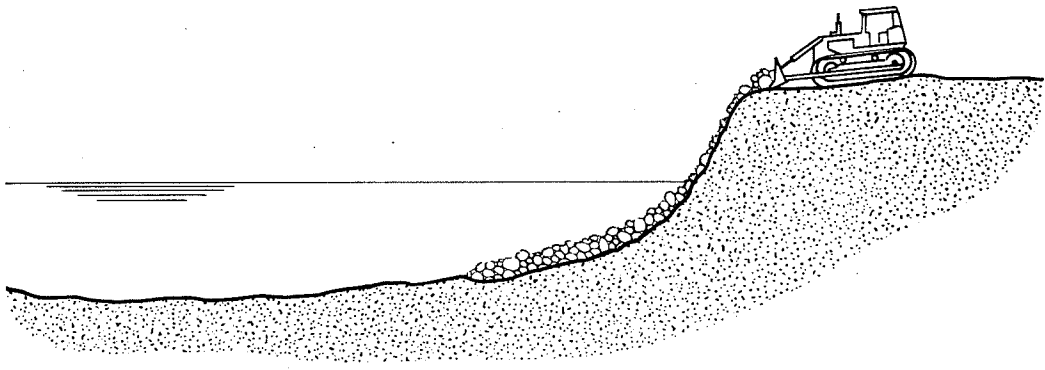
The hand placed revetment is obtained by placing the stones on a prepared slope in some definite manner. The stones are placed individually by hand or by using cranes. The stones of this revetment are usually smaller in size and more closely packed than in the dumped riprap revetment



a). BY DUMP TRUCK



b). BY BARGE



c). BY BULLDOZER

FIGURE 1. PLACEMENT OF A DUMPED RIPRAP REVETMENT

and the structure is more rigid. This revetment does not adjust to settlement as well as the dumped riprap revetment and failure is likely if bank material is lost from behind the structure. Because of the close arrangement of the stones, a filter layer between the revetment and the bank may be unnecessary. The toe of this revetment must also be protected from undermining and scour by means of a toe apron. The various configurations for a toe apron are shown in Figure 2.

2.2.3 Grouted Riprap Revetment

The grouted riprap revetment consists of stones dumped on the bank and then secured in position by means of a concrete grout. For the same degree of attack, the stones of a grouted riprap revetment are smaller in size than those used in a dumped riprap revetment or hand placed revetment. To resist displacement, the stones are cemented (in place) together to make one solid structure. The revetment is very rigid and can tolerate only very minor movement of the support material. A competent toe apron or retaining wall must be used to ensure no deflection or sliding of the revetment takes place. The revetment is impermeable and likely to fail if significant uplift pressures are exerted on the bottom face of the revetment. Uplift is caused by water, trapped behind the structure, being unable to flow freely to the river. Relief of this pressure is possible by providing weep holes in the

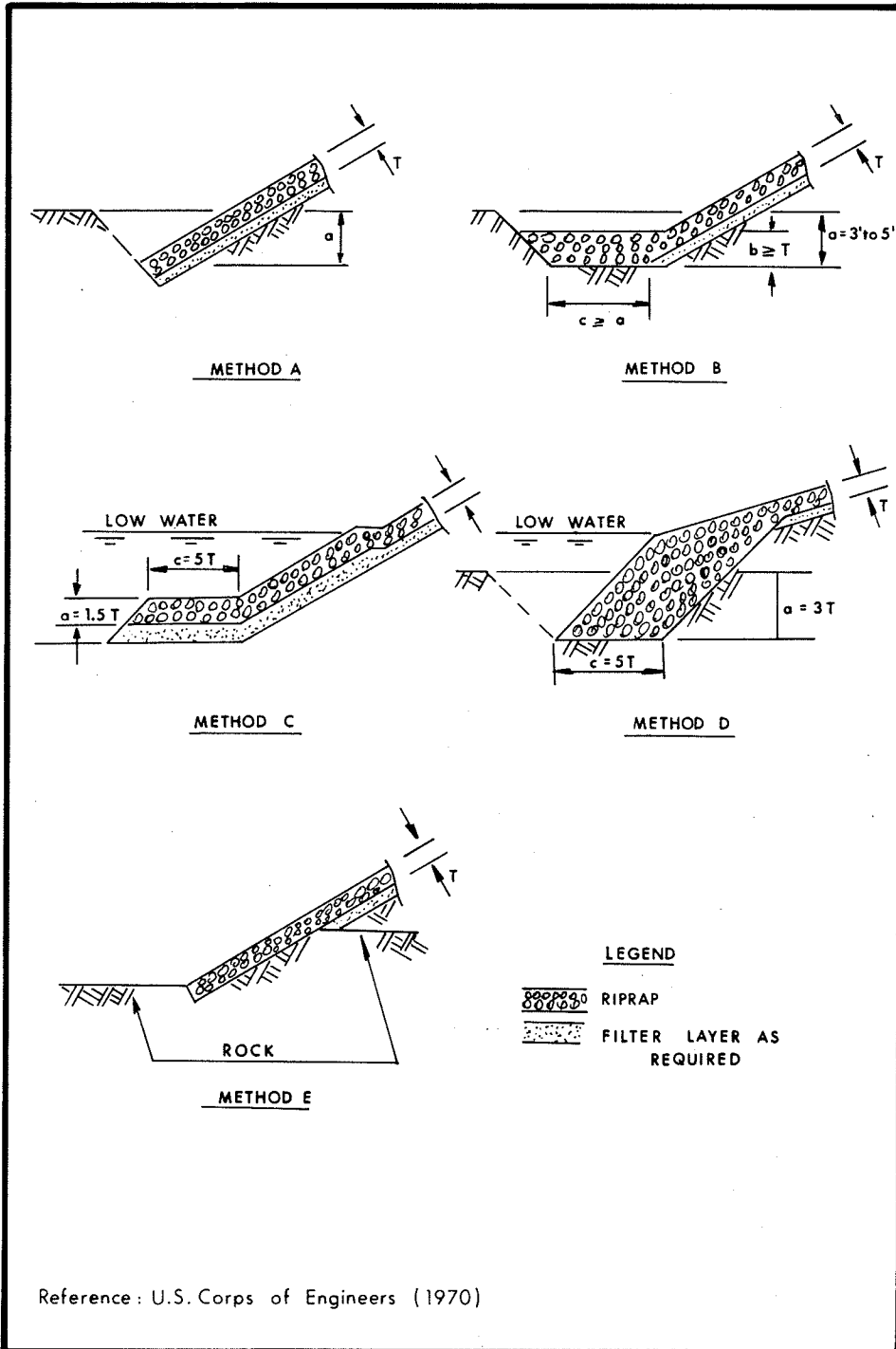
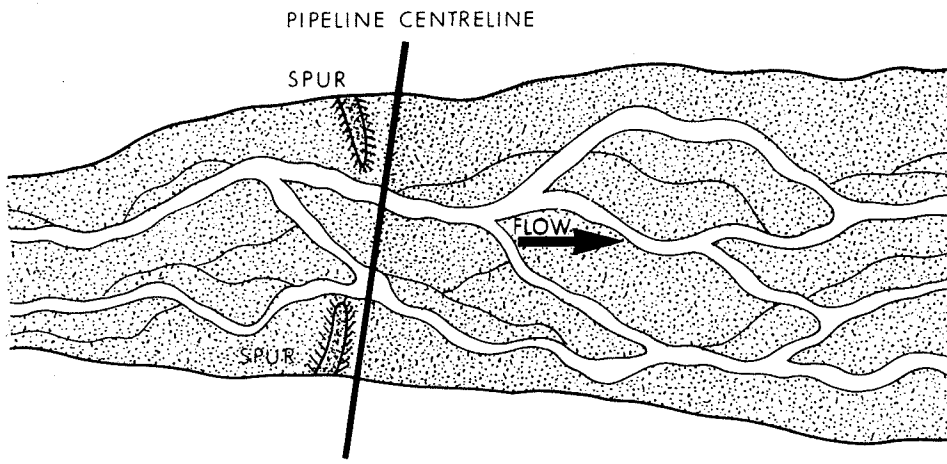


FIGURE 2. RIPRAP TOE PROTECTION

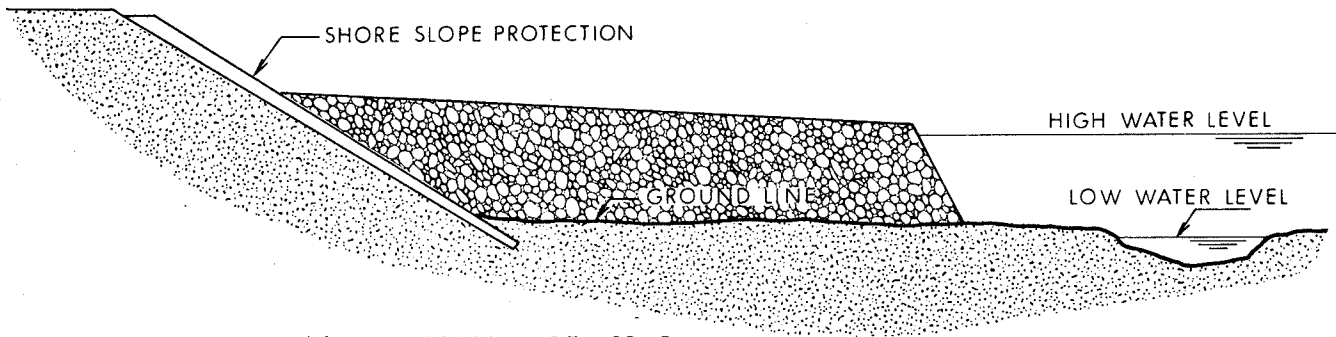
revetment through which the water can drain freely. A filter layer of limited extent is required between the bank and a weep hole. This prevents the loss of bank material. Grouted riprap revetments may be used when stone of adequate size for a dumped riprap revetment is unavailable.

2.2.4 Other Uses for Riprap Revetments

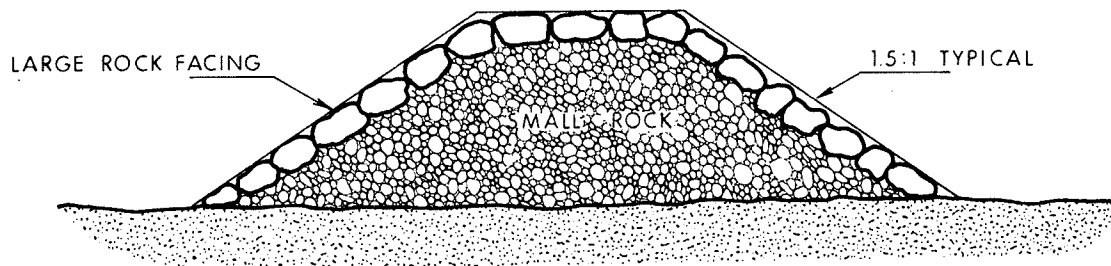
The revetments described in the above are used on the banks of rivers but they may be used in other situations. Spurs, guide banks and dykes are frequently protected from the hazards of erosion and scour by resistant liners (revetments). Spurs are structures built obliquely to the primary motion of the water, designed to deflect the high velocity currents away from critical areas. Scour holes of great magnitude may occur at the noses of spurs and in order to protect the spur, revetments and toe aprons are used to line the scour holes. Guide banks and dykes are used to guide and/or contain the flow to a desired path within the channel or flood plain. The faces of these structures (which are essentially embankments) are protected with revetments. Figure 3 shows a spur with head and shank protected with riprap.



a). PLAN OF RIVER AND SPUR PLACEMENT



b). ELEVATION OF SPUR



c). SECTION

FIGURE 3. RIPRAP PROTECTED SPUR

3. EROSION AND SCOUR

3.1 Introduction

A bank may fail owing to any one of, or a combination of, the following:

1. The washing away of soil by the stream - erosion;
2. Sliding of the upper bank due to a loss of material at the base of the slope - scour;
3. Sliding due to an increase in pore pressure in the bank;
4. Piping caused by water, stored on flood plains and within the bank, returning to the river;
5. Additional loading at the top of the bank.

Of immediate concern here are the processes of erosion and scour at the bend in a channel. The ability of the stream to erode and scour is a function of the state of the flow, and the type of materials making up the boundaries of the channel. The revetment placed on the bank of a channel disturbs the natural processes and introduces changes which must be taken into account when designing the revetment structure. The characteristics of flow within a river bend will be discussed.

3.2 Flow Behavior in Bends

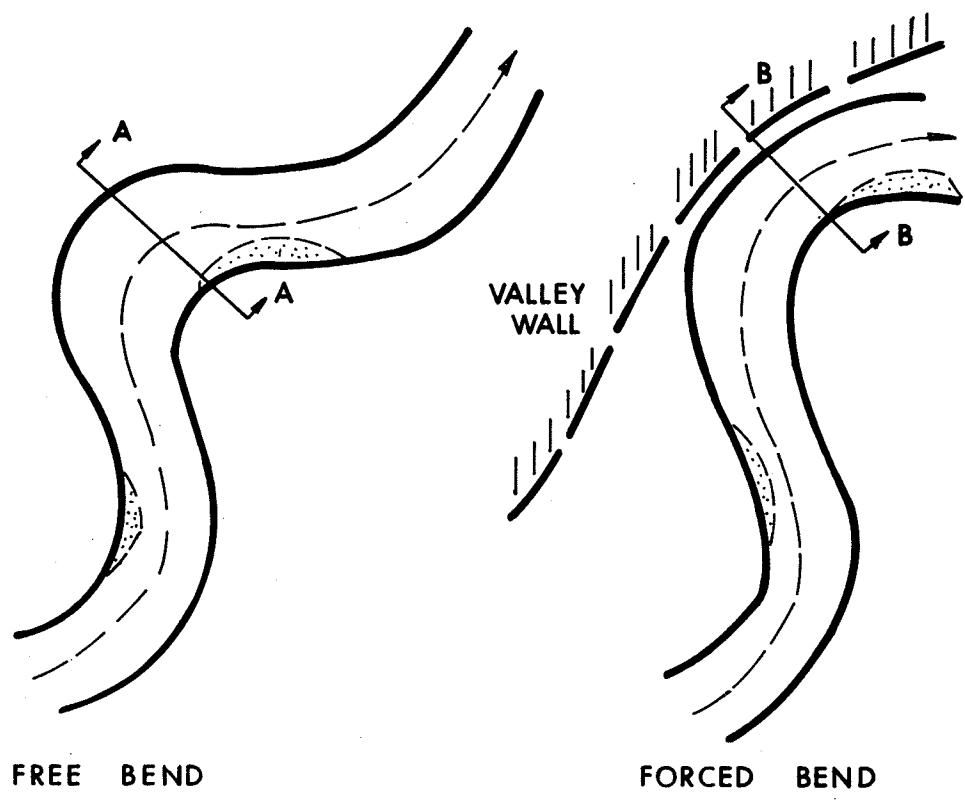
When the water flowing along a straight reach of a channel enters a curve or bend, a secondary circular motion is superposed on the general downstream direction of the

flow. The two flows combine to produce a spiral flow pattern within the curve.

This spiral flow pattern owes its existence to the interaction of frictional, inertial and centrifugal forces on the water flowing through the curve. In the vicinity of the channel bed the flow is retarded because of boundary resistance at the bed. The surface streamlines tend to maintain their direction down the channel and as a result the slower moving fluid near the bottom is forced to follow a more sharply curved path to maintain a balance between centrifugal and pressure forces. The net effect is a current flowing down the outer bank, across the bottom of the channel towards the inner bank, up along the inner bank and across the surface to the outer bank. This flow is responsible for the characteristic shape (Figure 4) of alluvial channels in bends.

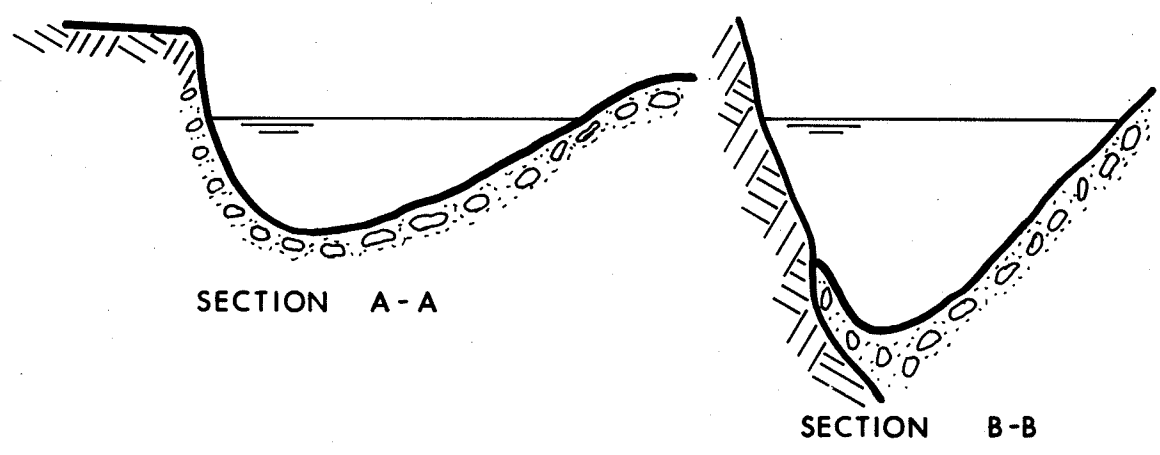
The spiral current transports material eroded from the outer bank and scoured from the toe of the bank, across the bed of the channel and deposits some of it on the bed at the toe of the inner bank. Deposition in this region tends to force more of the flow towards the concave bank. The high shear forces generated at the bed along the toe of the concave bank causes movement of bed material and deepening occurs until the shear forces are reduced and/or more resistant bed material is exposed.

In channels having very sharp and short radius bends,



FREE BEND

FORCED BEND



SECTION A-A

SECTION B-B

FIGURE 4. TYPES OF BENDS

zones of separation may form along the convex bank. This very slow moving body of water also helps to force the flow towards the outer bank. The potential for erosion and scour is increased when this zone of separation is formed. Figure 5 shows the typical zone of separation likely to form at sharp bends.

3.3 Types of Bends

There are two types of bends: free or forced (Figure 4). A free bend is capable of migrating laterally outwards across the flood plain or progressing in a downstream direction due to erosion of the concave bank. A forced bend is one which is unable to move freely across the valley floor and/or progress downstream. Forced bends are usually formed when the river impinges on the valley wall, a bedrock outcrop, or at some man-made control such as a revetment.

The depth to which a river scours is greater for the forced bend than the free bend. For the free bend, widening of the river is likely and hence there is a reduction in velocity. Material eroded from the bank contributes material to the bed along the base of the bank. This, together with the reduction in velocity (due to widening) causes the hole to be less deep than the hole formed at a forced bend where no widening is possible and little or no bank material is available to fall into the scour hole.

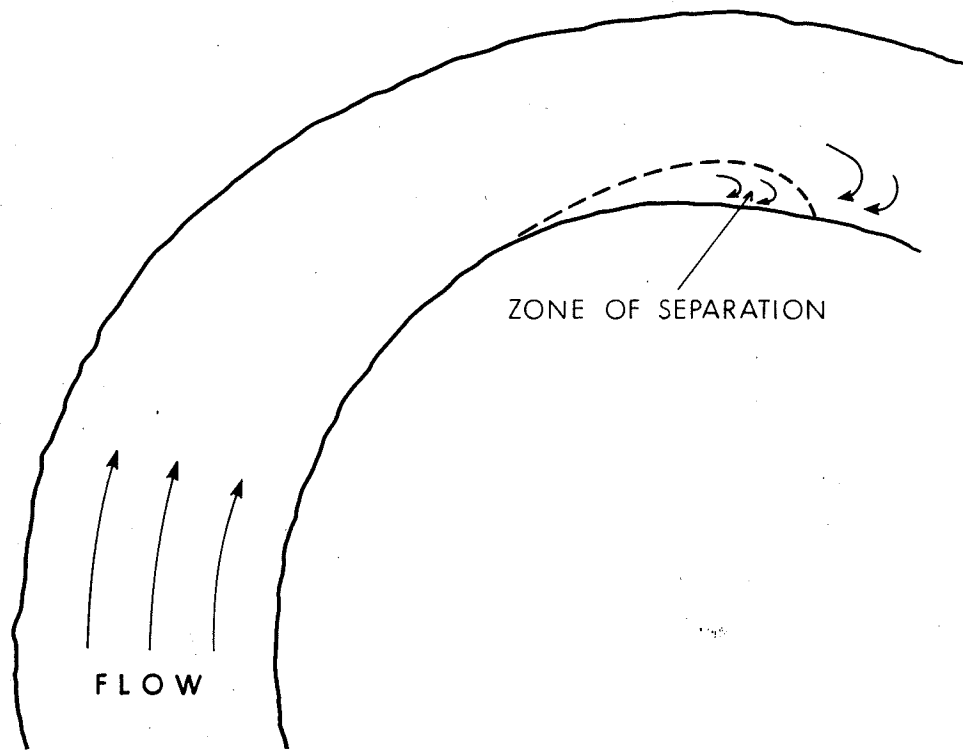


FIGURE 5. FLOW SEPARATION AT SHARP BENDS.

3.4 Extent of Erosion and Scour

The extent of erosion and scour varies from one situation to another. The deflection angle and the radius of curvation of the bend, the nature of the bed and bank materials, the length of the bend, the width of the river and the velocity of flow in the bend influence the erosion and scour processes. Because the high velocity currents do not approach the outer bank until some distance into the curve, Figure 6, the erosion and scour forces at the entrance to the curve are fairly low. These forces become greater in the downstream direction until a point is reached where a general movement of the bed occurs and deepening begins. Once movement of the bed material begins, a series of scour holes and dunes form on the bed of the channel. The dunes formed on the inner half of the channel bed tend to be larger than those formed on the outer half. The flow is pushed towards the concave bank and the concave bank downstream of the exit of the bend is likely to erode.

To protect the bank, the revetment must begin and end in areas where the velocities are incapable of causing erosion and scour. This implies in most cases, that the revetment must start near the entrance of the bend and end some distance downstream of the exit. Because the attack on a revetment is low at the beginning of the curve, maximum at some point within the curve and low at

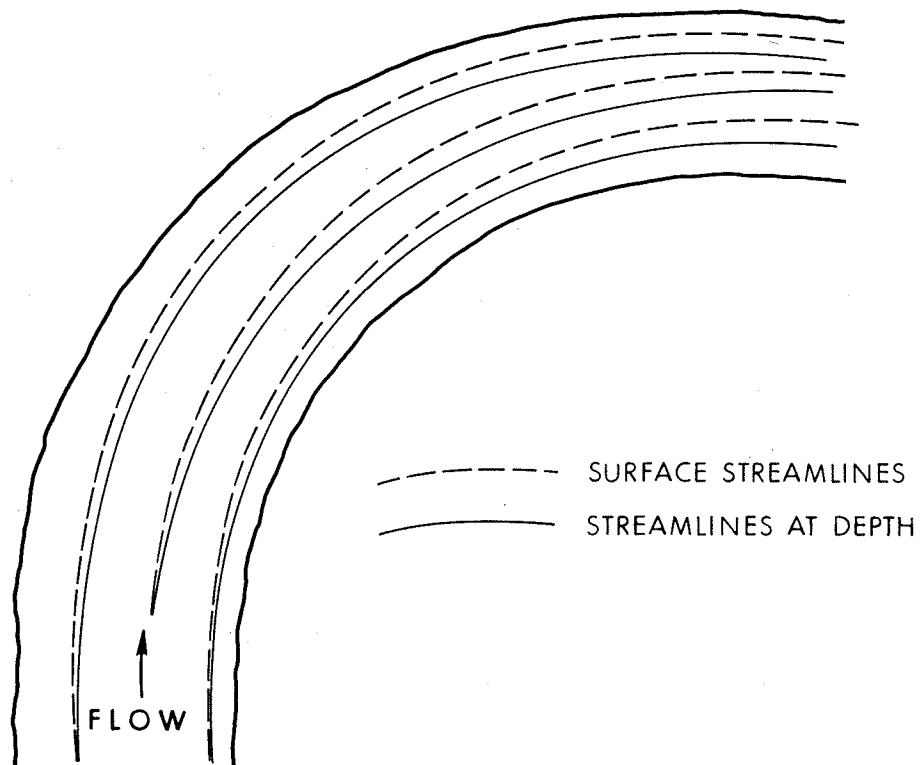


FIGURE 6. STREAMLINES IN A BEND

the end of the curve it is not necessary to design a revetment of uniform strength throughout. Starting from about mid curve, the strength of the revetment may be reduced in the upstream and downstream directions but care must be exercised when designing a revetment of varying strength. In some instances, the zone of heaviest attack may remain fairly constant but, in many cases, this zone will vary in position along the curve. Improper identification of the zones of heaviest attack is likely to cause failure of a revetment of non-uniform strength.

3.5 Forces of Erosion and Scour

The principal force causing movement of particles on the bed or banks of a channel is the shear force. This force is essentially a frictional force caused by the motion of water over the particles within the channel boundary. The theory which provides the means of calculating shear force is called the "Tractive Force" theory. The theory says that for uniform flow, the mean force exerted by the flowing water on the bed within a straight reach of a trapezoidal channel is given by the equation:

$$\tau_0 = \gamma_w R S \quad 3.1$$

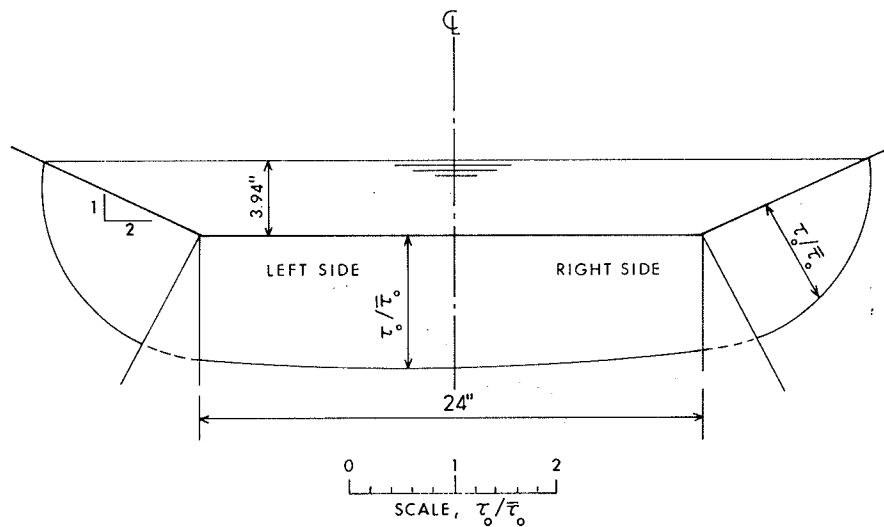
where τ_0 = mean shear force per unit area of bed
 γ_w = unit weight of water (62.4 lb. per cu. ft.).
 R = hydraulic radius (equal to average depth for wide channels)
 S = slope of energy grade line.

The tractive force which is just sufficient to cause motion of bed particles is called the "critical tractive force". Because of the difficulty in deciding when motion is initiated, the critical tractive force is likely to vary from one researcher to another.

In a straight reach of river having banks and bed composed of the same material, the tractive or shear force varies from zero at the surface to some finite value at the toe of the bank (Figure 7). The maximum value for the bank occurs at or near the toe of the bank. The maximum value for the bed occurs at the centreline of the channel. In a curve the distribution of the shear forces is very irregular and varies in magnitude in the downstream direction. Although the tractive force is usually largest in zones of highest velocities, high shear forces may occur in zones of low velocity.

High shear forces may occur in regions of low velocity. The movement of bed material along the toe of the inner bank of the entrance to a bend demonstrates this fact. This phenomenon has been observed by previous researchers and by the author while performing his tests.

The maximum value of the shear force within a bend is substantially greater than the value given by Equation 3.1. Figure 8, taken from the U.S. Corps of Engineers (1970) gives the ratio of the shear force required to move a particle on an inclined plane to that required to



- NOTES.
- 1 SHEAR DISTRIBUTION BASED ON
 - a. ROUGH CHANNEL
 - b. $\bar{\tau}_o$ = AVERAGE BOUNDARY SHEAR IN REACH
 - c. τ_o = LOCAL BOUNDARY SHEAR IN SECTION
 - 2 $\tau_{o,r} = 1.05 \bar{\tau}_o$
 - a. $\tau_{o,r}$ = LOCAL BOUNDARY SHEAR AT TOE OF SIDE SLOPE

Reference: U.S. Corps of Engineers (1970)

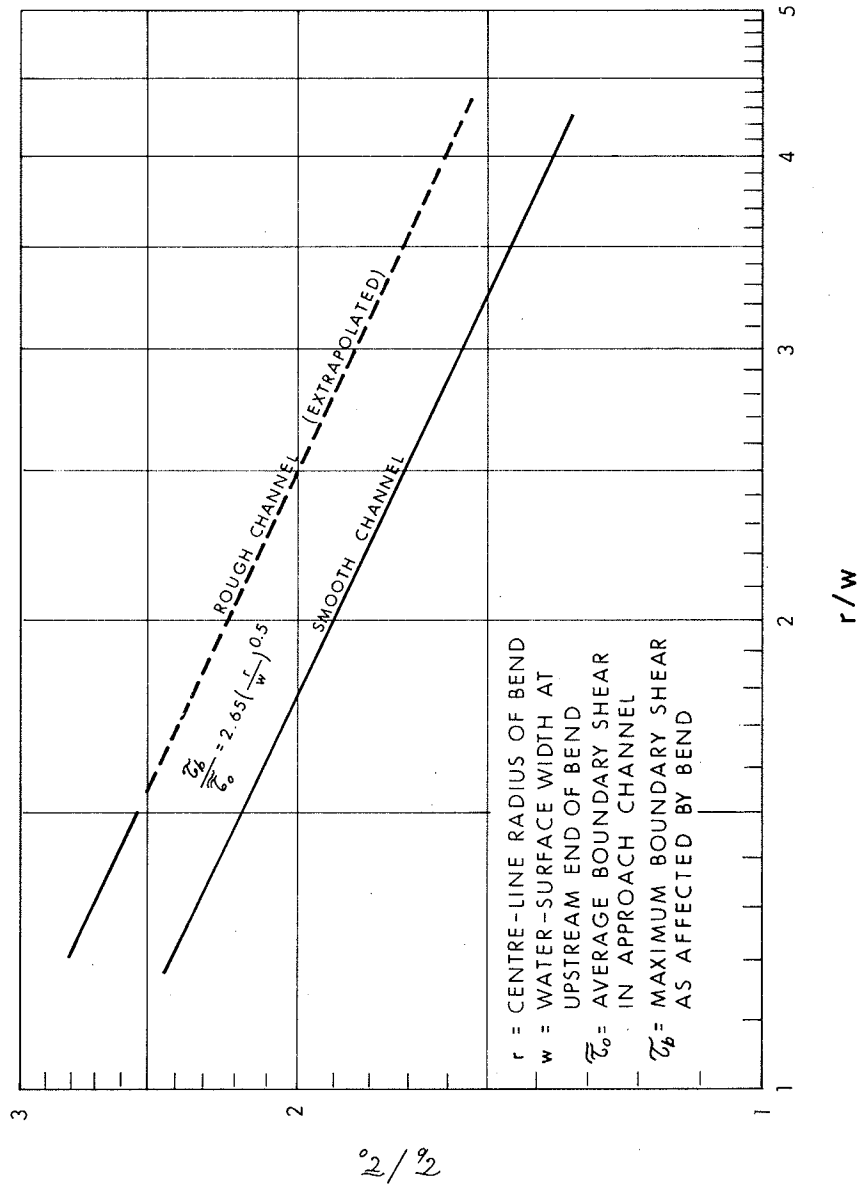
TRAPEZOIDAL CHANNEL
STRAIGHT REACH

FIGURE 7. BOUNDARY SHEAR DISTRIBUTION

move a particle on a level surface and Figure 9 taken from the same reference shows the relationship between the shear force in a bend and the average shear force τ_0 in a straight reach. The riprap particles placed on the outer bank must be capable of resisting the shear forces generated at the side slope and the toe of the slope if effective protection is to be provided by the revetment.

Turbulence caused by fluctuations in the flow and the shedding of eddies at irregularities in and along the bank sets up pressure fluctuations at the surface and near surface particles of the bank (revetment) which tend to lift the particles. This process adds to the instability of the bank (revetment) material but sufficient knowledge is presently unavailable to quantify the intensity of turbulence of the flow.

Before the test results are discussed it is necessary to discuss briefly the factors affecting revetment stability and stone size. These are covered in Chapters 4 and 5. Chapter 4 introduces the factors affecting revetment stability. A method of arriving at the size of stone required to protect an eroding bank has been proposed by Stevens et al (1974). The theoretical development of this method is presented in Chapter 5.



Reference : U.S. Corps of Engineers (1970)

FIGURE 9. MAXIMUM SHEAR AT CHANNEL BENDS

4. FACTORS AFFECTING REVETMENT STABILITY

4.1 Introduction

The revetment and the bank it is to protect must perform as a unit if effective protection is to be maintained. The factors affecting the performance of the revetment may be listed as follows:

1. Size, weight and shape of the stones
2. Composition of the stones
3. Gradation of the stones
4. Revetment slope
5. Depth of water
6. Velocity of the flow
7. Angle of attack
8. Waves
9. Nature of the banks
10. Construction procedures

The factors listed above will be discussed in the following sections.

4.2 Size, Weight and Shape of Stones

Size refers to the diameter, in feet, of a spherical stone that would have the same weight as the 50 percent size of stone, weight refers to the actual physical mass of the stone and shape reflects the relationship between the three main dimensions of the stone. The revetment depends partly on the interaction between stone particles for its effectiveness. Smooth round stones are capable

of rolling over each other with relative ease whereas angular stones are difficult to dislodge. The stones used in revetments must therefore be large, heavy and blocky in shape rather than small, light and rounded.

4.3 Composition of Stones

The majority of revetments located on river banks or dyke and spur embankments, etc. are subjected to heavy attack by flowing water, waves and, in temperate and arctic zones, ice block movement. To withstand the forces generated by these three agents and the physically disruptive processes of wetting and drying and/or freezing and thawing, the stones must be hard, durable and free from cracks. Shale, for example, is an unacceptable material for riprap because it rapidly disintegrates when subjected to alternate periods of wetting and drying. It becomes friable and cannot withstand impact.

The stones used for riprap revetments must meet certain specifications if the revetment is to perform well. Although the revetment may have withstood the maximum possible attack in its first few years of operation, its performance could deteriorate rapidly because of a lack of stone durability. The California Division of Highways (1970) suggests the following guidelines for stone:

1. The specific gravity of the stones should be greater than or equal to 2.65. The higher the specific gravity, the heavier the stones and the smaller the

size required for the same level of attack.

2. The stones shall be hard, durable, angular in shape, and free from cracks.
3. Neither breadth nor depth of a single stone shall be less than one-third its length. This ensures that the stones will be more angular than either rounded or elongated.

The necessity for the above can readily be seen. If the recommendations are followed the stones will:

1. be more resistant to chemical and mechanical weathering processes and will not easily break up.
2. be difficult to move because of the effect of interlocking.

4.4

Gradation of Stones

The interlocking of stones of varying sizes is greater than that of stones of only one size. The stones should be graded for the revetment to perform properly. The gradation recommended by the U.S. Corps of Engineers (1970) is based on past experience and stability analyses and is as follows:

1. The lower limit of W₅₀ stone should not be less than the weight of stone required to withstand the design shear forces.
2. The upper limit of W₅₀ stone should not exceed that weight which can be obtained economically from the quarry or that size which will satisfy layer thickness requirements specified in Section 4.6 below.

3. The lower limit of W_{100} stone should not be less than two times the lower limit of W_{50} stone.
4. The upper limit of W_{100} stone should not exceed: five times the lower limit of W_{50} stone, that size which can be obtained economically from the quarry, or that size which will satisfy layer thickness requirements specified in Section 4.6 below.
5. The lower limit of W_{15} stone should not be less than one-sixteenth the upper limit of W_{100} stone.
6. The upper limit of W_{15} stone should not be less than the upper limit of W_{50} stone as required to satisfy the criteria for graded stone filters, Section 4.7.
7. The bulk volume of stone lighter than the W_{15} stone should not exceed the volume of voids in the revetment without this lighter stone.
8. W_0 to W_{15} stone may be used instead of W_{15} stone in criteria (5), (6), and (7) if desirable to better utilize available stone sizes.

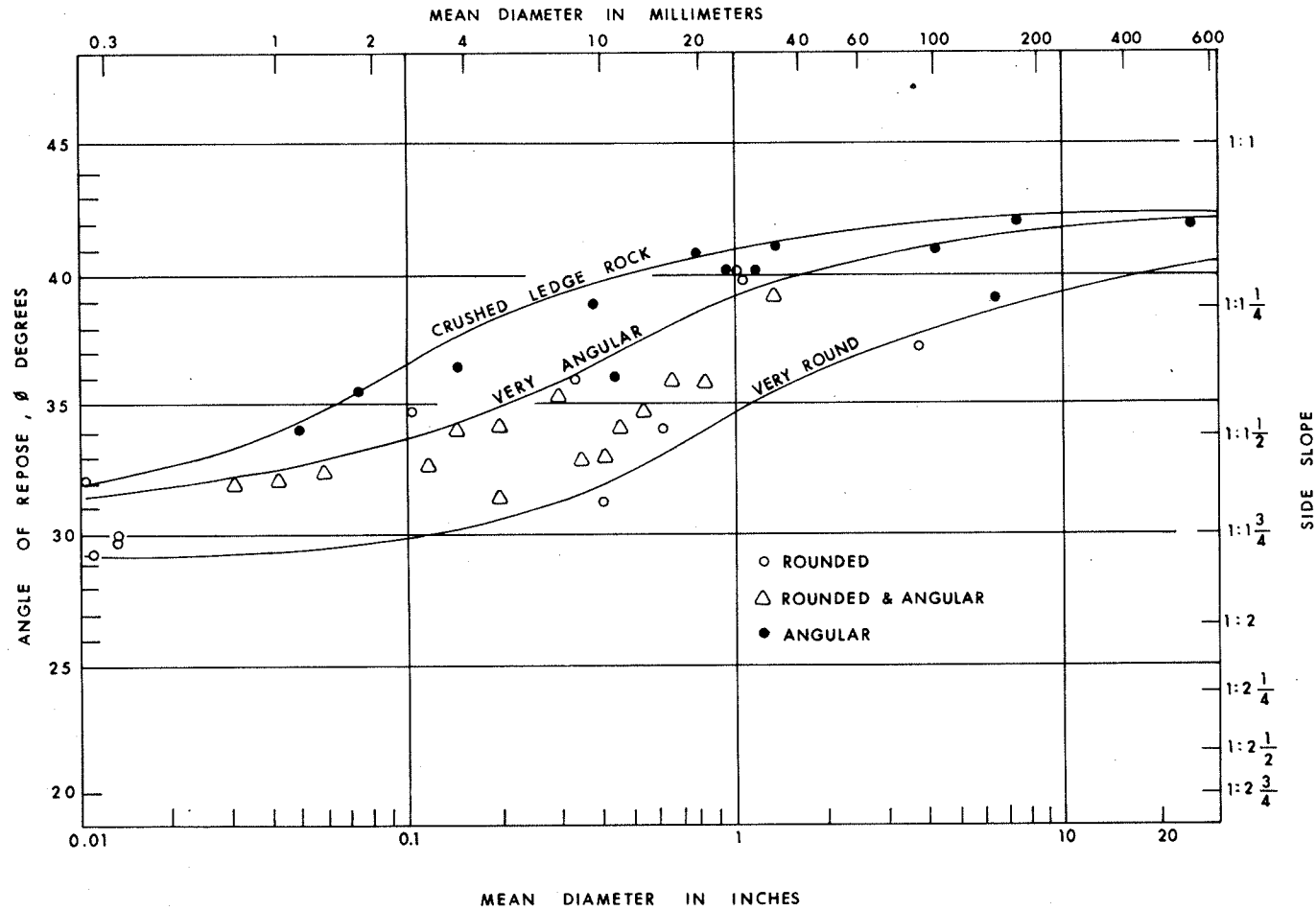
W is the weight of the stone in lb, and the subscript refers to the percent by weight finer than as produced by a sieve analysis of the stones.

4.5 Revetment Slope

A mass of stone on an essentially level surface assumes a stable cone like configuration dependent on gravity and the interlocking effect of stone against stone. The slope at which this mass of stone will stand gives the angle of

repose of the stones. By using various gradations of stone the angle of repose can be varied. The relationship between stone size, expressed in terms of a representative diameter, and the angle of repose is obtained from Figure 10. The factor of safety against sliding, which is a measure of the stability of the face slope of a mass of stones inclined at an angle to the horizontal, is equal to unity when the slope angle is equal to the angle of repose of the dumped stone mass. The median grain size, D_{50} , of the stone gradation is used as the representative stone size.

Disturbing forces which have components of force acting in a downslope direction cause the stability of the revetment to be reduced and may cause dislodgment of marginally stable stones. This situation exists for the riprap revetment placed on a bend where the spiral nature of the flow produces velocities which act down the revetment slope. The lift forces, caused by the reduction in pressure as the spacing of the streamlines above the riprap particles becomes closer, together with the effect of bouyance reduce the effective weight of the stone particles. This, plus the effect of shear force acting at the face of the revetment causes the stability of the stone mass to be reduced. In design, the factor of safety of the revetment (ratio of the forces resisting failure to those tending to cause failure) is usually taken as 1.5 although the design engineer may accept a lower factor of safety if conditions warrant it.



Reference: Simons (1971)

FIGURE 10. ANGLE OF REPOSE OF NON-COHESIVE MATERIAL

The revetment has two faces; the outer or upper face (face slope) and the bottom face. The two slopes (faces) may have the same angle of inclination or different slopes. The stability of the revetment, although affected principally by the flow, is also dependent on the slope of the bank or embankment on which it rests. Because river banks are generally steep in actively eroding areas it is necessary, both from stability and economic concerns, to grade the bank to a more gradual slope. Slope stability concerns will usually dictate the amount of grading required on a river bank.

4.6 Revetment Thickness

The stones used in the revetment should be contained reasonably well within the riprap layer to provide maximum resistance to the erosive forces and reduce the drag forces exerted by the flow on oversized stones protruding from the main body of the revetment. The oversized stones may cause riprap failure by creating excessive local turbulence that removes smaller stones and destroys the filter layer beneath. The oversized stones should be removed and replaced with stones of smaller size. The following criteria which apply to riprap layer thickness, have been proposed by the U.S. Corps of Engineers (1970):

1. It should not be less than the spherical diameter of the upper limit W_{100} stone or less than 1.5 times the spherical diameter of the upper limit W_{50}

- stone, whichever results in the greater thickness.
2. It should not be less than 12 inches for practical placement.
 3. The thickness determined by either (1) or (2) should be increased by 50 percent when the stones are placed underwater to provide for uncertainties associated with this type of placement.
 4. An increase in thickness of 6 to 12 inches, accompanied by an appropriate increase in stone sizes, should be provided where riprap revetments will be subject to attack by large floating debris or by waves caused by power craft and high winds.

4.7 Filter Blanket

A filter blanket is usually needed beneath the riprap cover to prevent the water from removing bank material through voids in the structure. Removal of material from the protected bank leaves cavities behind the revetment that could cause failure, especially of the more rigid types of revetments. The dumped riprap revetment is capable of deflecting into the cavity but the new configuration may cause increased turbulence and continued loss of both bank material and stone. Failure of the revetment need not necessarily occur immediately. It may take place after a number of high water and low water cycles.

Filter layers are not always required. If the gradation of the riprap layer satisfies filter layer design criteria,

no loss of bank material should occur. And if the bank consists of cohesive material the strength of the turbulence eddies beneath the stones are likely to be too weak to transport bank material away.

One or more layers of material may be used between the riprap and the bank to ensure no loss of bank material.

The requirements for filter blankets are as follows:

1. $\frac{D_{50} \text{ (riprap)}}{D_{50} \text{ (base)}} < 140$ 4.1
2. $5 < \frac{D_{15} \text{ (riprap)}}{D_{15} \text{ (base)}} < 140$ 4.2
3. $\frac{D_{15} \text{ (riprap)}}{D_{85} \text{ (base)}} < 15$ 4.3
4. The gradation curves for a riprap layer and the bank should be essentially parallel.

The words "riprap" and "base" should be changed to "coarse" and "fine" when investigating the requirements for two layers of filter material.

The gradation guidelines listed above are taken from Searcy (1967).

The filter requirements described above apply to gravel filters. Filter cloths are becoming increasingly popular. They are made of a synthetic material and while allowing the passage of water prevent the movement of bank material. The cloths may be used with any size stone. They are strong and durable and easy to install. Figure 11

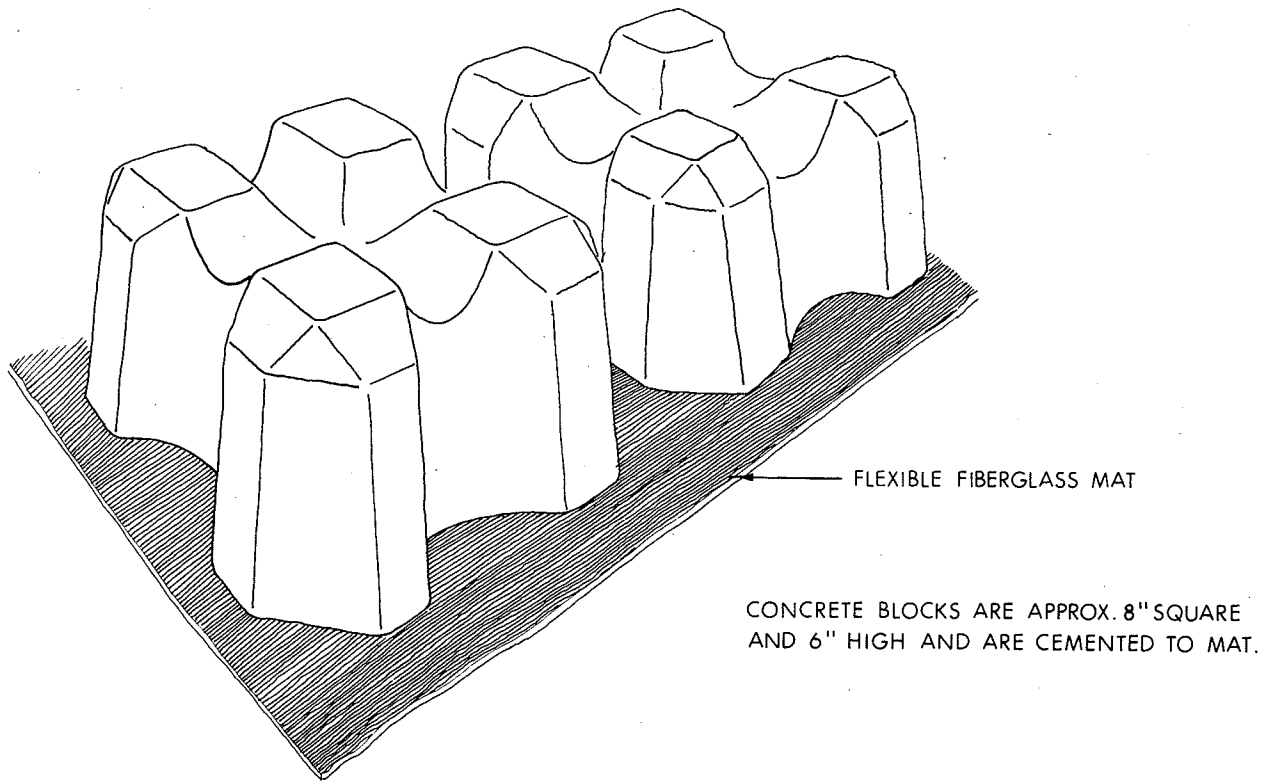
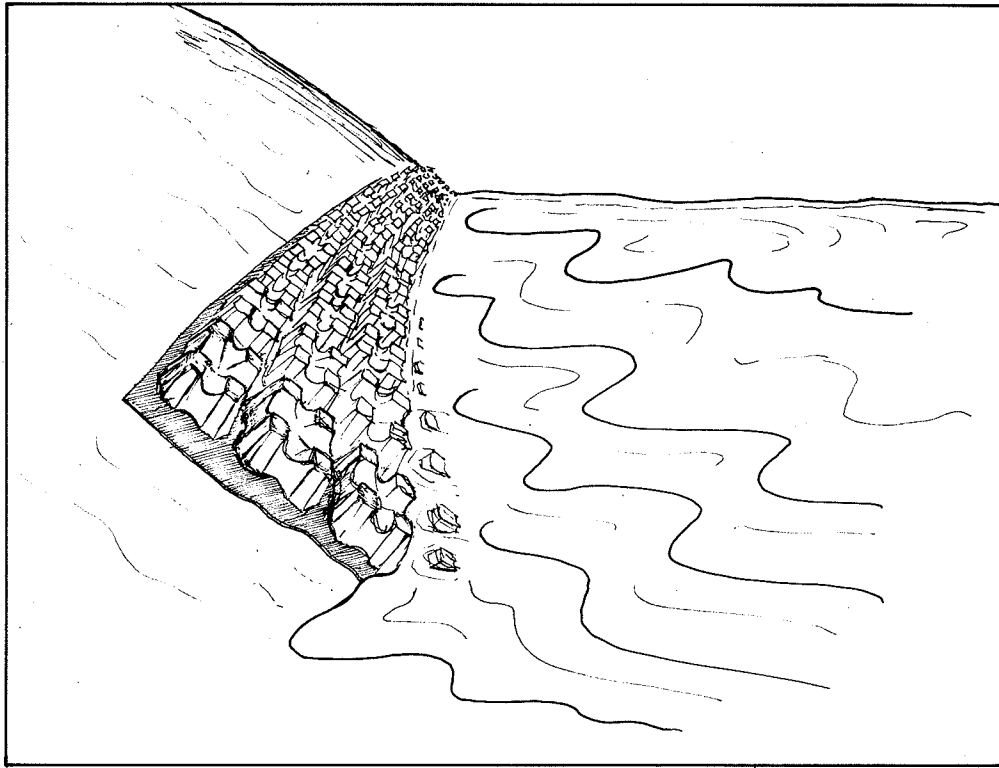


FIGURE 11. BANK PROTECTION WITH FILTER ATTACHED (GOBIMAT).

shows a bank protection device which includes a filter cloth. The cloth is an integral part of the revetment and it is added at the time the blocks are cast at the factory.

4.8 Depth of Water

The height of water above a sloping surface increases with depth along the slope. As can be seen from Figure 7, the shear forces acting on the slope increase from zero to a maximum at, or near, the toe of the slope. The deeper the channel the greater the shear force at the toe and the greater the size of stone required at the toe of a revetment. Because the shear force varies, the gradation of stone used may vary but for ease of construction and simplicity of design the same gradation may be used throughout the slope length of the revetment. The need to provide protection against wave action may boost the size of stone required at the surface and changing the size of stone may also prove to be uneconomical.

A uniform gradation of stones was used for the revetments in the model study. The same gradation was used for the slope paving and the toe apron (when one was used).

4.9 Velocity of Flow

The disruptive forces acting on a stone particle in a riprap revetment are those of gravity, drag and lift. The last two are velocity dependent and vary with the direction of flow and the turbulence in the vicinity of the stone.

The components of the force of turbulence are difficult to separate and quantify. Drag and lift forces are more easily computed. Drag acts in a direction essentially parallel to the flow and lift acts upwards perpendicular to the slope. The equations of drag and lift, as proposed by Albertson et al (1961), are as follows:

$$F_D = C_D \rho_f \frac{V^2}{2} A \quad 4.4$$

where F_D = drag force

C_D = drag coefficient (dependent on Reynolds Number, shape factor and relative roughness of the stone particles)

ρ_f = density of the fluid

V = velocity of the flow near particle

A = perpendicular projected area of a particle in the flow

and,

$$F_L = C_L \rho_f \frac{V^2}{2} A \quad 4.5$$

where F_L = lift force

C_L = coefficient of lift (dependent on Reynolds Number, shape factor and relative roughness of the stone particles)

A = horizontal projected area of a particle.

The forces of drag and lift act at right angles to each other.

Allowance may be made for the forces of turbulence by

increasing the velocity "V" but this does not give a true representation of how the forces of turbulence act.

Eddies around the stone are capable of generating forces which act alternately into the revetment (aids stability) and out of the revetment (reduces stability). More research is necessary before the forces, due to turbulent eddies, can be expressed in equation form.

Drag and lift forces tend to cause rotation of individual particles out of the revetment. Should the flow succeed in moving a particle, a void may be formed. Movement of stones into the void and movement of the displaced stone over the downslope stones generate impact forces. These forces acting together with the other forces must be less than the resisting forces if the revetment is to remain stable.

The intensity of the forces acting on the stone particles may be computed from a knowledge of the velocity against the revetment but it is sometimes difficult to obtain all the field data necessary to compute, fairly accurately, the velocity against the revetment. In the absence of adequate data, the velocity against a stone particle may be taken to be:

1. $\frac{2}{3}$ the average velocity of the flow for revetments constructed in a straight reach of a river, and,
2. $\frac{4}{3}$ times the average velocity of the flow for revetments constructed in moderate bends
3. 2 times the average velocity of the flow for revetments constructed in severe bends.

These specifications were taken from Bank and Shore Protection by the California Division of Highways (1970). The velocities against the revetments in the model tests may be taken as the maximum velocities obtained by timing weighted floats as they moved through the bend (see Table 3).

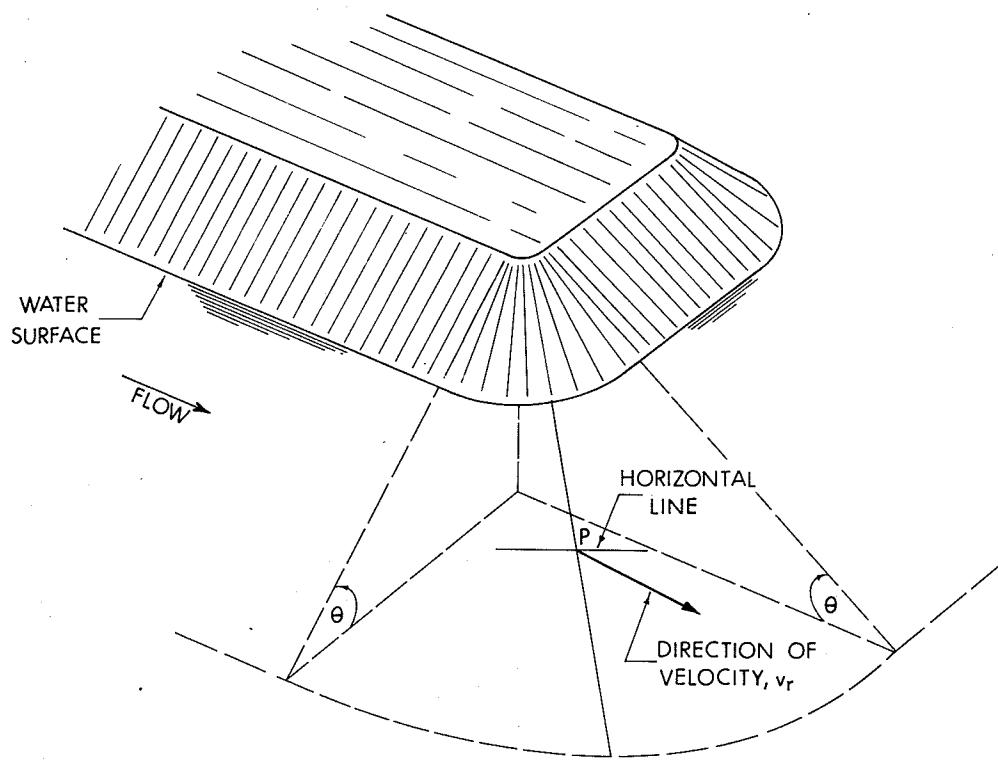
Figure 12 is a definition sketch or a free body diagram showing the forces acting on a stone particle in a riprap revetment.

4.10 Angle of Attack

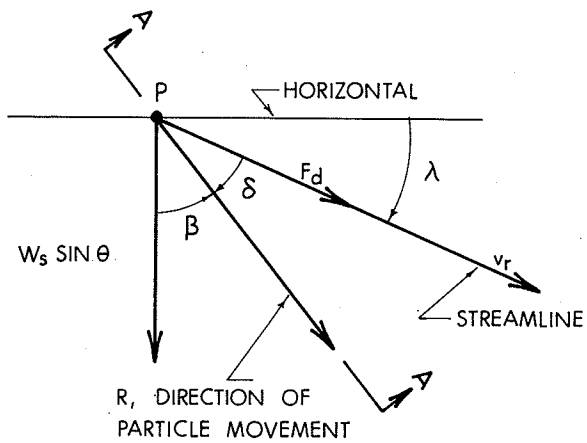
The momentum transferred from a jet of water to a rigid surface increases as the angle between the water jet and the surfaces changes from 0 to 90°. The direction change at a bend or curve in a river influences the forces of erosion and scour on the bed and banks. The sharper the curve the greater are the disturbing forces.

4.11 Waves

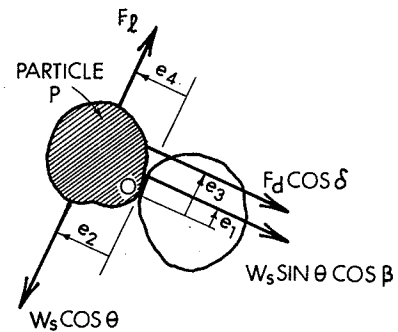
Waves are generated by storm surges, wind and power craft plying the river. The breaking of waves on an inclined surface releases significant quantities of energy and may cause the washing away of surface material. The revetment must be capable of withstanding the forces caused by waves. Because of wave run up, a revetment should usually extend to an elevation high enough to prevent overtopping. On small rivers this additional height above high water level may be 1 - 2 feet, but on larger rivers the freeboard allowance should be of the order of 3 - 4 feet above the



(a) GENERAL VIEW



(b) VIEW NORMAL TO THE SIDE SLOPE



(c) SECTION A-A

FIGURE 12. FORCES ON RIPRAP PARTICLES.

high water level for the design flood.

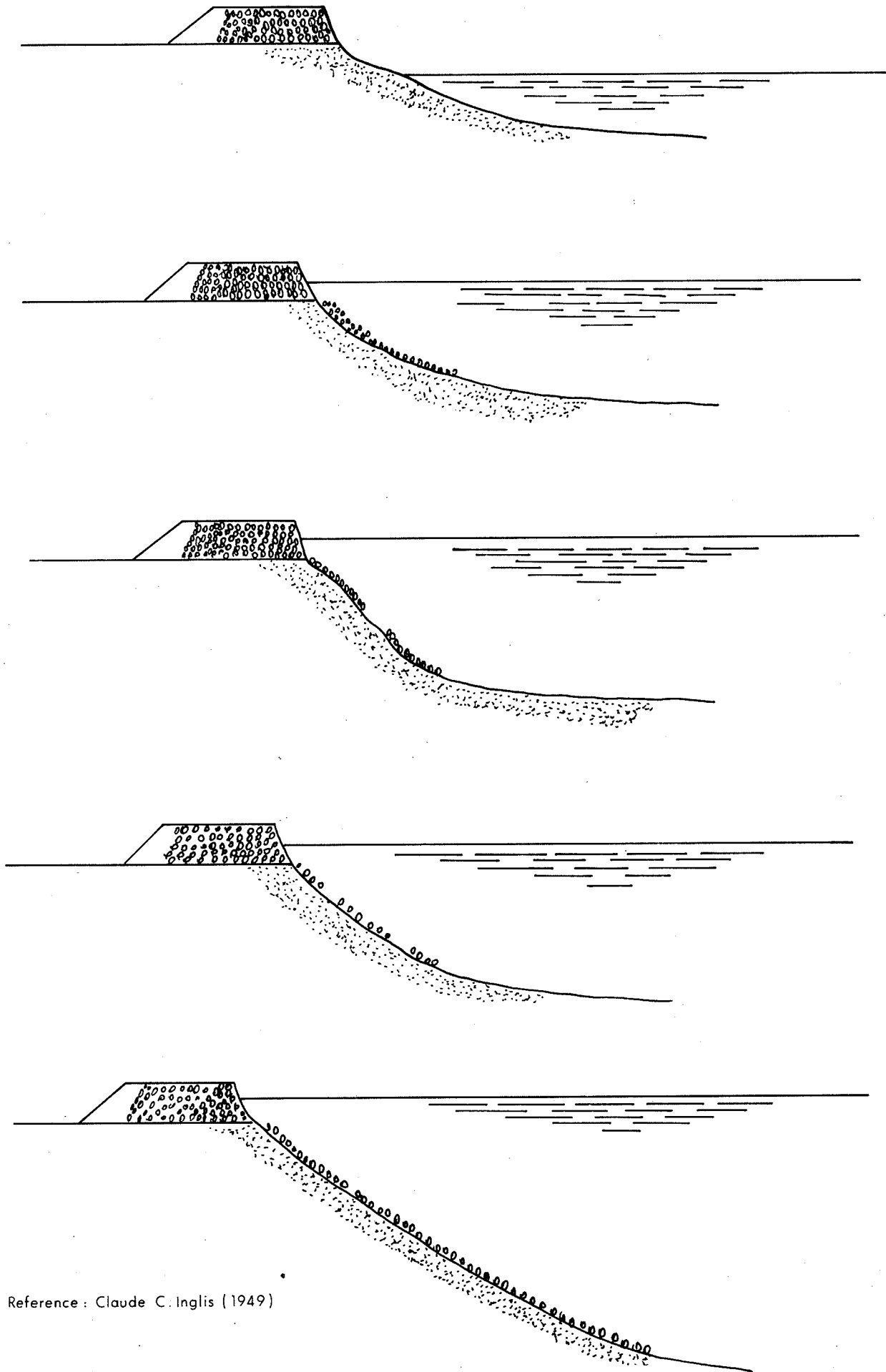
4.12 Nature of the Banks

The revetment armouring a bank depends on the foundation material for support. The revetment is in danger if the bank is likely to fail by slumping or sliding (typical landslide modes of failure).

Revetments put in position by the launching process are particularly dependent on the nature of the bank material. The revetment will only launch properly, Figure 13, if the bank and bed of the channel consists of non-cohesive materials which scour and erode evenly.

Uneven surfaces are caused by the differences in the rates of scour and erosion of cohesive and non-cohesive material. Cohesive material stands at much steeper angles than non-cohesive material. The surface of an eroding bank having alternate layers of cohesive and non-cohesive material is shown in Figure 14. It is impossible to provide, at a reasonable cost, a launched revetment to protect such a bank. A placed revetment is necessary. The slope must be trimmed and graded before placement of the revetment.

For both the placed revetment and the launched revetment, the bank must maintain its stability for the life of the revetment. Any conditions, within the bank, likely to cause instability and sliding must be controlled, or if possible, eliminated. An example of such a condition is a high water table. The danger of sliding due to this



Reference : Claude C. Inglis (1949)

FIGURE 13. THE LAUNCHING OF A REVETMENT

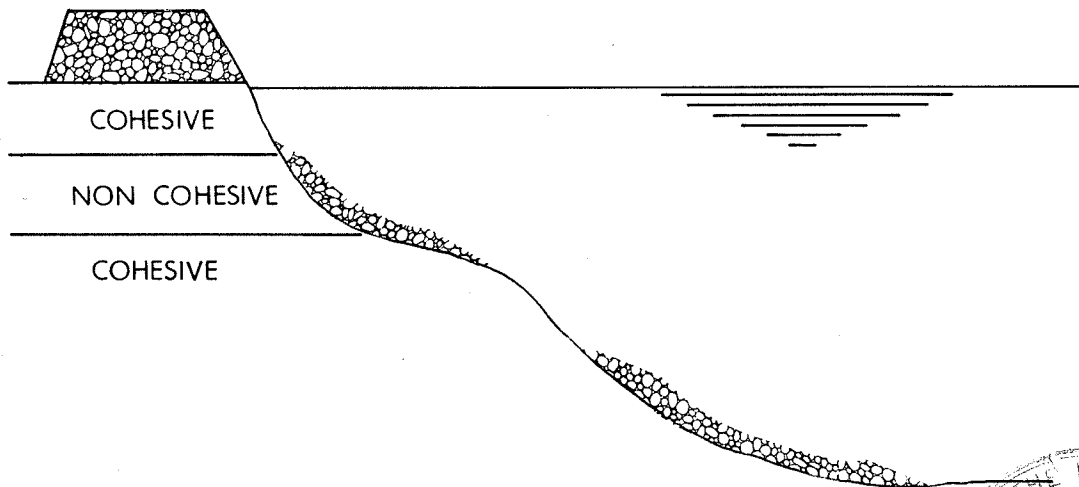
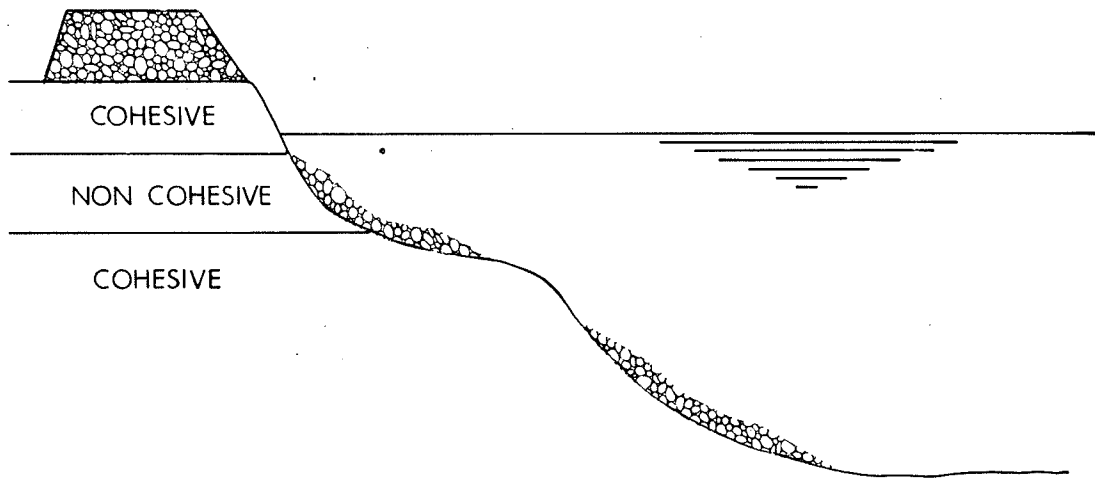
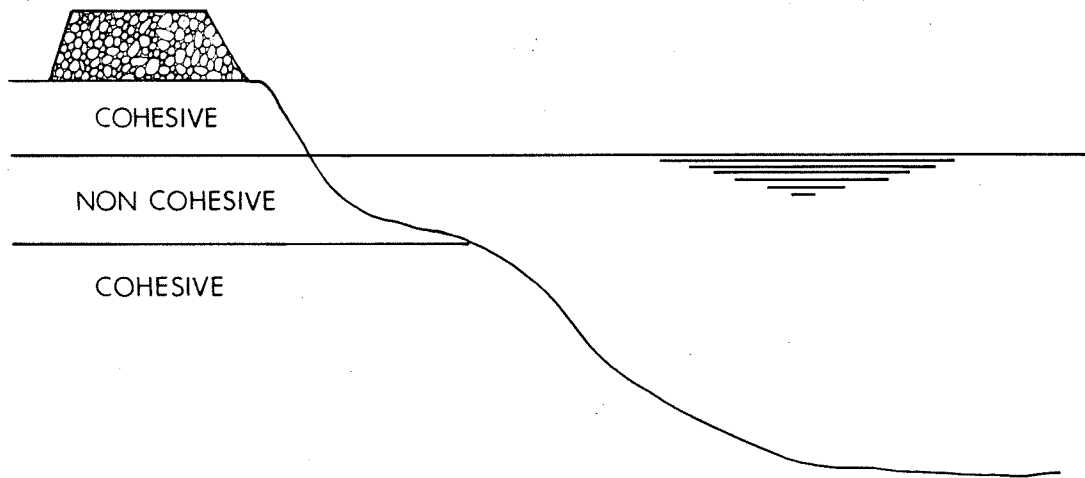


FIGURE 14. IMPROPER USE OF A LAUNCHED REVETMENT



condition may be reduced by construction of drainage ditches at the top of the slope or installing subsurface drainage conduits (perforated tile drains) to reduce the pore pressure build-up within the bank.

5. RIPRAP REVETMENT DESIGN

5.1 Introduction

The safety of a revetment constructed on an endangered bank is assured by following proper design and construction guidelines. These guidelines will be presented with reference to revetment configuration, riprap placement and stone size. A method for arriving at the size of stone required to protect an eroding bank has been proposed by Stevens et al (1974). The theoretical development of this method is presented.

5.2 Revetment Configuration

5.2.1 Revetment Toe Protection

All structures require stable foundations if they are to function properly. The same is also true for riprap revetments. The scouring process at a bend causes a steepening of the underwater slope along the base of the bank. If material is available from the bank, the slope of the hole is reduced because of the sloughing of bank and bed material into the hole. However, at a revetted bank no material is available from the bank and removal of bed material undermines the structure. The integrity of the upper slope revetment is assured by construction of a toe apron structure on the bed of the channel. The apron deflects into the scour hole and, in effect, produces a lining which is continuous from the top of the revetment to the bottom of the scour hole.

The toe apron structure may be located in two ways. The first method involves no excavation. The apron is constructed by dumping stones directly onto the bed of the channel. In the second case the apron is placed within a trench excavated in the bed of the channel. Figure 2 illustrates five configurations that may be used for riprap toe aprons. These configurations apply only to the placed revetment.

Although it is usual to use riprap toe aprons when using riprap revetments, toe aprons may be constructed of wire baskets, willow branches and lumber or articulated pre-cast concrete blocks. If the structure is placed on the surface of the bed its outer edge is expected to drop downwards as scouring takes place. If riprap is used, sufficient stone must be provided beforehand, so that as stones fall into the scour hole, a layer of stones having adequate thickness is formed. If a mattress of wire-and-stone or concrete blocks is used, there must be sufficient flexibility between adjacent components and between apron and upper slope protection, so that the apron can settle properly onto the side slope of the scour hole. The quantity of stone in a riprap toe apron must be such that adequate coverage of the scour hole side slope is achieved after redistribution of the stones.

The riprap apron placed in the bed of the channel must have a configuration either as shown in Figure 2 (a),

(b) or (d). Figure 2 (a) or 2 (b) is used when the trench can be excavated in the "dry". The configuration shown in Figure 2 (d) may be used when the trench is excavated under water. The following criteria apply to the various methods of toe protection illustrated in Figure 2:

1. Method A

When toe excavation can be made in the dry, the normal riprap layer should be extended below the existing groundline a distance equal to the anticipated depth of scour.

2. Method B

When the low water surface or groundwater level is near the existing groundline so that excavation is in the wet, a horizontal stone layer should be provided to a depth 'a' equal to 3 - 5 feet, a thickness 'b' not less than the layer thickness 'T' and a base width 'c' not less than 'a', except that when the anticipated erosion depth is more than 2 or 3 feet below the stone toe, 'b' and/or 'c' should be increased to provide sufficient stone for adjustment of the toe and protection of the revetment as scour occurs.

3. Method C

When the riprap is to be placed under water and design velocities will not cause appreciable stream bed erosion, the toe should be placed on the existing channel bottom with 'a' and 'c' equal to $1.5T$ and $5T$ respectively.

4. Method D

When the riprap is to be placed under water and appreciable stream bed erosion may occur, a thickened stone toe should be placed in a trench with 'a' and 'c' equal to 3T and 5T respectively.

5. Method E

When the bottom of the channel is in rock, the normal layer of riprap should be keyed into the rock strata at stream bed level.

5.2.2 Revetment End Protection

The extent of a revetment is governed by the extent of erosion and scour. Although it is good practice to continue revetments to zones of non-eroding velocities, this is sometimes impractical. The revetment is therefore terminated in zones having velocities capable of transporting bank material. In this situation the protection of the ends of the revetment is of vital importance.

Protection is provided by using an end wall extending into the bank. This wall may either go into the bank for some distance, Figure 15 (d), or the revetment may be thickened as shown in Figure 15 (c). The purpose of the end wall is to prevent eddies, formed at the ends of the revetment, from undermining the revetment. Because the change in channel roughness at the revetment end is likely to cause the generation of eddies, some end thickening may be beneficial in revetments terminated in zones of non-eroding

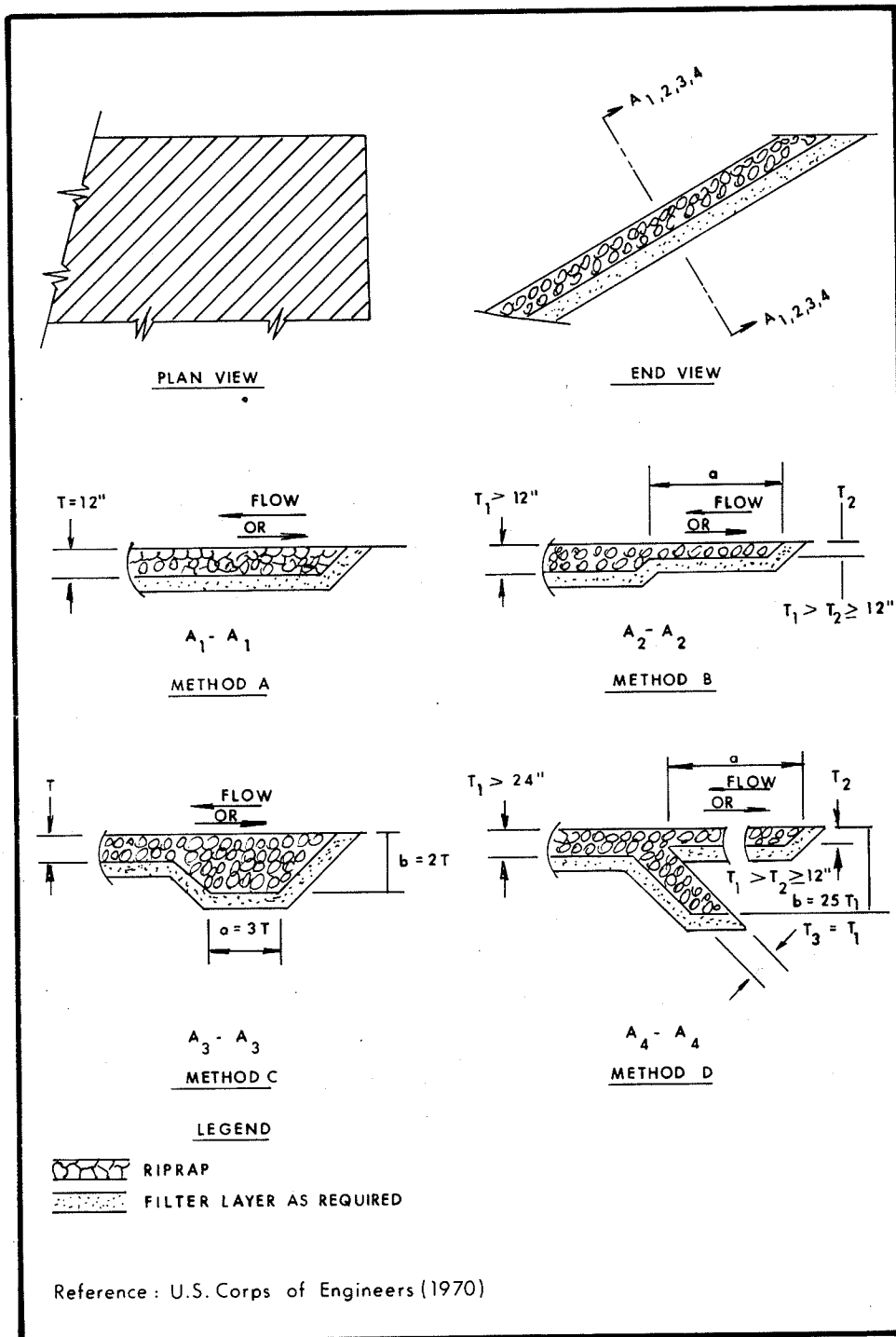


FIGURE 15. RIPRAP END PROTECTION

velocities. The following criteria apply to the various methods and protection illustrated in Figure 15.

1. Method A

For riprap revetments 12 inches thick, the normal riprap layer should be extended to areas where velocities will not erode the natural channel bank.

2. Method B

For riprap revetments exceeding 12 inches in thickness, one or more reductions in riprap thickness and stone size may be adopted for a distance 'a' in which velocities decrease to a non-eroding natural channel velocity.

3. Method C

For all riprap revetments that do not terminate in non-eroding natural channel velocities, the ends of the revetment should be enlarged as shown in Figure 15. The dimensions 'a' and 'b' should be 3 and 2 times the layer thickness, respectively.

4. Method D

For riprap revetments exceeding 24 inches in thickness, consideration should be given to the economy of adopting method D instead of method C. The stub, with thickness T_3 equal to T , should be placed at the extremity of the revetment proper and the revetment extended a distance 'a' with smaller stone size and thickness T_2 to a non-eroding location. The stub 'b' should equal 2.5 times T_1 .

End walls were provided in all the revetments used in the model tests except those placed by the launching process. Launched revetments do not have end walls or thickened ends.

5.3 Riprap Placement

The stones used in a riprap revetment may be positioned by dumping from trucks or cranes or spreading by bulldozers. When dumping is from trucks or cranes small increments of stone should be introduced as close to their final positions as practical. This ensures that the stones are not damaged by impact of one stone against the other and that dislodgment of the previously placed stones does not occur. Although stones may be placed on a side slope by pushing the stones over the crest of the slope this method is not recommended. A large amount of segregation and breakage can occur. Smoothing and other rehandling activities required to smooth the revetment face also lead to segregation and breakage and are not recommended.

The direct application of stone to the bank or slope in accordance with a predetermined design is referred to in this thesis as a "placed revetment". The "launched revetment" is an artificial lining formed by the actual erosion and scour process. Stones, dumped on a bench on the slope or on the top of the slope, are undermined due to the loss of bank material and slide down the bank.

Progressive movement of stones down the slope eventually produces a lining approximately one stone size thick. This is the launched revetment. The configuration of a launched revetment has already been shown in Figure 13.

Revetment designs with variations in toe apron configuration, revetment thickness, height, extent and placement, etc. will be tested in the series of laboratory tests and their performances compared.

5.4 Theoretical Development for Stone Size

In the absence of waves and seepage forces, the stability of stone riprap particles on a side slope is a function of the following:

1. The magnitude and direction of the stream velocity in the vicinity of the stone particles
2. The angle of the side slope.
3. The characteristics of the stones, including stone shape, size and density
4. The angle of repose of the stones

The functional relationships between the variables are developed below. The development is that given by Stevens et al (1974).

5.4.1 Oblique Flow on a Side Slope

Consider flow along an embankment as shown in Figure 12. The fluid forces on a stone particle, Figure 12 (b), result primarily from fluid pressures around the particle. The fluid force acting normal to the plane of the bank is

the lift force F_L . The lift forces are zero when velocity of the flow is zero and increases as the velocity of the flow and the area of exposed stone increases. The drag force, F_D , is defined as the fluid force acting on the particle in the direction of the velocity field near the particle. The drag and lift forces act at right angles to the flow. The submerged weight of the stone particle is W_S .

The stone particles in a placed revetment move by rolling instead of sliding. It is therefore appropriate to consider the stability of stone particles in terms of moments about the point of rotation. In Figure 12 (b), the direction of movement is defined by the vector R. The point of contact about which the upper stone particle moves is identified as point "0" in Figure 12 (c).

The forces acting in the plane of the side slope are F_D and $W_S \sin\theta$, as shown in Figure 12 (b). The angle θ is the side slope angle measured from the horizontal. The lift force acts normal to the side slope and $W_S \cos\theta$, one component of the submerged weight of the stone acts normal to the side slope but opposite to F_L .

At incipient motion, there is a balance of moments about the contact point "0" such that

$$W_S \cos\theta = e_1 W_S \sin\theta \cdot \cos\beta + e_3 F_D \cos\delta + e_4 F_L \quad 5.1$$

The moment arms e_1 , e_2 , e_3 and e_4 are defined in Figure 12 (c) and the angles δ and β are shown in Figure 12.

The factor of safety "S" of the particle against rotation is defined as the ratio of the moments resisting rotation out of the riprap layer to the moments tending to cause rotation. Accordingly,

$$S = \frac{e_2 W_s \cos \theta}{e_1 W_s \sin \theta \cos \beta + e_3 F_D \cos \delta + e_4 F_L} \quad 5.2$$

If there is no flow and the side slope is increased to the angle of repose ϕ for the stone material, the safety factor becomes unity. Then

$$S = 1.0$$

where

$$\theta = \phi$$

$$\beta = 0^\circ$$

$$\lambda = 0^\circ$$

$$\begin{aligned} \delta &= 90 - (\lambda + \beta) \\ &= 90^\circ \end{aligned}$$

with these values, Equation 5.2 reduces to

$$\frac{e_2 W_s \cos \phi}{e_1 W_s \sin \phi} = 1 \quad 5.3$$

or

$$\tan \phi = \frac{e_2}{e_1} \quad 5.4$$

That is, the ratio of the moment arms $\frac{e_1}{e_2}$ is characterized by the natural angle of repose ϕ . Further, it is assumed that the ratio $\frac{e_2}{e_1}$ is invariant to the direction of particle motion indicated by the angle β .

Dividing both numerator and denominator by $e_1 W_s$, equation 5.2 is transformed to

$$S = \frac{\cos\theta \cdot \tan\phi}{n' \tan\phi + \sin\theta \cdot \cos\beta} \quad 5.5$$

in which

$$n' = \frac{e_3 F_D}{e_2 W_s} \cos\delta + \frac{e_4 F_L}{e_2 W_s} \quad 5.6$$

The variable n' is called the stability number for the particle on the side slope and is related to the Shield's parameter $\frac{\tau_0}{(S_s - 1) \gamma D_{65}}$

Here τ_0 is the average frictional force on the bed, S_s is the specific weight of the stone, γ is the unit weight of water and D_{65} is the representative grain size of the stone particles (D_{65} is the diameter of the stone which is 65 percent finer by weight).

The angle λ shown in Figure 12 is the angle between the horizontal and the velocity vector (or drag force) measured in the plane of the side slope. Then

$$\delta = 90 - (\lambda + \beta) \quad 5.7$$

so

$$\begin{aligned} \cos\delta &= \cos [90 - (\lambda + \beta)] \\ &= \sin (\lambda + \beta) \end{aligned} \quad 5.8$$

also

$$\begin{aligned} \sin\delta &= \sin [90 - (\lambda + \beta)] \\ &= \cos\lambda \cdot \cos\beta - \sin\lambda \cdot \sin\beta \end{aligned} \quad 5.9$$

It is assumed that the moments of the drag force F_D and the component of submerged weight $W_s \sin\theta$ normal to

the path R are balanced so that the direction of particle motion will be along R. Thus

$$e_3 F_D \sin \delta = e_1 W_s \sin \theta \cdot \sin \beta \quad 5.10$$

It follows then from Equations 5.9 and 5.10 that

$$\begin{aligned} \sin \beta &= \frac{e_3 F_D \sin \delta}{e_1 W_s \sin \theta} \quad 5.11 \\ &= \frac{e_3 F_D (\cos \lambda \cdot \cos \beta - \sin \lambda \cdot \sin \beta)}{e_1 W_s \sin \theta} \end{aligned}$$

or

$$\tan \beta = \frac{\cos \lambda}{\frac{e_1 W_s}{e_3 F_D} \sin \theta + \sin \lambda} \quad 5.12$$

The stability number n for particles on a plane bed ($\theta = 0$) with $\delta = 0$ would be

$$n = \frac{e_3 F_D}{e_2 W_s} + \frac{e_4 F_L}{e_2 W_s} \quad 5.13$$

according to Equation 5.6. Also, Equation 5.5 becomes

$$S = \frac{1}{n} \quad 5.14$$

for flow over a plane flat bed.

For incipient motion conditions for flow over a plane flat bed, $S = 1.0$ by definition so from Equation 5.14, $n = 1.0$. When the flow along the bed is fully turbulent, the Shields' parameter for incipient motion has the value of 0.047 according to Gessler (1971). That is, with $n = 1.0$

$$\frac{\tau_0}{(S_s - 1) \gamma D_{65}} = 0.047 \quad 5.15$$

For flow conditions other than incipient n is the ratio

$$\frac{1}{0.047} : \frac{\tau_0}{(S_s - 1) \gamma D_{65}}$$

or

$$n = \frac{21 \tau_0}{(S_s - 1) \gamma D_{65}} \quad 5.16$$

For convenience, let

$$M = \frac{e_4 F_L}{e_2 W_s} \quad 5.17$$

and

$$N = \frac{e_3 F_D}{e_2 W_s} \quad 5.18$$

In terms of these two new variables, Equation 5.6 becomes

$$n' = M + N \cos \delta \quad 5.19$$

and Equation 5.13 becomes

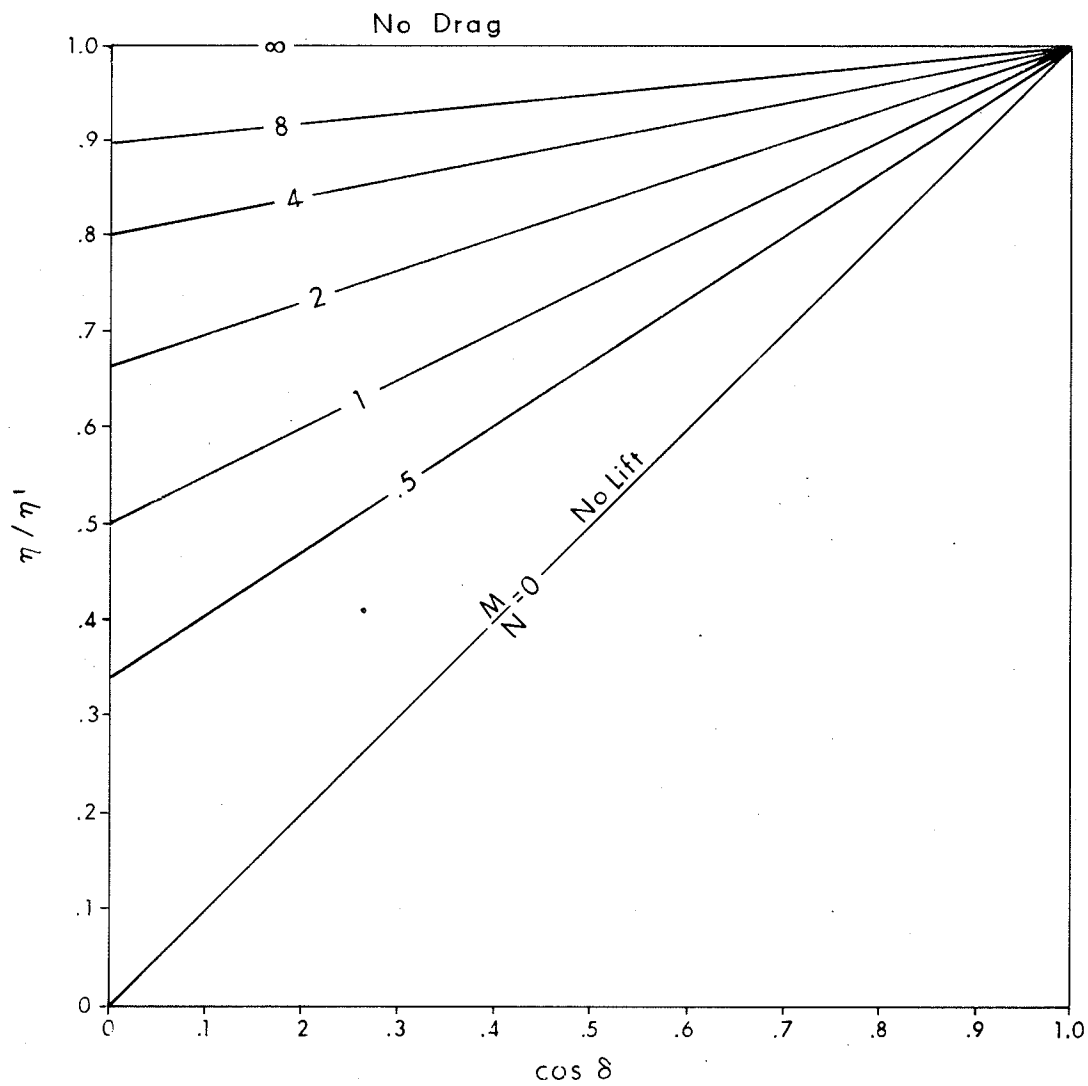
$$n = M + N \quad 5.20$$

Thus n' and n are related by the expression

$$\frac{n'}{n} = \frac{\frac{M}{N} + \cos \delta}{\frac{M}{N} + 1} \quad 5.21$$

Equation 5.21 is represented graphically in Figure 16.

The problem is to select the proper value of the ratio so that the stability factor on a slide slope n' can be related to the stability factor on a plane horizontal bed, n , which in turn is related to the Shields' parameter. The assumption that the drag force is zero means M/N is infinite, is zero and $n' = n$. The assumption of zero lift force F_L



Reference: Karaki et al (1974)

FIGURE 16. RATIO OF STABILITY FACTORS.

means M/N is zero and $n'/n = \cos \delta$. For finite values of lift and drag forces, the stability factor ratios are between the limits zero and $\cos \delta$.

In considering incipient motion of stone particles, the ratios F_L/F_D and e_4/e_3 vary depending on the turbulent conditions of the flow and the interlocking arrangement of the stone particles. In referring to Figure 12 it is reasonable to assume that

$$\frac{e_4}{e_3} \approx 2 \quad 5.22$$

and

$$\frac{F_L}{F_D} \approx 1/2 \quad 5.23$$

so that

$$\frac{M}{N} = \frac{e_4 F_L}{e_3 F_D} \approx 1 \quad 4.24$$

with $M/N = 1$, Equation 5.21 becomes

$$\frac{n'}{n} = \frac{1 + \cos \delta}{2} \quad 5.25$$

or by using Equation 5.8

$$\frac{n'}{n} = \frac{1 + \sin(\lambda + \beta)}{2} \quad 5.26$$

In Equation 5.12, the term $e_1 W_s / e_3 F_D$ can be written

$$\begin{aligned} \frac{e_1 W_s}{e_3 F_D} &= \frac{e_2}{e_3} \frac{W_s}{F_D} \frac{e_1}{e_2} \quad 5.27 \\ &= \frac{1}{N} \cdot \frac{1}{\tan \phi} \end{aligned}$$

according to Equations 5.18 and 5.4.

For $M/N = 1$, Equation 5.20 Becomes

$$N \approx \frac{n}{2} \quad 5.28$$

If we substitute Equation 5.27 and 5.28 into Equation 5.12, the expression for β becomes

$$\tan\beta = \frac{\cos\lambda}{\frac{2 \sin\theta}{n \tan\phi} + \sin\lambda} \quad 5.29$$

In summary, the safety factor for stone riprap on side slopes where the flow has a non-horizontal velocity vector is related to properties of the stone, side slope and flow by the following equations:

$$\delta' = \frac{\cos\theta \cdot \tan\phi}{n' \tan\phi + \sin\theta \cdot \cos\beta} \quad 5.30$$

in which

$$= \tan^{-1} \frac{\cos\lambda}{\frac{2 \sin\theta}{n \tan\phi} + \sin\lambda} \quad 5.31$$

$$n = \frac{21 \tau_0}{(S_s - 1) \gamma D_{65}} \quad 5.32$$

and

$$n' = n \left[\frac{1 + \sin(\lambda + \beta)}{2} \right] \quad 5.33$$

Given a stone gradation having a stone specific gravity S_s , angle of repose ϕ and a velocity field at an angle λ to the horizontal, producing a tractive force τ_0 on the bed and a side slope angle of θ , the set of four equations (5.30, 5.31, 5.32 and 5.33) can be solved to obtain the safety factor S . If S is greater than unity, the riprap is safe from failure; if S is unity, the riprap is at the condition of incipient motion, if S is less than unity, the riprap will fail.

5.4.2 Horizontal Flow on a Side Slope

In many circumstances, the flow angularity with the horizontal is small, i.e., $\lambda = 0$. Equations 5.31 and 5.33 reduce to

$$\beta = \tan^{-1} \left[\frac{n \tan \phi}{2 \sin \theta} \right] \quad 5.34$$

and

$$n' = n \left[\frac{1 + \sin \beta}{2} \right] \quad 5.35$$

When Equations 5.34 and 5.35 are substituted into Equation 5.30, the expression for the safety factor for horizontal flow along a side slope is

$$S = \frac{S_m}{2} \left[(\xi^2 + 4)^{1/2} - \xi \right] \quad 5.36$$

in which

$$\xi = S_m \cdot n \sec \theta \quad 5.37$$

and

$$S_m = \frac{\tan \phi}{\tan \theta} \quad 5.38$$

If we solve Equations 5.36 and 5.37 for n , then

$$n = \left[\frac{S_m^2 - S^2}{S \cdot S_m^2} \right]^{1/2} \cos \theta \quad 5.39$$

The term S_m is the safety factor for riprap on a side slope with no flow. Unless the flow is up the slope, the safety factor for the riprap cannot be greater than S_m .

5.4.3 Flow on a Plane Sloping Bed

Flow over a plane bed at a slope of α degrees in the downstream direction is equivalent to oblique flow on a side slope with $\theta = \alpha$, and $\lambda = 90^\circ$.

Then, according to Equation 5.31, $\beta = 0$ and from Equation 5.33

$$n' = n \left[\frac{1 + \sin(90 + 0)}{2} \right] \quad 5.40$$

It follows from Equation 5.30 that

$$S.F = \frac{\cos\alpha \cdot \tan\phi}{n \tan\phi + \sin\alpha} \quad 5.41$$

for flow on a plane bed sloping α degrees to the horizontal.

Alternatively solving for n in Equation 5.41

$$n = \cos\alpha \left[\frac{1}{S.F} - \frac{\tan\alpha}{\tan\phi} \right] \quad 5.42$$

5.4.4 Flow on a Horizontal Bed

For fully developed rough turbulent flow over a plane horizontal bed ($\alpha = 0$) of stone riprap, Equation 5.41 reduces to

$$S.F = \frac{1}{n} \quad 5.43$$

If the riprap particles are at the condition of incipient motion, $S.F = 1$, so $n = 1$ and from Equation 5.32

$$\frac{\tau_0}{(S_s - 1) \gamma D_{65}} = 0.047 \quad 5.44$$

which is Shields' criteria for the initiation of motion.

The first part of the thesis dealt with the types of riprap revetments, the suitability of stone as revetment material, the factors influencing riprap stability, the factors affecting erosion and scour, the processes of erosion and scour and finally the theoretical development of the stability analysis for riprap liners on river banks.

The second part of the thesis, Chapters 6 and 7, describe the test procedures and the tests themselves, and discusses the results of the tests. Chapter 8 presents the conclusions resulting from the model study and the recommendations for future studies pertaining to the launching of riprap revetments are to be found in Chapter 9.

6. TESTING OF THE MODEL

6.1 Introduction

The objective of the study was to compare the performance of the launched revetment and the placed revetment with respect to the following:

1. The change in scour hole depth and formation when going from a placed revetment configuration, with and without toe protection, to the launched revetment configuration.
2. The behaviour of revetments lining the entire concave bank vs the behaviour of revetments which do not fully line the concave bank.
3. The most efficient method of placing stones for the launching of a revetment.
4. The likelihood of significant loss of stones from a launched revetment.
5. The movement of bed material along the toe of the concave bank.
6. The movement of stones down the slope (whether by rolling or sliding).
7. The need for inner bank protection when using concave bank revetments of limited extent.

6.2 Model Layout

6.2.1 Model Material

The sand available in the laboratory was too large

in size for use in the model; the size of the model being controlled by the space available in the laboratory. The crushed walnut shell available was used in a test run and this material was found to be suitable. Bed movement, as would take place in a natural channel, and Froude Numbers between 0.25 and 0.4 could be attained. The crushed walnut shell was therefore used. The grain size analysis curve for the crushed walnut shell is shown in Figure 17.

Because of the small scale of the model and for ease of collecting and separating the model materials after each test run, no filter material was used. Starting with the grain size analysis of the crushed walnut shell, a gradation of stone which would satisfy filter layer requirements (see Section 4.7) could be computed. Small size material was separated from gravel available in the laboratory and a grain size analysis performed. As stated in Section 4.7, the best relationship between the grain size curves of the riprap layer and the bank is a parallel one. The two grades of riprap used agree with this specification, with Grade 1 riprap agreeing very closely with the parallel criterion. Figure 17 also presents the grain size analysis curves for both grades of riprap.

The pebbles used in the test runs also satisfied another criterion. The gradations were chosen so the revetments would be stable under the flow conditions likely

BED MATERIAL

$D_{85} = 0.56 \text{ mm}$

$D_{50} = 0.40 \text{ mm}$

$D_{35} = 0.38 \text{ mm}$

$D_{15} = 0.28 \text{ mm}$

RIPRAP

Grade 1	Grade 2
---------	---------

$D_{85} = 4.2 \text{ mm}$	9.5 mm
---------------------------	------------------

$D_{50} = 3.2 \text{ mm}$	5.8 mm
---------------------------	------------------

$D_{35} = 3.0 \text{ mm}$	5.3 mm
---------------------------	------------------

$D_{15} = 2.5 \text{ mm}$	4.1 mm
---------------------------	------------------

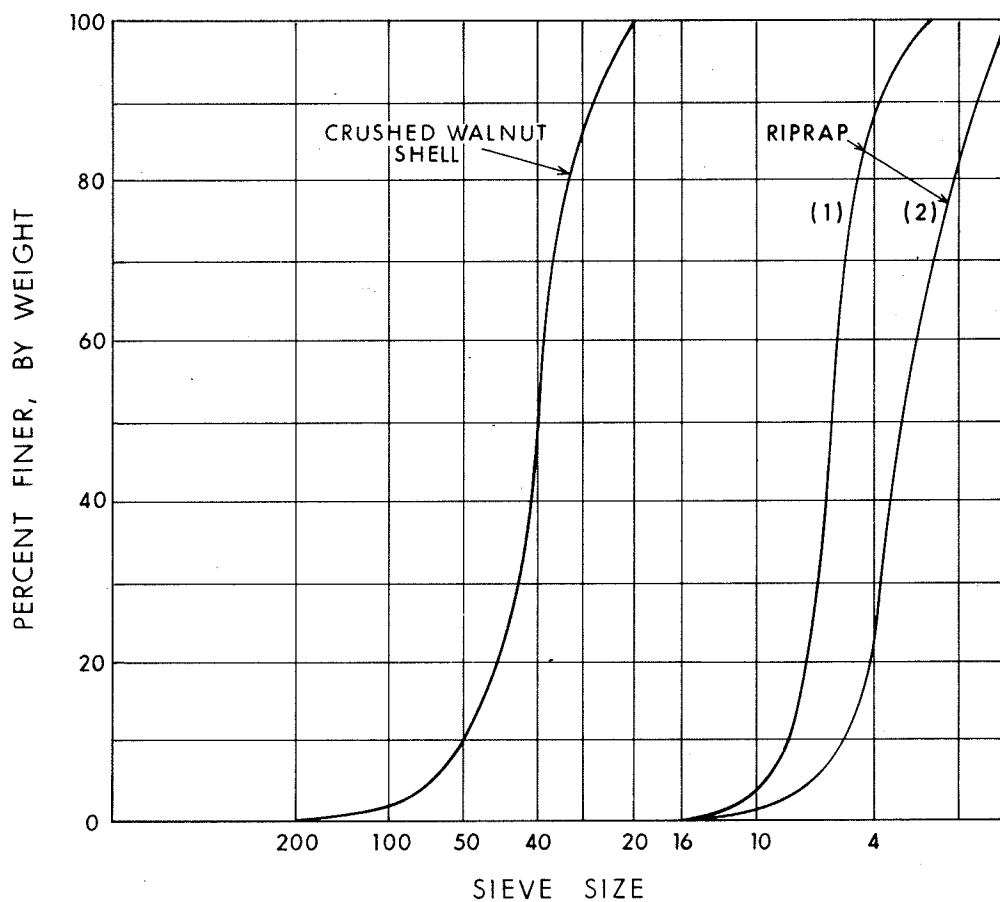


FIGURE 17. GRAIN SIZE ANALYSIS OF CRUSHED WALNUT SHELL AND RIPRAP.

to be achieved in the model. The movement of the riprap in the model during a test run agreed with what would be expected in a prototype channel and the factors of safety for the riprap gradations were greater than unity.

6.2.2 Model Scales

The model was set up to represent a sand bed channel subject to bank erosion at a concave bend. The dimensions of the model were chosen because:

1. Bed movement was as would occur in nature.
2. Riprap movement was as would occur in nature.
3. Froude Numbers as would be attained in a prototype channel were attainable.
4. Overall model behaviour was acceptable.

The model results may be used to predict the behaviour of a prototype channel by means of the Buckingham Pi Theory. This theory provides the engineer with a method of comparing the behaviour of model and prototype. The scale relationships for the model and prototype are expressed in the form of dimensionless numbers.

Because it was of interest to know the depths within scour holes, a true hydrograph was not run. The discharge was increased to a maximum value and then maintained at that value until the movement of material at the bottom of scour holes became very slow. At this stage in the test run, the gate at the end of the channel and the valve controlling the supply of water to the model were adjusted

so that the bed patterns were retained. Depths could not be measured during a test because the introduction of the point gauge near the bed of the channel would cause turbulent eddies, shed by the gauge, to move bed material.

6.2.3 Model Construction and Testing Apparatus

The model, Figures 18 and 19, is contained within an 8 ft. wide by 2 ft. 4 in. high L-shaped box constructed of plywood. The dimensions of the long limb are 20 ft. and 12 ft. respectively and those of the short limb are 16 ft. and 8 ft. respectively. Sand is placed within the box, tapering from an upstream depth of 1 ft. 6 in to a downstream depth of 12 in. The central portion is so shaped as to accommodate a channel of crushed walnut shell which is separated from the sand by a plastic membrane. Stilling basins, 1 ft. wide by 8 ft. long are partitioned off at the beginning and end of the channel. A baffle and a concrete apron, 2 ft. long, are constructed at the beginning of the channel to reduce entrance turbulence and lead the flowing water smoothly into the channel. A gate at the end of the box is used to control the depths of flow in the channel.

Two in. x 2 in. angle iron is used to provide tracks along the tops of four sides of the box. Two trolleys which run on these tracks and a third trolley, much smaller in size, to which a point gauge is bolted are all made with the same size angle iron. The trolleys are equipped with

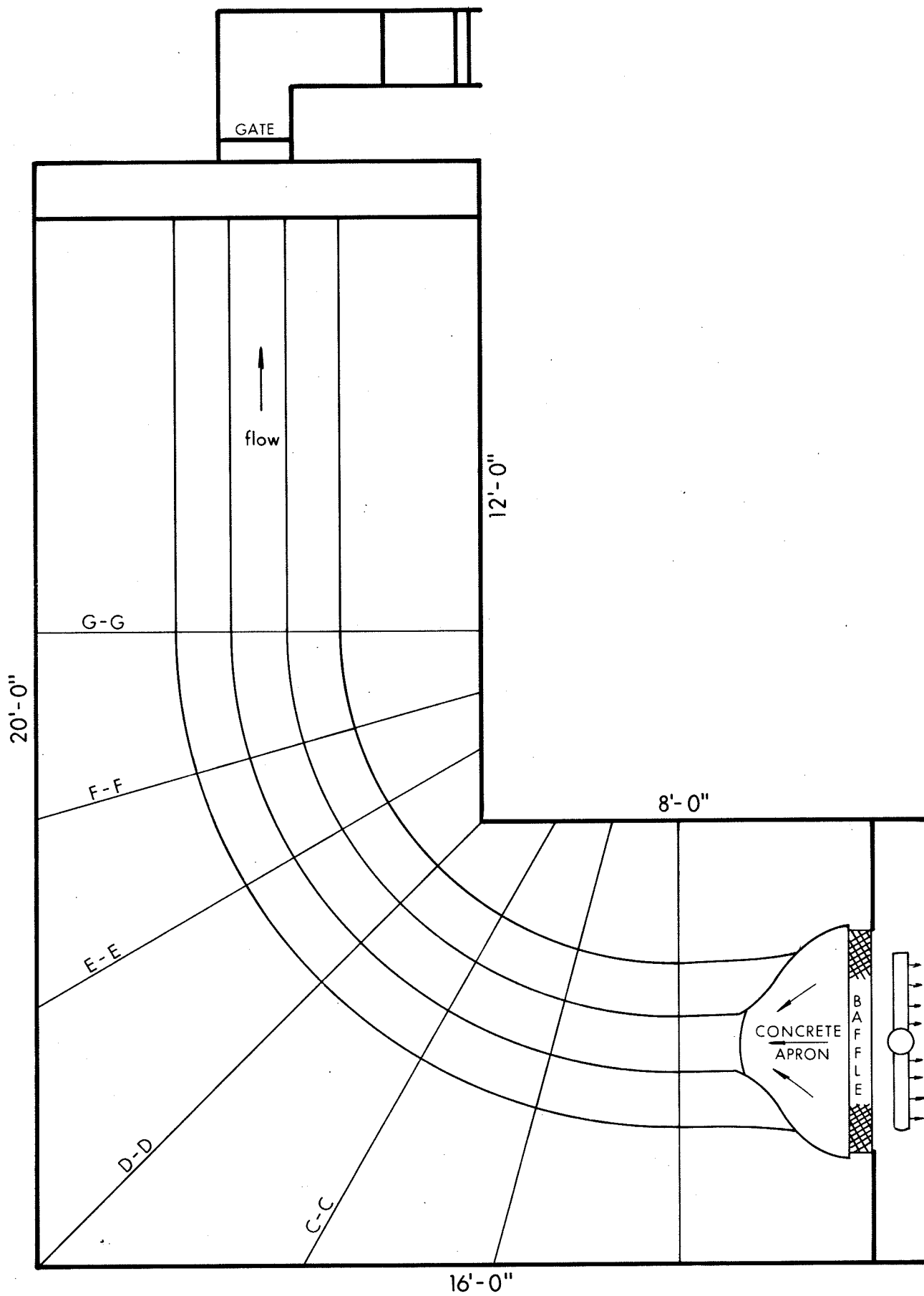


FIGURE 18. PLAN OF MODEL

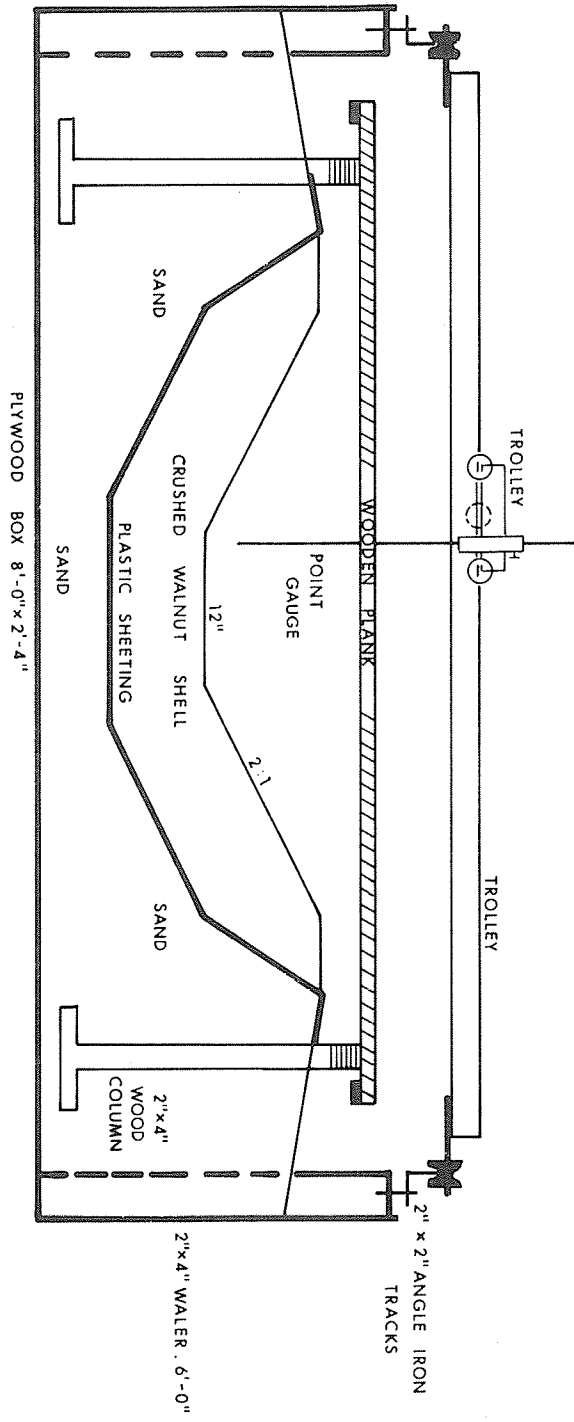


FIGURE 19. MODEL CROSS-SECTION

wheels for easy handling. All important areas of the model channel are covered by using this system of trolleys. Cross-sections of the channel and water surface levels are measured using the point gauge. Cross-sections are established every 15° of curve with the first and second to last cross-sections established 3 in. upstream and downstream of the tangent points of straight portions of the channel. The radius to the centre-line of the channel is 7 ft. 3 in., the bottom width of the channel is 12 in. and the side slopes are 2:1. The shape of the channel is obtained by using two templates; one is attached to a trolley that covers the straight portions of the channel and the second is attached to a rotating arm which pivots about a point 'O' outside the limits of the box.

Water is supplied to the model from a main sump by means of a recirculating pump. The discharge is obtained by measuring the time taken to collect a known quantity of water in a large capacity calibrated tank. The sump is located on the ground floor of the laboratory while the model is on the first floor. The sump is 10 ft. x 30 ft. x 20 ft. deep. Ordinary table tennis balls, plus balls weighted with small quantities of mercury are used to observe the high velocity stream lines within the flow. By timing these floats over a specific distance along the channel, the average surface and near surface velocities of the flowing water are obtained.

6.3 Testing Programme

The first three tests are run without riprap protection. These tests are used as control tests and are performed at three different discharges and at essentially the same Froude Numbers. The behaviour of the free bend in each test is compared with respect to scour depth, movement of bed material, areas of attack and the need for inner bank protection.

Tests 4 to 14 are performed with various configurations of revetment and revetment type (placed or launched) and two grades of riprap. Tests 4 to 10 are run with riprap having a median grain size of 5.8 mm and tests 11 to 14 are run with riprap having a median grain size of 3.2 mm. The behaviour of the stones in the two gradations and the overall performance of the revetments having different size stones are compared.

Test 15 is run for comparison with Tests 1 to 3. The water used in this model study was used in a flume study where surface tension effects were reduced by the addition of surface tension reducing agents. Test 15 showed that the addition of these additives did not affect the model material. Test 15 also indicated that the presence of a small percentage of riprap material in the bed of the channel did not significantly affect the performance of the model (complete removal, after each test, of the riprap particles present in the bed material would be time

consuming and likely not practical. A few riprap particles remained after each test).

6.4 Testing Procedure

Water was introduced to the model by filling the downstream stilling basin and allowing the water to travel very slowly up the channel. The control valve between the sump and the model was opened very slowly and the upstream stilling basin was filled until water was just covering the concrete apron. The valve was closed until the water moving up the channel had covered the concrete apron to a depth of about 1 to 2 in. By introducing water to the channel in this manner no disturbance of the contoured bed was possible. The discharge is increased by opening the valve and the depth of flow is controlled by lowering or raising the gate.

By opening the control valve slowly, the discharge was increased until a state of "incipient motion", as judged by the author, was attained. This state was reached when a slow general movement of bed material was observed over the width of the channel. Measurements of the water surface elevations were then made and the discharge measured by recording the time required to collect a known volume of water in the measuring tank.

The discharge was then increased between 45 - 300 percent and the channel eroded and scoured. Measurements of the water surface were taken and the discharge measured.

By using floats, the surface and near surface velocities within the bend could be obtained. The average velocity of the flow was obtained by dividing discharge by cross-sectional area. The floats were also used to describe the paths of high velocity currents.

Each test was run for approximately five hours. By this time the movement of bed material within the scour holes had slowed appreciably and it was unnecessary to continue the tests any longer.

A test is halted by reducing the discharge and at the same time raising the control gate. The rate of flow is slowly reduced to zero and the water remaining in the channel and stilling basins is syphoned off utilizing two syphons; one in the lower stilling basin and the other in the upper basin. By draining off the water in this manner the bed patterns are preserved. Point gauge readings enable the changes in cross-sections to be plotted as shown in Figures 20 to 34.

7. DISCUSSION OF TEST RESULTS

7.1 Introduction

To ascertain that the model would produce acceptable results, a typical model channel was allowed to erode and scour and the bed forms and dune patterns observed. The following observations were made:

1. The movement of bed material first began at the inside bank between sections B-B and C-C.
2. The material in 1 moved directly downstream for a short distance and was then directed towards the inner bank at sections C-C and D-D.
3. Bed material displaced from along the concave bank at section C-C and was being moved diagonally across the channel towards sections D-D and E-E.
4. Movement of material from the concave bank at section F-F began just before movement at the concave bank in 3.
5. As the dune along the inner bank between sections D-D and E-E became larger in extent and height, erosion of the concave bank at section F-F began progressing upstream.
6. With increasing discharge and increased bank irregularity, erosion and scour at the concave bank became greater.
7. Turbulent eddies began forming at the concave bank as a result of local geometric irregularities at the bank.

8. The bed consists of a series of dunes progressing downstream.
9. After the first scour hole is formed (usually in the vicinity of C-C and D-D) more holes begin forming along the concave bank.
10. Scour holes merge to form larger holes.
11. With the passage of a dune, scour holes are alternately filled in and scoured out.
12. The scour holes formed along the concave bank eventually merge to form a longer hole.
13. Movement of material from the bottom of scour holes eventually ceases when the fluid forces become too weak to move bed particles up and over the downstream lip of the hole.

The observations listed above indicate that the model behaves as a natural channel would behave and can be used to predict prototype behaviour.

7.2 Preliminary Tests

The preliminary Tests 1, 2 and 3 were performed without riprap protection. It was observed while performing these tests, and this is shown in Figures 20, 21 and 22, that deposition occurred at the toe of the convex bank between sections D-D and G-G and on the lower part of the bank. In addition to this, it was observed that the bed material deposited in the vicinity of section E-E is usually less

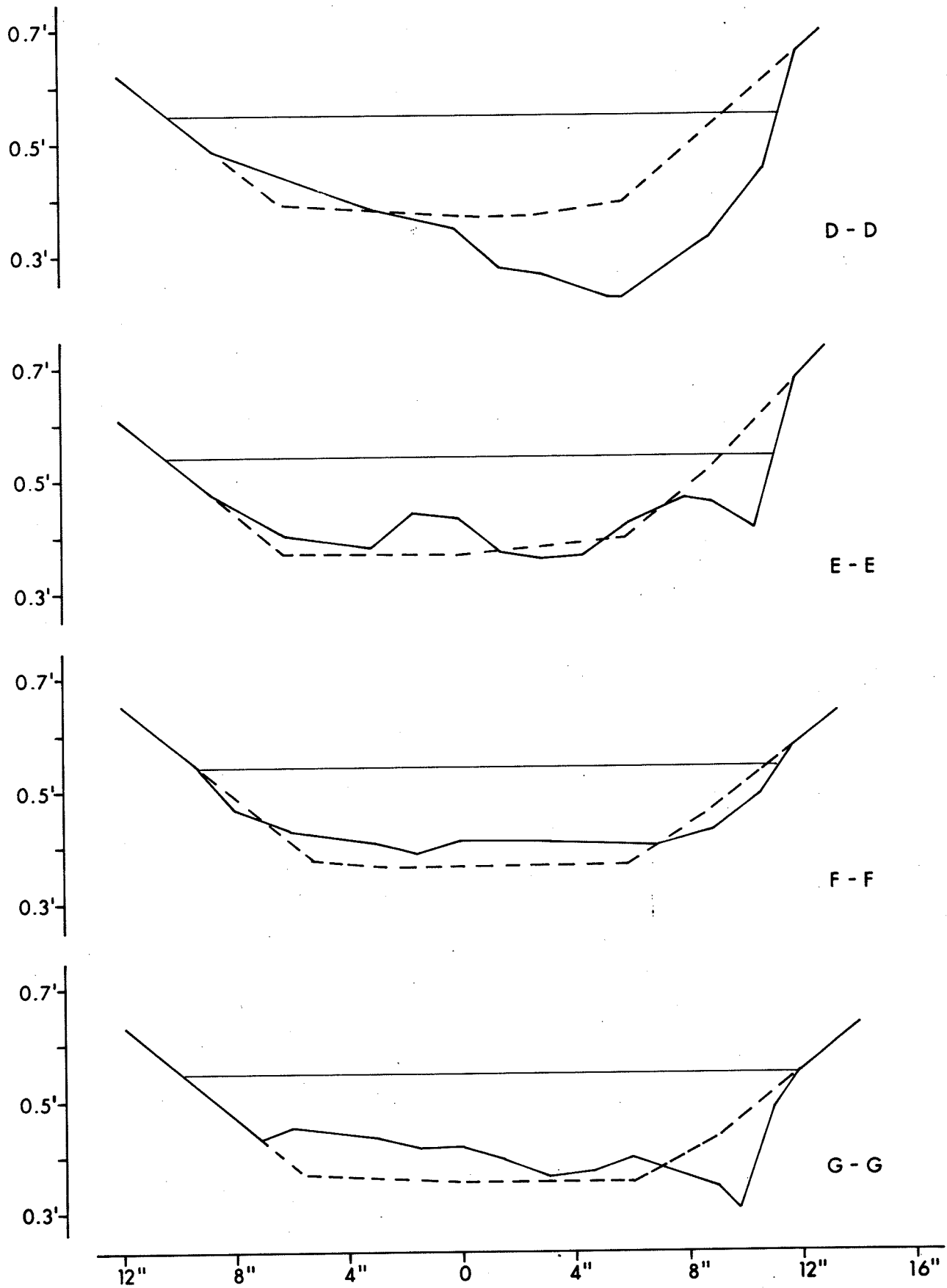


FIGURE 20. CROSS-SECTIONS FOR TEST No. 1.

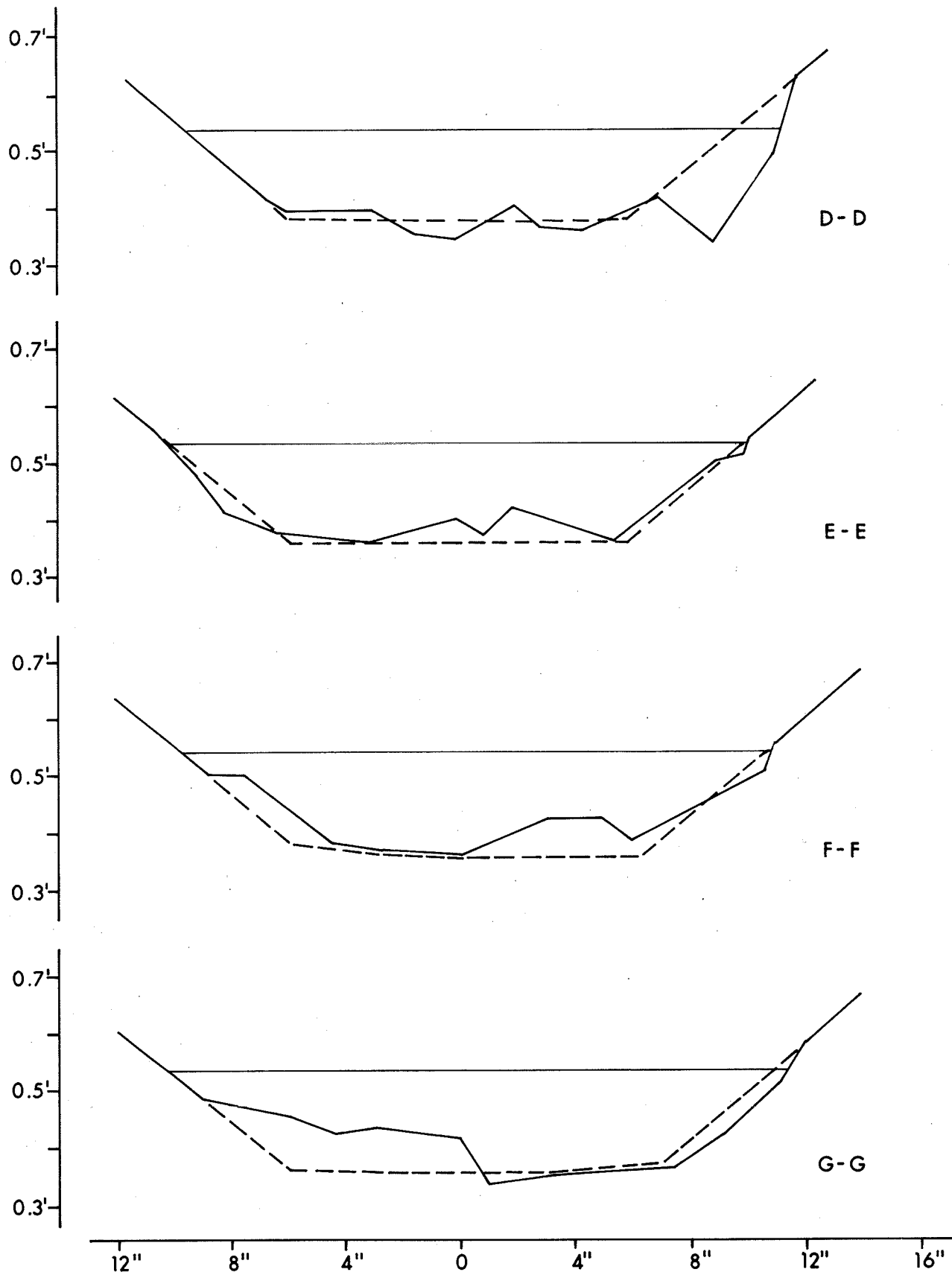


FIGURE 21. CROSS-SECTIONS FOR TEST No. 2.

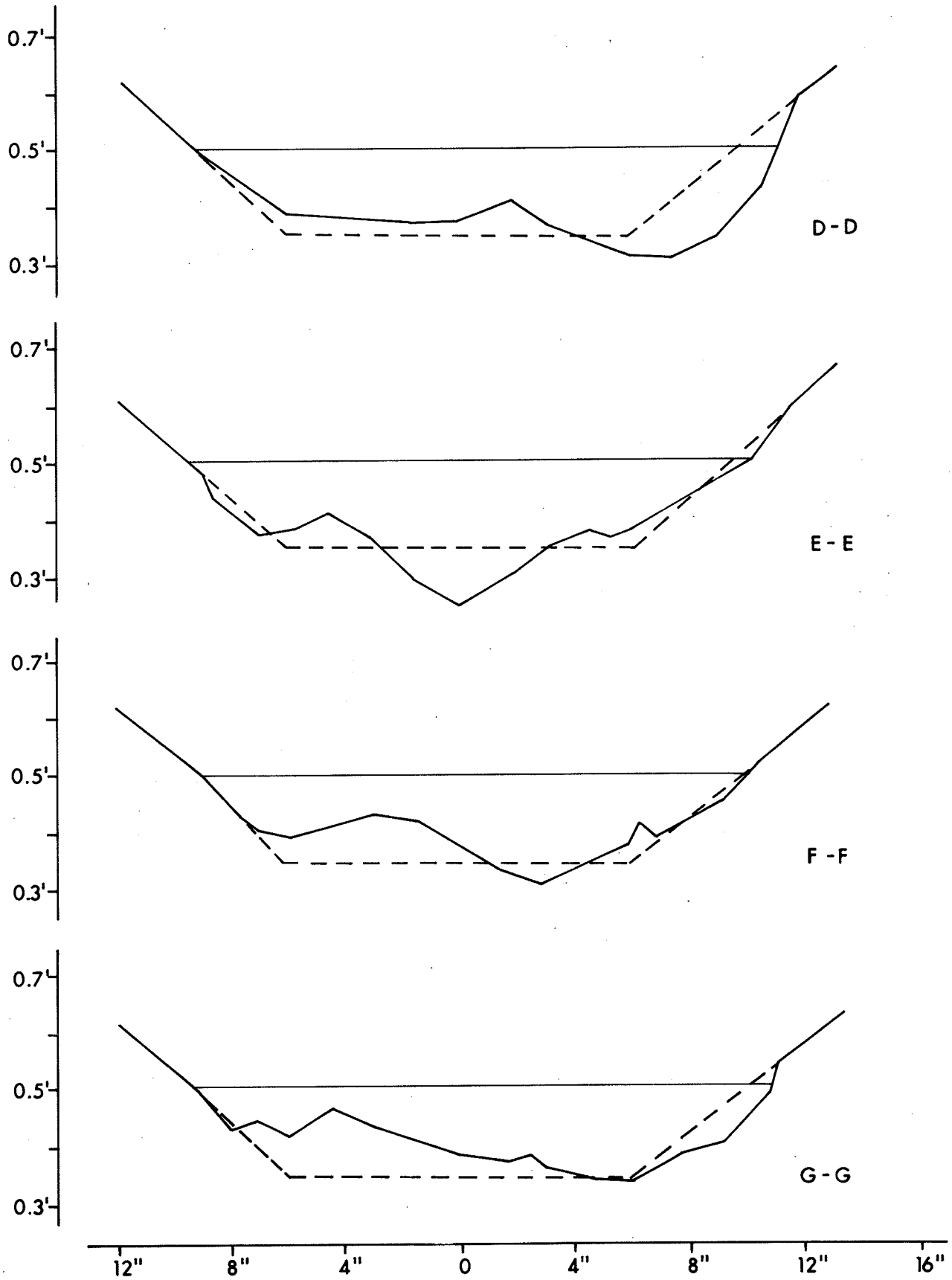


FIGURE 22. CROSS-SECTIONS FOR TEST No. 3.

than that deposited at sections D-D, F-F and G-G and that erosion of the inner bank at the waterline at section E-E occurs. This process agrees with results that previous researchers have obtained with movable bed models and indicates that deflection of currents from the concave bank can cause some erosion to occur at the inner bank of natural channels.

Before an advanced stage of scour hole development is attained at section D-D, the velocity streamlines are directed towards the concave bank. This is caused by the action of centrifugal forces acting on the body of moving water. These centrifugal forces combine with the main current acting down the channel and produce a spiral motion within the flow. This spiral characteristic of the flow is partly responsible for moving bed material from the toe of the concave bank to the toe of the convex bank. As material is shifted towards the convex bank, dunes are formed. These dunes grow in size and cause a progressive shift in flow direction towards the concave bank. The forces of scour are increased and turbulence increases.

The increase in turbulence causes the first scour hole and then the scour hole itself increases turbulence within the bend. The transfer of bed material from the bed at the toe of the concave bank becomes faster and turbulence causes the finer bed particles to become trapped in the flow. This suspended material is transported further downstream

than the heavier saltating material near the bed. Eventually the scour hole advances to the very bottom of the bank and the bank material begins to slide into the hole. The scour holes first formed tend to have their longer axis in a direction somewhat diagonally across the bed of the channel. This causes a high velocity current to be directed towards the inner bank near the end of the bend. It is this high velocity current which initiates the erosion of the convex bank. Dune building along the base of the convex bank continues and eventually erosion at the inner bank slows appreciably until it ceases altogether. The scour hole at the concave bank continues to develop until movement becomes so slow that it is almost imperceptible with the naked eye. The tests are stopped at this time and the water drained off slowly to preserve the bed patterns. The bed is then profiled using a point gauge.

The degree of scouring at bends and other natural channel configurations such as confluences and constructions is represented by the so called "Z" factor, where Z is the ratio of maximum depth in the scour hole to the average depth in the channel. The Z factors for the three preliminary tests are 2.55, 2.62 and 2.45 respectively. The average for the three tests is 2.45.

Floats were used to describe the paths of the high velocity currents in the channel. In addition, the floats were timed over a specific distance to provide an estimate

of the surface velocities. These velocities were approximately 40 - 50 percent greater than the average velocities of the flow and better represented the velocity against the concave bank. This method of obtaining velocities was used because introduction of velocity measuring devices near the bed and banks would have caused additional unwanted turbulence within the flow.

7.3 Riprap Placed Before Erosion

The riprap configurations tested are shown in Figures 23 to 28. Besides having changes in their vertical profiles, the revetments also have changes in their horizontal extent. This allows the researcher to study the effect that shortening or lengthening a revetment has on its performance.

Tests 4 - 9 involve riprap structures which were placed before the introduction of water to the model. These arrangements represent revetments with upper slope structures that usually remain unchanged during the scouring process and subsequent rearrangement of the toe apron. The differences in the various designs are shown in Figure 23 to 28 and in the photographs presented in Appendix A.

Test 4 consisted of a revetment having an embedded riprap toe trench and Tests 5 and 6 involved revetments having toe aprons of different lengths resting on the bed of the channel. For Test 7, the revetment is essentially the same length as the revetments in Tests 4, 5 and 6, but this revetment has no apron at its toe. Test 8 incorporates an inner bank

lining with a split revetment on the concave bank. Test 9 has a shorter revetment on the concave bank. No inner bank protection is used in Test 9.

7.3.1 Test 4

As in the previous tests, the first area to undergo significant movement in Test 4 was in the left quarter of the channel midway between section B-B and C-C. This material was shifted towards the inner bank at section D-D and further downstream. Because of the revetment and the sunken toe trench the attacking water is turned smoothly along the bend and the deflection of high velocity currents from the concave bank is not as severe as in the previous tests. The turbulent eddies associated with an eroding bank are eliminated and because the toe apron extends for some distance out into the channel most of the high velocity flow is contained in an area of the channel which is armoured with resistant material. Although a scour hole is formed in the bed it is not as deep as the holes formed in Tests 1, 2 and 3. Only a very small quantity of riprap material is displaced into the scour holes. (Figure 23). The performance of this revetment is excellent and if space and time is of little concern this type of revetment is recommended. With the toe apron embedded in the bed, maximum support is provided to the upper slope structure and the reduction in flow area due to the revetment is kept to a minimum. This revetment provides a wider channel section of nearly constant depth from approximately

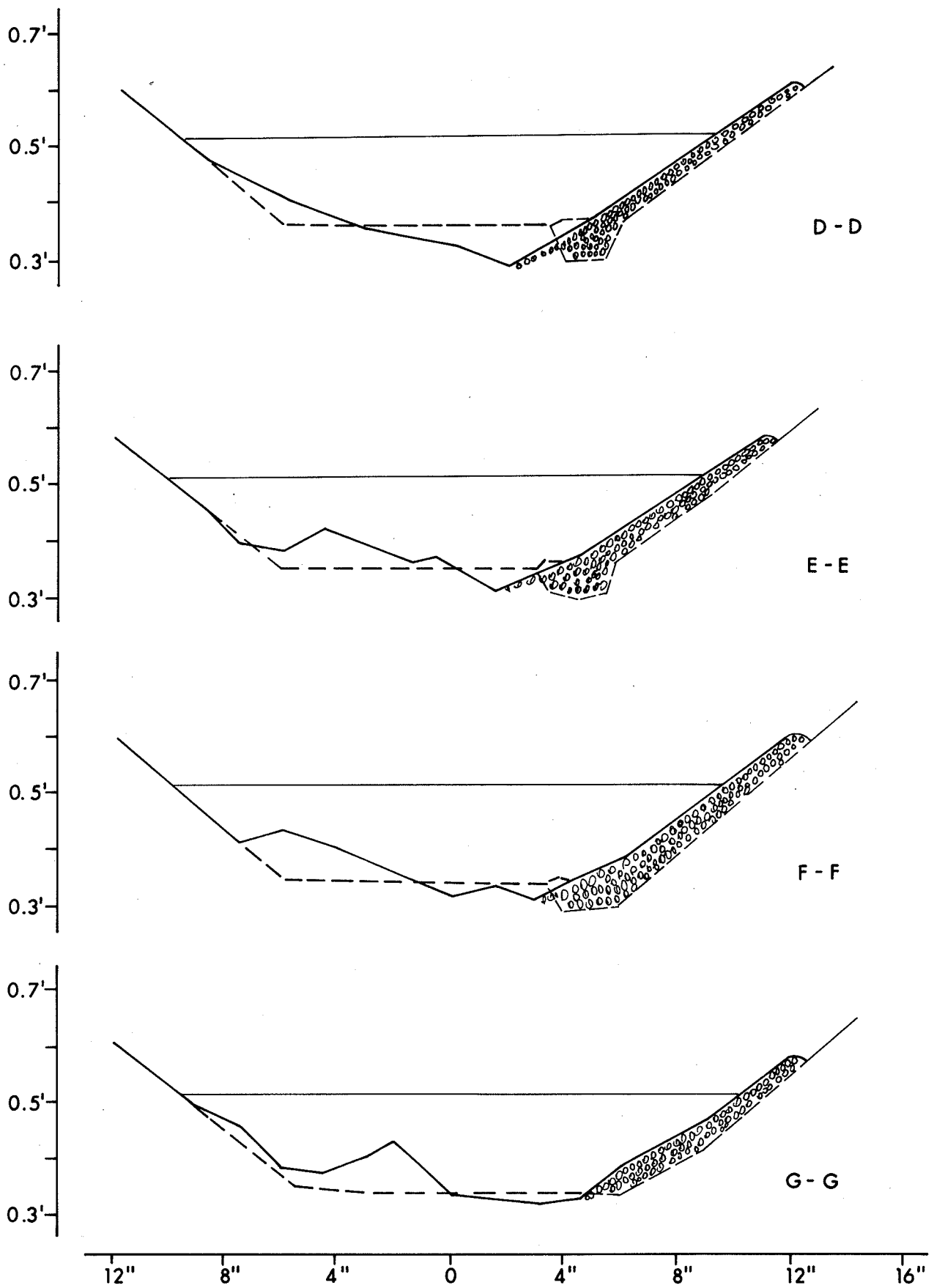


FIGURE 23. CROSS-SECTIONS FOR TEST No.4.

mid-channel to the concave bank when compared with the sections obtained after Tests 1, 2 and 3. The height of dunes between scour holes at the outside of the bend is much reduced. Velocities against the concave bank are greater because of the smoother alignment of the flow and the high velocity currents remain near the concave bank for a greater distance downstream. This effect was anticipated so the revetment was terminated in an area where the high velocity currents were in the central portion of the channel cross-section. Attempts to initiate failure of the revetment were unsuccessful. A Z factor of 2.3 was obtained with this revetment.

7.3.2 Tests 5 and 6

In Tests 5 and 6 the toe apron is placed above the bed, with the apron in Test 6 being half the width of the apron in Test 5. (Figures 24 and 25). Because the area available for the flow is reduced by the toe aprons, more of the flow is shifted towards the inner bank. This shift occurs early in the test runs and causes significant erosion at the convex bank. Although this erosion slows as the tests progress, the overall effect is greater erosion at the inner bank than in Tests 1 to 4. The depths of the deepest scour holes along the concave banks are greater than for Test 4, but the revetments remained stable because of the toe aprons. Although the revetments in Tests 5 and 6 performed well in their function of protecting the concave bank, significant

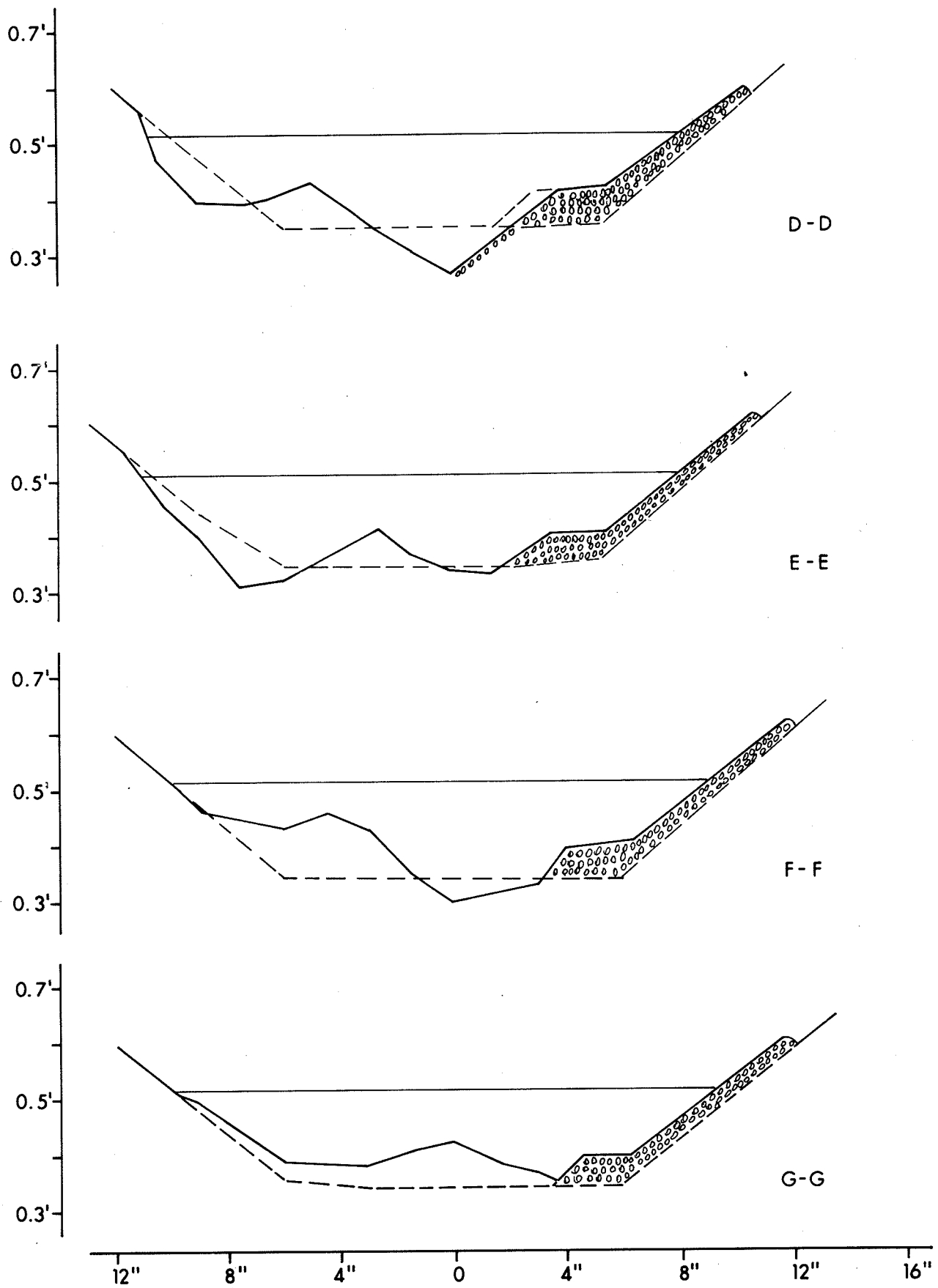


FIGURE 24. CROSS - SECTIONS FOR TEST No. 5.

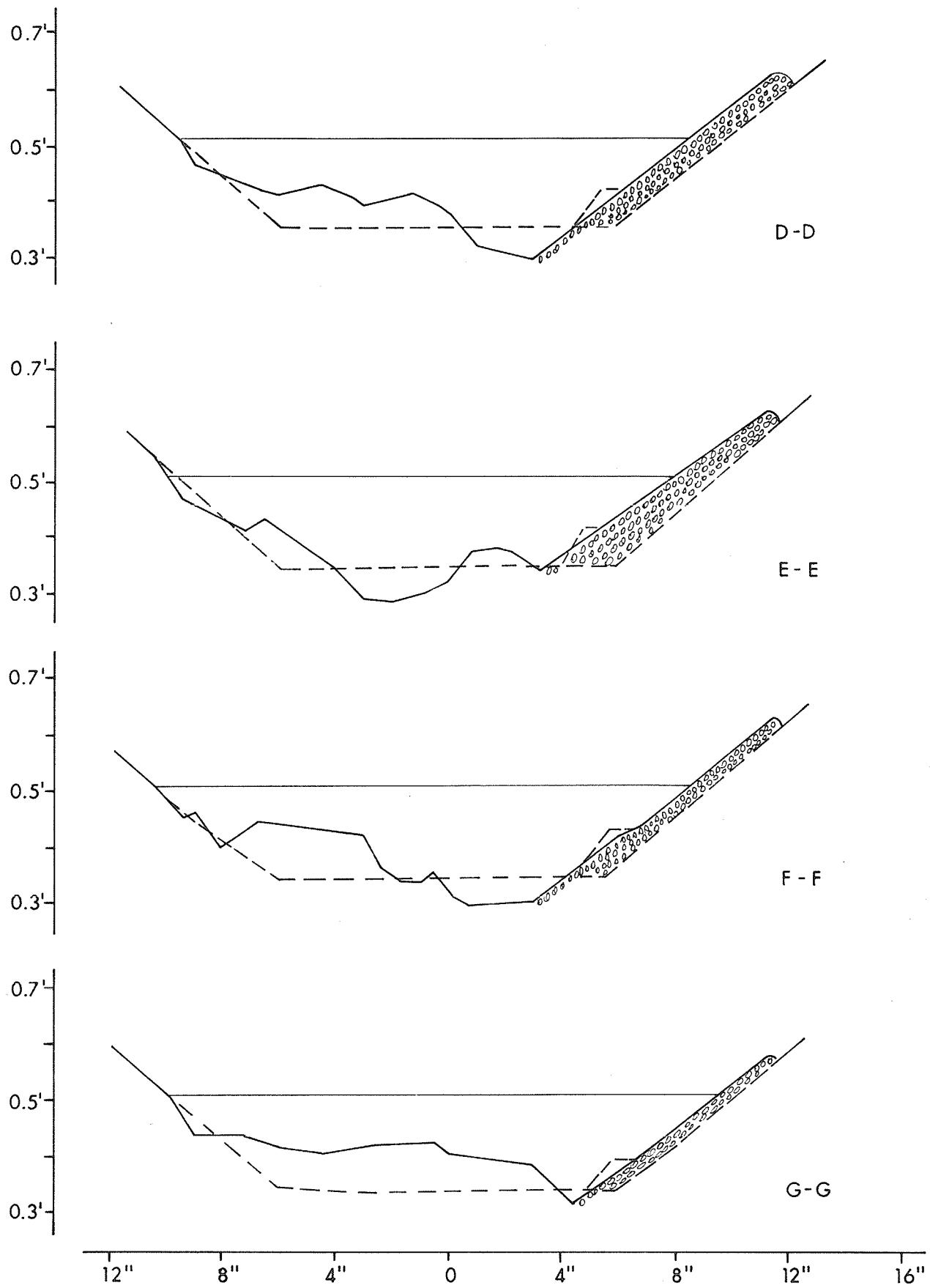


FIGURE 25 . CROSS - SECTIONS FOR TEST No. 6 .

erosion occurred at the inner bank in Test 5. This is one reason why the design used in Test 4 is preferred. In Test 6, the erosion of the inner bank was much less than in Test 5, whereas the depth of scour was greater. When bank protection is the prime reason for the revetment, bed deepening will usually be of secondary importance. Should this be the case, the revetment of Test 6 is preferred to the structure used in Test 5, but the revetment is still inferior to the revetment of Test 4.

Of the six tests, Test 6 provided the best opportunity for observing the "launching of riprap" process. Figure 25 plots four cross-section profiles from Test 6 and shows the changes undergone by the toe apron. It was noticed that when a stone particle moves over the face of the revetment it usually moves by rolling over the lower stones but when the stone moves down the side slope of a scour hole it sinks partially into the bed material and slides, rather than rolls, from higher to lower elevations within the hole. Movement of the stone is caused by the loss of bed material from around the stone particle. The stone therefore moves in a series of stop and go motions.

Eventually, the matrix of stone particles and bed material is adequate to provide protection against further scour. The performance of the launched section of the toe apron illustrates that there is no need to have a continuous riprap covering over the side slope of the scour hole.

It has been suggested that revetments depending on the "launching" process, are likely to fail due to the loss of riprap material to the stream. While it seems possible for a few stones to be transported to the centre of the channel (as was the case in Tests 5 and 6) it does not appear feasible that riprap particles can be lost in appreciable quantities after falling into a scour hole. For a particle to be removed it will have to be raised over the downstream crest of the scour hole before it can be relocated away from the main body of the launched apron.

From the tests run, loss of riprap to the stream is of no consequence and it is anticipated that as long as the bank erodes and scours evenly there is no need to make allowances for the loss of riprap material to the stream. The Z factors for Tests 5 and 6 are 2.5 and 3.0 respectively.

7.3.3 Test 7

In Test 7 the revetment was made thinner and without any toe support. (Figure 26). The changes on the bed along the concave bank were similar to those in the previous tests and riprap was displaced from the revetment. On the revetment itself, the smaller less resistant particles rolled over the more resistant larger particles, but on arriving on the slope of the scour hole they moved by sliding. This reaffirms the findings of Tests 4, 5 and 6. The Z factor is 2.4.

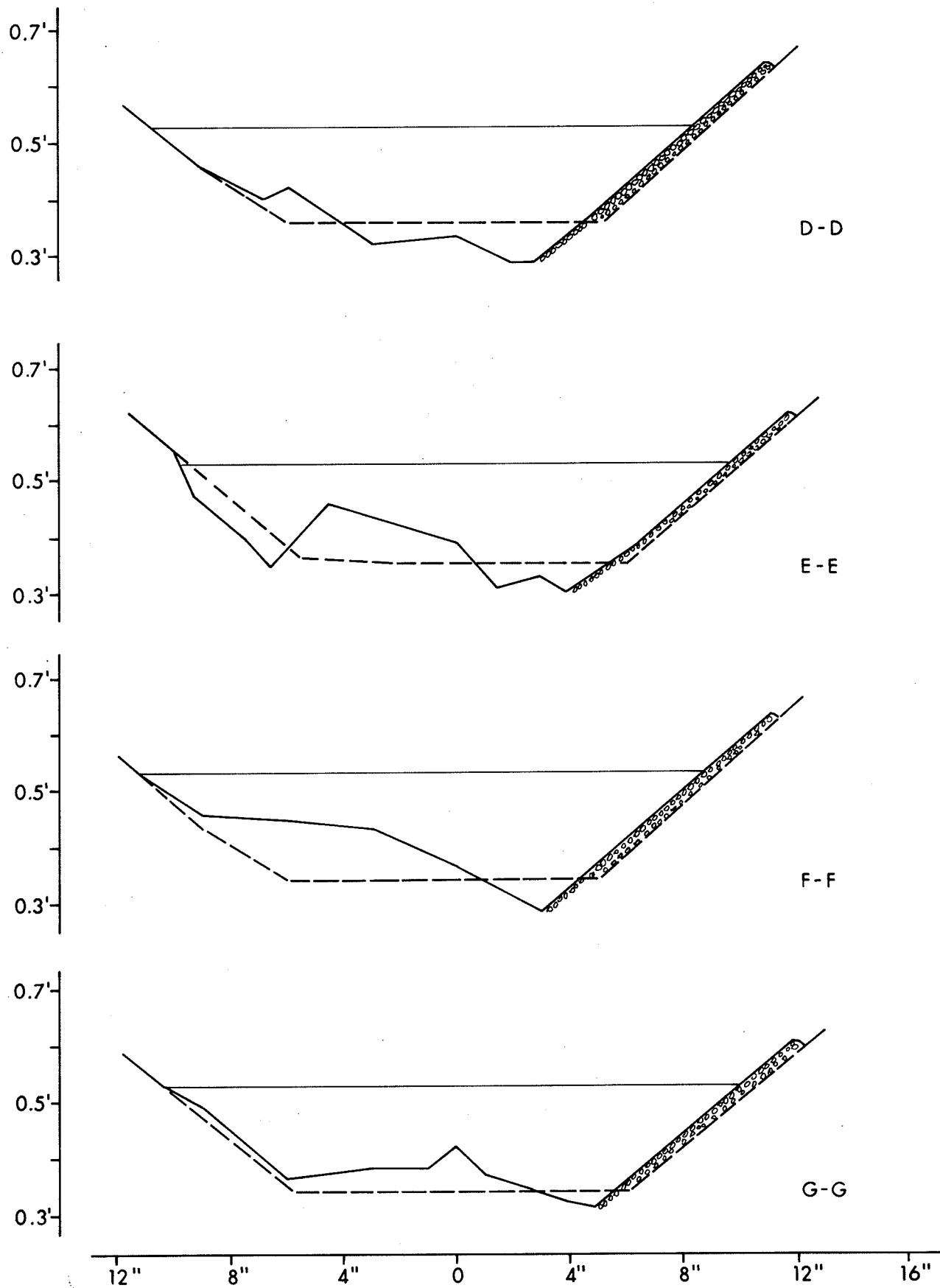


FIGURE 26. CROSS - SECTION FOR TEST NO. 7.

7.4 Riprap Placed During Erosion Process

7.4.1 Tests 8 and 9

The revetment on the outer bank in Test 8 is split into two parts (see photographs for Test 8 and Figure 17) and a short section is placed on the portion of the inner bank susceptible to erosion during the previous tests. In Test 9 the revetment on the outer bank is shortened (see photographs, Test 9 and Figure 28). No riprap is placed on the inner bank.

These tests are performed for the purpose of investigating the performance of the split and shortened concave bank revetments and to observe the effects dumping would have on an eroding bank.

The inner bank revetment in Test 8 was attacked by high velocity currents and scour of the bed caused launching of the riprap particles. The upstream end of this revetment was partially flanked by the flow and the alignment of the revetment plus the irregularity of the eroding section of the concave bank caused erosion to occur downstream of the revetment. The revetment adjusted to withstand the upstream attack but the erosion downstream of the revetment continued for a time.

As the unprotected section of the concave bank between revetments began eroding, the upper end of the downstream revetment was attacked. Many riprap particles were dislodged. To control the attack additional riprap was introduced. Actual dumping (from trucks, etc.) was simulated by using a small laboratory scoop to introduce the riprap.

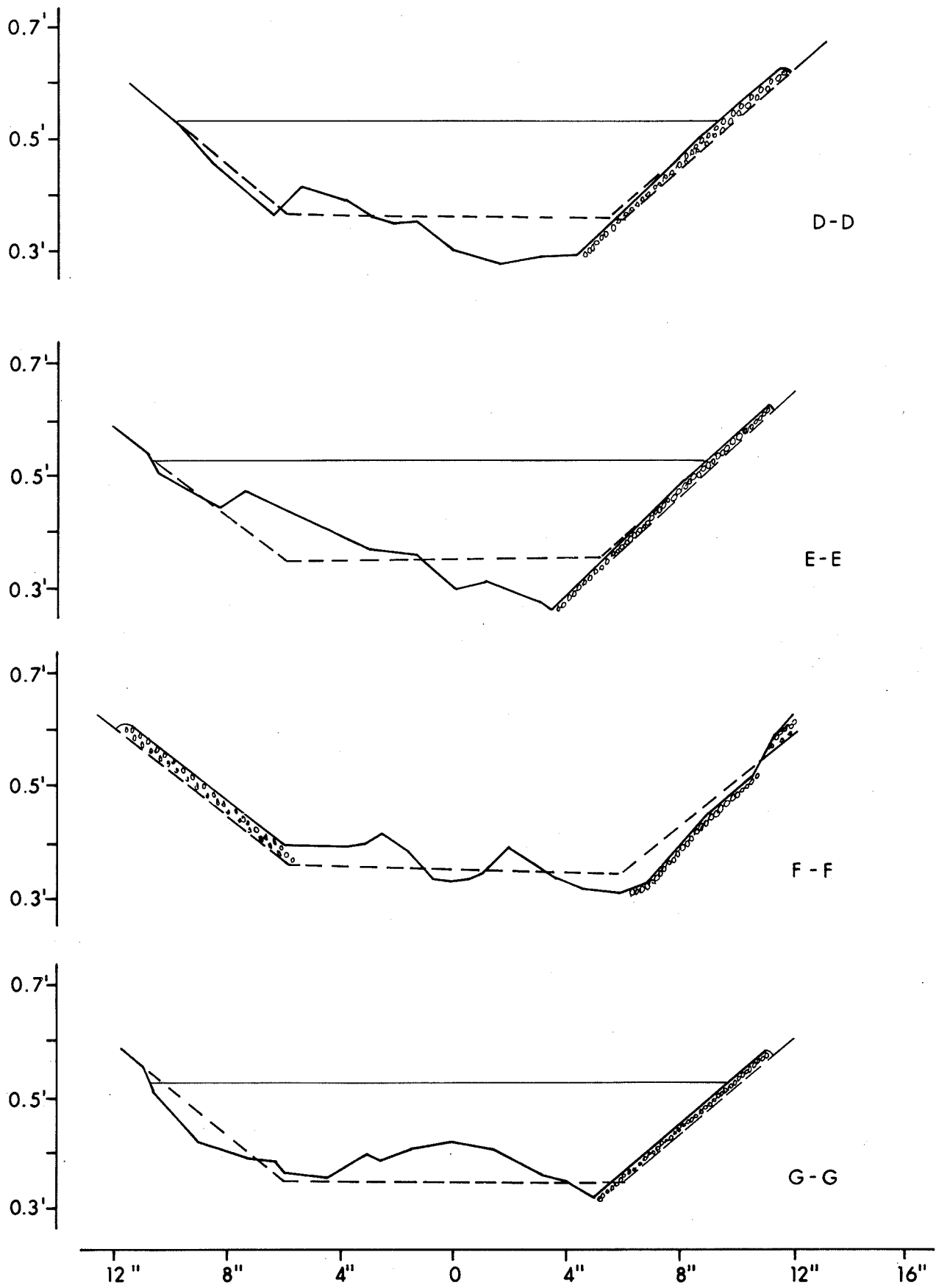


FIGURE 27. CROSS-SECTIONS FOR TEST No. 8.

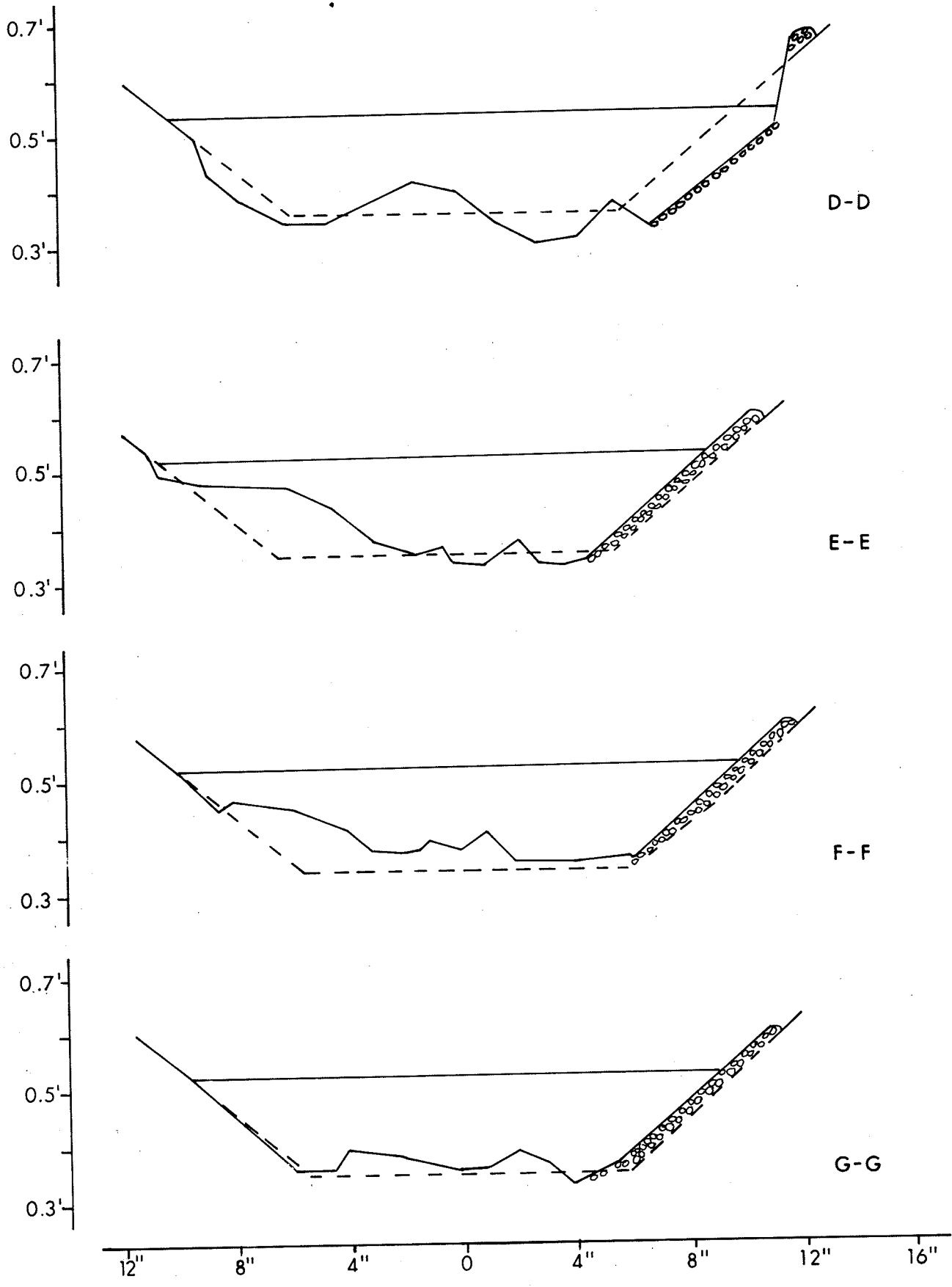


FIGURE 28. CROSS-SECTIONS FOR TEST No.9.

The riprap-bed material matrix eventually provided adequate resistance to erosion. The loss of bank material was slowed and bed deepening quickened. The test showed that this method of introducing riprap to an eroding bank will provide protection, but the method is not recommended for three reasons.

The first reason is the increased turbulence caused by the riprap particles falling onto the bank. Impact forces are added to the forces of erosion at the bank and a greater quantity of bank material is removed. The second reason is the danger associated with having machinery near the edge of an eroding bank, and the third is the unsightly appearance of the new bank.

In Test 9, the length of the revetment was reduced. Instead of beginning at section C-C the revetment begins at section E-E. The main revetment performs well, but erosion occurs upstream of the revetment. Riprap was dumped onto the bank to control this erosion. Figure 28 shows the changes in the channel and the photographs show the channel before and after the test. The Z factors for Tests 8 and 9 and 2.2 and 2.4 respectively. These values are somewhat low for channels having a concave bank protected with riprap. The scour holes may have been only partly developed at the time the tests were discontinued. Larger Z factors can be expected in prototype channels.

7.5 Riprap on Berm

7.5.1 Tests 10 and 11

The formation of scour holes and the dune patterns

obtained in these tests are similar to those of the previous tests. (Figures 29 and 30).

As the discharge increases, lateral migration of the underwater slope of the concave bank causes subsidence of the edge of the berm and riprap particles begin moving down the slope. The movement of riprap is exactly as has been previously described but one fact must be emphasized. Movement under these conditions is slower and more quiet than that caused by dumping in either Test 8 or 9. This is to be expected because the stones do not possess the kinetic energy of dumped stones. This method is a better method of forming a launched revetment than that used in Tests 8 and 9. The new bank configuration is more even and little or no erosion occurs on the convex bank. Unused riprap material can be easily removed if sufficient protection has been provided or bank protection is no longer required. The revetment formed using this method is an ideal way of providing protection when time and money precludes the building of a more permanent and orderly structure.

The depths of the scour holes at the end of Tests 10 and 11 (Z factors 2.5 and 2.5) are similar to those obtained in the tests having solid riprap revetments but there is one difference. The solid revetments produce scour holes which are longer than those formed at the toes of launched revetments. This may be a direct result of bank migration. When the outer bank is fully restrained from lateral

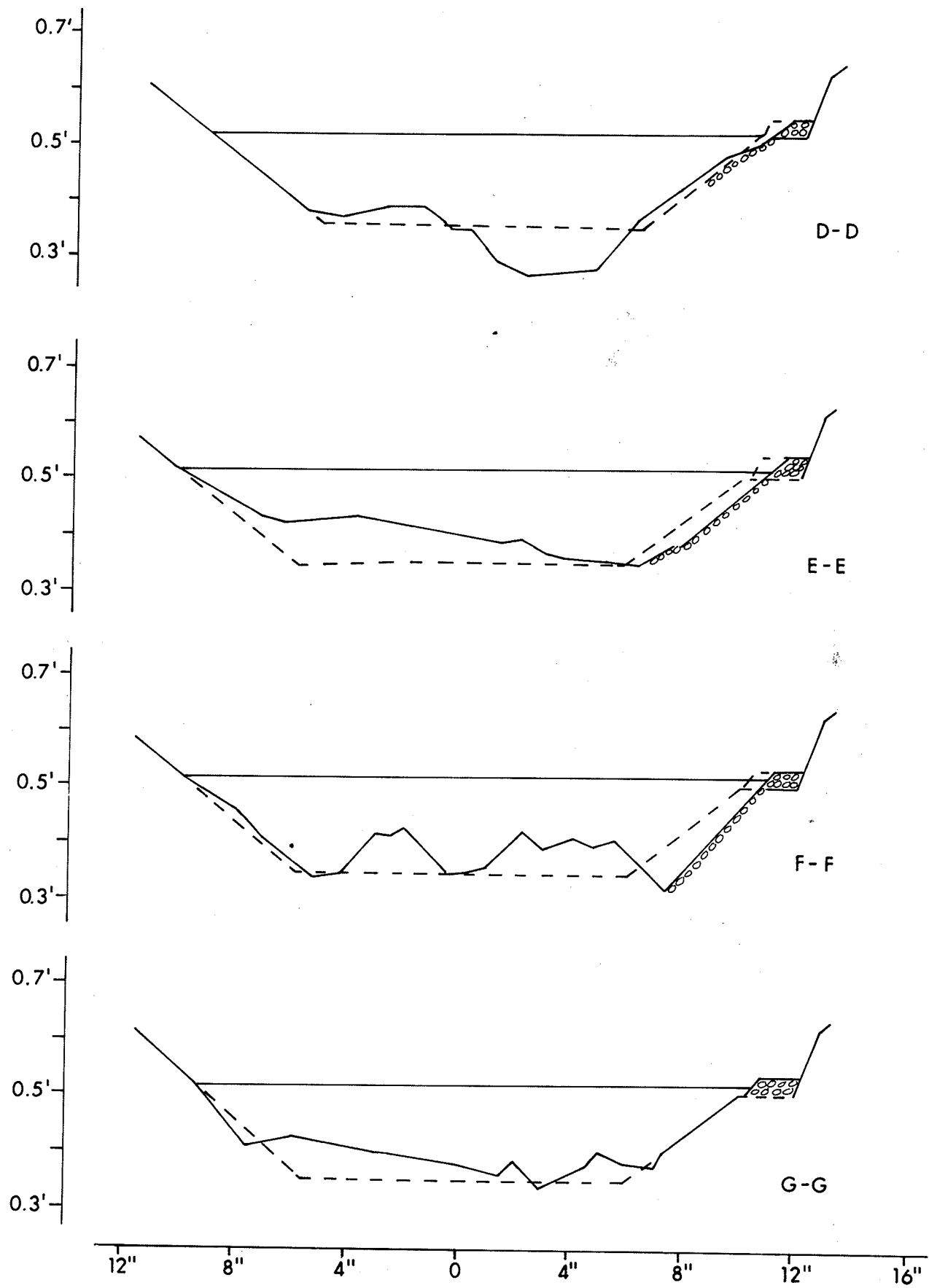


FIGURE 29. CROSS - SECTIONS FOR TEST No.10.

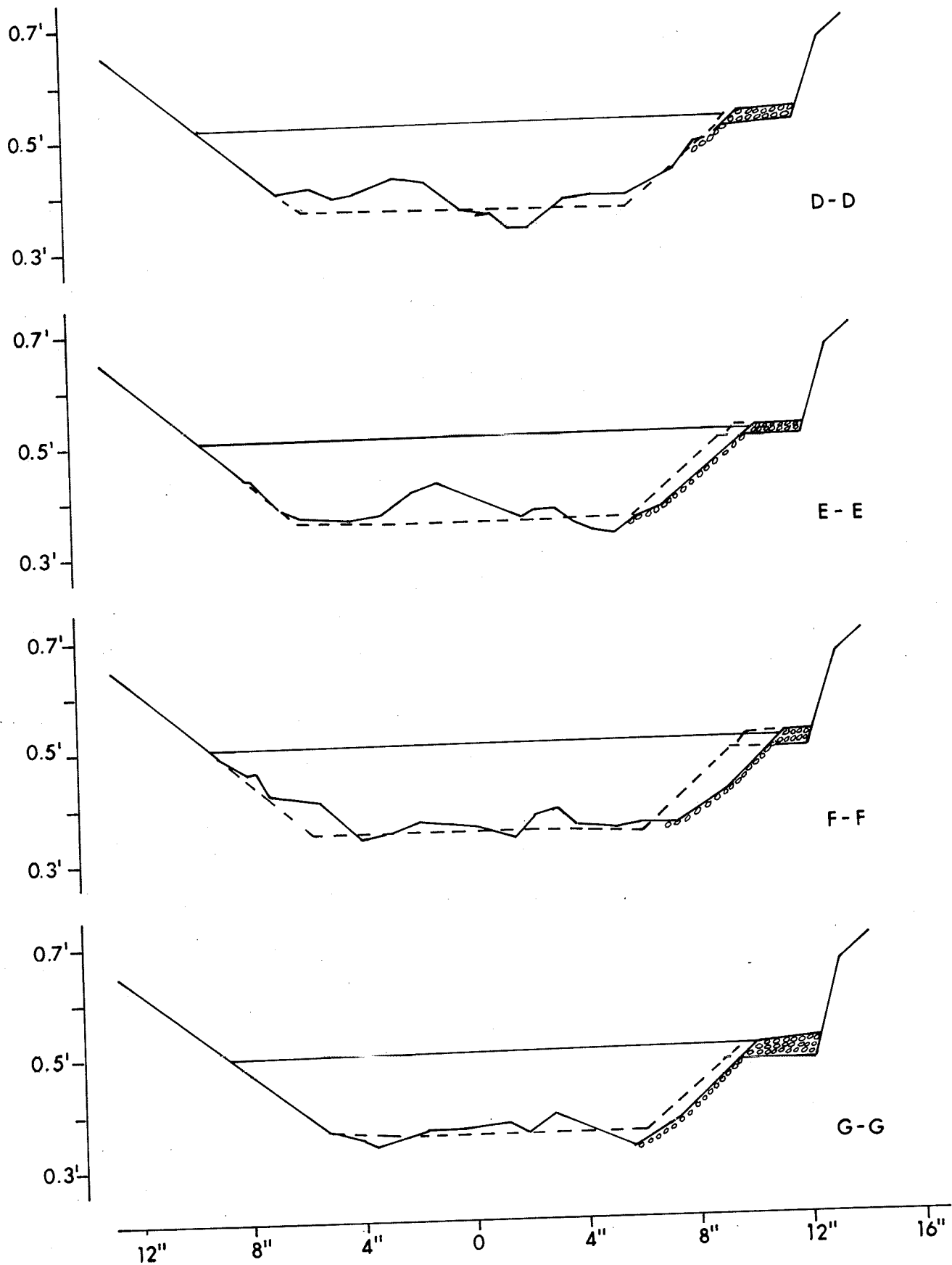


FIGURE 30. CROSS - SECTIONS FOR TEST No.11.

migration, bed deepening occurs to allow the channel to carry the discharge. Where lateral migration is allowed, as in Tests 10 and 11, deepening is not as severe. Here, then, is a system whereby a compromise can be reached between bed deepening and outward movement of the concave bank. However, two factors limit the use of this method. They are the quantity of land available for construction of the berm and the nature of the bank material. A launched revetment is not possible if the bank erodes and scours unevenly. (Figure 14).

7.5.2 Tests 12, 13 and 14

These channel and revetment configurations, Figures 31, 32 and 33, were arranged to allow overflow of the berm. The configurations allowed some increase in flow area and was used to investigate the performance of overtopped revetments. In Test 13, riprap was introduced by dumping stones onto the berm.

The results of these tests are comparable to the results obtained in the previous tests. Unfortunately, the overflow onto the berm was not great enough to affect the revetments. It was hoped that revetment failure could be induced in Test 13, but the overflow was inadequate. Too much material from the channel would have been lost to the sump if the discharge was increased further. The reader is reminded that no revetment was intentionally constructed with the hope of failure in mind. Attempts were made to cause failure

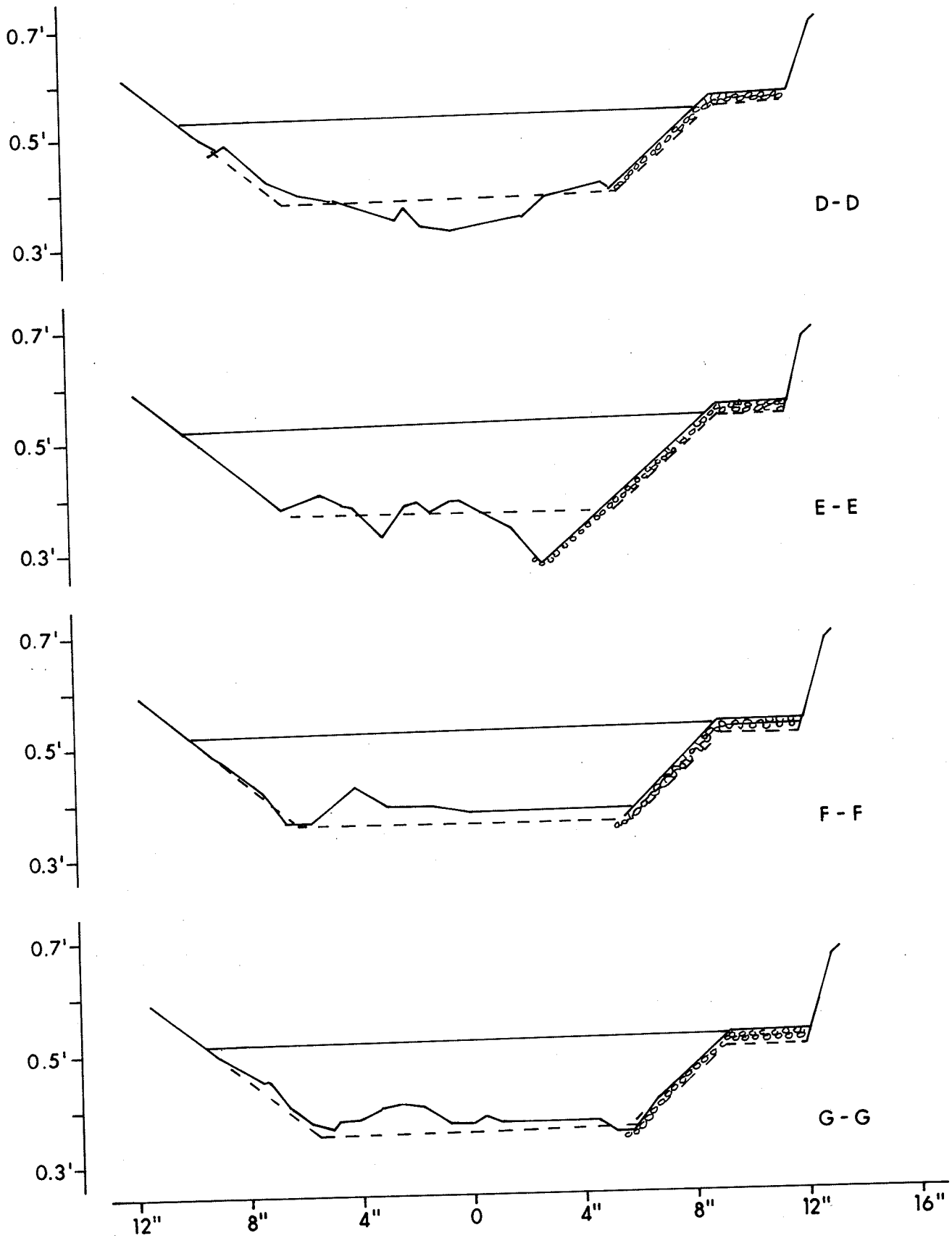


FIGURE 31. CROSS-SECTIONS FOR TEST No.12.

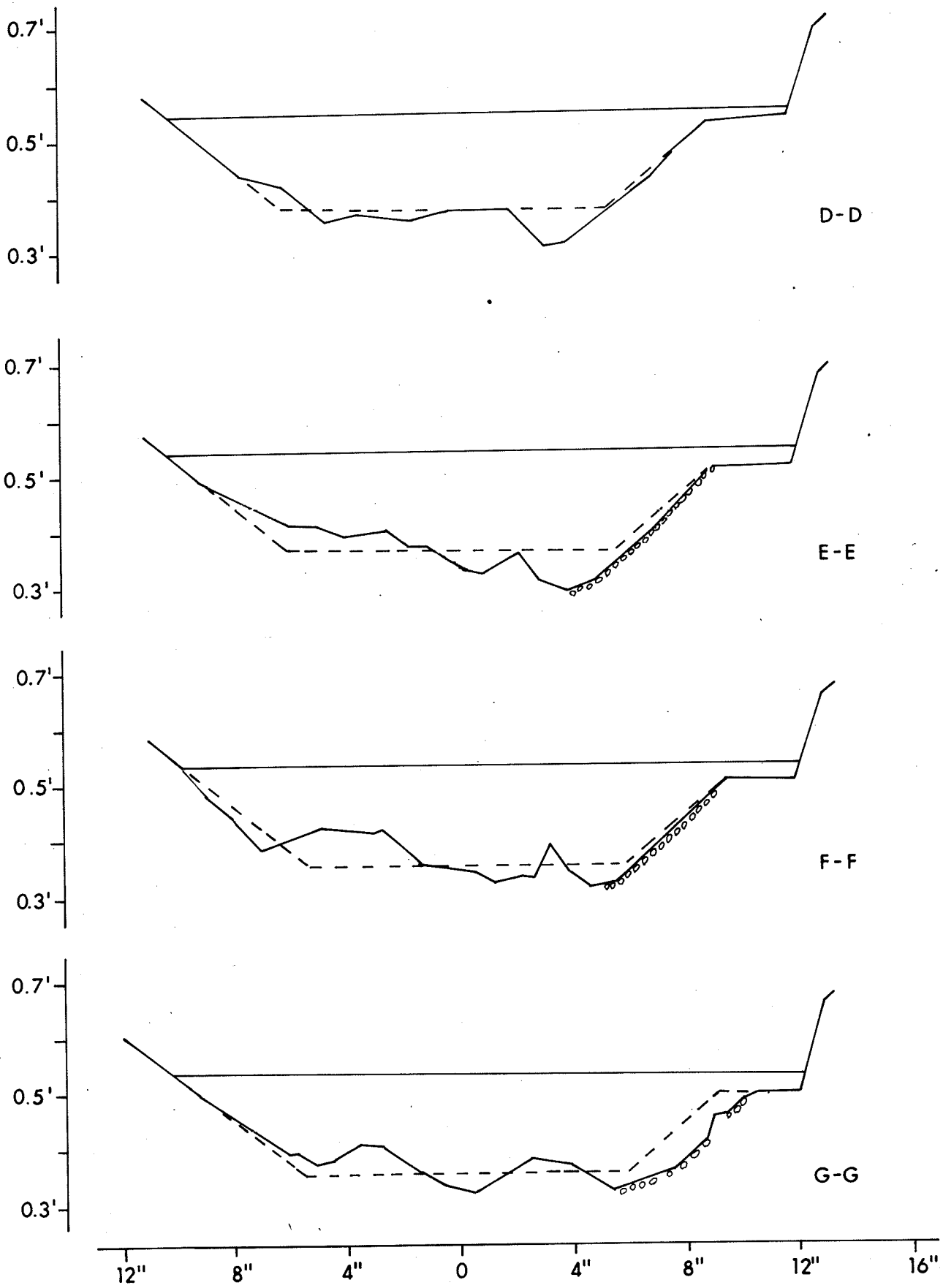


FIGURE 32. CROSS-SECTIONS FOR TEST No.13.

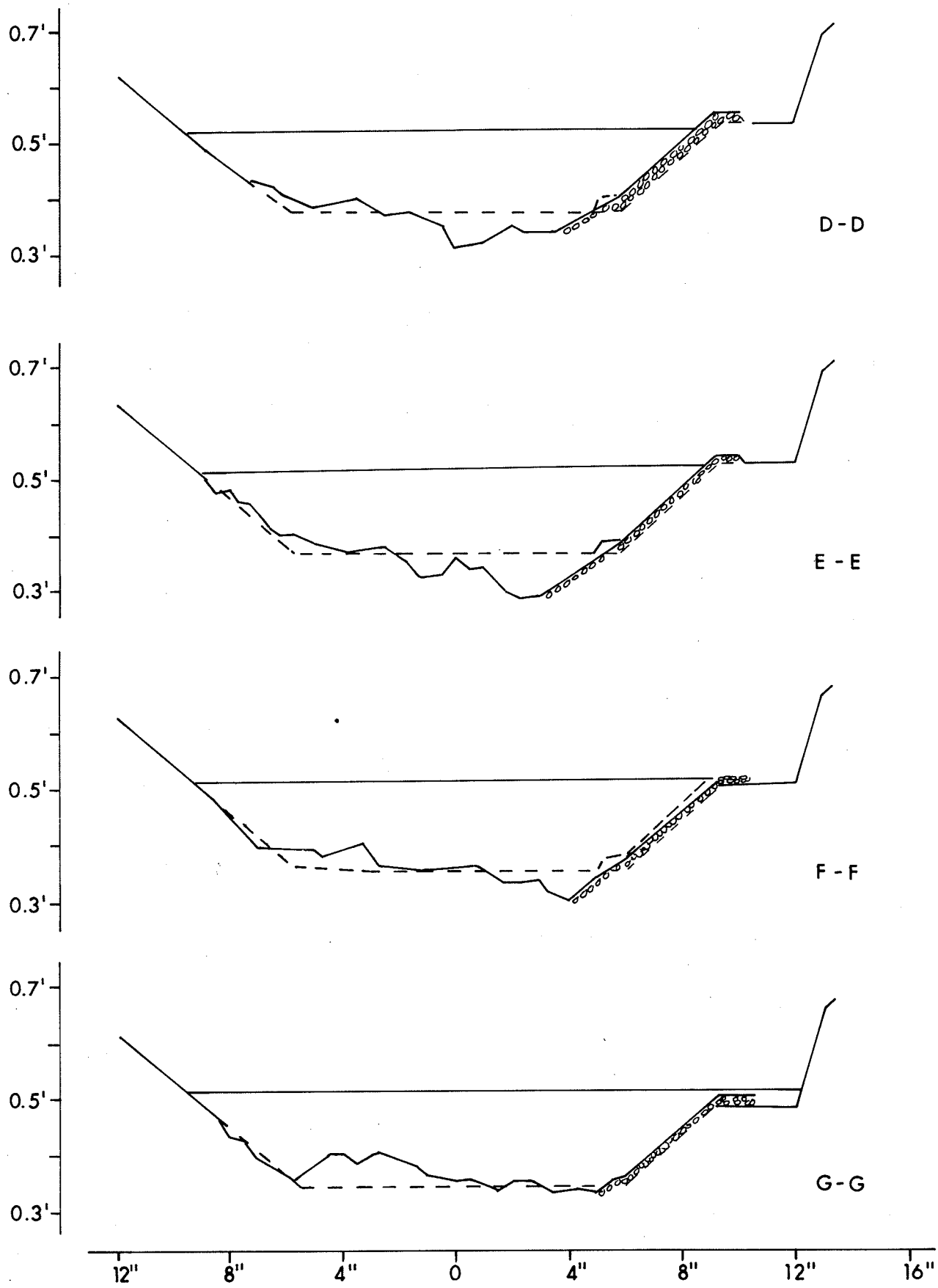


FIGURE 33. CROSS-SECTIONS FOR TEST No.14.

of the suitably constructed revetments, but the complete loss of channel material would have occurred before failure could be accomplished.

7.6 Test 15

The complete removal of revetment material from the bed of the channel was time consuming and impractical. Test 15 was run to ensure that the few pebbles remaining in the channel did not affect the behaviour of the model and that the addition of a surface tension reducing agent to the water supply (for use in another model study) did not influence the model performance. Figure 34 indicates the changes undergone by the channel at the end of the test run.

The model behaviour in Tests 1, 2, 3 and 15 was similar.

7.7. Summary of Results

The model results are presented in the Summary Sheets 1 to 5 and in Tables 1 and 2. A summary is presented in Table 3 of Appendix A. Although the scour factors obtained with and without revetments were of the same order of magnitude (for unprotected banks the scour factors should be in the range 1.4 to 2.5, whereas for the rigid banks the factor should range from 1.4 to 4) it must be emphasized that a probe could not be used to monitor the deepening of scour holes. Turbulent eddies, shed at the probe, would cause movement of the crushed walnut shell. Larger factors may have resulted if the tests with riprap were run longer.

At this point, some indication of the model's reliability will be given. The formation and location of dunes and holes

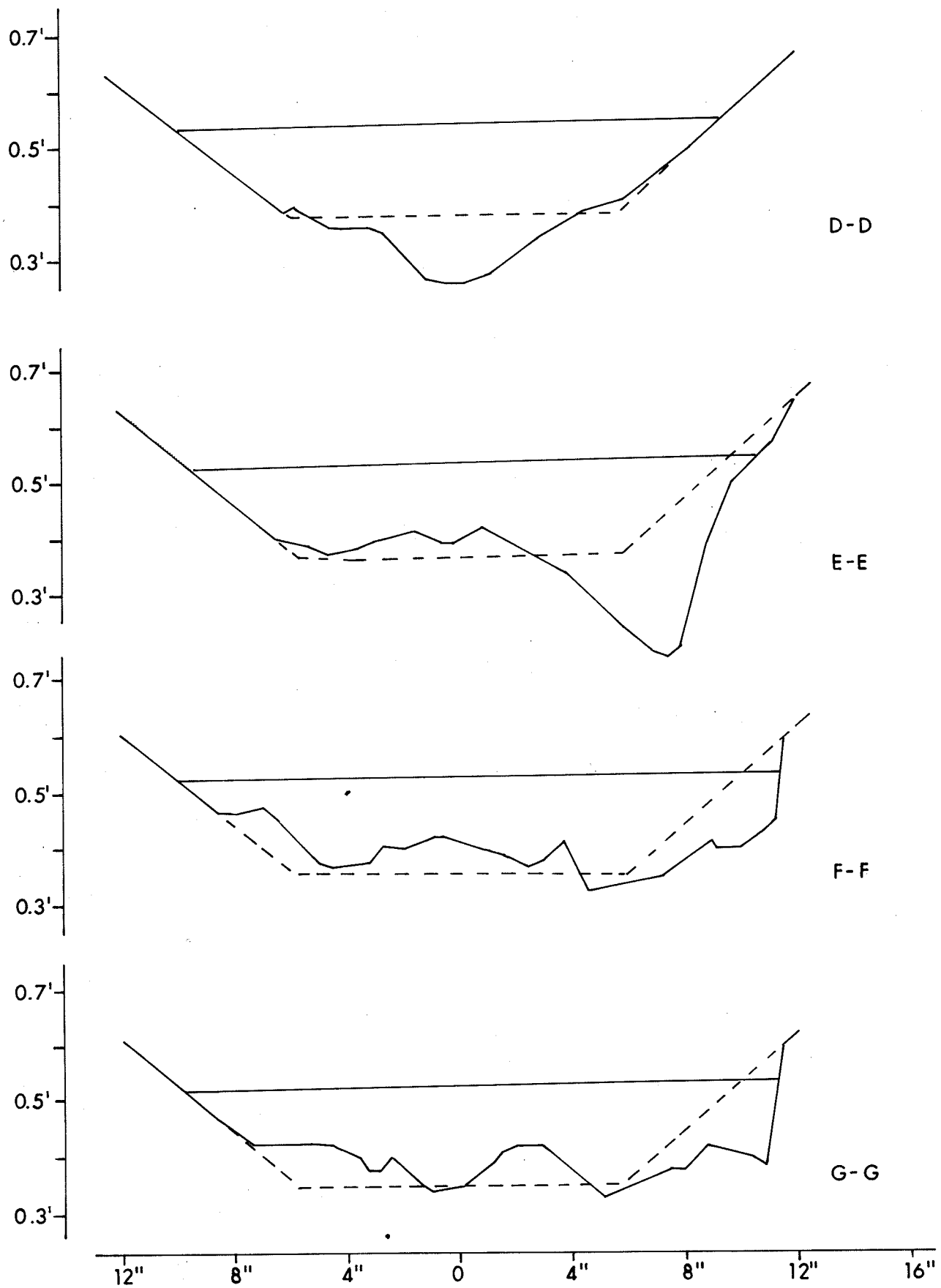


FIGURE 34. CROSS - SECTION FOR TEST No.15.

were as they would be in actual channels because of the mobility of crushed walnut shell. Eddies were formed in scour holes in much the same way as in real channels. Surface eddies which indicate very minor currents in the upstream direction also occur at the water-bank line. This phenomenon also occurs in actual channels.

The problem of stone size is a bit more difficult to deal with. Scaling the revetment model stone gradation size to channel material relationship up to a prototype would most likely result in a situation where the packing of prototype stones could not physically be attained with the size of stones necessary for protection. Filter layers, which were not used in the model, would then become a requirement for the prototype case. The fact that the actual scaling up of the stone sizes in the model to the stone sizes for the prototype could lead to some difficulty should not suggest a deficiency in the model study. Much larger models are required to properly duplicate the behaviour of prototype revetments.

Inglis (1949) stated that "Falling aprons should never be used where the angle of repose of the underlying material is steeper than that of the stones to be used in the apron, or where there are layers of cohesive material in the bank or in the bed above the level of maximum scour". The introduction of this quote is prompted by a few observations made by the author while carrying out his test.

programme. Referring to Figure 32, Section G-G of Test 13, it is readily noticed that no riprap exists on the very steep portion of the concave bank. A few areas of the channel have exhibited this cohesive-like tendency; possibly due to deterioration of the crushed walnut shell or the introduction of very fine grained material to the channel by the water. This area of Section G-G, because of its greater resistance to erosion, eroded more slowly than the other areas. Its slope is, as a result, steeper and cannot maintain riprap particles. This effect is even more detrimental to the lining if it occurs at the lower elevations on the channel side slopes. All riprap particles, on encountering this feature of resistant material between layers of less resistant material, will be dislodged and will accumulate at the toe of the slope where they are no longer required. The quantity of stones used in such a location will be very great if using the launched revetment method of protection. Launched linings should only be used on eroding banks, having bank and bed material with lower angles of repose than that expected for riprap particles.

The stones used in the revetments in Tests 4 to 9 (Grade 1) were larger than those used for Tests 10 to 14 (Grade 2). The behaviour of individual stones in both grades was similar but a number of important points must be brought to the attention of the reader. These are as

follows:

1. The efficient protection offered by the larger stones is matched by the protection provided by the smaller stones.
2. The disturbance of the flow in the immediate vicinity of the larger stones is greater than for the smaller stones.
3. The downstream motion of the smaller stones is greater but this is not a significant factor in the stability of the launched lining.
4. The reduction in the area available to accommodate the flow is less when using the smaller stones since the revetment is essentially thinner. The difference is, however, small.

The loss of bank material through the voids of a revetment could not be investigated. In all tests, channel material was deposited within the voids of the revetment during high flow. Loss of this material, together with bank material from beneath the revetment, could only be initiated by increasing the discharge greatly or increasing the water surface slope. The success of such an exercise is in doubt. All patterns that had developed on the bed of the channel would likely be obliterated and the changes in channel cross-sections impossible to assess.

8. CONCLUSIONS

1. A launched riprap revetment provides efficient protection to the concave bank of channels having bed and bank material that scour evenly.
2. It is unnecessary to have a continuous riprap lining. Spaces between individual stone particles can be tolerated.
3. The riprap lost from the scour hole is a very small percentage of the quantity available in the revetment.
4. A more uniform launching is obtained by placing riprap on a berm before the attack is expected, rather than dumping from mechanical equipment while the scour process is in progress.
5. Stones within a "placed" revetment move by rolling over each other.
6. Stones within a launched revetment or apron move by sliding rather than rolling.
7. Placement of stones for a launched revetment eliminates expensive construction procedures.
8. A launched revetment develops a concave upwards shape which is more in keeping with the configuration attained by undisturbed channels.
9. A launched revetment is possible only when a filter layer is unnecessary.
10. The depths of scour holes are essentially the same for launched revetments as for placed revetments.
11. Some lateral migration must be expected when protection is provided with a launched revetment.

12. The packing of stones in a placed revetment decreases if a toe apron is not provided at the base of the revetment.
13. The movement of bed material in the form of dunes covers and uncovers the lower slope of a scour hole. Riprap, which has launched, may be covered by these dunes so the absence of riprap does not necessarily signify the loss of riprap. The riprap may be exposed as the dune progresses downstream.
14. To eliminate the unsightly appearance of a partially protected bank, revetments should extend to zones of non-eroding velocity.
15. Protection of the inner bank is generally unnecessary.
16. Revetments formed by the launching process should be started from a berm at or above high water level. Some overtopping is permitted if an apron is provided at the top of the revetment.
17. Cut-off walls, extending into the bank for a short distance, should be incorporated into revetments that do not extend to zones of non-eroding velocity. This condition prevents turbulent eddies from removing the bank material from behind the revetments.
18. Toe aprons constructed within the bed of a channel are preferred to those placed on the bed.
19. Launched revetments may be used instead of placed revetments when the bank material erodes evenly.

9. RECOMMENDATIONS

This model provides qualitative information and not quantitative data on the launching of revetments. To obtain qualitative results, larger models are required.

Although the launched revetment concept worked well in the model used, future studies are necessary to provide information on:

1. The loss of riprap particles from the revetment to the channel.
2. The performance of the riprap-bank matrix in actual field installations.
3. The probability of failure of revetments designed to meet certain deterministic design criteria, e.g. a discrete safety factor. This may be done by utilizing the principles of statistics to develop probability distributions which will take into account the variability of the forces acting on the riprap particles, the intensity and duration of the critical shear stresses and the frequency at which this critical shear stress is exceeded.

Because of the small scale of the model, applying model results for 1 and 2 to a field situation may lead to erroneous conclusions. Larger scale models and actual field installations are therefore required to firm up the results obtained from the model used in this study. Because force and velocity parameters are more easily measured in large models, mathematical relationships applicable to launched revetment design, may then be possible.

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APPENDIX A

TEST RESULTS

RUN: NO. 1

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.83'	0.339	0.323'	0.185'	0.34 I/S
E - E	1.75'	0.217	0.178'	0.124'	0.534
F - F	1.68'	0.201	0.153'	0.120'	0.577
G - G	1.79'	0.233	0.232'	0.130'	0.50

FROUDE NO. = .23, DISCHARGE = 0.116 c.f.s.

RUN: NO. 2

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.75'	0.230	0.196'	0.131'	0.46 I/S
E - E	1.71'	0.207	0.170'	0.121'	0.51
F - F	1.68'	0.207	0.171'	0.123'	0.51
G - G	1.77'	0.211	0.188'	0.119'	0.50

FROUDE NO. = .25, DISCHARGE = 0.106 c.f.s.

RUN: NO. 3

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.67'	0.202	0.191'	0.121'	0.37 I/S
E - E	1.65'	0.200	0.251	0.122	0.38
F - F	1.60'	0.167	0.187'	0.104'	0.45
G - G	1.67'	0.178	0.164'	0.107'	0.42

FROUDE NO. = .21, DISCHARGE = 0.075 c.f.s.

RUN: NO. 4

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.58'	0.173	0.227'	0.109'	0.61 I/S
E - E	1.58'	0.172	0.204'	0.109'	0.61
F - F	1.63'	0.189	0.207'	0.116	0.56
G - G	1.63'	0.190	0.195'	0.117'	0.55

FROUDE NO. = .30, DISCHARGE = 0.105 c.f.s.

RUN: NO. 5

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.58'	0.168	0.248'	0.106'	0.47 I/S
E - E	1.58'	0.185	0.206'	0.117'	0.43
F - F	1.58'	0.163	0.214'	0.103'	0.49
G - G	1.63'	0.152	0.164'	0.093'	0.52

FROUDE NO. = .26, DISCHARGE = 0.079 c.f.s.

RUN: NO. 6

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.50'	0.150	0.213'	0.100'	0.59 I/S
E - E	1.58'	0.172	0.219'	0.109'	0.51
F - F	1.58'	0.172	0.210'	0.109'	0.51
G - G	1.63'	0.148	0.190'	0.091'	0.60

FROUDE NO. = .31, DISCHARGE = 0.088 c.f.s.

RUN: NO. 7

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.58'	0.205	0.245'	0.130'	0.46 I/S
E - E	1.63'	0.197	0.228'	0.121'	0.48
F - F	1.65'	0.191	0.243'	0.116'	0.50
G - G	1.67'	0.215	0.218'	0.129'	0.44

FR OUDE NO. = .24, DISCHARGE = 0.095 c.f.s.

RUN: NO. 8

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.60'	0.223	0.256'	0.139'	0.41 I/S
E - E	1.63'	0.195	0.262'	0.120'	0.47
F - F	1.67'	0.221	0.216'	0.132'	0.42
G - G	1.70'	0.196	0.204'	0.115'	0.47

FR OUDE NO. = .22, DISCHARGE = 0.092 c.f.s.

RUN: NO. 9

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.79'	0.231	0.229'	0.129'	0.40 I/S
E - E	1.65'	0.153	0.203'	0.093'	0.61
F - F	1.67'	0.190	0.174'	0.114'	0.49
G - G	1.58'	0.193	0.191'	0.122'	0.48

FR OUDE NO. = .26, DISCHARGE = 0.093 c.f.s.

RUN: NO. 10

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.67'	0.203	0.256'	0.122'	0.44 I/S
E - E	1.75'	0.160	0.169'	0.097'	0.56
F - F	1.75'	0.182	0.197'	0.113'	0.50
G - G	1.58'	0.167	0.178'	0.113'	0.54

FROUDE NO. = .27, DISCHARGE = 0.09 c.f.s.

RUN: NO. 11

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.58'	0.152	0.185'	0.096'	0.60 I/S
E - E	1.63'	0.158	0.180'	0.097'	0.58
F - F	1.69'	0.197	0.172'	0.117'	0.46
G - G	1.58'	0.181	0.175'	0.115'	0.50

FROUDE NO. = .29, DISCHARGE = 0.091 c.f.s.

RUN: NO. 12

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.54'	0.184	0.209'	0.119'	0.52 I/S
E - E	1.56'	0.184	0.256'	0.118'	0.52
F - F	1.56'	0.171	0.168'	0.110'	0.56
G - G	1.54'	0.168	0.171'	0.110'	0.57

FROUDE NO. = .28, DISCHARGE = 0.095 c.f.s.

RUN: NO. 13

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.83'	0.213	0.238'	0.116'	0.62 I/S
E - E	1.85'	0.223	0.248'	0.121'	0.59
F - F	1.83'	0.232	0.218'	0.127'	0.57
G - G	1.85'	0.241	0.208'	0.130'	0.54

FROUDE NO. = .29, DISCHARGE = 0.131 c.f.s.

RUN: NO. 14

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.50'	0.167	0.207'	0.111'	0.57 I/S
E - E	1.48'	0.181	0.229'	0.122'	0.53
F - F	1.54'	0.178	0.209'	0.116'	0.54
G - G	1.80'	0.198	0.182'	0.110'	0.49

FROUDE NO. = .28, DISCHARGE = 0.096 c.f.s.

RUN: NO. 15

CROSS-SECTION	TOP-WIDTH	AREA	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY
D - D	1.60'	0.217	0.283'	0.129'	0.49 I/S
E - E	1.69'	0.239	0.346'	0.141'	0.45
F - F	1.77'	0.217	0.209'	0.123'	0.49
G - G	1.75'	0.223	0.197'	0.127'	0.48

FROUDE NO. = .23, DISCHARGE = 0.107 c.f.s.

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TABLE 1. TEST RESULTS FOR SCOUR.

TEST NO.	MAX. TOP WIDTH	MAX. DEPTH	AVE. DEPTH	AVE. VELOCITY	FROUDE NO.	DIS-CHARGE
1	1.83'	0.357'	0.140'	0.49 1/S	0.23	0.116 c.f.s.
2	1.77'	0.326'	0.124'	0.50	0.25	0.106
3	1.67'	0.279'	0.114'	0.41	0.21	0.075
4	1.63'	0.260'	0.113'	0.58	0.30	0.105
5	1.63'	0.258'	0.105'	0.48	0.26	0.079
6	1.63'	0.309'	0.102'	0.55	0.31	0.088
7	1.67'	0.300'	0.124'	0.48	0.24	0.095
8	1.70'	0.280'	0.127'	0.44	0.22	0.092
9	1.79'	0.276'	0.115'	0.50	0.26	0.093
10	1.75'	0.279'	0.111'	0.51	0.27	0.09
11	1.69'	0.262'	0.106'	0.54	0.29	0.091
12	1.56'	0.309'	0.114'	0.54	0.28	0.095
13	1.85'	0.271'	0.124'	0.58	0.29	0.131
14	1.80'	0.268'	0.115'	0.53	0.28	0.096
15	1.77'	0.346'	0.130'	0.48	0.24	0.107

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TABLE 2. LIST OF Z FACTORS.

TEST NO.	$Z = \frac{\text{MAX. DEPTH}}{\text{AVE. DEPTH}}$
1	2.55
2	2.62
3	2.45
4	2.30
5	2.46
6	3.00
7	2.42
8	2.20
9	2.40
10	2.51
11	2.47
12	2.71
13	2.19
14	2.34
15	2.66

TABLE 3. SUMMARY OF TEST RESULTS

TEST NO.	DISCHARGE	VELOCITY AVE. IN CURVE	BANK PROTECTION	TYPE OF REVETMENT	TYPE OF APRON	REMARKS
1	0.116 c.f.s.	0.49/0.73	-	-	-	Lateral migration of concave bank. Typical dune movement along the bed of the channel. Slight attack on inner bank.
2	0.106 c.f.s.	0.50/0.71	-	-	-	Lateral migration of concave bank. Typical dune movement along the bed. Slight attack on inner bank.
3	0.075 c.f.s.	0.41/0.61	-	-	-	Essentially the same as 1 and 2.
4	0.105 c.f.s.	0.58/0.78	Concave bank only. Extent - from C-C to 1 ft. downstr. of G-G.	Continuous. Placed.	Toe trench. Riprap level with bed.	Launching of toe apron stone. No movement of upper slope stone. Revetment stable. Efficient protection.
5	0.079 c.f.s.	0.48/0.63	Concave bank only. Extent - from C-C to 1 ft. downstr. of G-G.	Continuous. Placed.	Toe apron above bed.	Greater number of stone particles launched than in Test 4. No movement of upper slope stone. Although the cross-sections E, F and G show no launching, stones did move into the holes between these sections. Inner bank erosion more extensive. Likely caused by loss of flow area.
6	0.088 c.f.s.	0.55/0.65	Concave bank only. Extent - from C-C to 1 ft. downstr. of G-G.	Continuous. Placed.	Toe apron above bed. One half width of apron in Test 5.	Greater number of stone particles launched than in Test 4. No movement of upper slope stone. Less erosion on inner bank than in Test 5. Revetment constructed too thick.
7	0.095 c.f.s.	0.40/0.72	Concave bank only.	Continuous. Placed.	No toe apron.	Thinning of upper slope stones as launching of stones takes place at the toe. Some erosion of the inner bank. Revetment remains stable even after thinning has taken place.
8	0.092 c.f.s.	0.44/0.67	Both banks.	Concave: split. Convex: short single lining. See photographs.	No toe aprons.	Erosion of unprotected centre area of concave bank. Attack at the downstream end of upper lining and upstream end of lower lining. Migration slowed by introduction of stones. Some erosion of the inner bank downstream of the inner bank revetment.
9	0.093 c.f.s.	0.50/0.62	Concave bank only.	Continuous. Placed. Extent: Just upstr. of E-E to 1 ft. downstr. of G-G.	No toe apron.	Attack of exposed concave bank. Attack at the upstream end of revetment. Dumping of stones on exposed bank area as erosion in progress. Significant disturbance of the bank caused by dropped stones. System of protection not recommended.
10	0.09 c.f.s.	0.51/0.70	Concave bank only. Stones placed on bench in bank.	Launched. Extent: from C-C to 1 ft. downstr. of G-G.	No toe apron.	Some erosion of the concave bank. Little erosion of the inner bank. No apparent loss of stones to the centre of the channel. Efficient protection. This method preferred for a launched revetment.
11	0.095 c.f.s.	0.54/0.75	Concave bank only. Stones placed on bench in bank.	Launched. Continuous.	No toe apron.	No erosion of the inner bank. Performance as good as in Test 10
12	0.095 c.f.s.	0.54/0.72	Concave bank only. Side slope plus overbank apron. Extent: C-C to G-G	Continuous. Placed.	No toe apron. Head apron on bench.	No erosion of inner bank. Thinning of upper slope revetment as launching into the scour holes occurs. This revetment performed as well as the other placed revetments. The head apron was used as overflow of the bench was expected.
13	0.131 c.f.s.	0.58/0.76	Concave bank only. Stones dumped.	Irregular. Launched.	No toe apron.	Some erosion of inner bank. Overflow of unprotected bench. Erosion of the concave bank controlled by dumping stones onto bench but this method is not recommended because of the danger to equipment and personnel, and because the erosion has to be monitored. The revetment is irregular and not aesthetically pleasing.
14	0.096 c.f.s.	0.53/0.72	Concave bank only. Extent: D-D to G-G	Continuous. Placed.	Toe and head aprons. Toe apron above bed.	No erosion of inner bank. All the stones used in the toe apron were launched into scour holes. No loss of stones even when overflow of the revetment occurred. Very good revetment.
15	0.107 c.f.s.	0.48/0.73	-	-	-	Essentially same as 1. Model unaffected by surface tension reducing agents used for another model study.

A P P E N D I X B

P H O T O G R A P H S

Plates for Tests 1 to 4, inclusive, are not available
due to poor photographic results.

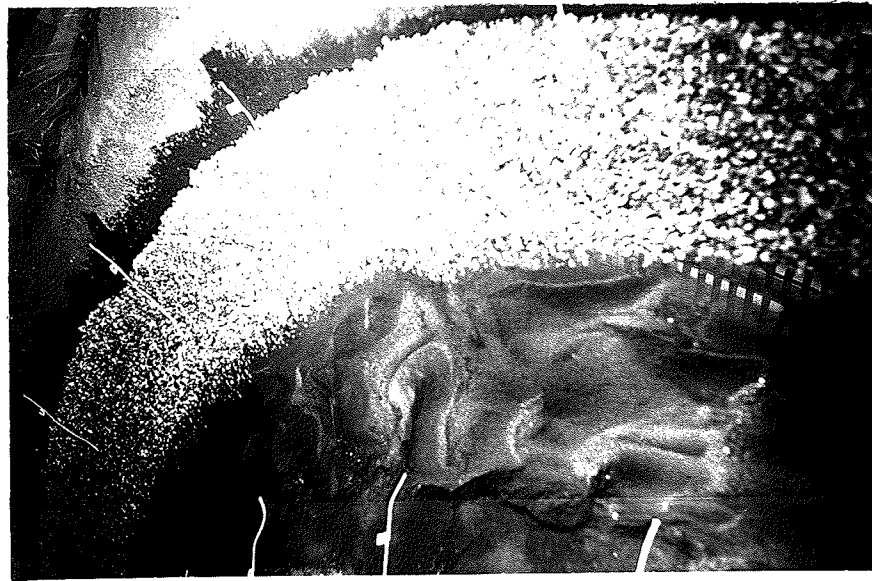


Photo #1. 2.0 hours

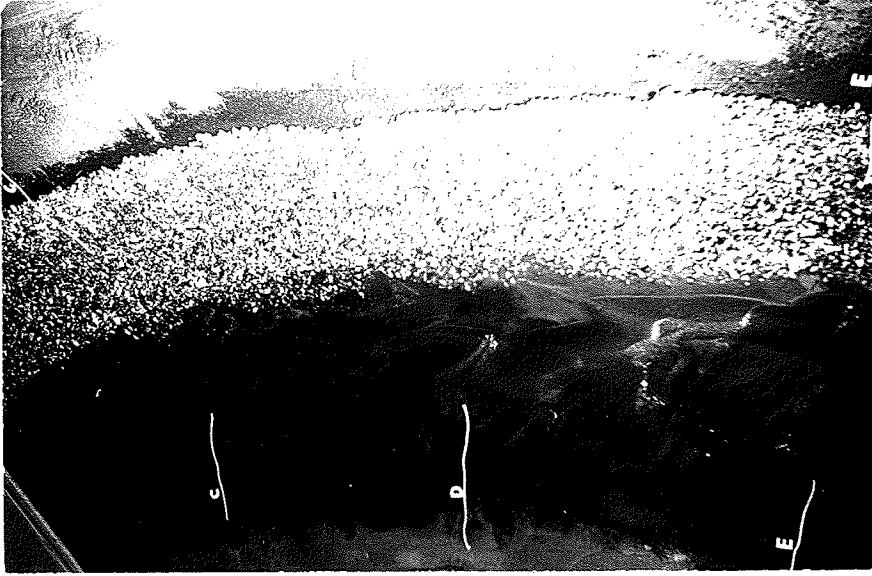


Photo #2. 4.0 hours

PLATE 1. PHOTOGRAPHS FROM TEST 5.

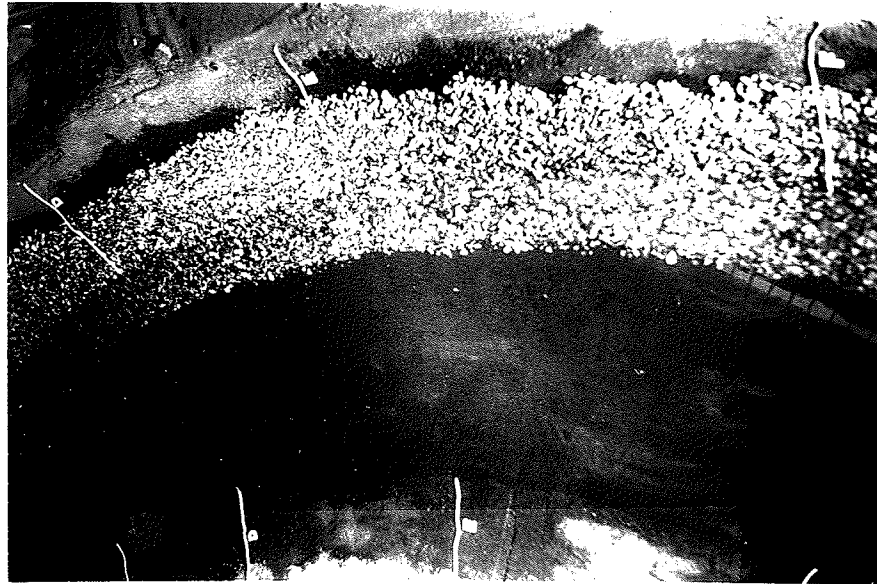


Photo #1. 0.00 hours



Photo #2. 2.5 hours



Photo #3. 4.75 hours

PLATE 2. PHOTOGRAPHS FROM TEST 6.



Photo #1. 0.00 hours
Channel before test run.

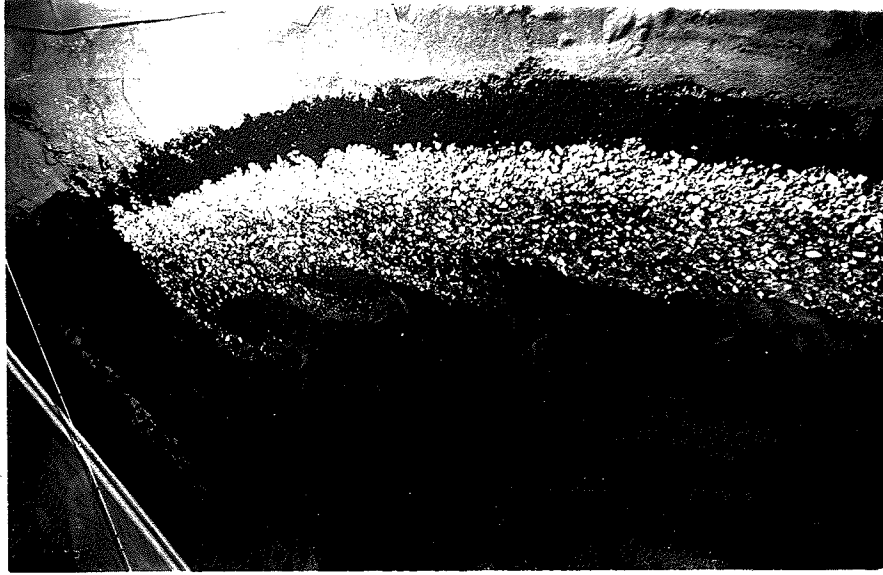


Photo #2. 2.75 hours
Channel during test run.
Note deposited material
covering some sections
of launched stones and
the downstream displacement
of stones at start of the
revetment.



Photo #3. 4.75 hours
Note end wall at end of
revetment and the pebbles
in diagonal scour hole in
mid-photo.

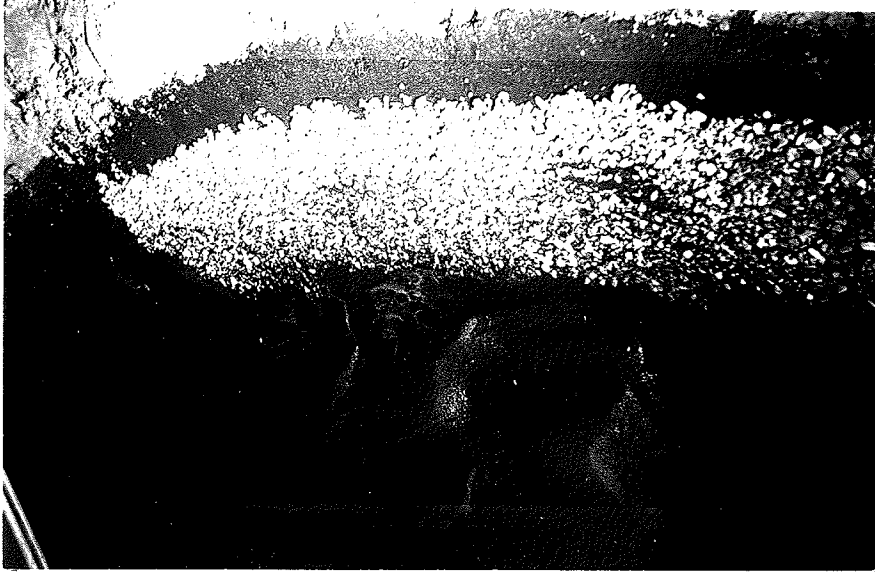


Photo #4. 4.75 hours: Close-up
Note end wall at start of
revetment. Note also the
looser packing of stones at
the base of the revetment.



Photo #1. 0.00 hours



Photo #2. 0.45 hours
Note attack upstream of the
inner bank revetment.

PLATE 4(a). PHOTOGRAPHS FROM TEST 8.

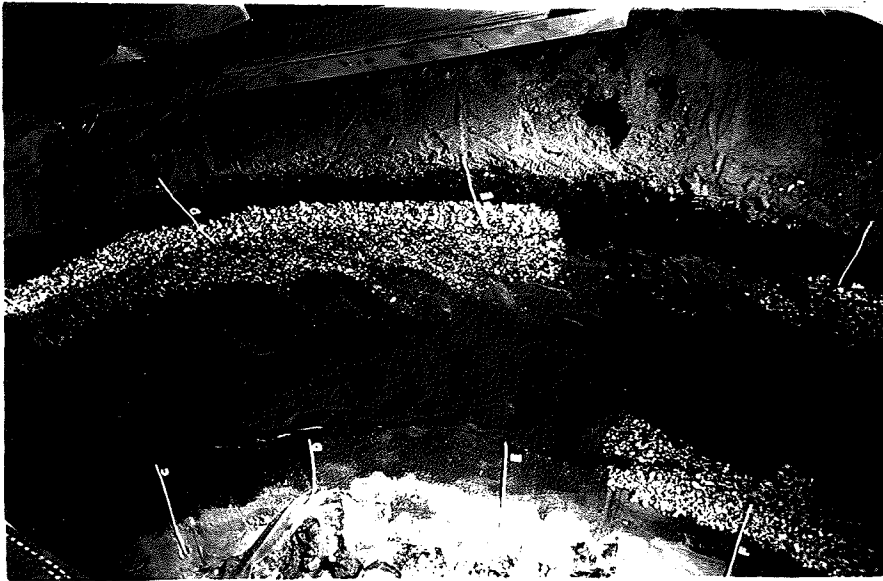


Photo #3. 1.00 hours



Photo #4. 1.5 hours

PLATE 4(b). PHOTOGRAPHS FROM TEST 8.



Photo #5. 2.5 hours



Photo #6. 4.5 hours

PLATE 4(c). PHOTOGRAPHS FROM TEST 8.



Photo #1. 0.00 hours



Photo #2. 4.5 hours

PLATE 5. PHOTOGRAPHS FROM TEST 9.

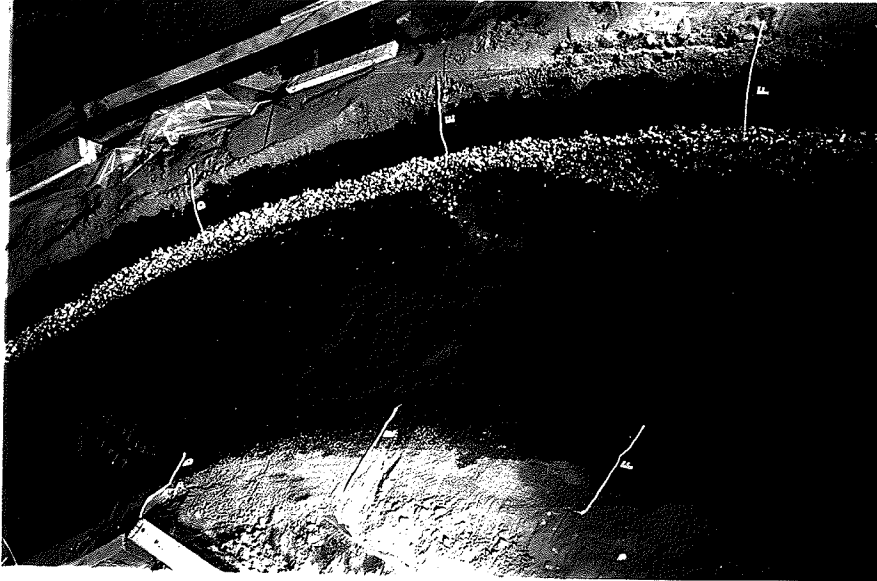


Photo #2. 1.00 hours



Photo #1. 0.00 hours

PLATE 6(a). PHOTOGRAPHS FROM TEST 10.

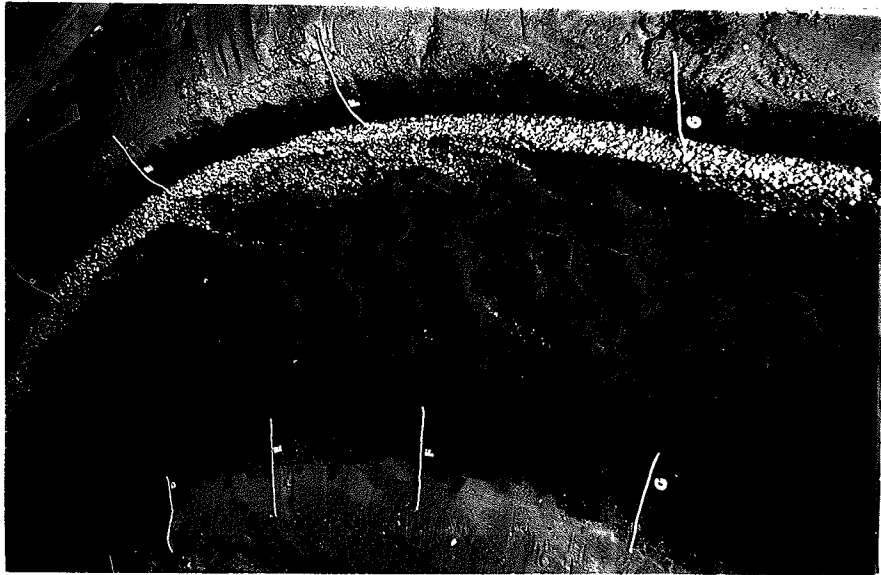


Photo #3. 2.5 hours



Photo #4. 3.5 hours

PLATE 6(b). PHOTOGRAPHS FROM TEST 10.

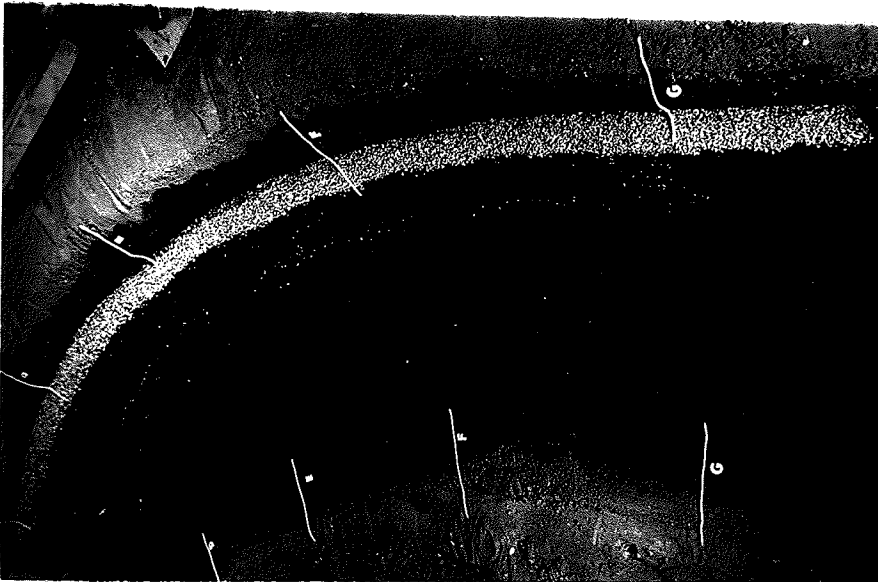


Photo #1. 0.00 hours



Photo #2. 1.5 hours

PLATE 7 (a). PHOTOGRAPHS FROM TEST 11.

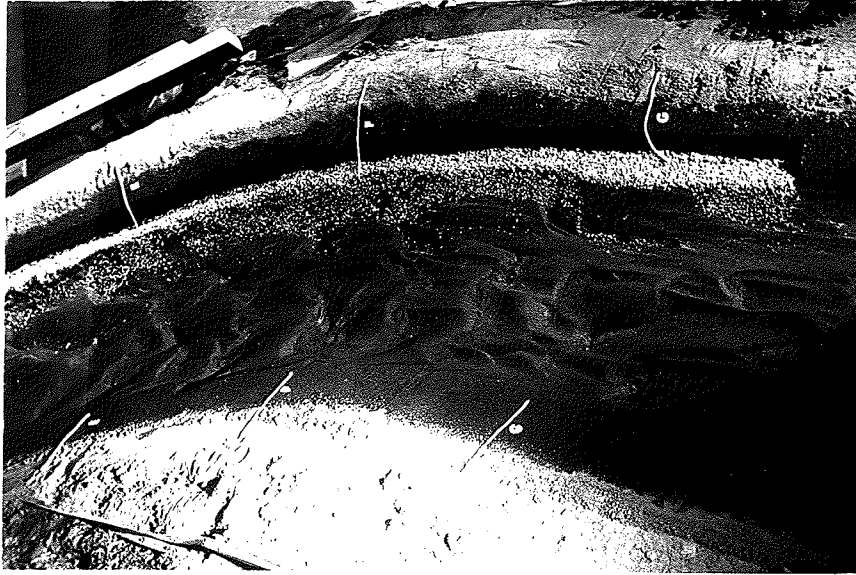


Photo #4. 4.5 hours

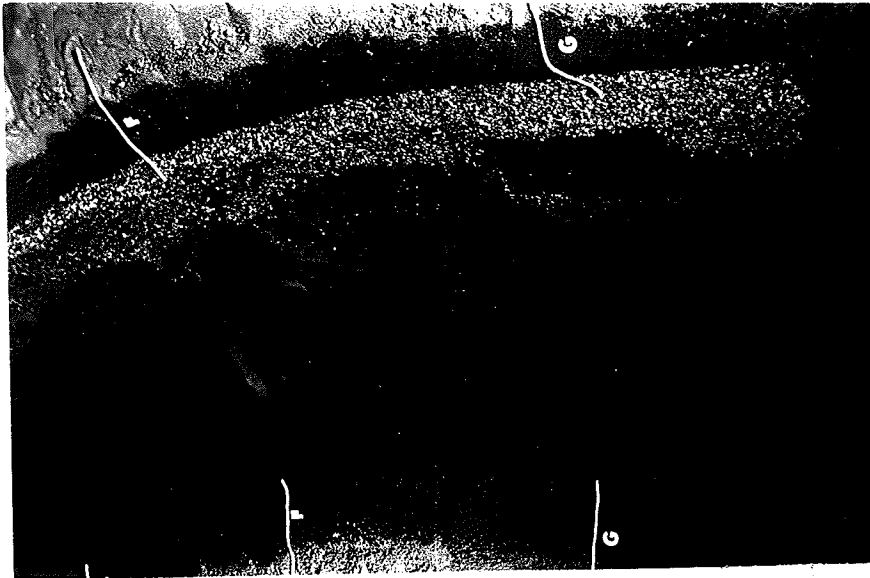


Photo #3. 2.5 hours

PLATE 7(b). PHOTOGRAPHS FROM TEST 11.



Photo #2. 1.5 hours

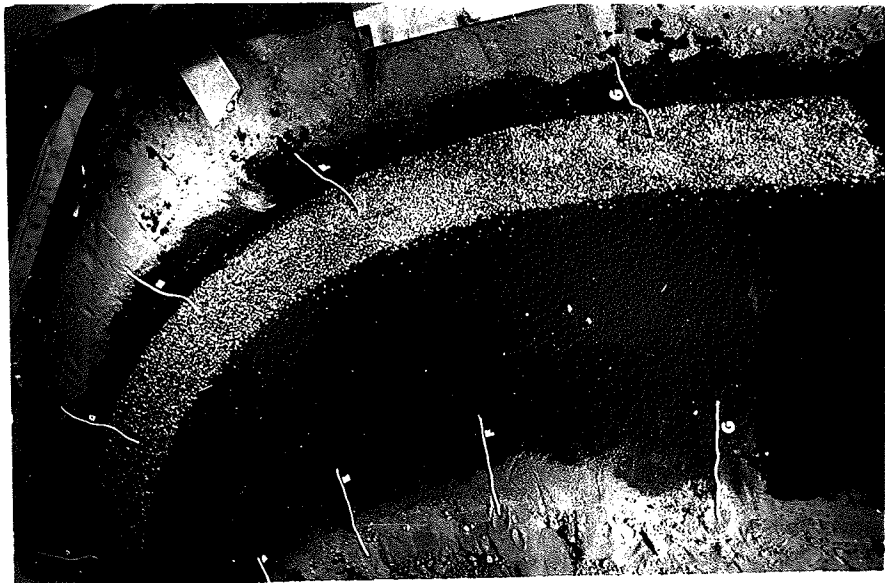


Photo #1. 0.00 hours

PLATE 8(a). PHOTOGRAPHS FROM TEST 12.



Photo #4. 4.5 hours

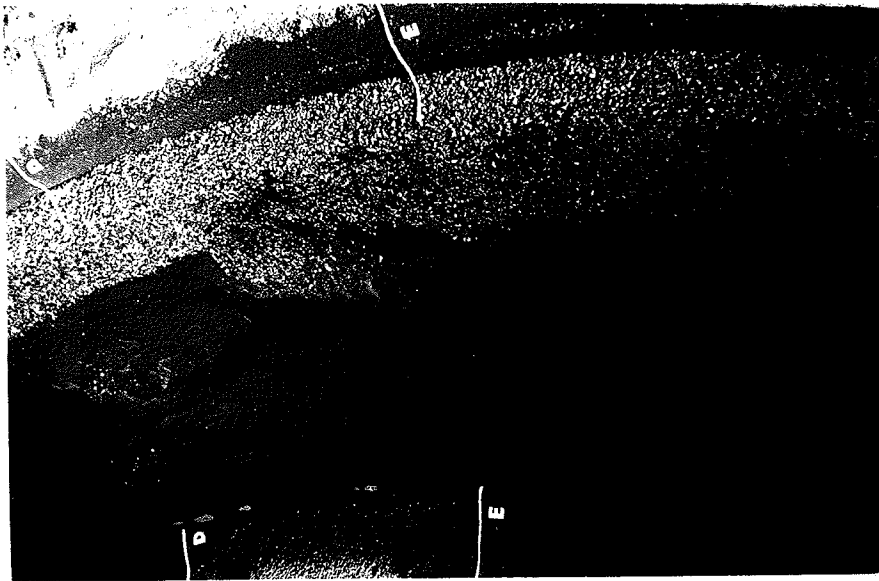


Photo #3. 2.75 hours

PLATE 8(b). PHOTOGRAPHS FROM TEST 12.

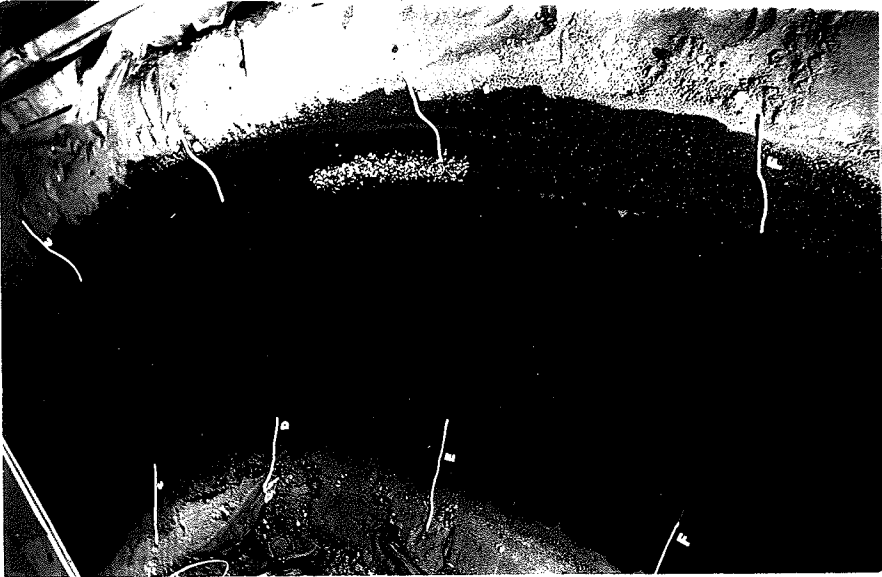


Photo #2. 0.75 hours

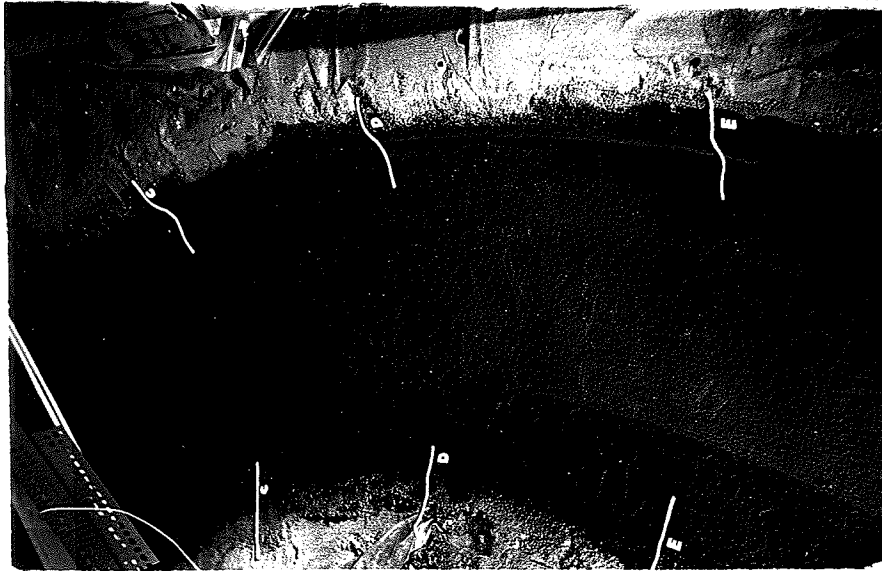


Photo #1. 0.00 hours

PLATE 9 (a). PHOTOGRAPHS FROM TEST 13.



Photo #4. 2.15 hours



Photo #3. 1.5 hours

PLATE 9(b). PHOTOGRAPHS FROM TEST 13.



Photo #5. 3.5 hours



Photo #6. 4.5 hours

PLATE 9(c). PHOTOGRAPHS FROM TEST 13.

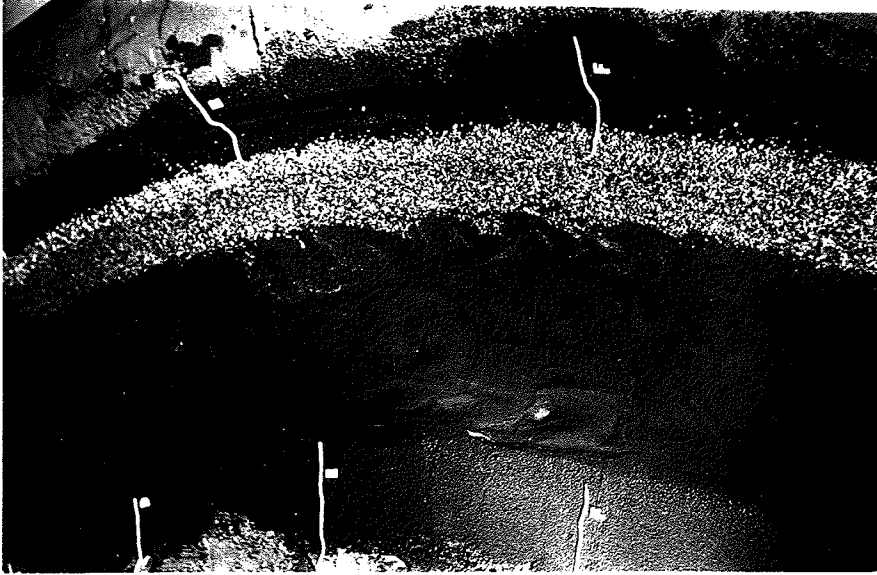


Photo #2. 0.75 hours



Photo #1. 0.00 hours

PLATE 10(a). PHOTOGRAPHS FROM TEST 14.

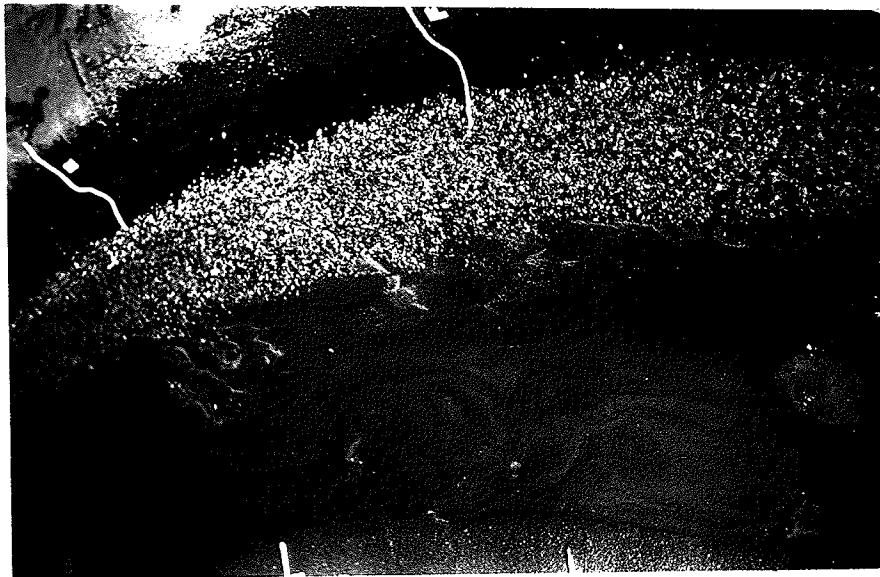


Photo #3. 2.00 hours

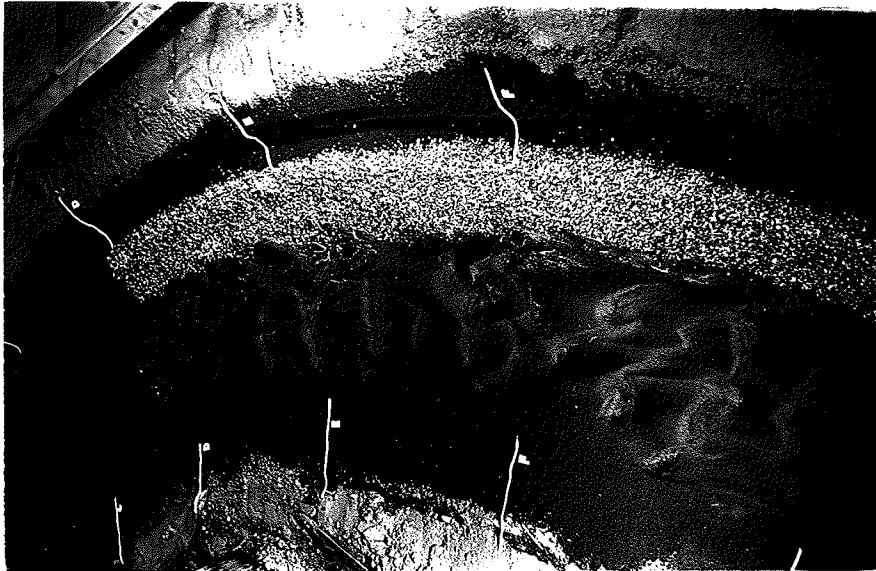


Photo #4. 4.0 hours

PLATE 10(b). PHOTOGRAPHS FROM TEST 14.

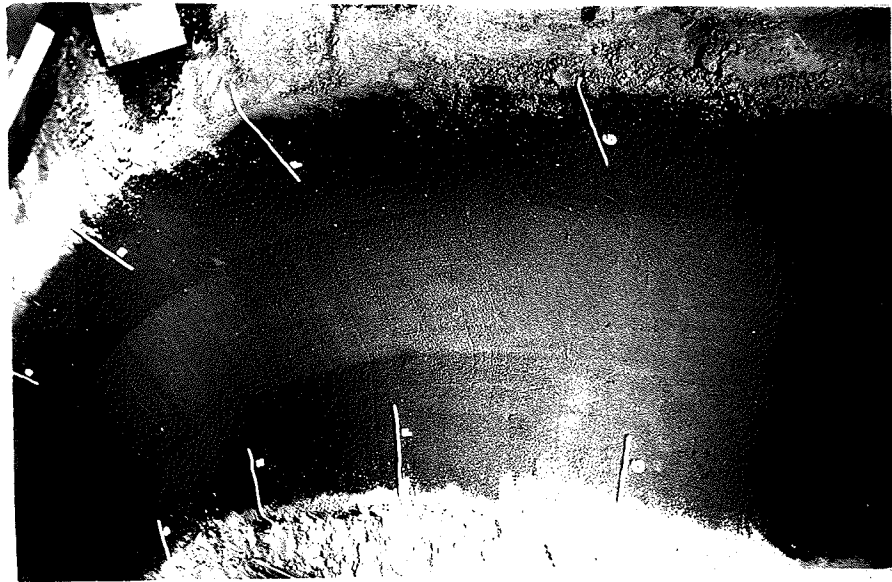


Photo #1. 0.00 hours



Photo #2. 0.75 hours

PLATE 11(a). PHOTOGRAPHS FROM TEST 15.



Photo #4. 2.5 hours



Photo #3. 1.25 hours

PLATE 11(b). PHOTOGRAPHS FROM TEST 15.

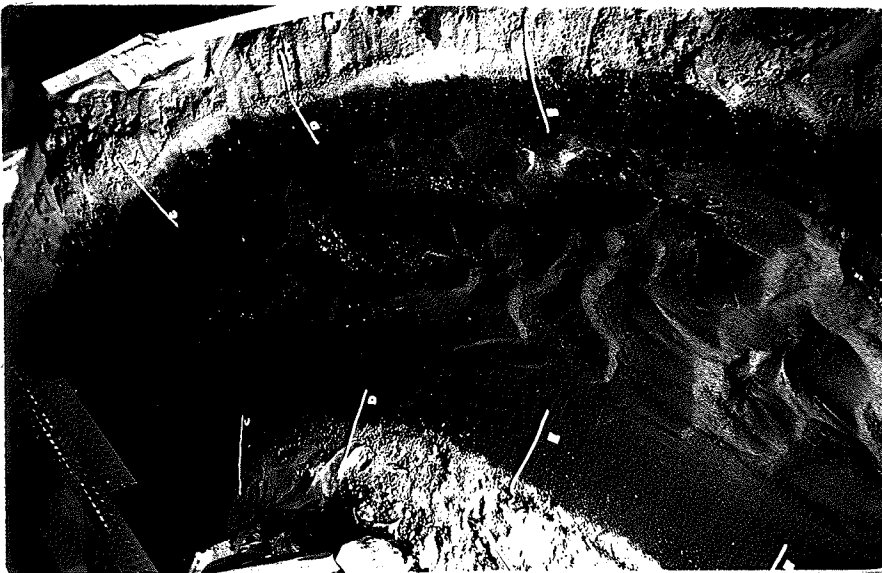


Photo #6. 4.0 hours: Close-up



Photo #5. 4.0 hours

PLATE 11(c). PHOTOGRAPHS FROM TEST 15.