THESIS

AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF LOCATION AND PROJECTION OF SINGLE GROIN IN A BEND

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OE MASTER OF SCIENCE IN ENGINEERING
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED BY MD. ABU OBAIDA ANSARI KHAN ENTITLED AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF LOCATION AND PROJECTION OF SINGLE GROIN IN A BEND BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENGINEERING (WATER RESOURCES)

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ABSTRACT

This study was taken to investigate the effect of location and projection of single groin in a bend. The Hydraulics and River Engineering Laboratory of the Department of Water Resources Engineering of Bangladesh University of Engineering and Technology, Dhaka, provided required facilities for the study. Six test runs were made, three with single groin placed at the centre of the bend and the rest three with single groin placed at a distance of ten percent of the average channel width upstream of the bend. The projection of the groins were varied from five percent to twenty-five percent of the average channel width. These groins were placed at the concave bank of the test channel when the channel achieved a quasi-stable nature.

It was observed that with the increase of groin projection ratio, the downstream protected length increased when placement of the groin was centrally located. Beyond projection ratio of seventeen percent, the protected length decreased. For groins placed at ten percent upstream of bend centre, same trend of variation of downstream protected length was found. The maximum value of groin projection ratio for maximum length of downstream protection in this case was twenty three percent. The downstream protected length was found to be higher for groins placed at bend centre. Strong statistical correlations were obtained for both the cases.

The maximum depth of scour hole at the toe of the groin was found to increase with the increase of groin projection for groins placed both at the centre and at ten percent upstream of the bend. It was also found that the scour area increased with the increase of groin projection ratio. Good statistical correlations were obtained for both the cases. The trend obtained for variation of scour depth conforms with the equations of Ahmed (2) and Hossain (20).

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NOTATION

SYMBOLS	DEFINITION	UNITS
$A_{p,r}$	Co-efficient	-
a_r	Co-efficient	-
A_s	Maximum scour area	ft^2
b	Projection length of groin	ft
c	Sediment concentration	ppm
C	Curvature	-
D	Particle diameter	ft
d_s	Maximum scour depth	ft
d_{50}	Median bed material size	ft
d/s	downstream	-
f	Lacey's silt factor	-
L_d	Downstream length protected by groin	ft
$P_r(y)$	Orthogonal polynomial	-
Q	Flow rate	$ft^3/sec.$
q	Discharge per unit width	$ft^3/sec/ft$
r	co-efficient of correlation	-
S	[illegible] slope	-
u	Velocity in x-direction	ft/sec
u/s	upstream	-
W	Average width of the channel	ft
x	CO-ordinate axis	
y	Distance perpendicular to river axis	ft
$Z_b(y)$	Bed level	ft

CHAPTER ONE

INTRODUCTION

1.1 General

From time immemorial, rivers played a very important role in human civilization. The availability of enough water for drinking and irrigation, the convenience in travel and trade through waterways and the fertile agricultural land of the flood plains have attracted people to start living near a river considering it as the fundamental heirarcy of their development. As a result cities, factories and other important structures have been built along the river banks.

Besides these blessing of the river, it caused tremendous hazard to man by occasional flooding of the land adjacent to the river and by severe erosion of its banks during high discharge and flood. This unchecked erosion causes loss of natural resources, destruction of engineering works and loss of lives. Also, the sediment produced from the bank erosion and bed scour can damage flood plains, urban areas, navigation facilities, downstream reservoirs and other channel improvements. To check these losses man has attempted to stabilize the river banks.

The problem of river bank erosion in Bangladesh is quite aggravating. The three major rivers, the Ganges, the Brahmaputra and the Meghna, together with their numerous tributaries and distributaries, carry a huge discharge and sediment. The banks of these alluvial rivers, specially at the bends, are being continually eroded. A recent study by Rahman (36) showed that the rate of migration of the Ganges-Brahmaputra confluence is about 6880 feet per year. The study also showed that the rate of bank erosion is about 1100 feet per year.

A huge amount of money are being spent every year to stabilize the eroding bends. Various methods of bank stabilization are in use of which groin is common in Bangladesh because of its advantage in larger rivers carrying higher sediment load (10). The protection of Kushtia twon from erosion of Gorai river, protection of Chandpur town from erosion of Meghna river, protection of Sirajganj town from Jamuna river and protection of Shovapur bridge on Feni river are some of the examples of the extensive use of groins in this country (5).

A good number of complex factors and interdependant variables guide the problem of bank erosion and stabilization work. It is very difficult to study the effect of these variables separately and hence analytical solution of the problem is yet to be obtained. So, small scale laboratory study may be a good approach to have a better understanding of the problem and the obtained results may be used to predict the behaviour of the stabilization work.

Small scale laboratory study does not always give a true picture of the actual situation. For example, siltation resulting from deposition of materials in suspension can not be reproduced accurately in the laboratory channel because bed load movement in such a channel is due to particle which move on or near the bed and very little material goes into suspension (19). Also, silting in laboratory channel is slower than in natural channel, whereas occurance of scour is quicker. Therefore an attempt to permit more silt deposition may result in excessive scour. Even with this limitations, results obtained from small scale laboratory study can be useful in predicting the prototype behaviour thereby eliminating serious errors in design.

1.2 Objective of the study

The present day knowledge regarding the behaviour of groins in the stabilization of bends of the alluvial river is inadequate. So, this study has been taken up with the following main objectives:

i. To observe the area and depth of scour at the toe of single straight groin for different projections.

ii. To observe the area protected in the bend both upstream and downstream of the single groin.

iii. To observe the effect of the position of the groins on scour and area protected by them.

iv. To investigate the morphological changes at upstream and downstream of a bend due to placement of single straight groin.

CHAPTER TWO

REVIEW OF LITERATURE

2.1 Introduction

An alluvial channel reaches an equilibrium status by the prolonged interaction between the water and sediment discharge, the characteristics of sediment, composition of bed and bank material and the geometry of the channel. An additional mechanism of channel adjustment is probably the channel pattern which is tied to the channel gradient and cross-section. An understanding of the nature of these channel patterns and the factors that are related to their occurance is important for both river regulation and channel stabilization works. In the following a brief review is made on channel pattern, stable alluvial channel, bank stabilization work with special emphasis on groin and scour.

2.2 Channel Pattern

The channel patterns that have been recongised are straight, braided and meandering. However, this classification is arbitrary and all channel forms in the field are not covered by these three categories. Perhaps a more logical classification would be that rivers have either a single channel or multiple channels (38).

Rivers are seldom straight through a distance greater than about ten channel widths and so the designation of straight implies irregular, sinuous or non-meandering. Observations of Gibson, Vanoni and Leliavsky (28) imply that a straight channel is neither of a uniform bed nor of a straight line of maximum depth.

A braided channel is one that is divided into several channels, which successively meet and redivide. The seperate channels of a braided stream are divided by islands or bars. The building of central and lateral bars is an important part of the process of development and shifting of braided channels. A braided channel will have steeper slope. The ratio of slopes of divided and undivided channels was found to range from 1.4 to 2.3 in field situations and 1.3 to 1.9 in the flume (28). The equation of a line which seperates data from meandering and braided channel was given by Leopold and Wolman (28) as:

$$S = 0.06\ Q^{-0.44} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (2.1)$$

where S is the channel slope and Q is the bankfull discharge. Because the braided reach is wide and shallow and the channel banks are unstable the ratio of sediment transport per unit width of channel may be relatively low.

A large number of literature on river patterns are available of which reference can be made to standard books (28, 22) and publications (12, 15). In the following section a brief description of the meandering pattern of alluvial streams, which is by far the most common one, will be given.

2.2.1 Meandering Channel

A meandering channel consists of two consecutive loops, one flowing clockwise, and the other anticlock wise. These types of stream patterns are usually associated with broad flood plains consisting of relatively erodible materials. However, it is also known that many stream cut into solid rock or hard strata in deep gorges and exhibit meandering pattern similar to that of rivers in flood plains.

Several investigators have conducted laboratory investigations to observe initiation and development of meanders in alluvial streams and have established relationships between geometrical and flow characteristics. Amongs these the investigations of Freidkin (14) Shahjahan (38), Inglis (16), Kinoshita and Yano(16) are worth to mention here. Friedkin concluded that meandering results primarily from local bank erosion and consequent overloading and deposition by the river of the heavier sediments moving along the bed. This process produces a series of bends along the stream. The experiments conducted by Friedkin and Inglis show that the meander pattern as a whole slowly moves downstream. Such tendency has been found in many alluvial streams such as the Ganges (8). Shahjahan concluded that river and sediment discharge along with valley slope mainly control the geometry of stream in meander.

2.2.2 Theories of Meandering

Several attempts have been made in the past to stipulate condition under which the process of meandering is initiated and to explain the mechanism of meander development. But none of these theories are able to explain satisfactorily the mechanism of meander formation. These theories may be divided into six general groups, namely -

a. Earth's rotation theory
b. Helicoidal flow theory
c. The concept of graded stream
d. Minimum energy concept
e. Disturbance theory
f. Dynamic instability theory

A very brief description of these theories are given below:

2.2.2.1 Earth's Rotation Theory

Coriolis force, which causes an object moving over the surface of earth to experience a transverse force normal to its path, may cause rivers to have the tendency to erode preferentially their right bank on the northern hemisphere and their left bank on the southern hemisphere. However, it has been shown by Quaraishy (after 38 and 16) that the tendency of the stream to deflect either to the right or to the left is merely a chance phenomenon, having hardly anything to do with the earth's rotation.

Neu (33) has shown that secondary circulation is developed in a stream because of earth's rotation. The relative intesity of this secondary circulation depends on latitude of the place and the ratio of depth to the average velocity of flow.

2.2.2.2 Helicoidal Flow Theory

According to this theory, meandering is the result of helicoidal or secondary flow. Apparently, any disturbance which produces secondary circulation can lead to meandering. The phenomena of secondary currents have been extensively studied by several researchers e.g., Einstein and Li, Einstein and Shen, Shen and Komura, Goldstein (after 39), Leopold Tanner (after 38), Prus-cha cinsky, Fujiyoshi (after 16). However,most of the authors fail to offer any cause for the initiation of the secondary currents and their periodical reversal of sign along the channel.

2.2.2.3 The Concept of Graded Stream

According to this concept, the river would seek itself a winding course until its bed has been lengthened to such an entend that the river would be at grade. But there appears to have no reason why a river, even if it is not at grade, would scour sideways instead of deepening its channel.

2.2.2.4 Minimum Energy Concept

It is often supposed that the process of meandering is related to the energy content of the stream. According to this theory, a channel having excess energy tries to increase its length by meandering thereby decreasing its slope. This idea was elaborated interms of either a random walk theory or a thermodynamic analogy (38).

The concept of minimum energy has been questioned by many like Joglekar (8). They contend that the primary cause of meandering is an excess of sediment load during floods. A river tends to build up a steeper slope by depositing sediment load on the bed when the load is in excess of that required for equilibrium. This increase in slope leads to a decrease in depth and this tends to increase the width of the channel if the banks are not resistant. Only a slight deviation from uniform axial flow is then necessary to cause more flow towards one bank than the other. Additional flow is then necessary to cause more flow towards former bank, leading to shoaling along the latter, accentuating the curvature of flow and producing meander in its wake. On the other hand, Leopold and Wolman reported some cases of meander fromation which do not fit in with the theory based on excess sediment load.

2.2.2.5 Disturbance Theory

According to this theory, the disturbance caused in an otherwise straight channel travels downstream in such a way as to cause change in flow pattern resulting in meanders. The initial disturbance could be caused by various circumstances. Werner (16) postulated that meanders are initiated by some disturbances which, in turn, starts transverse oscillation in the straight alluvial stream. This transverse oscillation from one bank to the other starts erosion and the first bend forms.

2.2.2.6 Dynamic Instability Theory

According to this theory, the formation of meanders is due to the instability of the bed. Hansen and Callender (38) made an elaborate stability analysis of meandering, working on the assumption that the bed of the stream could be treated as initially plane. Quick (35) also argues that meandering is an instability phenomenon which tends to be self exaggerating. His main contention is that meandering is due to the cycle change in the direction of rotation of streamwise secondary flow,which itself is merely the streamwise component of the vorticity vector. The vorticity is generated due to the bed shear and hence exists initially only as a cross-channel vorticity vector. Because of the variation in velocity across the channel, a streamwise components of vorticity is generated as it is transported in the downstream direction. Obviously erosion occurs when the secondary sprial flow has a downward component of velocity at the stream boundary and deposition occurs when it has an upward component. The direction of streamwise voritcity is changed due to upstream channel deflections. The wavelength of the meander is related to such reversal of vorticity.

Whatever be the mechanism of formation of meanders, these is no cirterion available which will indicate, with certainty, whether a stream of given characteristics will meander or not. The empirical criterion is therefore the only available means of predicting the probable plan-form of the stream.

2.2.3 Geometry of Meandering Channel

Chitale (9) has classified meanders as regular and irregular and also as simple and compound. Regular meanders are a train of bends of nearly the same curvature and frequency. Irregular meanders are deformed in shape and may vary in anplitude and frequency. Simple meanders have bends with a single radius of curvature whereas, in compound meanders, each bend is made up of segments of different radii and varying angles. If the meanders are irregular and compound. meander characteristics will change along the length of the stream considerably and it may be difficult to define average meander characteristics.

The geometry of meandering streams can be described by meander length M_L, and the width of the meander belt M_B or by the sinuosity or the tortuosity. Many field engineers and research workers have attempted to relate these average characteristics to the flow characteristics. Relationship proposed by the investigators for rivers and flood plains may be found in many books (28,22,16).

2.2.3.1 Meander Bends

A typical feature of meandering rivers is the bend. In each bend a helical current is produced and causes a variation in bed level. It is important to predict this bed level in order to obtain information on (a) the available depth and width for navigation and (b) the level of the toe of the bank for the design of bank protection. Two methods are in use for this prediction. One is the deterministic approach which is restricted in its practical application because of the simplifications made in the analysis, and the other is stochastic approach. As yet both deterministic and stochastic models fail to describe the time variations of the bed level caused by the time dependant discharge.

2.2.3.2 Deterministic Approach for Predicting Bed Level in a Bend

For a circular bend with fixed banks under a constant discharge, the mobile bed will eventually assume a lateral slope such that the force on a grain at the bed will be zero. This implies that the resultant shear force due to current and friction of the bed is balanced by the component of force due to gravity. Considering the equation of the force due to current in a channel bend. NEDECO(1959) gives the equation for pr dicting bed level as

$$\left(\frac{1}{h} - \frac{1}{h_o}\right) = \left(\frac{1}{\gamma} - \frac{1}{\gamma_o}\right) \frac{1.5\alpha i_o \gamma_o}{\Delta D} \ldots \qquad \ldots \qquad \ldots \qquad (2.2)$$

where γ is the radial distance, h is the depth of flow α is the correction coefficient for non-uniform flow in the vertical, i is the slope of energy line, Δ is the relative density, D is the particle diameter and subscript zero stands for the value at outer bank. And also, $9.4 < 1.5\alpha < 11.5$.

For a given value of γ_o equation 2.2 describes the depth across the river with one unknown h_o. This equation can be used to design, for example, the required depth for bank protection. The equation shows the tendency for the lateral bed profile in a river bend to be convex, since in most cases $1.5\alpha\, i_o\gamma_o / \Delta D > 1$.

This equation is rather theoretical and generally inadequate for practical problems because of the following:

i. The discharge is assumed to be constant. This is not usually the case and the bed slope will change as a function of time.

ii. The derivation assumes uniform bed material. For non-uniform bed material, grain sorting takes place and this leads to phase lag between $u(x,r)$, $h(x,r)$ and $\bar{D}(x,r)$.

iii. The derivation assumes a fixed bank. If the banks are subject to erosion then in principle the derivation can be extended provided the degree of erosion is known (NEDECO,1959).

The degree of validity of equation 2.2 can be demonstrated by comparison of measured and computed cross-section. Agreement is fair but it should be noted that a specific discharge, expressed as a function of the boundary condition h_o, had to be chosen for the calculation.

2.2.3.3 Stochastic Approach for Predicting Bed Level in a Bend

The deterministic model does not give results accurate enough for design purposes. Better results can be obtained from scale models. Stochastic models can also be used to make the required prediction. Einstein (11) offered a framework that seems attractive in this respect. He assumed that the bed topography is dependant on (i) river regime, (ii) composition of bed material, (iii)upstream channel geometry, and (iv) wall effects.

For rivers of restricted length, (i) and (ii) are similar for all cross-section. Then, if wall effects are neglected, the difference occuring between the various corss-sections of the reach considered are determined by the upstream geometry. Each measured cross-section is now matched by least-square method with a linear series of orthogonal ploynomials, $P_r(y)$, in which y is measured perpendicular to river axis and thus the bed level $Z_b(y)$ is approached by

$$Z_b(y) = a_o p_o(y) + a_1 p_1(y) + \dots\dots\dots + a_r p_r(y) + \dots\dots + a_N p_N(y) \tag{2.3}$$

Legendre polynomials are very suitable in this respect as they are defined on a restricted interval. If the y-values are normalized by means of the width, their shapes are adequate to describe the river cross-section. The parameters a_r for any cross-section n are linked with the curvature C in a cross-section P upstream of n. A linear relation is assumed:

$$a_{r,n} = A_{0,r} + \sum_{p=1}^{p_o} A_{p,r} C_{n-p+1} \quad \ldots \quad \ldots \qquad (2.4)$$

The coefficients $a_{r,n}$ belong to a particular cross-section(n), whereas, the coefficients A apply to the whole river reach. By determining the coefficients A from the existing river geometry (Z_b and C), these coefficients can be used, together with the design values of C for the new bend, to obtain the coefficients a and thus the values of Z_b.

This method seems to be adequate for predicting bed level in new bends in rivers that do not vary too much in width. Moreover, the bed level near the banks can be estimated provided the banks are not protected by groins perpendicular to the river. To enlarge this method into a powerful tool for river engineering more research is required.

2.3 Stable Alluvial Channel

According to Lane (25) a stable channel may be defined as: A stable channel is an unlined earth channel (a) which carries water, (b) the banks and beds of which are not scoured objectionably by moving water, and (c) in which objectionable deposits of sediment do not occur. According to this definition, minor deposition and scour can take place in the channel, but over a long period of time the banks and bed must be stable. This definition refers to a channel carrying clear water through loose alluvial material in such a way that the sediment particles on the periphery do not move. Similarly a channel flowing through loose alluvial material and carrying water sediment mixture can be termed as a stable channel if the last two conditions listed by Lane are satisfied.

The characteristics of stable alluvial channel is the stability of the alignment of channel and slopes as well as its regime. These may change within a year but shows little variations from year to year. Changes such as scouring and silting of bed, advancement of the deltas into the sea and changes in bed and water slopes over a long period of time do take place, but these are significantly small (39). The characteristics of these rivers are such that most of the sediment load brought down by them is carried to the sea. The same river may have either aggrading, degrading, stable and other characteristics from its source to mouth. Its nature depend upon the amount and size of sediment entering the river, its load carrying capacity and other factors. Even the same reach may pass through various types depending on the variation of sediment load and discharge with time. But when this equations equalises over a period of time so that on the average the energy of the stream is just sufficient to transport the material supplied to it, the stream is stable.

Factors governing channel stability includes the distribution of shear stress at bed and banks, bank full discharge, longitudinal slope, sediment properties and its gradation, seepage from ground water to the channel or from channel to the ground and the composition of bed material which influences the critical tractive force. Vegetation along channel bank has been found to be helpful in channel bank stability.

2.4 Bank Stabilization Methods

When the stream banks become weak and susceptible to caving and erosion, the stability ofthe bed may be endangered in reaches where local flow conditions cause an increase in shear stress at bed in such cases the bed and bank must be stabilized. Stabilization of a river includes all the engineering works constructed on a river to guide and confine the flow of channel and to control and regulate the river bed configuration for effective and safe movement of floods and river sediments. Stabilization work are also required for navigation purposes (7). Also, erosion on account of the increased flow due to drainage from irrigated land may require stabilization work (30).

River stabilization may be done by different types of protective devices which may be classified as to the materials of which they are constructed, the general shape of the devices or according to their functions or application . Details of these methods can be found in many reports (10, 8, 42). The suitability of the method used for stabilization is dependent not only on the purpose but also on the fund available, convenience in use for short-run effect and ease of maintenance.

2.4.1 Groin

A groin is a continuous erosion resistant natural or man-made bank or barrier placed transverse to the primary motion of water, and is founded on ground wetted by the flow at any time running from a bank into the flow. It serves the purposes of (a) guiding or deflecting the axis of flow, (b) establishing normal channel width,(c) promoting scour and deposition of sediment where desired and (d) trapping sediment load to build up new river banks.

It is sometimes called as spur,spur dike or transverse dike. Groins may be classified according to the method and materials of construction, function served by them and their heights.

2.4.2 Classification of Groins according to the method and material of construction

According to the method and material of construction, groins can be classified as follows:

i. Impermeable groins

(a) Single line of steel or concrete sheet piling

(b) Double line of steel or concrete sheet piling, the space being filledup with various types of materials.

(c) Rock dike-plain cement concrete, grouted or asphalt surface

ii. Permeable groin

(a) Precast plain cement foncrete block

(b) Precast plain cement concrete cells

(c) Metal rectangular cell

(d) Pile groin

(e) Tree groin

i. Impermeable groin

Impermeable groin consists of rock fill or earth care armoured with resistance material like stone grouted precast plain cement concrete blocks. It acts as a solid obstructions and does not allow appreciable flow through them. The stream current is thus deflected and immediately down stream of it the stream have concave curvature towards the bank from which it extends. Such curvature is conducive to the movement of bed load towards this bank and hence silting takes place there.

To prevent slipping of stone of the groin nose and shank into the scour hole in the immediate vicinity, an apron is usually provided. This apron should be of sufficient length after lauching to shield the sloping faces of the land bank from below the bottom of the slope faces down to the deepest bed level.

A very flat slope for the nose of the groin is obviously expensive. Therefore groins are given normally a slope of 1:2 to 1:3. Scour protection can be reduced from head to bank because scour gradually diminishes from head to bank.

ii. Permeable groin

As distinguished from the deflecting or repelling action of an impermeable structure, permeability of a structure indicates a damping action on the velocity of flow. Materials suspended into water get deposited and the bank line starts building up. Therefore, permeable groins are more effective in stream that transport heavy sediment load. In comparatively clear rivers, this action results in damping the erosive strength and thus prevent bank erosion. As sedimentation occurs, the bank line becomes more or less permanent and the permeable groins do not require durable material to be used in its construction.

The materials used for the construction of permeable groins are cheaper and therefore, this type of groin is specially adaptable for river works where stone is difficult to obtain. Permeable groins when constructed does not create any abrupt change that does occur in the case of impermeable groin and so, no serious eddies and scour holes result. This is perhaps the reason why silt deposit is evenly and quiclky affected.

Permeable gorins are not strong enough to resist shocks and pressure from debris, floating logs etc. Therefore they are not suitable for upper reaches of the river.

2.4.3 Classification according function served

According to the functions served groins may be classified as follows:

i. Attracting groin
ii. Repelling groin
iii. Deflecting groin

i. Attracting type of groin

The groins pointing in the downstream direction of flow causing scour holes to form closer to the bank than the groin inclined at right angles are generally called attracting type of groins. They maintain the deep currents close to the bank. The main attack of the rivers on the upstream face of the groin and therefore requires better upstream protection compared to that on the down stream (Fig.2.1).

This type of groins are not generally recommended because they endanger the adjacent river banks causing failure of protecting certain structures from bank erosion.

ii. Repelling type of groin

Groins pointing upstream against the flow causing the flow to deflect away from the bank is generally called repelling groins. This has the advantage that during the flood the overflow is directed towards the centre of the river thus avoiding strong currents over the flood plains and near the flood diks. A groin pointing upstream produces a more desirable curvature to the flow downstream leading to pronounced deposition. Furthermore, such a groin has a larger stagnation region on the upstream side;therefore it is able to project a greater length of bank than a groin pointing downstream (16). Franco's finding also support this view (13).

The angle of deflection upstream varies 60° to 80° with the banks or in other words, the groin facing upstream make an angle of 10° to 30° with a line perpendicular to the bank or thalweg. Due to the disturbance caused by the head of the repelling groin, heavy scour occurs downstream. Therefore, these groins should have a strong head to resist the direct attack of the swirling current. As in the attracting groin scour diminishes from the head towards the bank and protection of the slope and apron can be reduced accordingly.

Recently, literal use of the metaphoric colloquial terms "repelling and "attracting" applied to groin action, has caused misunderstanding. The originator of the terms explains(6):

"The type of groin described in the paper was called a repelling groin at poona, where groins were differentiated into three types, namely, the fender groin, the idea of which was that the water should flow smoothly past it; the attracting groin, which attracted the river towards it; and the repelling groin. Groins repelled or attracted largely because of their position and not merely because of the angle relative to river flow; but provided the position was correct, a repelling groin worked more efficiently if it pointed slightly upstream whilst an attracting groin should face some 45 degrees downstream.

Actually, groins do not repel or attract· they interfere with the natural progression of meandering in a way that may give the impression of repulsion or attraction.

iii. Deflecting type of groin

A deflecting groin only deflects the flow. It is much shorter than a repelling groin and is generally constructed in river perpendicular to the bank (Fig.2.1).

2.4.4 Classification according to the height of groin below high water

These are mainly submerged or non-submerged type. Generally, non-submerged type of groin is preferred.

2.4.5 Special types of groins

Besides the groins described in the previous sections, several other special types of groins are in use. They are named after their shape, local use or persons contributed for it. These include hockey groin, Denehy's T-headed groin, L-shaped groin etc.

Denchy's T-headed groin was first constructed by Denehy at Okla headwork on the Yamuna river (India) and therefore it is also known as Denehy's groin. The front perpendicular arm of the head is parallel to the current. Usually, the downstream side of the head has a longer arm. A shorter length of these groins can protect more area from erosion compared to the other types. Therefore these are usually economical. Denchy's T-headed groin has been used in the protection of Kushtia town from the erosion of Gorai river and has been proved effective.

A groin with a curved head is known as hockey groin. It increases the tendency of attracting flow towards it and, therefore, is not likely to be helpful for bank protection. The L-headed groins with lower portion parallel to the flow on the downstream side are also in use and have been reported to be effective (16).

2.4.6 Functional design of groin

At first sight the function of a groin and hence design, might appear to be straightforward in that they are intended to provide some form of obstruction. However, the design difficulties and intricacies should not be underestimated due to their placement in a very complex and sensitive physical regime.

Functional design of the groin is the determination of its length, height, spacing, shape, angle of inclination and permeability. As the material of construction influences the performance of the structure, it is also considered in the functional design. No general rule has yet been formulated for the design of groin. However, a good number of attempts have been made to establish relationships among the pertinent factors of design. Recommendations for groin design in the technical literature have originated from three main fields of study: (a) Mathematical analysis (b) Physical model analysis (c) Field data under prototype condition.

A wide variety of groin designs have been used in parctice. Groin length, height, spacing, orientation shape and permeability can be varied. A number of different materials may be used for construction and these can also sometimes affect groin performance. Groin characteristics referred to in the papers when taken as a whole, there appears to be no consensus of opinion as to the functional design of groin.

Althoughthere are many papers in which some reference is made to prototype groins, there are relatively a few which provide sufficiently detailed data for an analysis to be made of groin performance. Some authors write their own conclusions drawn from many years of experience, but without giving any details of the groin-systems with which they have been involved. This is valuable but does not permit other research workers to make use of their data. For more details, reference can be made to the works of Ahmed (1,2) Akikusa and Kikkawa(3) Nagai(31), Nagai and Kubo (32), Monohar (29), Tomlinson (4) and reports of BWDB(4) and IDFCRC(21).

A large number of river training measures incorporating repelling groin constructed in India was analysed by Varshney and Mathur(44). They suggested a general equation as follows:

$$\frac{b}{w} = 0.374\ (A^{-0.29}/F_r^{-0.145}) \quad \ldots \quad \ldots \qquad (2.5)$$

where, b = length of groin

w = width of active river

F_r = flow Froude number

A = arc-chord ratio of worst loop

2.5 Scour

When alluvial streams are partially obstructed by hydraulic structures like groins bridge piers. abutments, guide banks etc., the bed level in the vicinity of the structure is lowered as a result of interaction between the high velocity flow and the loose bed and consequent modification in the flow pattern. Such a local drop in the bed level is known as scour. If the scour depth is great enough to uncover the supporting soil of these structures, it may subside there and ultimately washed out by the current.

Different methods of computation of scour have been proposed by various investigators. Distinction is made between general motion scour (where supply of sediment from upstream is assumed) and clear water scour (where absence of sediment supply from upstream is assumed). Reference can be made to Komura (23) and Laursen (26,27).

The methods proposed assume alluvial bed material down to the lowest layer uncovered. If bed rock is present at some depth a considerably smaller scour depth would be expected. The same is true if armouring effect interferes. Komura (24) has attempted to account for the formation of an armoured layer during scouring by applying the method of Gessler (37). The scour may be much greater than expected when the river bed consists of a layer of coarse or cohesive material overlying finer sand. If the upper layer is removed during the scour process, an unexpectedly large scour hole may develop, endangering the stability of piers and embankments(17).

Local scour around piers and abutments is caused by the so-called horse-shoe vortex system characterized by a three dimensional seperation of the viscous sub-layer. This vortex system is caused by the secondary flow and vorticity already pro present in the flow. It has not been possible to determine the depth of local scour around the nose of a pier from a theoretical analysis of the water movement around the pier. However, many investigators have been able to provide some insight into these problems by carrying out experiments. Reference can be made to Gill (18), Shen (39) and Inglis (37). The following remarks should be made about local scour around piers:

(a) It should be realized that the formulae and design graphs can at the best only yield rough estimate of the scour depths to be expected.

(b) Local scour around piers in cohesive and non-cohesive bed material shows different pattern.

(c) In debris-laden streams, the actual local scour may be considerably larger than determined by data from literature.

(d) The methods proposed determine the mean scour that will occur during an extended flood. When general sediment motion occurs and bed forms travel along the river bed, the maximum scour depth will be longer than mean one. Neil advises that one-half of the height of the dunes be added to the mean scour depth, however, the sum should not exceed clear water scour depth.

2.5.1 Scour at the toe of groin

From the model test of groins at the Ganges near Hardings Bridge, Inglis concluded that groin projecting from the bank into the channel give widely varying value of maximum scour depths, ranging from 1.7 to 3.8 D_L, where,

$$D_L = 0.473\ (Q/1.76\ d_m^{0.5}) \quad \ldots \quad \ldots \qquad (2.6)$$

Q = discharge in cfs

d_m = median particle size in mm.

depending upon the severity of the river curvature which in turn depends on the length, angle of projection and position of the groin in relation to the attack.

In an attempt to calculate the probable scour depth for various discharge intensities, Ahmed(2) conducted several studies in a laboratory channel. He suggested an equation of the following form:

$$d_s = Kq^{\frac{2}{3}} \quad \ldots \quad \ldots \quad \ldots \qquad (2.7)$$

where, K is a factor whose value depends on the position of groin and q is the discharge per unit width at the groin constiction. After analysing the scour problem by plotting different non-dimensional terms that affect it, he defined the term $d_s/q^{\frac{2}{3}}$ as scour constant. This constant has been widely accepted in the study of scour at the toe of groin.

Applying correction for velocity, Khosla connected the scour depth with discharge intensity using Kennedy's regime flow formula (2). He gave the relation in the following form:

$$d_s = 0.90\ (q^2/f)^{\frac{1}{3}} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (2.8)$$

where f is a function of silt size and is known as Lacey's silt factor and q is the discharge per unit width in cfs. This formula holds for regime channel. He also recommended multiplication factors in calculation of d_s for different types of bends.

CHAPTER THREE

LABORATORY SET UP AND MEASUREMENTS

3.1 Introduction

The Hydraulics and River Engineering Laboratory of the Department of Water Resources Engineering of Bangladesh University of Engineering and Technology, Dhaka, provided required facilities for the study. The existing alluvial sand bed flume together with the water supply system, measuring device, and automatic dry sand feeder were used in this study. The levelling instruments from the Department of Civil Engineering were used. A brief description of the facilities and the experimental procedure is given below:

3.2 The Alluvial Sand Bed Flume

The sand bed flume was 50 feet long, 15 ft wide and about 3 feet 6 inches deep having double walls along its length (Fig.3.1). The two adjacent walls were seperated by an annular space of 6" wide. The inner wall was provided with ½ inch diameter hole with a spacing of one foot both in horizontal and vertical direction to facilitate movement of water from the sand bed to the annular space between the two adjacent walls and vice versa. The water table was controlled and maintained to the desirable level in the sand bed by regulating the water level in the annular space. To avoid losses due to seepage, the outer wall and the bed of the flume was made water tight.

3.2.1 Water Supply System

A centrifugal pump installed near the tail water tank of the flume was used to supply water to the test channels. Water was allowed to enter the inlet of the channel through a delivery pipe line from the pump, which after flowing through the channel entered into the tailwater tank. It was recirculated by means of the pump and the process was followed to have a continuous supply through the test channel.

The loss line attached to the delivery pipe line was used to maintain the desired discharge. Required amount of water was allowed into the test channel and excess was diverted into the tailwater tank through the loss line.

3.2.2 Flow Measuring Device

An one-inch automatic flow meter connected to the delivery pipe line was used to measure the volume of water flowing through the line. This meter was provided with the facility of taking the volume readings with an accuracy, of one-hundredth of a gallon. The time required to flow 10 gallons of water was recorded by a stop watch and the discharge rate was calculated.

3.2.3 The Tailwater Tank

The tailwater tank at the downstream end of the flume was used as the source of supply of water for the pump. As the water was made to recirculate, this tank was provided with beffles for settling down the sediment carried from upstream. The tailwater level was maintained constant by supplying water from the main supply line of the laboratory. Approximately one foot length of the test channel at the downstream end, measured from the tailwater tank was kept submerged throughout the test. This arrangement permitted the stream to change its longitudinal water surface slope naturally, and to eliminate back water effect in the lower part of the test channel. This also helped the pump to operate under a constant head thereby maintaining a constant discharge.

3.2.4 The Sand Bed

A miture of fine and coarse sand was used as the bed and bank material of the test channel. The gradation curve of the sand is shown in Fig. 3.2. The median size (defined as 50 percent of the material is finer than the given size and denoted by d_{50}) was found to be about 0.147 mm. The gradation coefficient σ, which expresses the size distribution of the bank and bed material, was found to be 2.65. The gradation coefficient is defined as:

$$\sigma = \frac{1}{2} \left(\frac{d_{84}}{d_{50}} + \frac{d_{50}}{d_{16}}\right) \quad \ldots \quad \ldots \quad (3.1)$$

where, d_{84} and d_{16} are the size of the bed or bank material for which 84 percent and 16 percent materials respectively are finer. Hence, σ is the average slope of the two segments of the gradation curve.

3.2.5 Flow Entrance

An initial bend of about 30° with the longitudinal axis of the initial channel was provided in all test sets to develop uniform meander pattern. This also allowed a slow transition in velocity from the entrance to the channels. Thin steel plates of about four feet long was used for providing this initial bend.

3.2.6 The Dry Sand Feeder

An automatic dry sand feeder located at the upstream end of the flume was used for sediment feeding. The feeder was driven by a motor having a gear box with control devices of regulating the sediment feed into the channel. A calibration curve for the rate of sediment feed was prepared (Fig.3.3). This curve was used to maintain the desired sediment load in the channel.

Material same as that used for the preparation of the bed of the flume was introduced at the entrance of the test channel from the dry sand feeder. The rate of sediment feed was taken as 880 ppm and was kept constant throughout the test runs. This rate was determined by a few trial runs and was compared with the actual values for some rivers of Bangladesh (43). Also this rate was found to be in agreement with the sediment concentration versus Froude number plot by Wilis et al (45).

3.2.7 Initial Channel

The size of the initial channel was 8 inches wide and 2 inches deep. This size was kept constant in all the test. The channel was moulded in the flume bed by trowell and template as shown in Fig. 3.1. The initial channel dimensions were fixed by regime equations using the values of constants estimated by Nishat (34). These dimensions were subsequently checked by Lacey's regime equation(40).

3.2.8 Discharge and Slope

A constant discharge of 0.03222 cfs and a slope of 0.00333 was provided in all the tests. These values were kept constant throughout the study.

3.2.9 Measurement

A movable bridge with a point gauge mounted on it was used for taking reading. The bridge was marked in feet and inches with zero at the centre that coincides with the centre line of the initial channel. The bridge was operated manually over a rail placed on the top of the side wall. The rail was graduated in feet and the position of the bridge was read from this graduation. To avoid any error due to sage of the movable bridge, all the readings were taken with the help of a lavel with a fixed benchmark.

3.3 Experimental Procedure

For all of the test runs, the experimental procedure were as follows:

The sand in the flume was levelled and compacted. A channel was excavated along the longitudinal centre-line of the flume with the help of a trowel and template. To provide the initial channel with the pre-determined slope a string was held tightly along the centre line of the flume and elevations were taken at intervals. After the channel was excavated, the tailwater tank and the annular space, between the two walls were filled with water upto a level on a piece of wood in the tailwater box. This level was predetermined from previous trial runs. The channel was given sufficient time (about 12 hours) so that the groundwater level could be raised to the level of water in the tailwater box.

Water was supplied to the channel by operating the recirculating centrifugal pump. The discharge of the pump was maintained at a constant desired value with the help of the loss line attached to the delivery pipe. Dry sediment was fed at the entrance of the channel by the previously calibrated sand feeder. The rate of the sediment feed was kept at a predetermined value with the help of the gear-box indicatoor. The rate of change of bank formation was very high at the beginning of the test run. After several hours of running the channel was found to have obtained a stable shape. This was evident from more or less stable shape of the meanders. To test the stability of the channel, water surface and bed elevations at four different locations were taken and plotted in a graph paper. The water surface slope and bed slope were calculated. If these two slopes were equal, the channel was taken to be stable. Otherwise, the test run was containued until these slope were equal. The time required to achieve this condition varied from 72 to 125 hours depending on whether the channel was run continuously or intermittently. After the test run achieved this quasi-equilibrium status, the following data were collected:

i. Location of the left and right banks along its profile.
ii. Location and slope along the thalweg.
iii. Location of pools and crossings
iv. Cross-section of the channel at bends where groins were to be placed.
v. Cross-section of the channel at upstream crossings of the bends where groins were to be placed.
vi. Cross-section of the channel at downstream crossings of the bends where groins were to be placed.

Also, to observe the development of meanders, location data of the banks and the thalweg were taken at different interval of time after the starting of the test run.

Impermeable groins made of solid metal plates were placed at the desired locations after collecting the above data. Test run was then continued until stability was restored. Again, the water surface slope and bed slope were determined by taking elevations at four different locations to check the stability. At the end of this stage the following data were collected:

i. Location of left and right bank along its profile
ii. Location and slope of the thalweg
iii. Cross-section of the channel at bends where groins were placed and at corssings where earlier measurements were taken.
iv. Depth of scour hole formed at the toe of the groin at $\frac{1}{2}$ inch interval along lines paralle and perpendicular to the groin
v. Area of the scour hole
vi. Length of the area protected along the bank line of the channel, both at upstream and downstream from the groins placed at the aforesaid bends.

Single groins of different projection and placed at different locations were studied. A total of six test runs were made in the laboratory. In three of them, effect of single groins placed at the centre of the bends were studied. In the other three, single groins placed at a distance of 10 percent of the average channel width upstream from bend centre were studied. In all the runs, groins were placed at two different bends spacing between them was such that the flow characteristics at the downstream groins were not affected by the upstream groin. Thus six sets of results were obtained in the study of single groin placed at the centre of bend and another six sets in the study of single groin placed 10 percent upstream of the bend centre.

In the study, groin projections ratios were varied from 5 percent to 30 percent of the average channel width with an increase of about 5 percent.

CHAPTER FOUR

RESULTS AND DISCUSSION .

4.1 Introduction

To study the effect of location and projection of a single groin, data collected from the laboratory set up have been analysed. The downstream length protected by groin, L_d, the maximum scour depth d_s and scour area A_s formed at the toe of the groin, the length of groin projection b and average channel width W, have been considered for analysis.

In an attempt to establish non-dimensional parameters affecting scour at the toe of groin, Ahmed (2) suggested that b/W is a more useful independant variable than b and the discharge per unit width at the groin constriction q is an important variable. Also the scour constant K as used by Ahmed has been widely accepted for the study of scour at the toe of the groin. Because of the wide acceptibility of his sugg estions, these parameters have also been used in the analysis.

The depth of scour is very important factor in the design of groin and also in the prediction of the groin performance. So the scour depth as measured in the experiment has been compared with those obtained from different formulae presented in Chapter-2.

Attempt has been made to relate the parameters by statistical analysis using the computer of BUET Computer Centre. The relationships obtained have been compared with those given by Hossain (20).

The effect of location and projection of groins as observed from the laboratory test runs are described in the following sections:

4.2 Effect of groin on downstream length protection

It was found that deposition of sediment occurs at the downstream face of the groins. The length of this deposition was measured from the groin along the downstream bank. The major cause for the siltation at the downstream of the groins was the obstruction created by the groin projection to the main flow with a reduction of velocity in the vicinity of the area. It has been mentioned earlier that groins were placed at two different locations (at the bend centre and at ten percent upstream of bend centre) and their projections were varied. Figs. 4.1 to 4.12 show the location and projection of the groins and identify the position of banklines and thalweg before and after the placements of groin. Results obtained in relation to the downstream length protected are therefore discussed in the following two sub-sections:

4.2.1 Effect of projection of groin on downstream length protection

It is interesting to note that as the projection ratio of groin is increased, the downstream length protected increases upto certain value of projection ratio, but beyond this value the downstream length protected decreases with the increase of groin projection. This is evident from figure 4.37. The value of projection ratio at which downstream length protection becomes maximum is found from figure 4.37 to be 17% for groins placed at bend centre and 23% for groins placed at ten percent upstream of bend centre.

When a groin is placed at a bend it deflects the thalweg away from the bank (Fig. 4.1 to 4.12). As the groin projection increases, the shifting of the thalweg from its previous position starts from a greater distance upstream of groin. As we go on increasing the projection, the thalweg may take such a form that the flow hits the downstream bank and erodes it threby decreasing the downstream length protected. This may be the possible explanation of the obtained results.

The results obtained do not agree with those obtained by Hossain(20), This disagreement may arise because of the fact that in his study Hossain ignored the effect of groin location on the downstream length protected. Instead of analaysing data obtained for different projections at a fixed position he analysed data for different projections at different groin locations.

From the plotting of L_d/W and b/W of Irrigation, Drainage and Flood Control Research Council (Fig. RCP/2b/4 of (21)) it may be observed that the relationships between these dimensionless parameters is in agreement with that obtained in the present study. But the value of b/W for maximum L_d/W differs. The possible explanation to this dis-agreement may be that the bank and bed material used in that study was of different gradation.

In an attempt to establish a relationship between the downstream length protected and groin projection, the dimensionless parameter b/W has been chosen as independant variable and L_d/W as dependant variable. A polynomial variation upto seventh order was assumed. The best fit correlation was obtained when the polynomial variation taken was of the order five for groins at bend centre and four for grins 10% upstream of bend centre. The coefficients of correlation was found to be 0.984, and 0.972 respectively.

The equation obtained for single groin placed at the centre of the bend is as follows:

$$L_d/W = a_o + a_1 (b/W) + a_2(b/W)^2 + a_3(b/W)^3 + a_4(b/W)^4 + a_5(b/W)^5 \quad \ldots \quad \ldots (4.1)$$

where $a_o = 5.26814 \times 10^{-2}$

$a_1 = 3.45609 \times 10^{-2}$

$a_2 = 1.29468 \times 10^{-3}$

$a_3 = -3.11638 \times 10^{-4}$

$a_4 = 1.33688 \times 10^{-5}$

and $a_5 = -1.82269 \times 10^{-7}$

Though equation 4.1 is not recommended to be conclusive, it shows the probable trend of groin projection in protecting downstream length.

4.2.2 Effect of location of groin on the downstream length protected.

It has been observed that the groin when placed ten percent upstream of bend centre shows the similar behaviour in relation to the length of downstream bank protection as described in section 4.2.1. Fig. 4.37 shows the relationship of L_d/W with b/W. For same projection ratio, the groin placed at ten percent upstream of the centre of the bend was found to protect a length shorter than the length protected with groin placed at the bend centre.

The relation between L_d/W and b/W has been found to be as follows:

$$L_d/W = a_o + a_1\ (b/W) + a_2(b/W)^2 + a_3(b/W)^3 + a_4(b/W)^4 \quad \ldots(4.2)$$

where, $a_o = 6.86922 \times 10^{-2}$

$a_1 = 7.92330 \times 10^{-3}$

$a_2 = 9.58688 \times 10^{-4}$

$a_3 = -3.8427 \times 10^{-6}$

and $a_4 = -1.56500 \times 10^{-7}$

Comparison of the two curves presented in Fig. 4.37 indicates that groins placed at the centre of the bend have better performance over those placed at ten percent upstream of bend centre.

4.3 Effect of groin on bank erosion

Channel bank erosion was observed due to the placement of groins. The cause of this erosion may be due to the flow causing whirling motion on the backside of the groin.

Erosion observed was found to be of two types (a) upstream bank erosion and (b) downstream bank erosion. Both types of erosion was measured from the initial bankline along the length of groin.

It was noted that for small groin projections, the upstream bank eroded. The length of this erosion was found to decrease with increase in groin projection. When groin projection ratio was further increased no erosion of the upstream bank was found to occur. Also, the upstream bank erosion was found to be greater when the groin was placed at the centre of the bend, and to be less when groins were placed at ten percent upstream, for groins having smaller projection ratio. As the projection ratio increased the erosion in both cases decreased and there was almost no erosion in the upstream side when the ratio became little high.

Downstream bank erosion was observed at the higher groin projection ratio. This erosion was found to be pronounced for the groins placed at the ten percent upstream of the centre of the bend.

4.4 Effect of groin on the cross sectional area and velocity

The variation of cross-section at the bends where groins were placed, variation of cross-section at crossing upstream of the bend and variation of cross-sections at crossing downstream of the bend are shown in Figs. 4.25 to 4.36. The continuous firm line indicates the cross section before placing of groin and the broken line indicates the cross-section after placing of groin.

Erosion was observed at the opposite bank of the groin side. Little variation of cross section at crossing were observed. Placement of groin at the concave bend resulted in the reduction of channel width and the effective flow area. The velocity of flow was thus increased since the discharge was kept constant. This increase in velocity resulted in scour of bed vertically downward at the groin side bend and deep water channel was shifted away from the bend. The deflected and increased current at the bends may have lost its energy in scouring around groin toe forming vortex and eddies and that may be the probable reason for more or less stable nature of crossings(20).

4.5 Scour at the toe of groin

It was observed that in all the tests, scour holes were formed at the toe of the groin. The plan area and pattern of the scour hole, the maximum scour depth were observed during the test. It was found that the above features of the scour hole, together with the scour constant, varied with the variation of projection and location of the groin. The variations observed and the relationship obtained there from are discussed in the following sub-sections:

4.5.1 Effect of projection of groin on the scour area and pattern

Figures 4.13 to 4.24 show the plan area and pattern of the scour formed at the toe of the groin. Depth contours with an interval of 1 centimeter were drawn in the vicinity of each groins tested. The outer contour line gives the boundary of the scour area.

The size of the scour holes were found to increase with the increase of groin projection for both the groins placed at the bend centre and at ten percent upstream of bend centre. However, the rate of increase in the two cases were different. To ascertain the trend of increase of scour area with the increase of groin projetion ratio, the parameters A_s and b/W were analysed ststistically. Best fil correlation was calculated. Fig. 4.38 shows the best fit correlation with equations. For groins placed at the centre of the bend the equation takes the form.

$$A_s = 0.06684(b/W)^{0.656} \quad \ldots \quad \ldots \quad (4.3)$$

The correlation coefficient was found to be 0.9638.

The shape of the scour hole may be observed from Figs.4.13 to 4.24 to be a balloon shape with a bulge at one corner and pointing towards the downstream direction. The shape of these scour holes are more or less in agreement with those obtained by Ahmed(2). However some difference has been observed in some cases between the shape of scour holes formed but no definite remark can be made from the present study.

A strong vortex structure, fromed at the toe of the groin having vertical axis of rotation, widened the scour area with the increase of groin projection.

From groins placed at ten percent upstream of bend, the relationship between the scour area and the groin projection ratio was found to be

$$A_s = 0.12108\ (b/W)^{0.4305} \quad \ldots \quad \ldots \quad \ldots \quad (4.4)$$

The correlation coefficient in this case was 0.9640. Though equations (4.3) and (4.4) may not be recommended to be conclusive, but they show the trend of variation of scour area with the variation of groin projection ration and location.

4.5.2 Effect of projection of groin on the depth of the scour hole

Figure 4.39 shows the relationship between the maximum depth of scour hole and the groin projection ratio. It was observed that the non-dimensional plotting of d_s/W versus b/W instead of d_s versus b/W shows a better correlation. Therefore, the dependent variable was chosen to be d_s/W.

The maximum depth of scour hole was found to increase with the increment of groin projection ratio, for the both cases when groins were placed at bend centre and at ten percent upstream from bend centre.

The equations relating d_s/W and b/W for best correlation was found to be as follows:

For groins placed at bend centre

$$d_s/W = 0.03755\ (b/W)^{0.22694} \quad \ldots \quad \ldots \qquad (4.5)$$

The coefficient of correlation was 0.6777,

For groins placed at ten percent upstream from bend centre

$$d_s/W = 0.02442\ (b/W)^{0.35424} \quad \ldots \quad \ldots \qquad (4.6)$$

The coefficient of correlation was 0.6690.

In both the cases, the point of maximum depth was found to occur at a little downstream from the toe of the groin due to the combined action of vortex structure and flow velocity towards the downstream direction. Comparison of the maximum scour depth for the two cases shows that the observed scour depths for both the cases were almost of the same order of magnitude for the same projection ratio.

4.5.3 Effect of groin projection on scour constant, K.

It was observed that the scour constant, a measure of scour depth, when plotted with the groin projection ratio showed the trend to increase with the increase of groin projection ratio (Fig.4.40). The relationships obtained for the best form of correlation are as follows:

For groins placed at the centre of the bend:

$$K = 4.9404 + 0.02812(b/W) \quad \ldots \quad \ldots \quad (4.7)$$

The coefficient of correlation was found to be 0.8825.

For groins placed at ten percent upstream of bend centre.

$$K = 4.0822 + 0.0199\ (b/W) \quad \ldots \quad \ldots \quad (4.8)$$

The coefficient of correlation was 0.8582.

From figure 4.40 it may be observed that value of scour constant for groins placed at ten percent upstream of bend centre is less than the value for groins placed at the centre of the bend for the same projection.

4.6 Comparison of predicted scour depth

The maximum depth of scour observed at the toe of the groins were compared with those predicted by several investigators. Comparison was made with the equations given by Inglis, Ahmed, Khosla and Hossain.

When the maximum scour depth obtained was compared with that predicted by Inglis equation, (Eqn. 2.6) it was found that the results obtained are very close to the lower limit as specified in the Inglis equation. Results obtained from Ahmed's equation (Eqn.2.7) are in agreement with the present study. Also maximum scour depth as obtained from Hossain's equation (20) is in agreement with the present study. The maximum scour depth obtained in this study was found to be very high compared to the prediction by Khosla's equation (Eqn. 2.8).

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

A series of tests were carried out in the laboratory to study the effects of location and projection of a single groin in a bend. The groin projection ratio was varied from 5 percent to 30 percent with an increase of about 5 percent each time. The various groin projections were studied at two locations, one at the centre of the bend and the other at 10 percent upstream of the bend. Based on the study as described in chapter three, the following conclusions may be drawn.

1. With the increase of projection ratio, the downstream protected length increases when the the placement of the groin is centrally located. Beyond projection ratio of 17%, the protected length decreases. For groins placed at ten percent upstream of bend centre, same trend of variation of downstream length protected by groin is found. The maximum value of groin projection ratio for maximum length of downstream protection in this case is 23%.

2. There exists a good correlation between L_d/W and b/W (Eqn.4.3 and 4.4) and the data are in agreement with the results obtained by Ahmed (1). Moreover, groins placed at bend centre have better performance for the protection of

downstream length compured to the placement at ten percent upstream of bend.

3. The area of the scour hole increases with the increase of groin projection for groins placed both at the centre and at ten percent upstream of bend centre. A good correlation exists between scour area and groin projection ratio. The scour area formed at the toe of groin increases at a faster rate for the groins places at bend centre than for the groin placed at 10% upstream of the bend centre.

4. The maximum depth of scour hole at the toe of the groin increases with the increase of groin projection for groins placed both at the centre and at ten percent upstream. A fair correlation was obtained between the maximum depth of scour and different groin projections. The maximum depth of scour hole has been observed to be more in case of groin located at the bend centre than that incase of groin located at 10% upstream of bend centre.

5. The values of scour constant increases with the increase of groin projection for groins placed both at bend centre and ten percent upstream of bend centre. The values of scour constant for groins placed at ten percent upstream is less than compated to the placement at the centre of the bend.

A good correlation between the scour constant and groin projection ratio was found for both the locations of groins.

5.2 Recommendations for future study

The study of the effect of location and projection of a single groin in a bend may be extended by incorporating the following.

1. By using different size of bed and bank material
2. By varying the discharge over a wide range
3. By changing orientation of groin with respect to bend curvature.
4. By using groins of various shapes and types
5. By applying the tidal influence from downstream.

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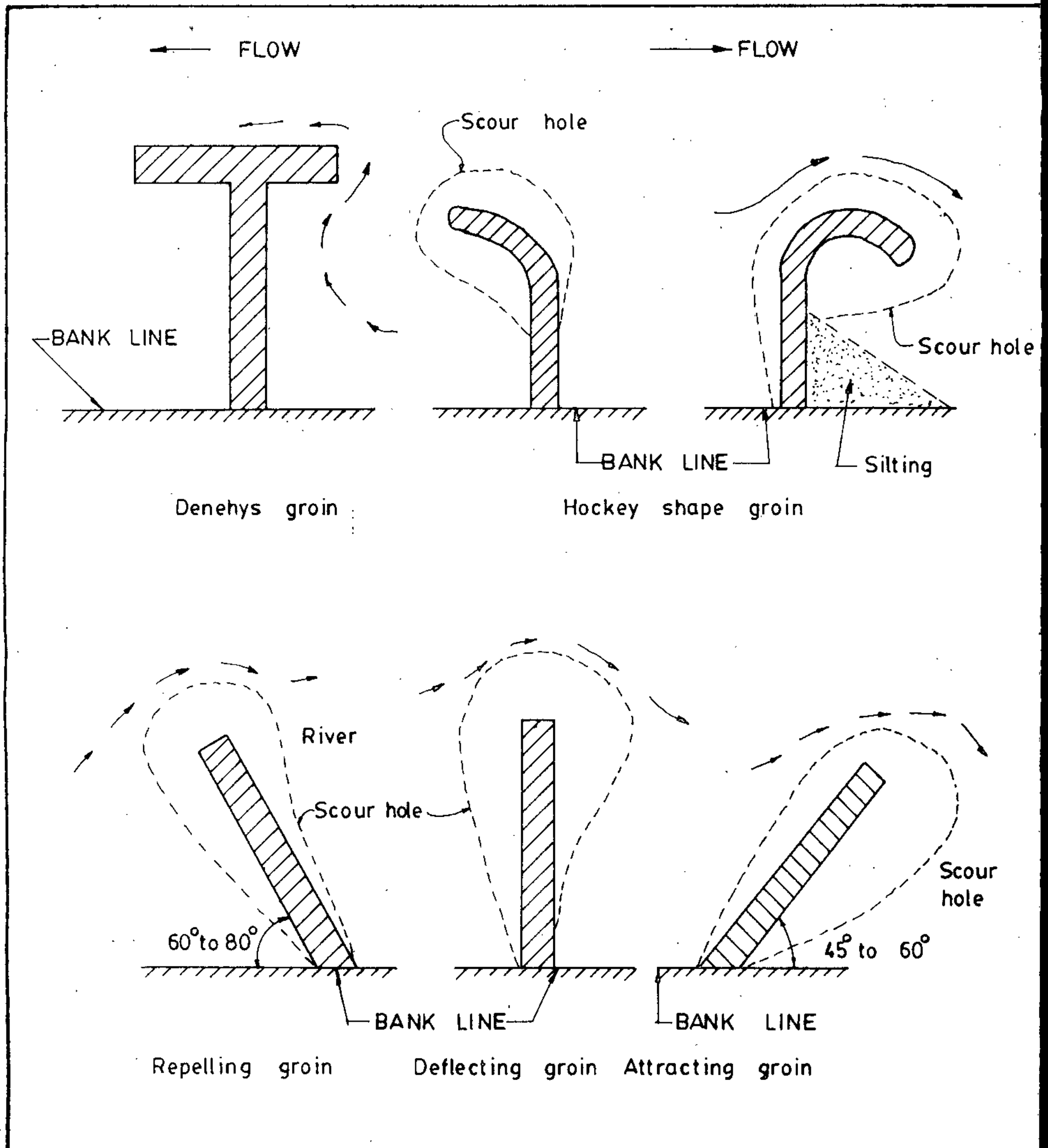
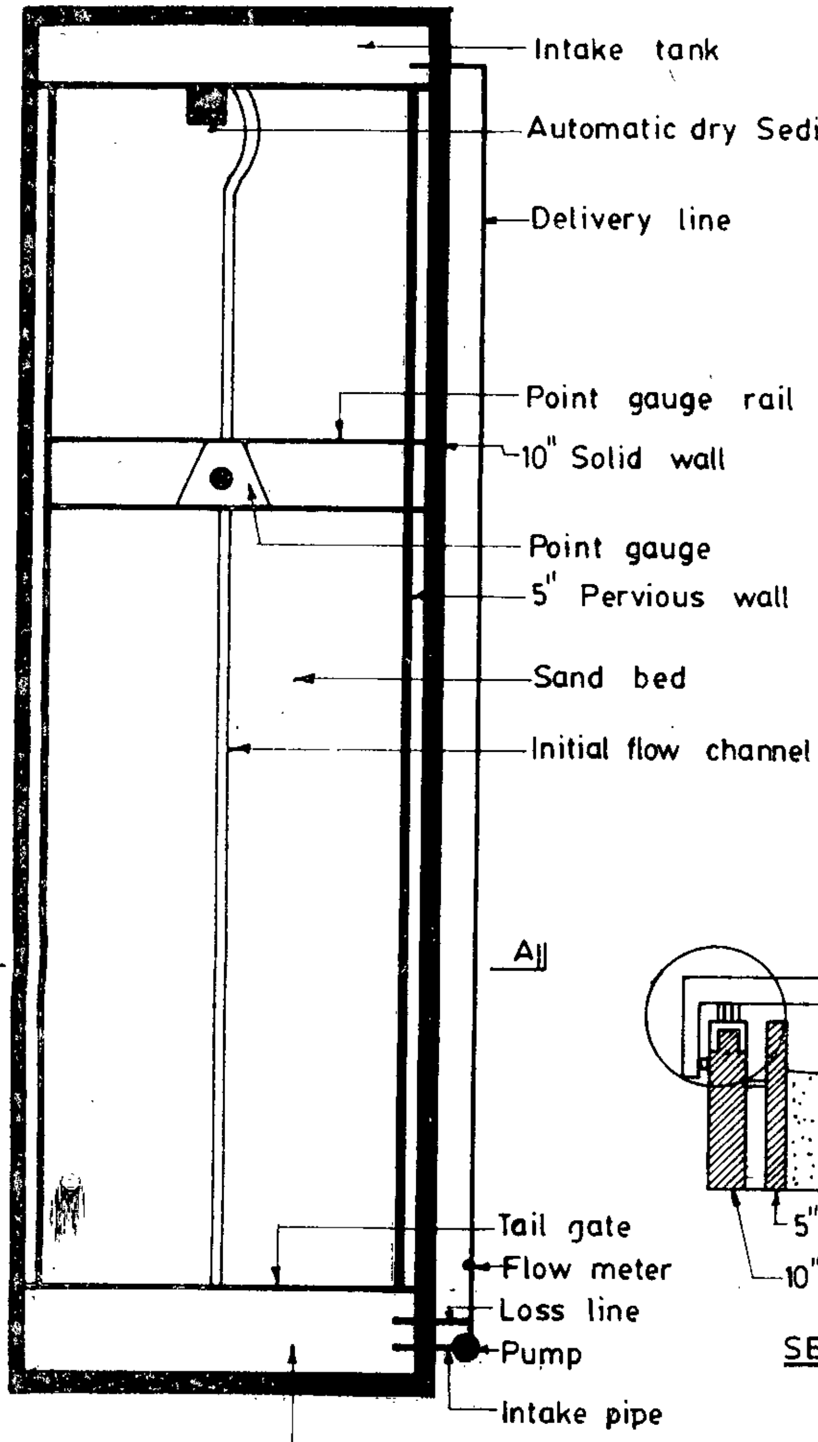
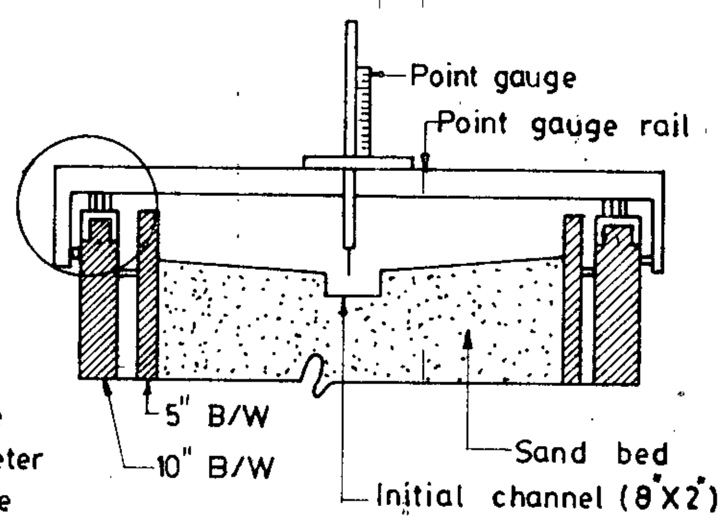


Fig. 2.1 Different types of groin (after punmia and Lal 1977)





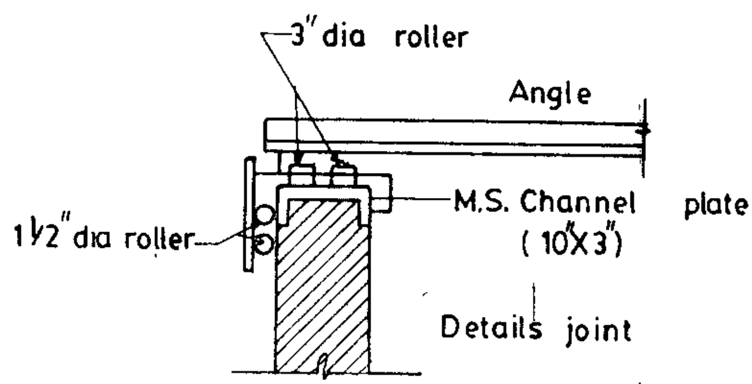


Fig. 3.1 Experimental set-up

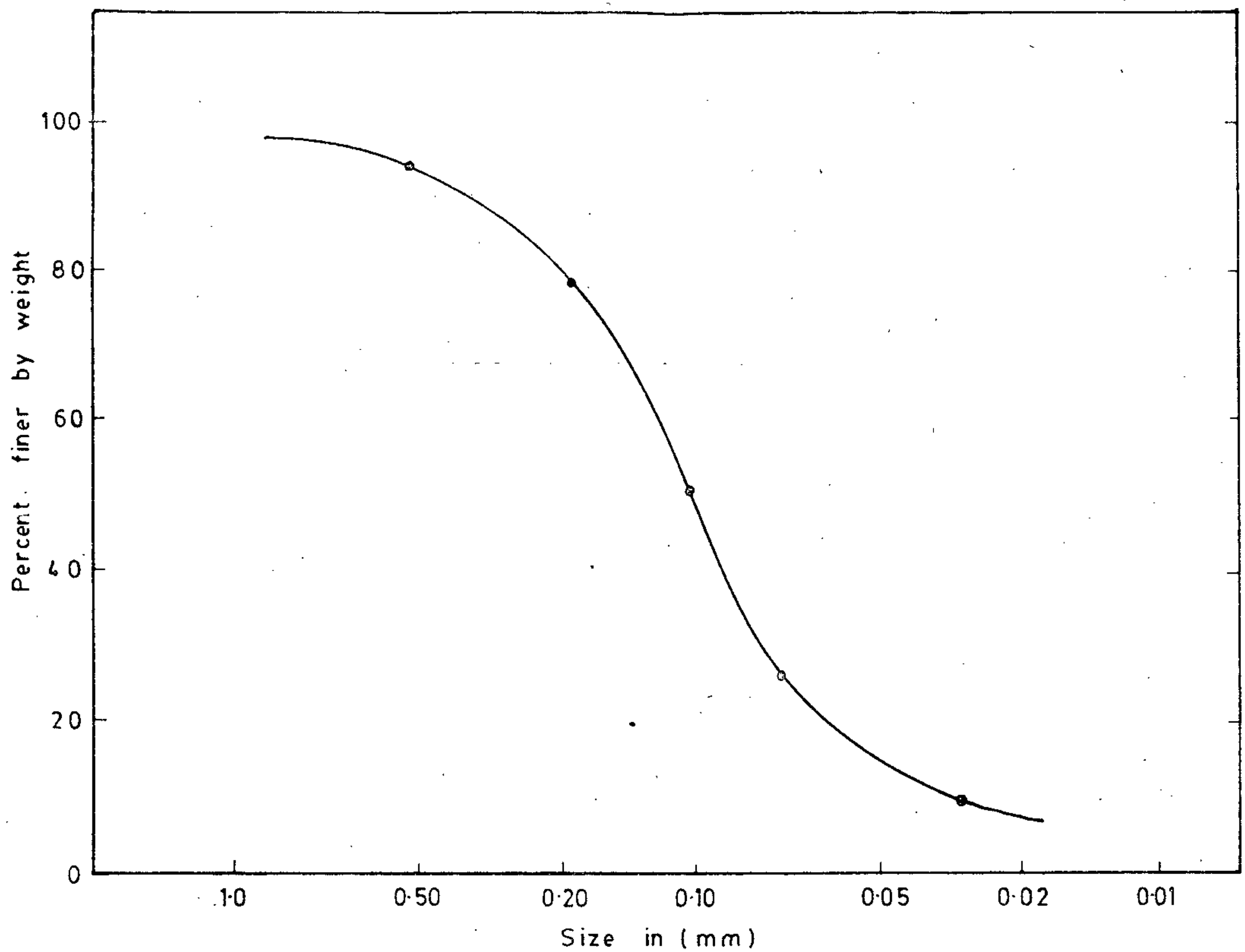


Fig. 3·2 Size distribution of bed material

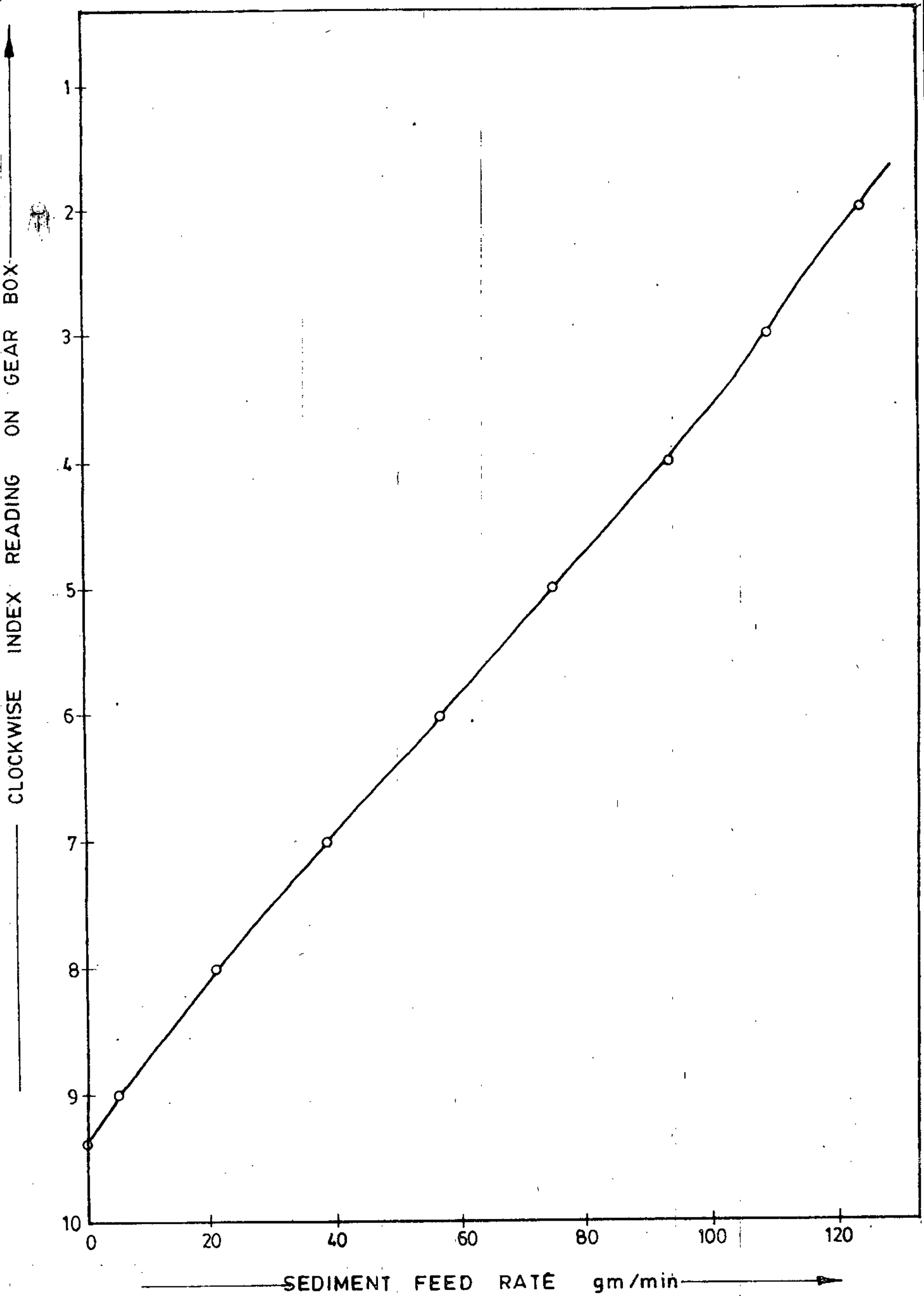


FIG. 3·3 CALIBRATION CURVE FOR DRY SAND FEEDER

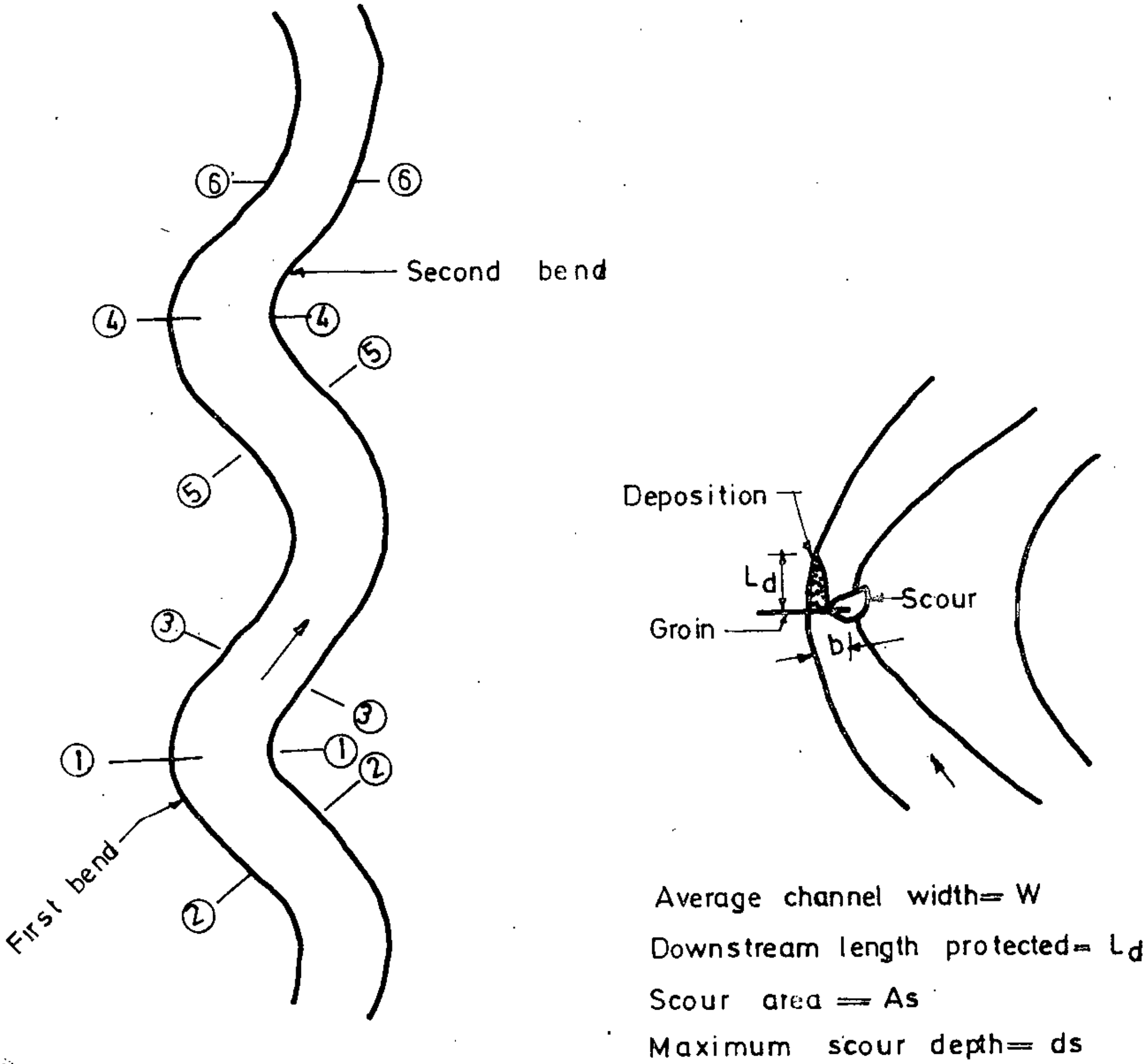


Fig. 4. 0 Definition Sketch showing location of bends where groins were placed and the measured cross-sections

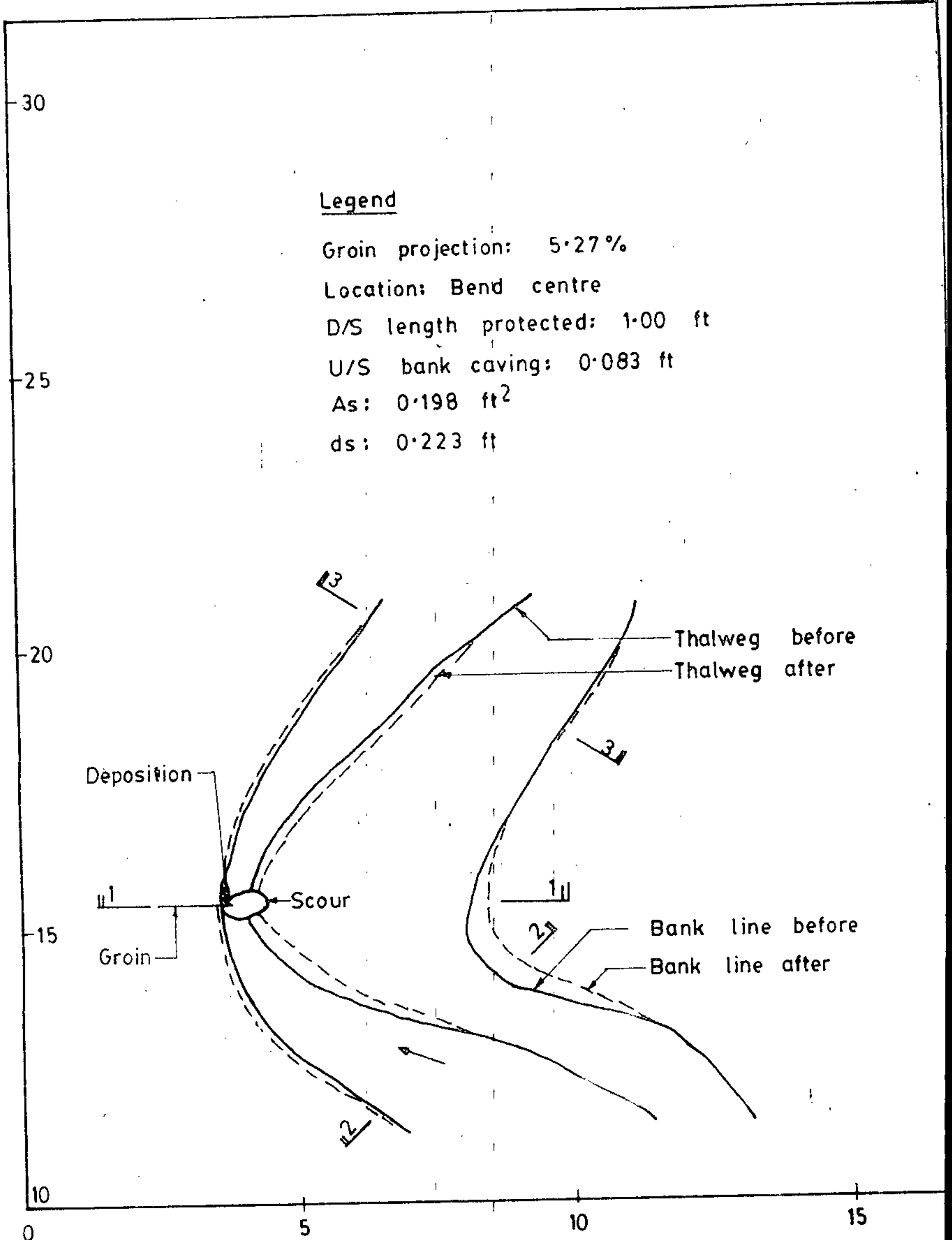


Fig. 4.1 Location of bank line thalweg and deposition for set ut 1

Scale: 1:30 Q = 0·03222 cfs

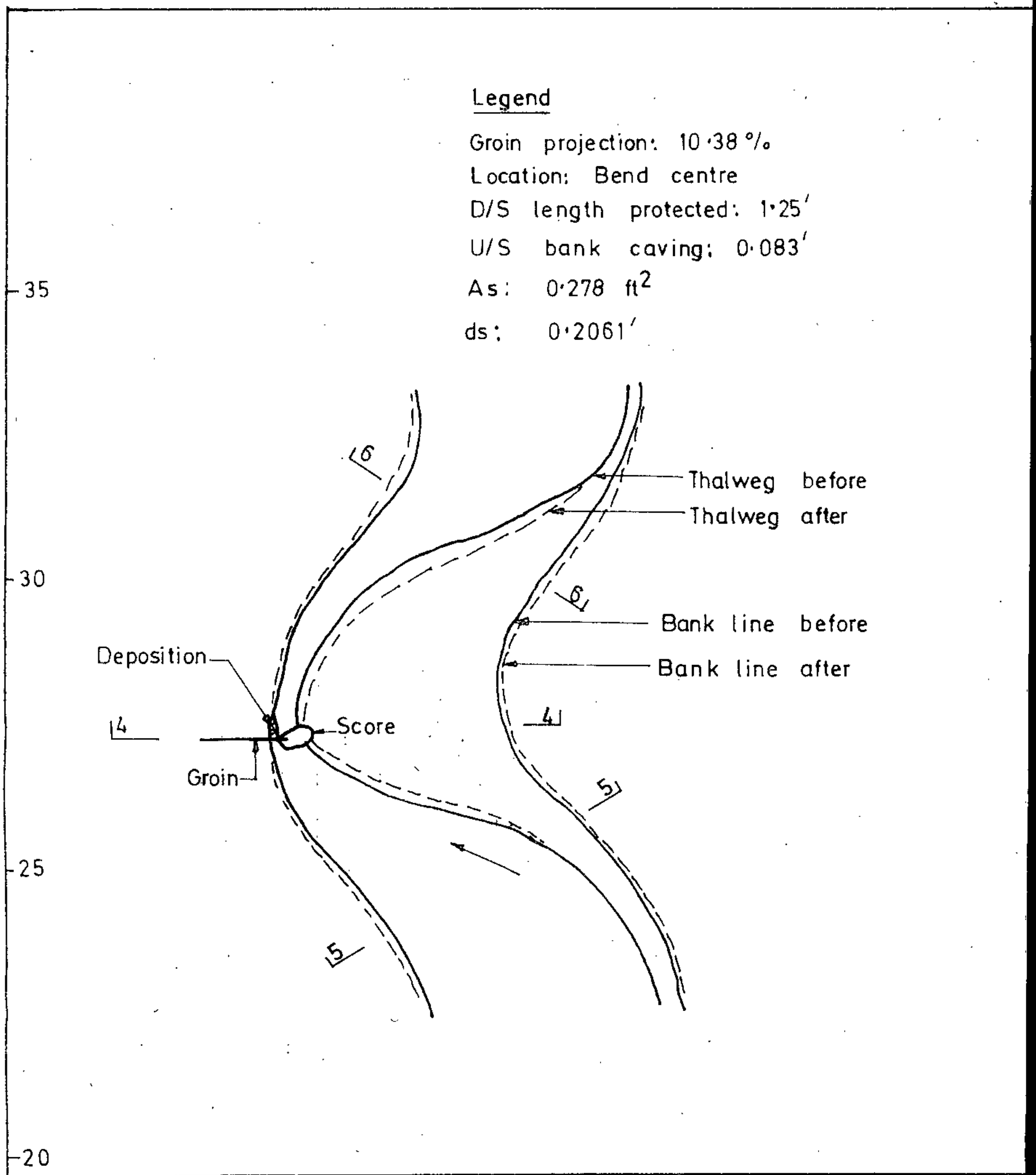


Fig. 4.2 Location of bank line thalweg and deposition for set up 1
Scale: 1:30 Q = 0·03222 cfs

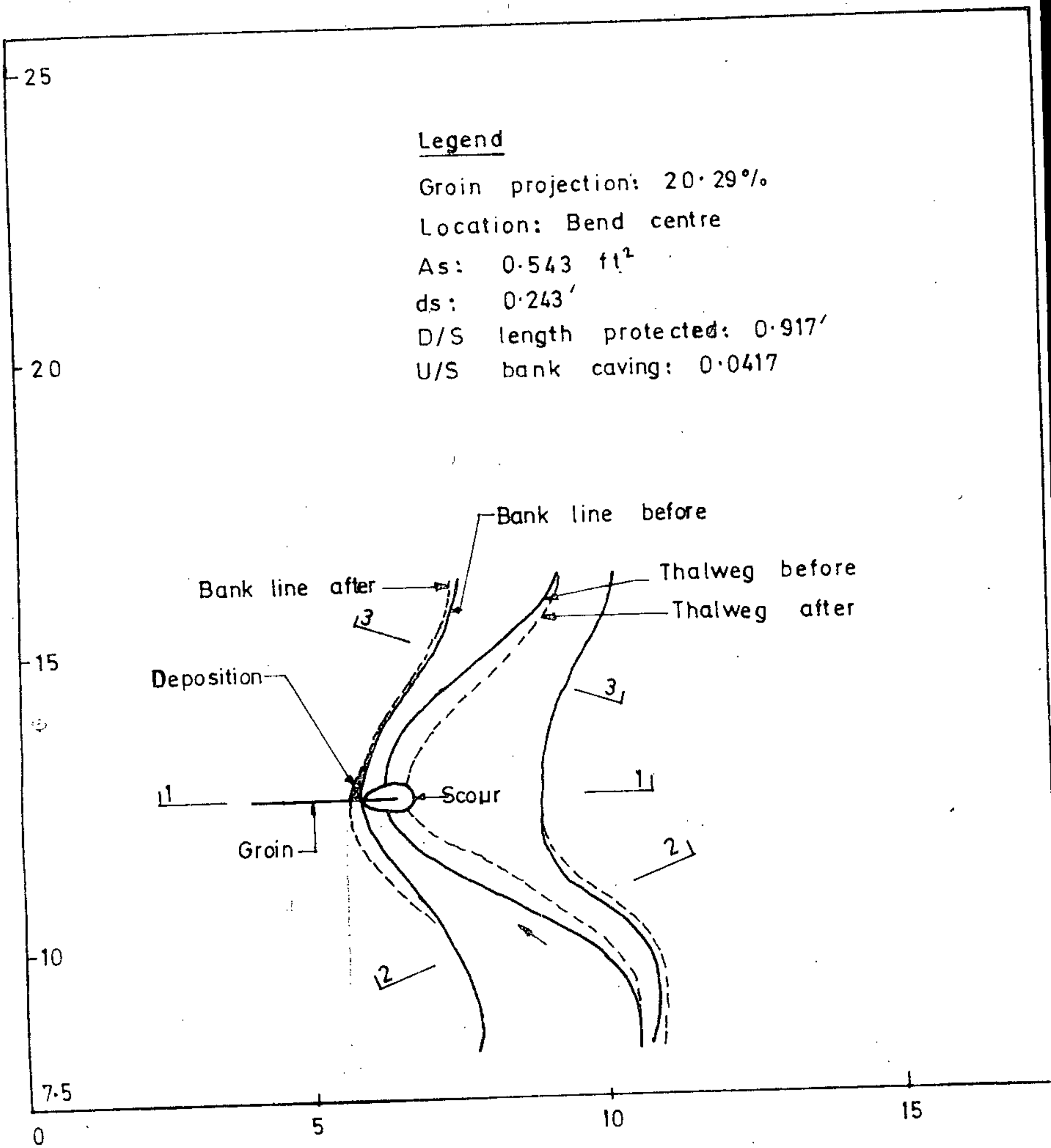


Fig. 4.3 Location of thalweg, bank line and deposition for set up 2
Scale: 1:30, Q = 0·03222 cfs

Legend

Groin projection: 15·69 %

Location: Bend centre

D/S length protected: 1·43′

U/S bank caving: 0·0417′

As: 0·458 ft^2

ds: 0·246

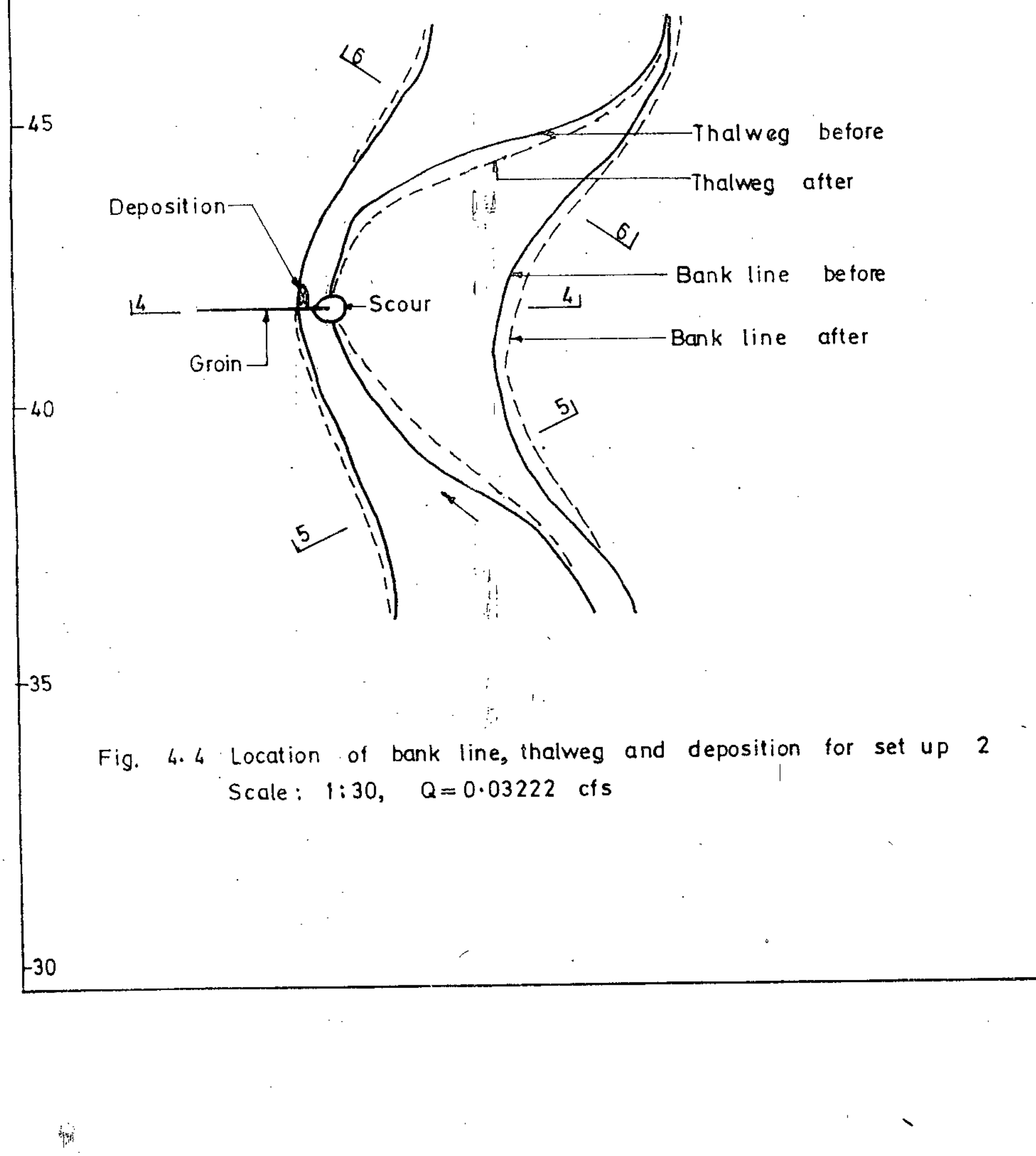


Fig. 4.4 Location of bank line, thalweg and deposition for set up 2
Scale: 1:30, Q = 0·03222 cfs

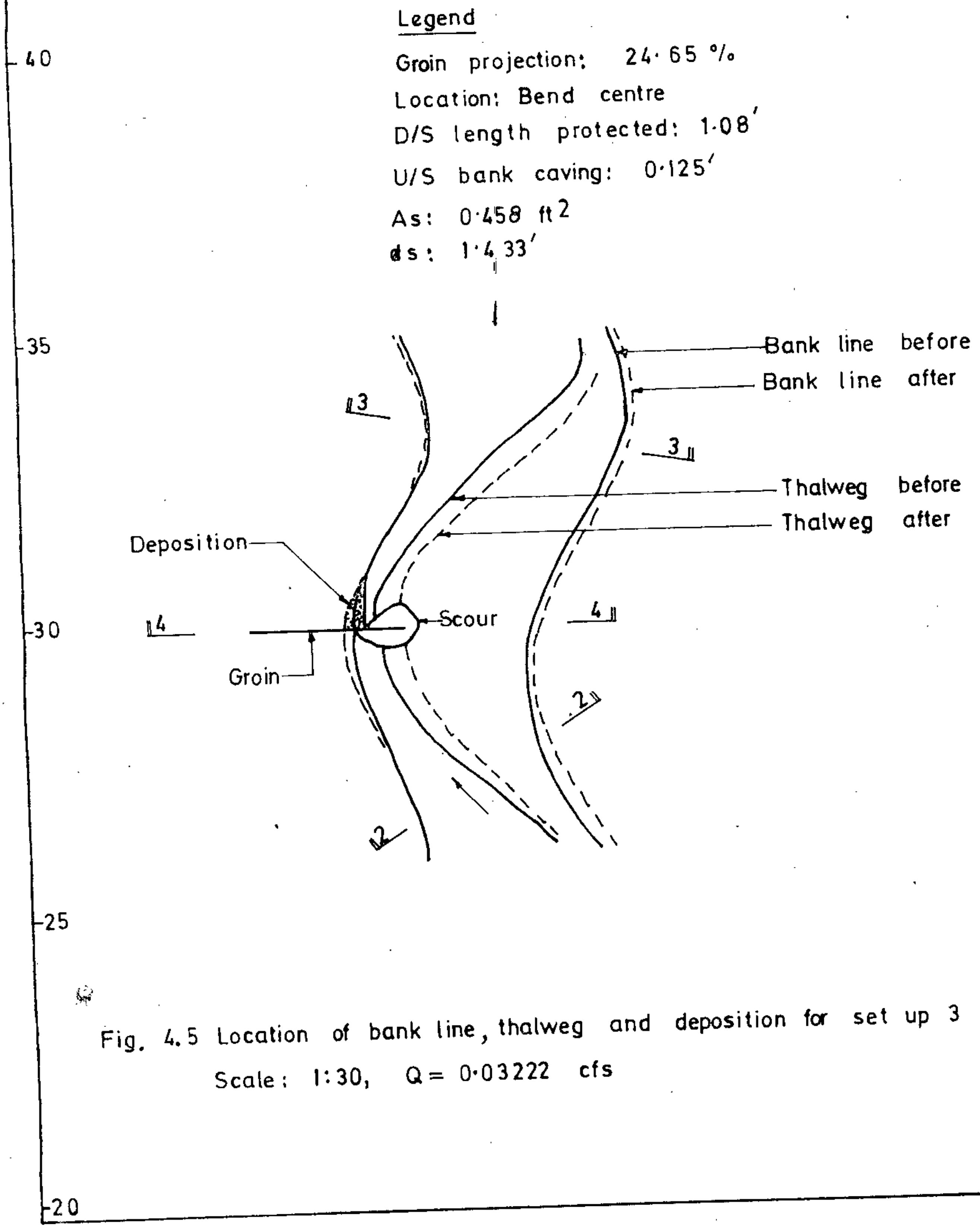


Fig. 4.5 Location of bank line, thalweg and deposition for set up 3

Scale: 1:30, Q = 0·03222 cfs

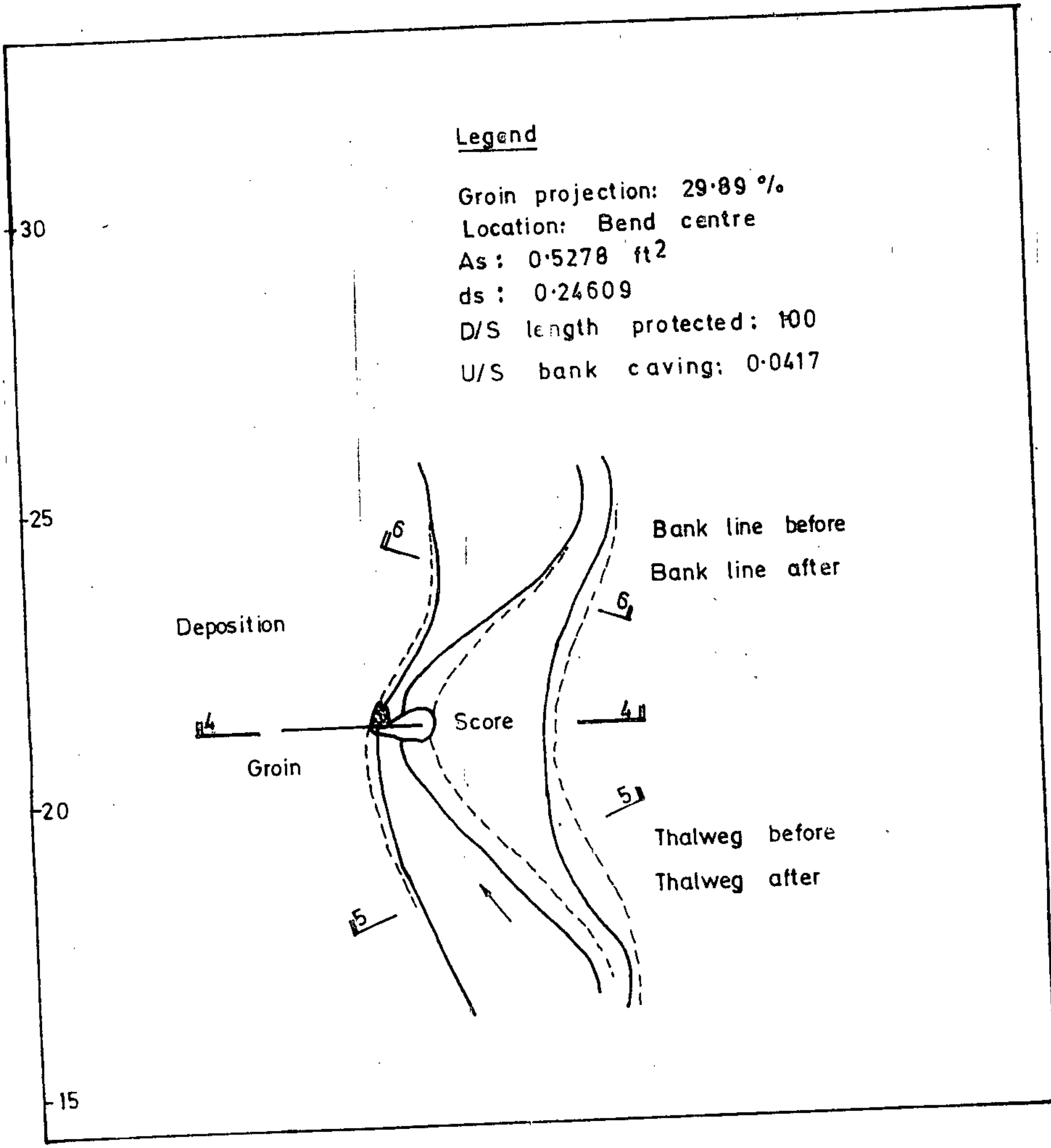


Fig. 4·6 Location of bank line, thalweg and deposition for set up 3
Scale : 1:30, Q = 0·03222 cfs

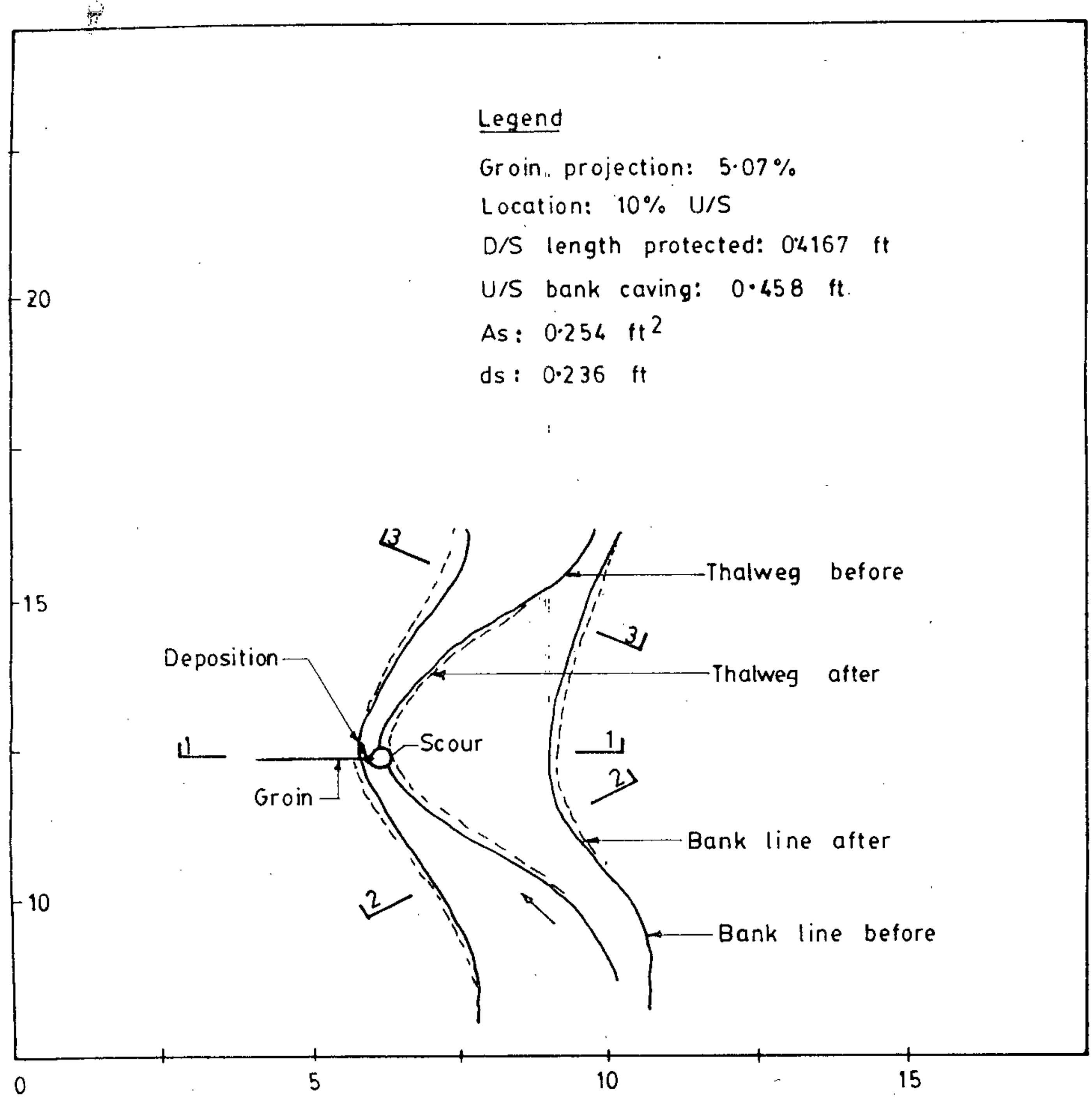


Fig. 4·7 Location of bank line, thalweg and deposition for set up 4
Scale: 1:30, Q = 0·03222 cfs

Legend

Groin projection: 10·42 %

Location: 10 % U/S

D/S length protected: 0·575 ft

U/S bank caving: 0·0833 ft

As: 0·322 ft^2

ds : 0·193 ft

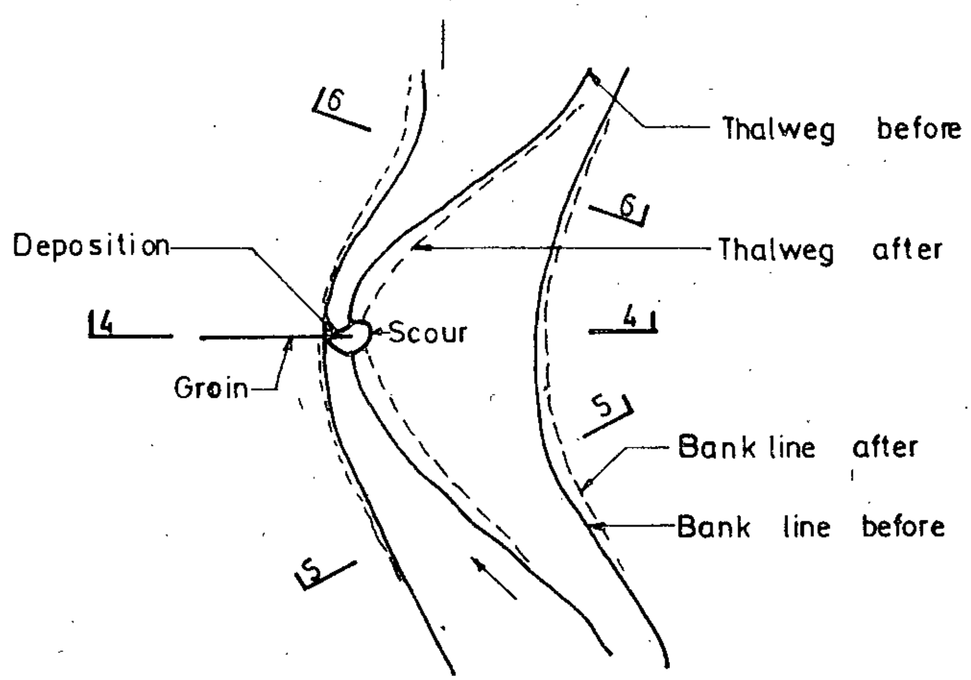


Fig. 4·8 Location of bank line, thalweg and deposition for set up 4
Scale: 1:30 Q = 0·03222 cfs

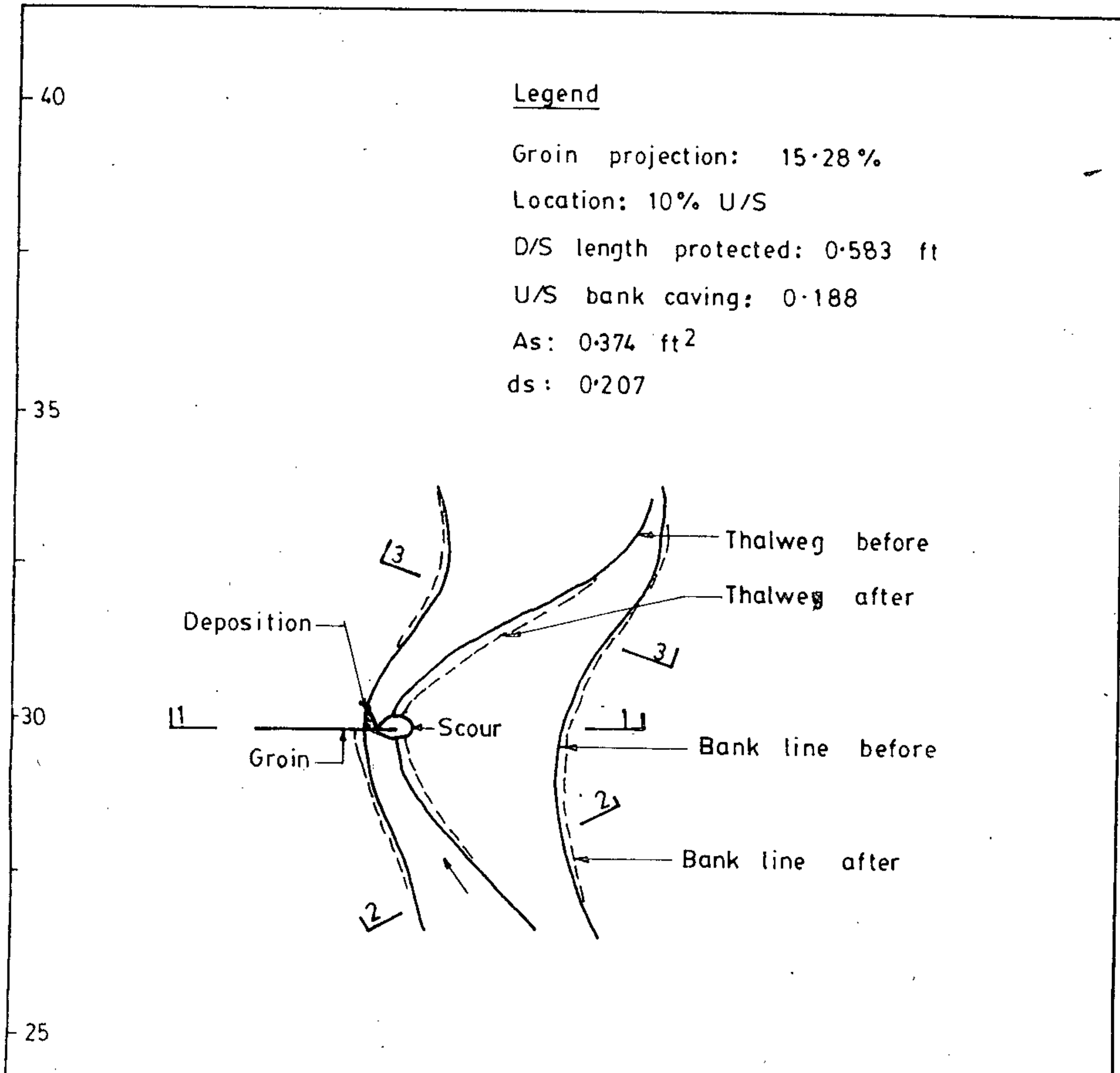


Fig. 4·9 Location of thalweg, bank line and deposition for set up 5
Scale: 1:30, Q = 0·03222 cfs

Legend

Groin projection: 19·87 %

Location 10% U/S

D/S length protected: 0·67 ft

U/S bank caving: 0·0417 ft

As: 0·434 ft^2

ds: 0·236

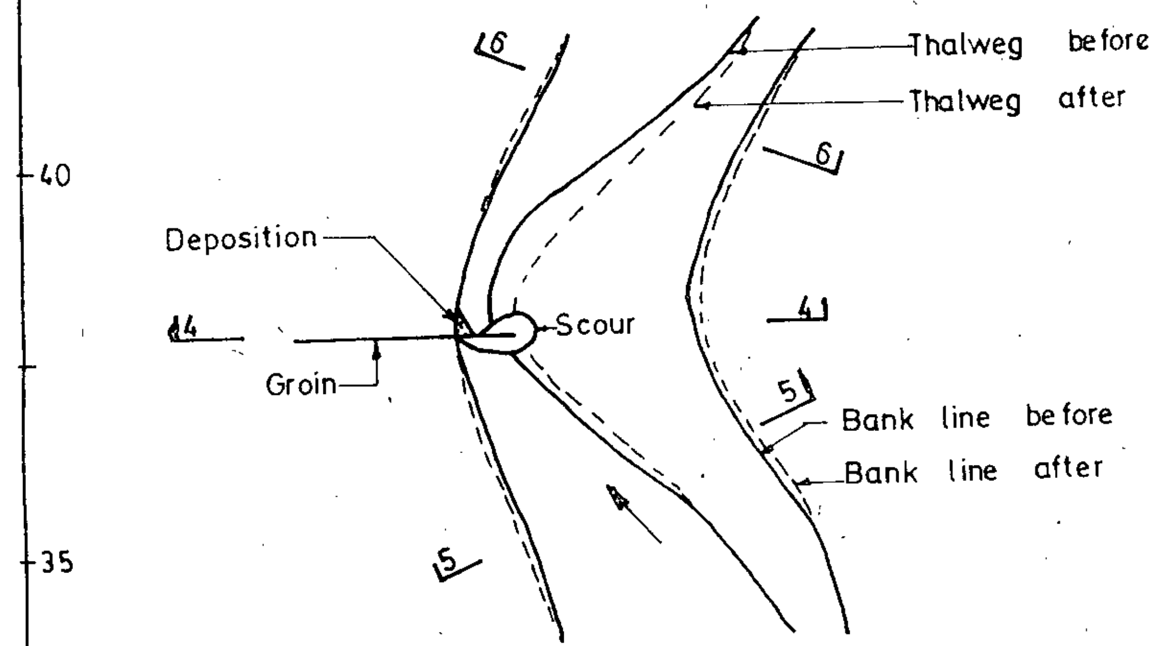
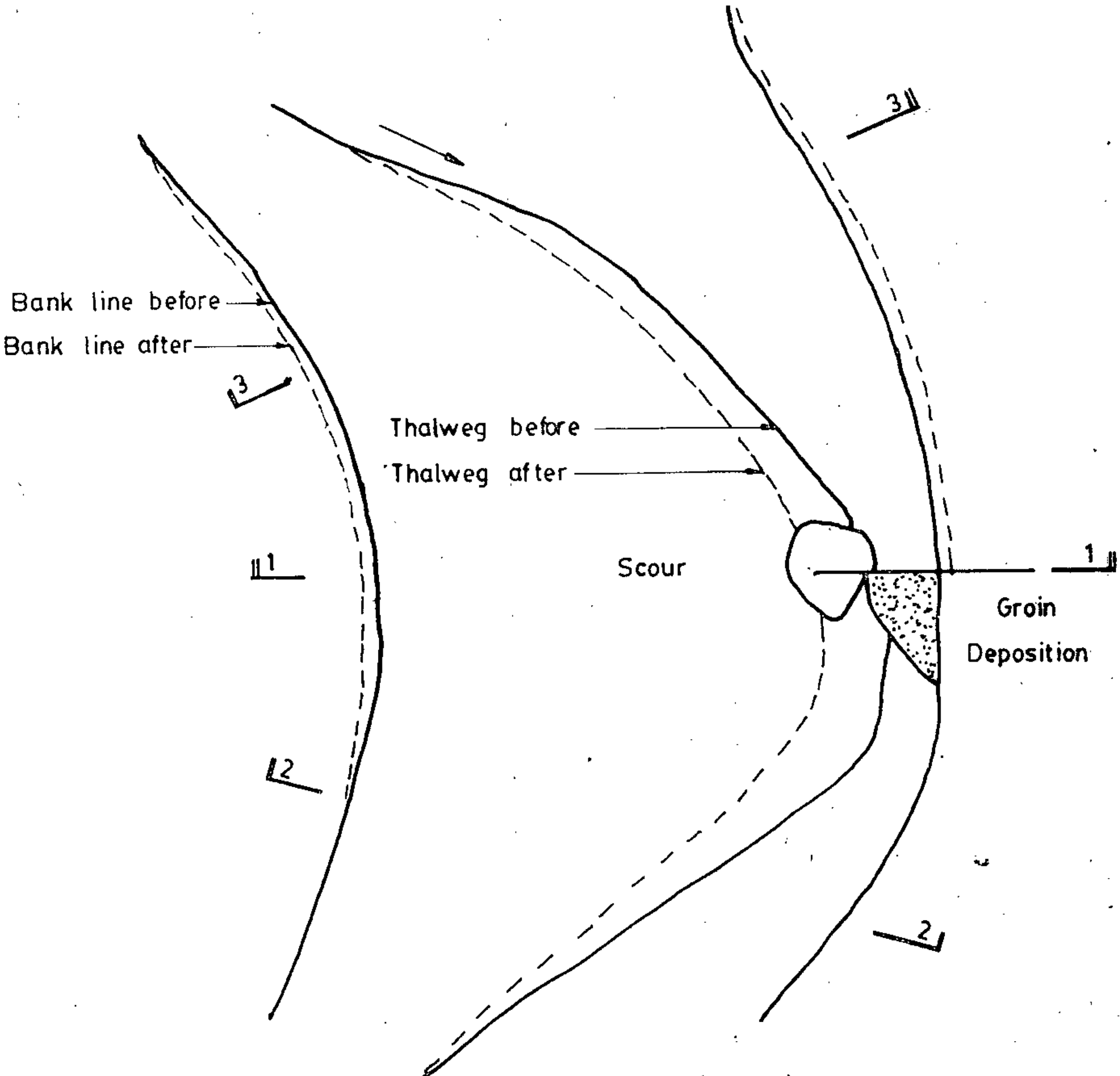


Fig. 4.10 Location of bank line, thalweg and deposition for set up 5
Scale: 1:30, Q = 0·03222 cfs



Legend

Groin projection: 25 %

Location: 10% U/S

D/S length protected: 0·813 ft

As: 0·461 ft^2

ds: 0·246 ft

Fig. 4.11 Location of bank line, thalweg and deposition for set up 6
Scale: 1:12 Q = 0·03222 cfs

Legend

Groin projection: 30·13 %

Location: 10 % U/S

D/S Length protected: 0·521 ft

U/S bank caving = 0

As: 0·575 ft^2

ds : 0·246 ft

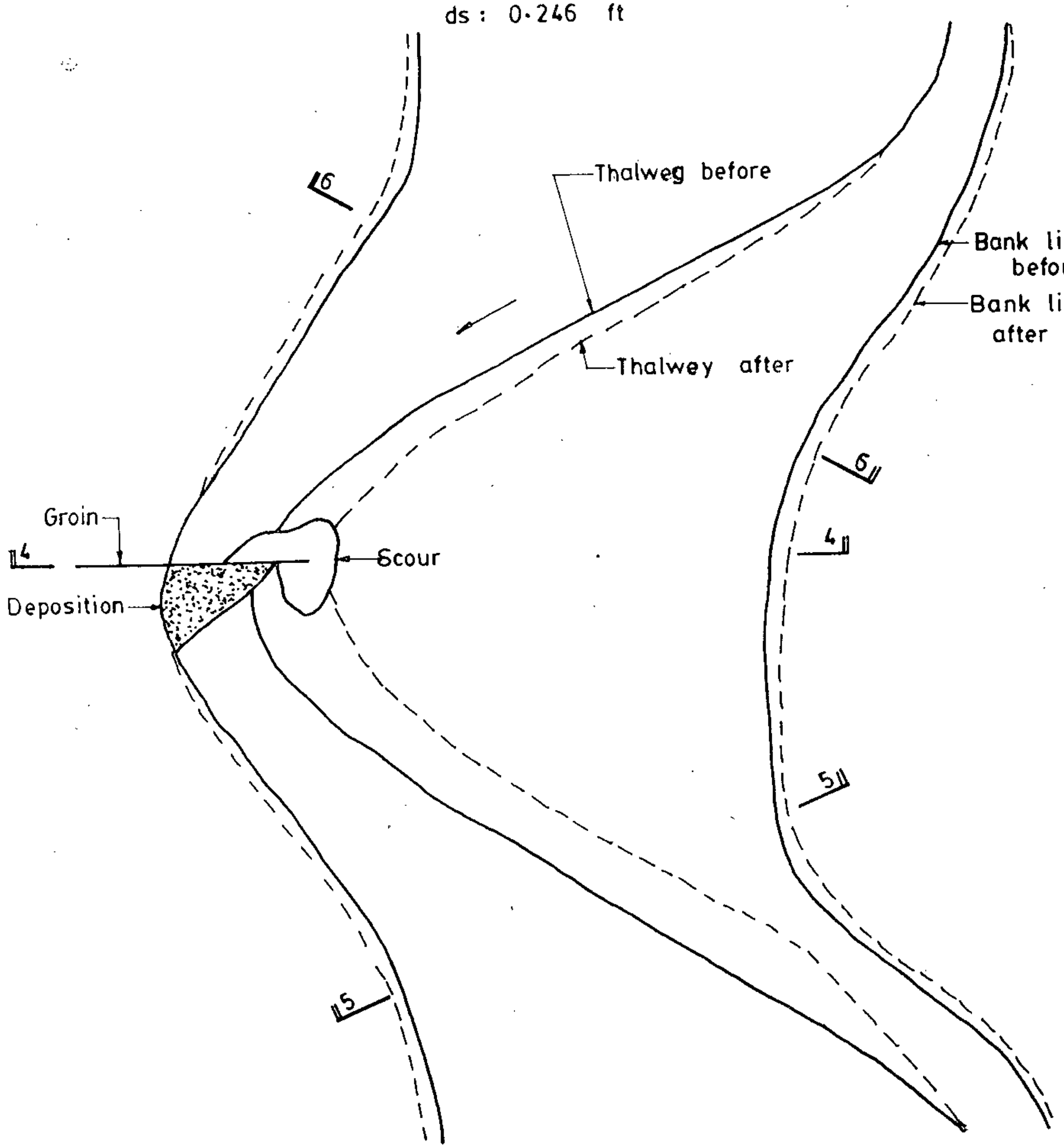


Fig. 4·12 Location of bank line thalwey and deposition for set up 6
Scale : 1:12, Q = 0·03222 cfs

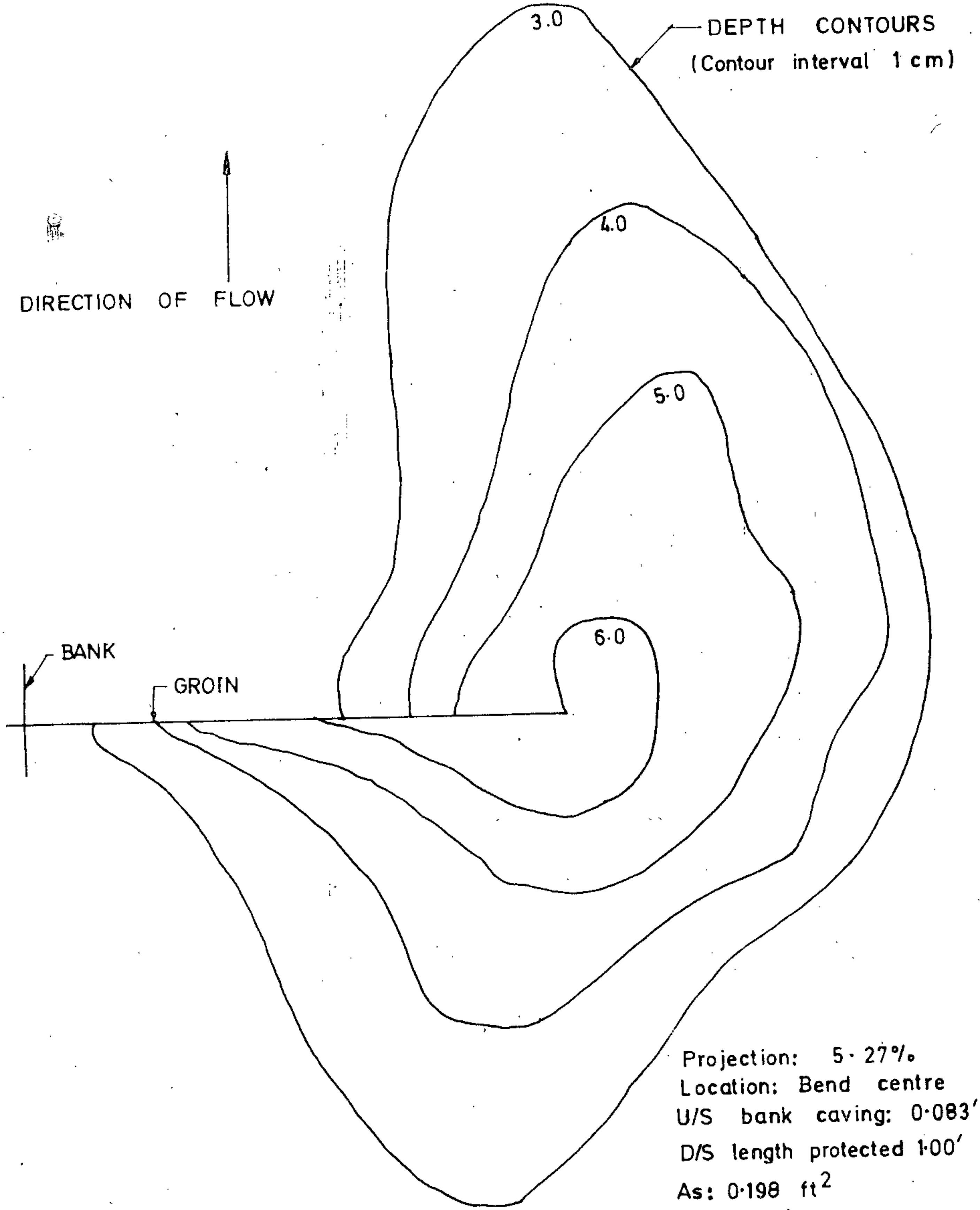
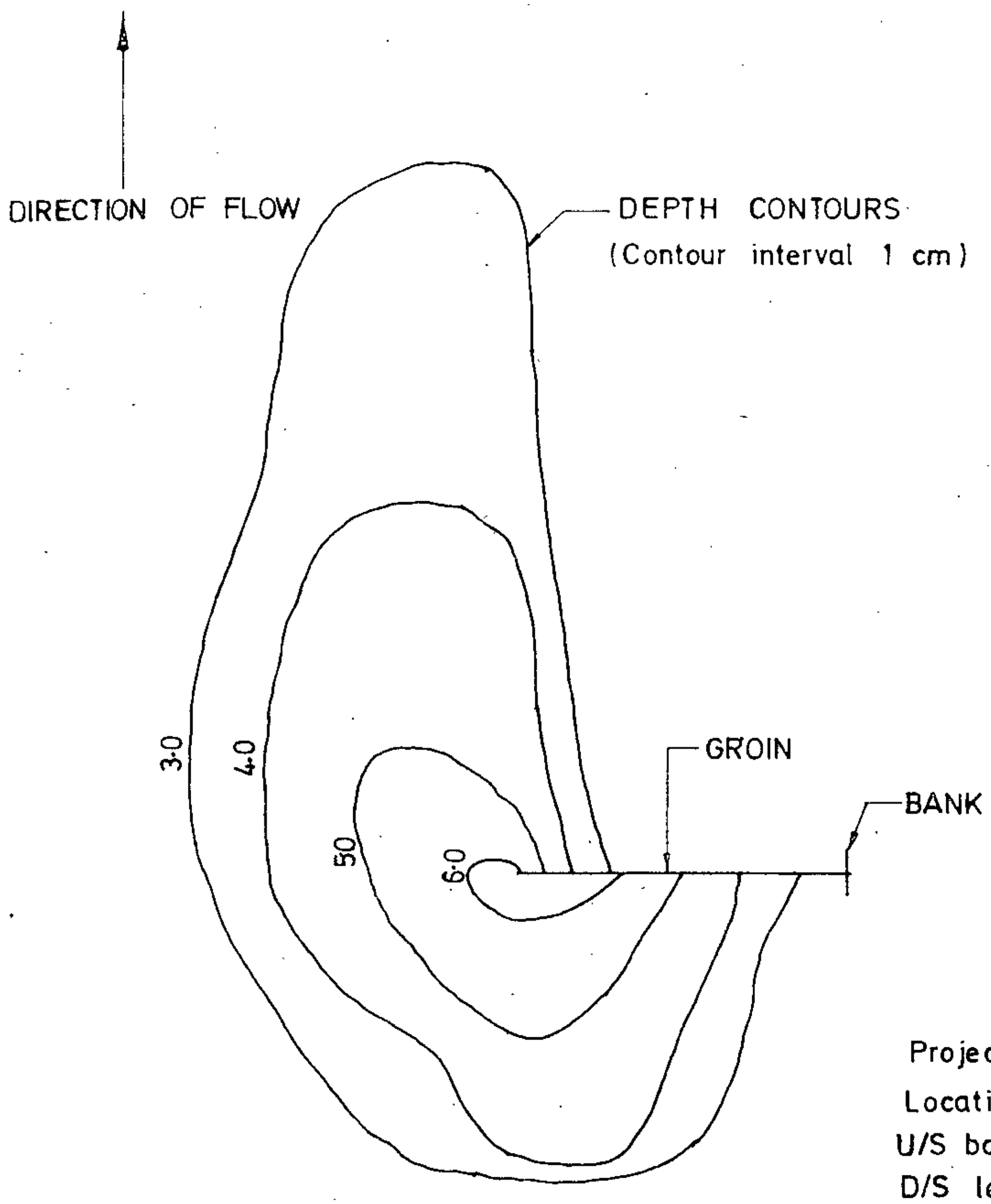
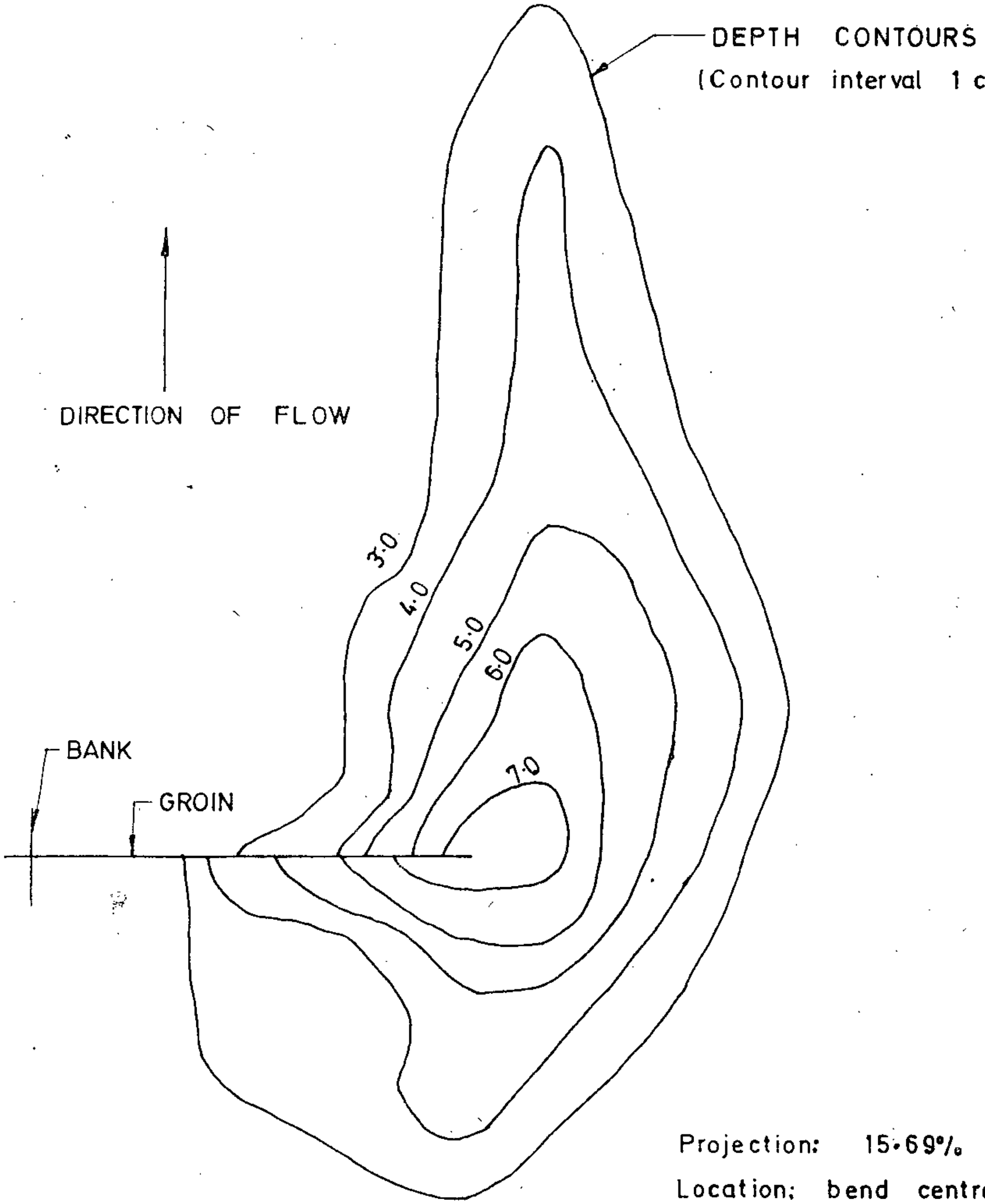


FIG. 4.13 SCOUR PATTERN AROUND GROIN, SET 1
SCALE: 1:1, (Q = 0·03222 cfs)



Projection: 10·38 %
Location: Bend centre
U/S bank caving: 0·083′
D/S length protected: 1·25′
As: 0·278 ft^2
ds: 0·206′

FIG. 4·14 SCOUR PATTERN AROUND GROIN, SET 1
SCALE: 1:2, (Q= 0·03222 cfs)



Projection: 15·69%

Location: bend centre

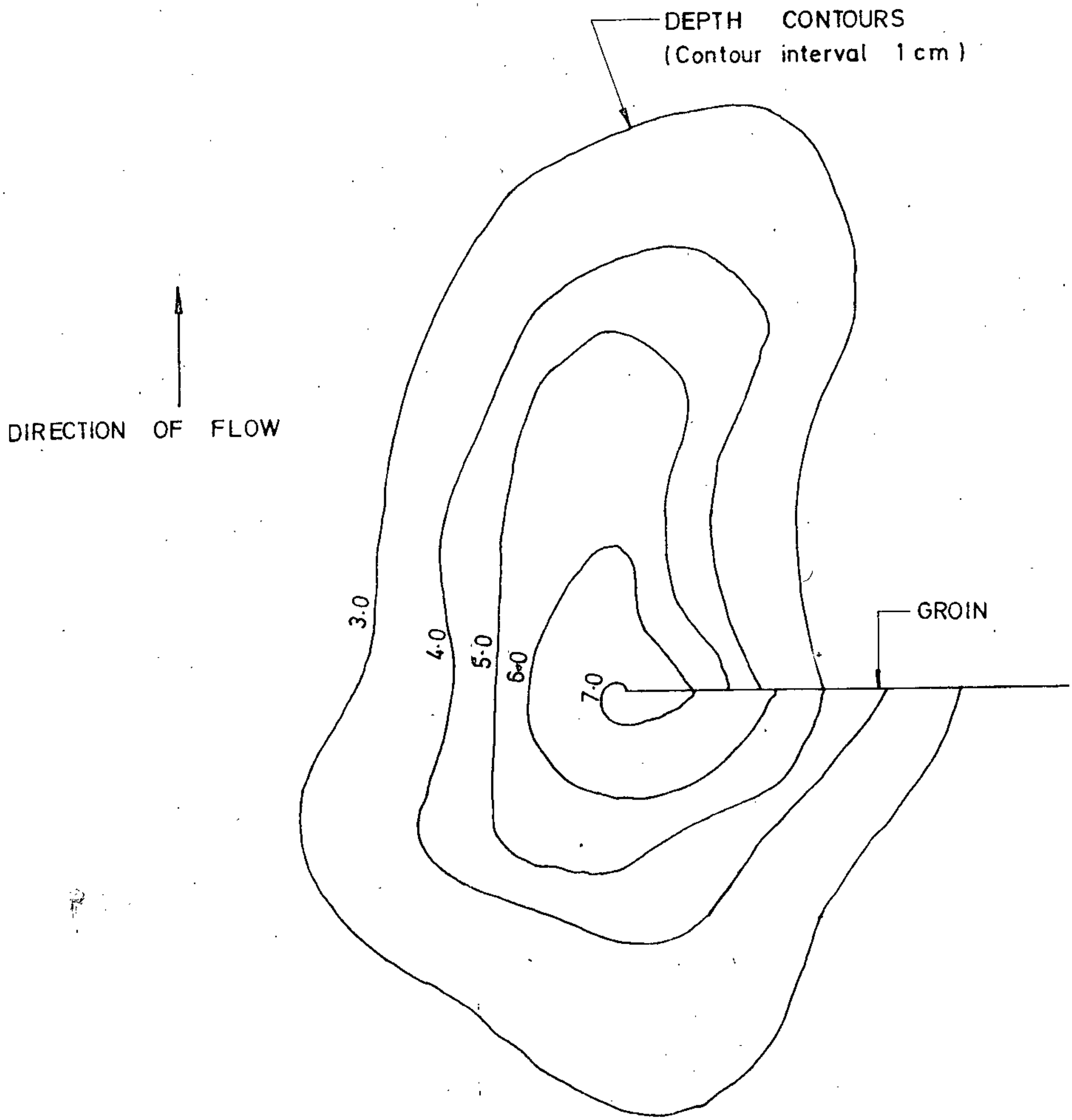
U/S bank caving: 0·0417′

D/S length protected 1·433′

As: 0·458 ft^2

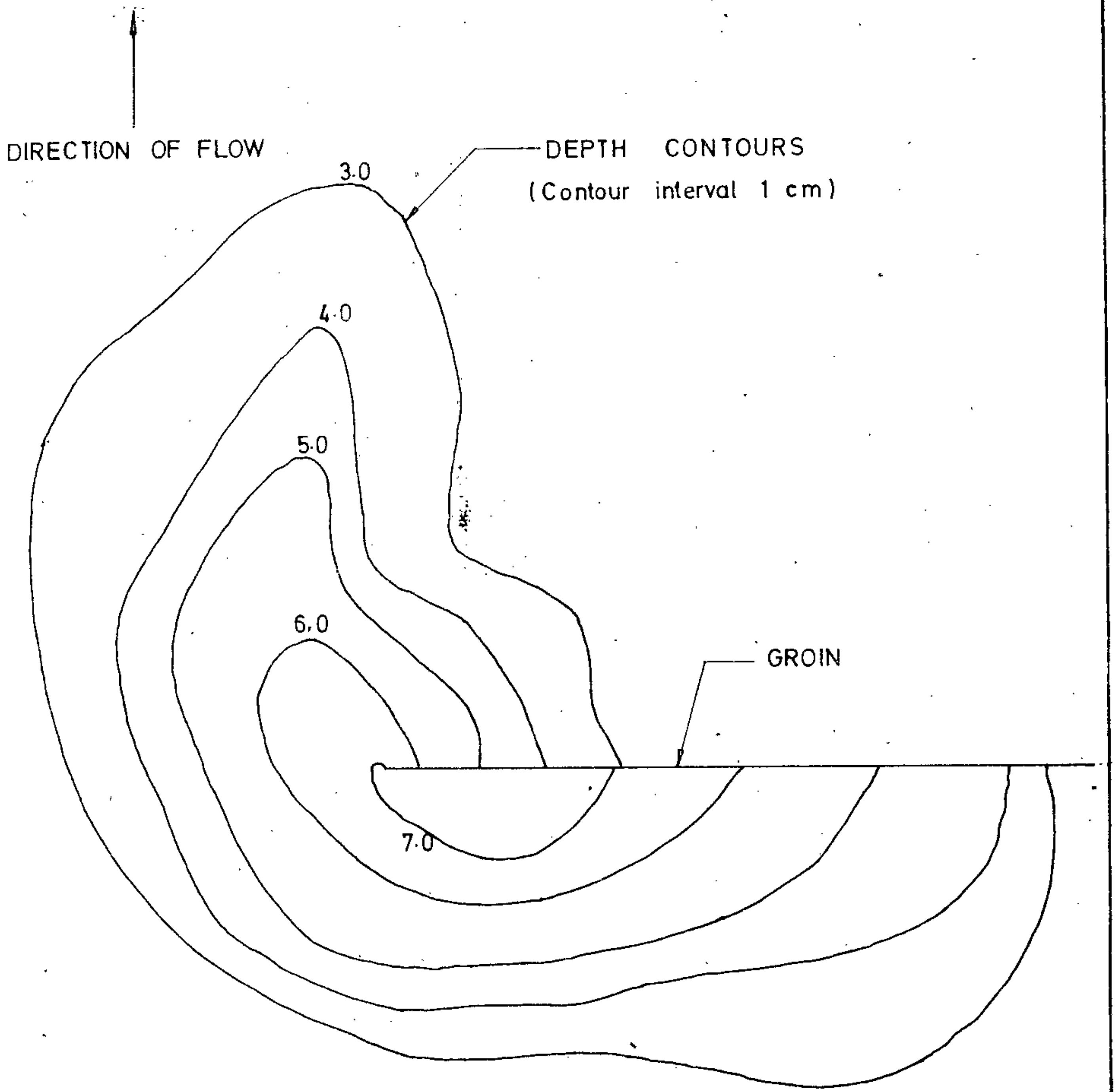
ds: 0·246′

FIG. 4.15 SCOUR PATTERN AROUND GROIN, SET 2
SCALE: 1:2 (Q = 0·03222 cfs)



Projection: 20·29 %
Location: bend centre
U/S bank caving: 0·0417′
D/S length protected: 0·917′
As: 0·543 ft^2
ds: 0·243′

FIG. 4·16 SCOUR PATTERN AROUND GROIN, SET 2
SCALE: 1:2 (Q = 0·03222 cfs)



Projection: 24·65%

Location: Bend centre

U/S bank caving: 0·125′

D/S length protect: 1·083′

As: 0·581 ft^2

ds: 0·249′

FIG. 4.17 SCOUR PATTERN AROUND GROIN, SET 3
SCALE: 1:2, (Q= 0·03222 cfs)

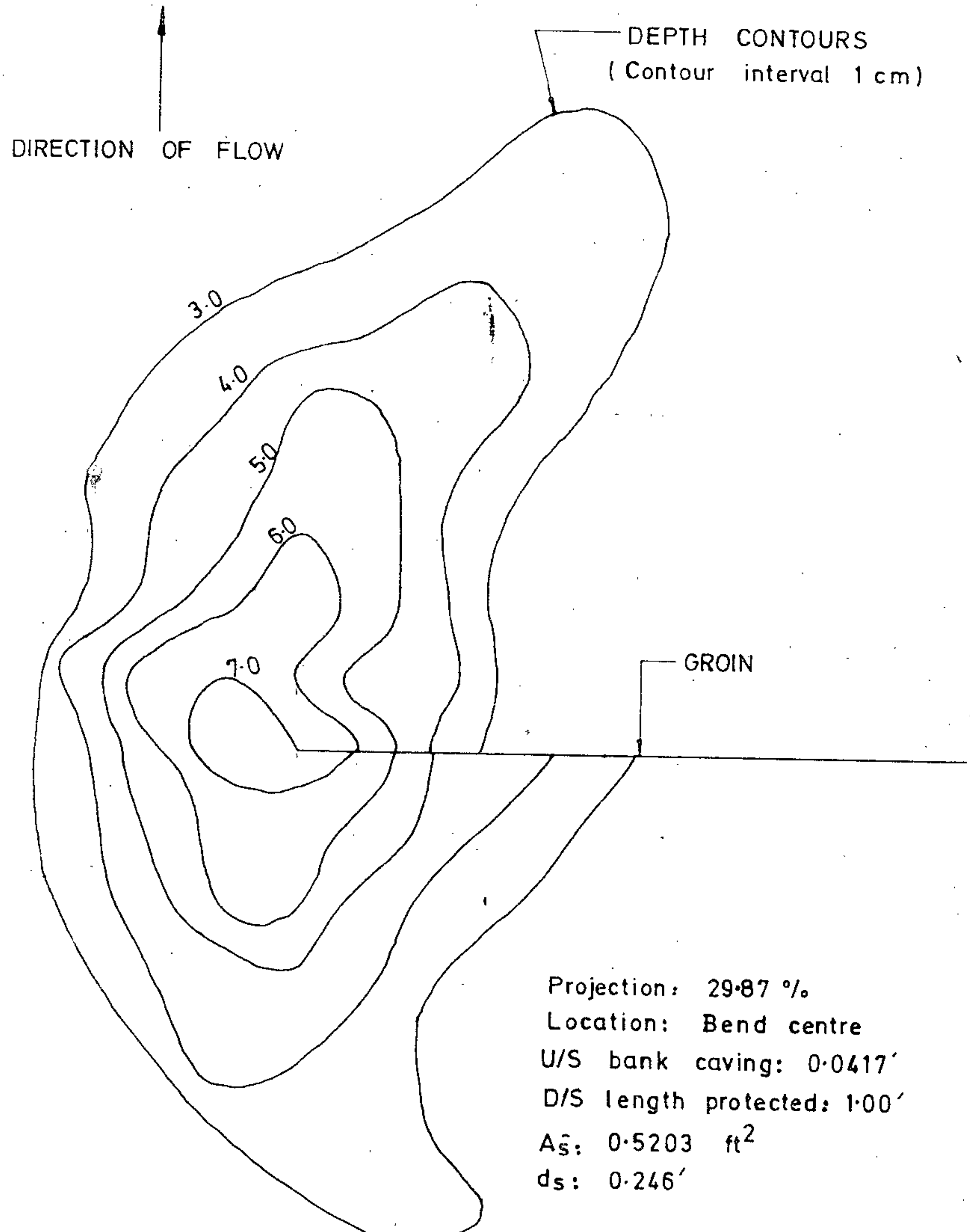
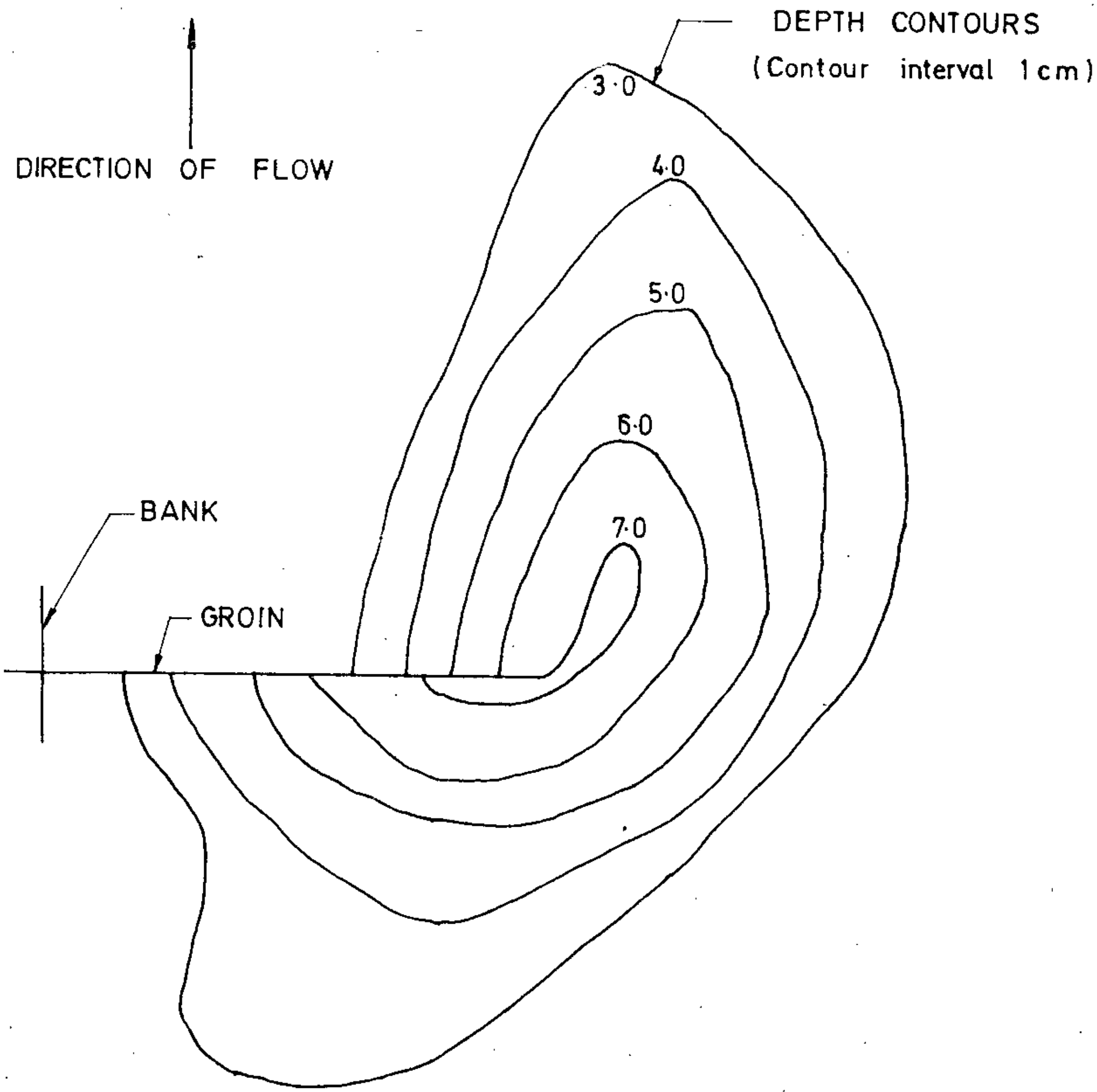


FIG. 4.18 SCOUR PATTERN AROUND GROIN, SET 3
SCALE: 1:2, (Q = 0 03222 cfs)



Projection: 5·07%

Location: 10% U/S from bend centre

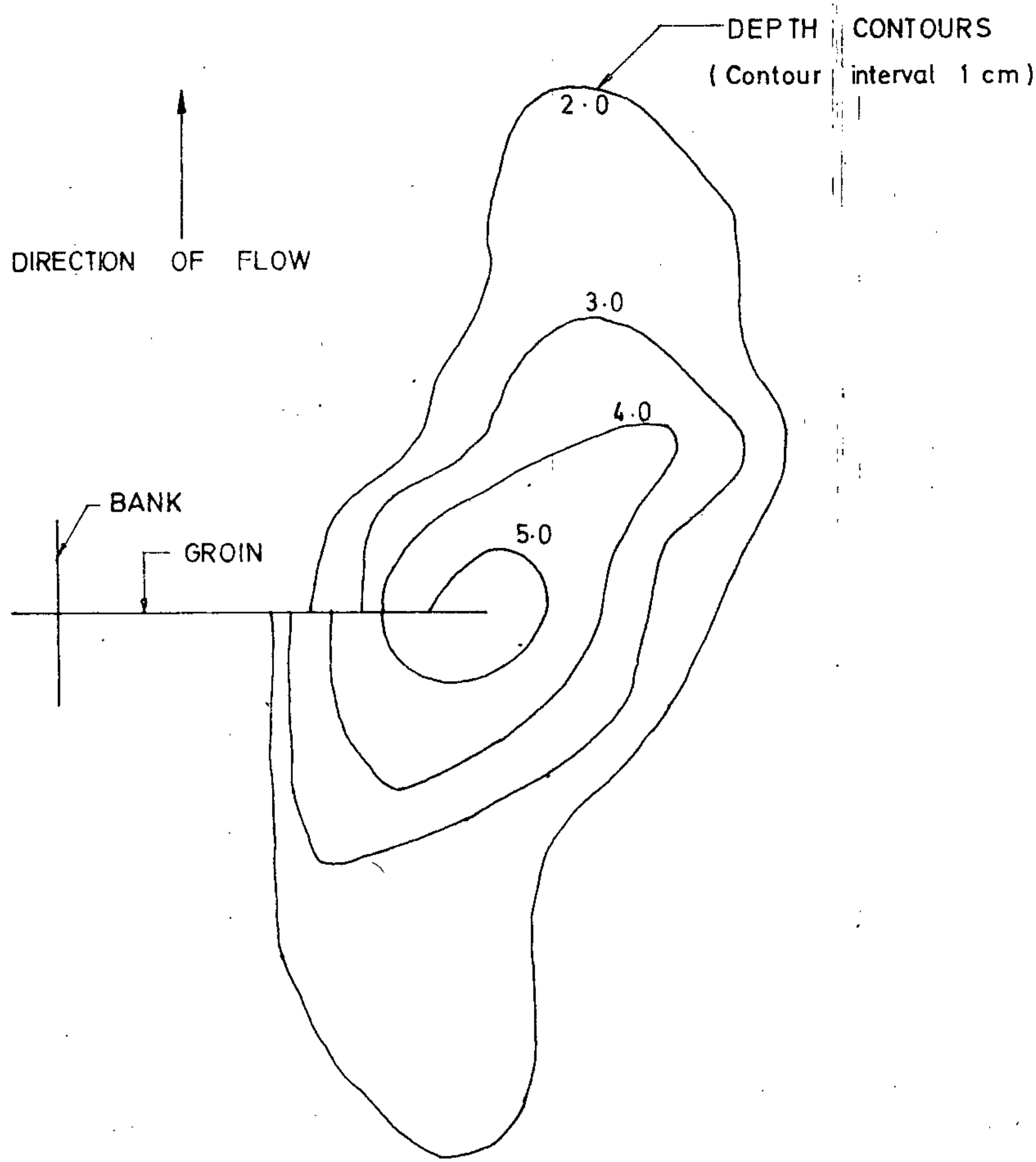
U/S bank caving: 0·458′

D/S length protected: 0·417′

As: 0·254 ft^2

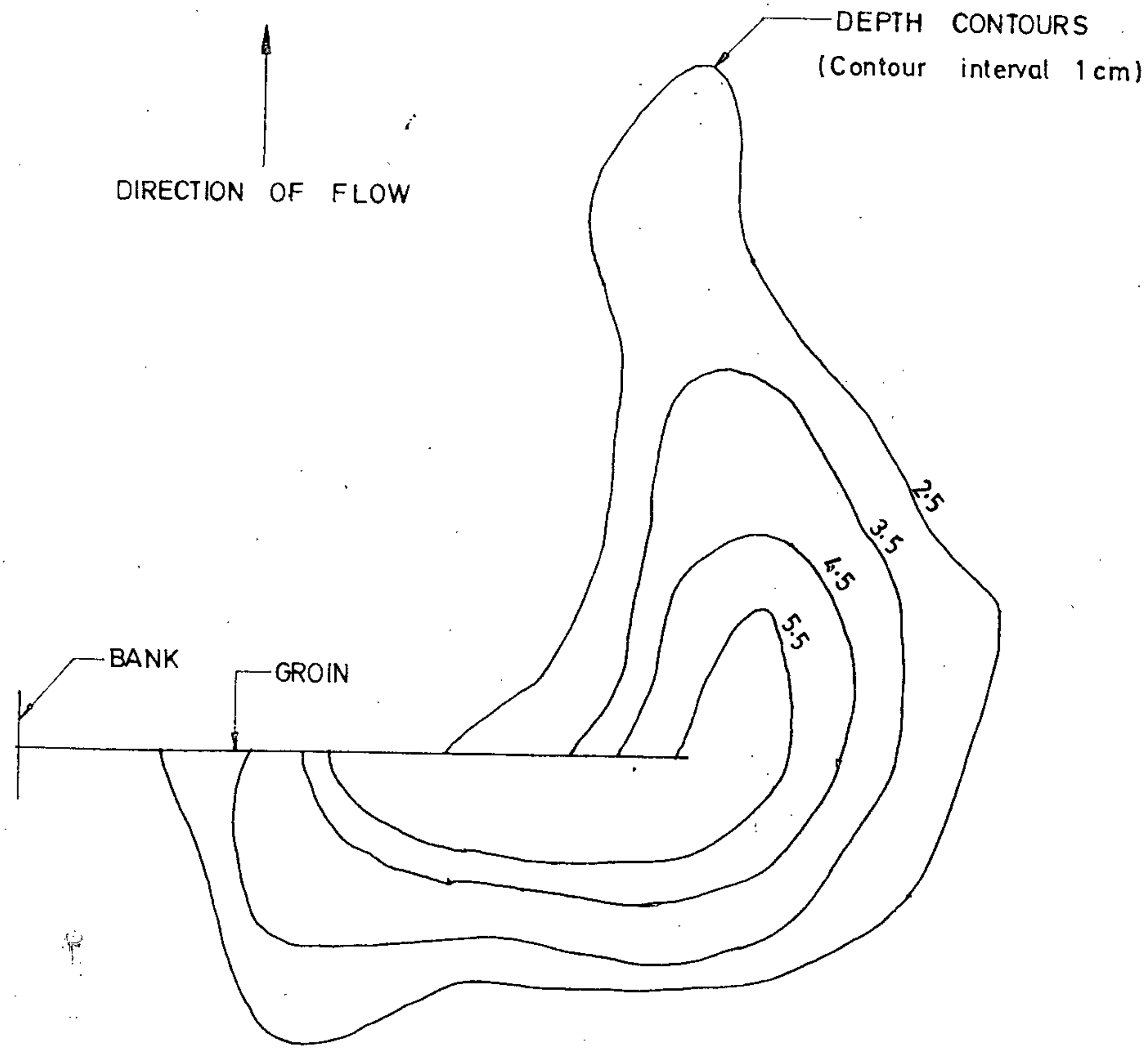
ds: 0·234′

FIG. 4.19 SCOUR PATTERN AROUND GROIN, SET 4
SCALE: 1:2, (Q = 0·03222 cfs)



Projection: 10·42%
Location: 10% U/S from bend centre
U/S bank caving: 0·083′
D/S length protected 0575′
As; 0·322 ft^2
bs; 0·194′

FIG. 4.20 SCOUR PATTERN AROUND GROIN, SET 4
SCALE: 1:2, (Q = 0·03222 cfs)



Projection: 15 28%
Location: 10% U/S from bend centre
U/S bank caving: 0·409′
D/S length protected: 1·273′
As: 0·374 ft^2
ds: 0·207′

FIG. 4.21 SCOUR PATTERN AROUND GROIN, SET 5
SCALE: 1:2, (Q= 0·03222 cfs)

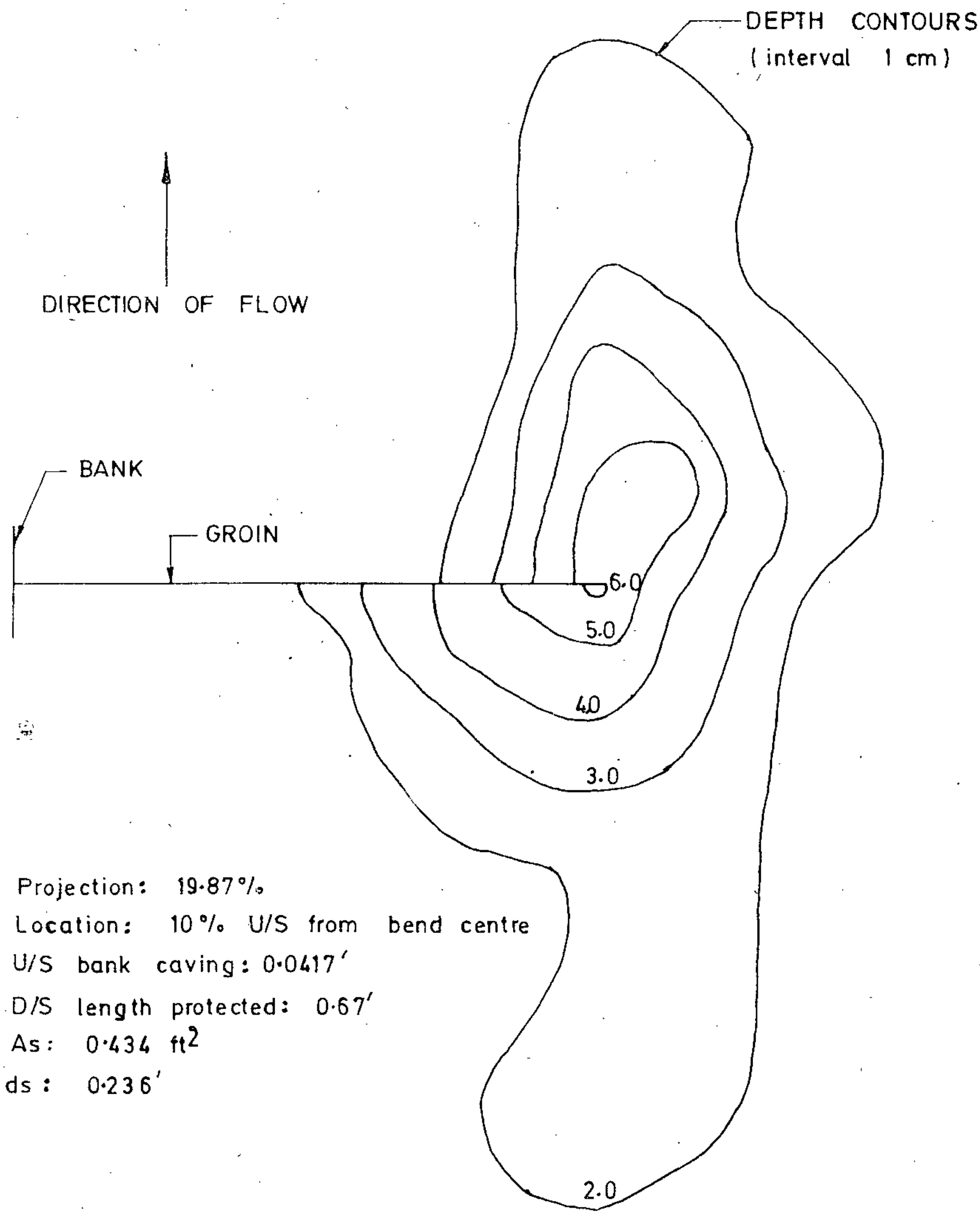


FIG. 4.22 SCOUR PATTERN AROUND GROIN, SET 5
SCALE: 1:2, (Q = 0.03222 cfs)

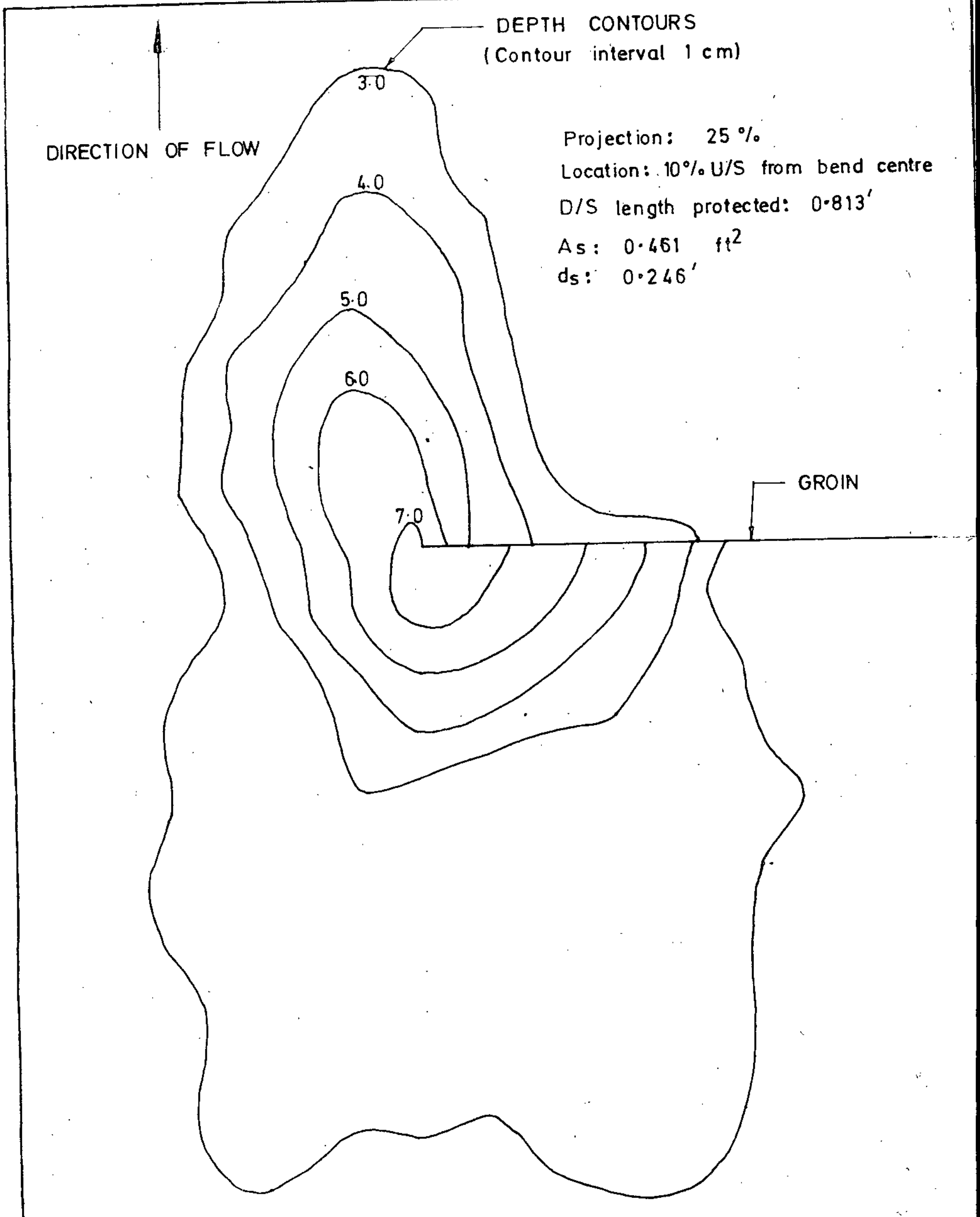
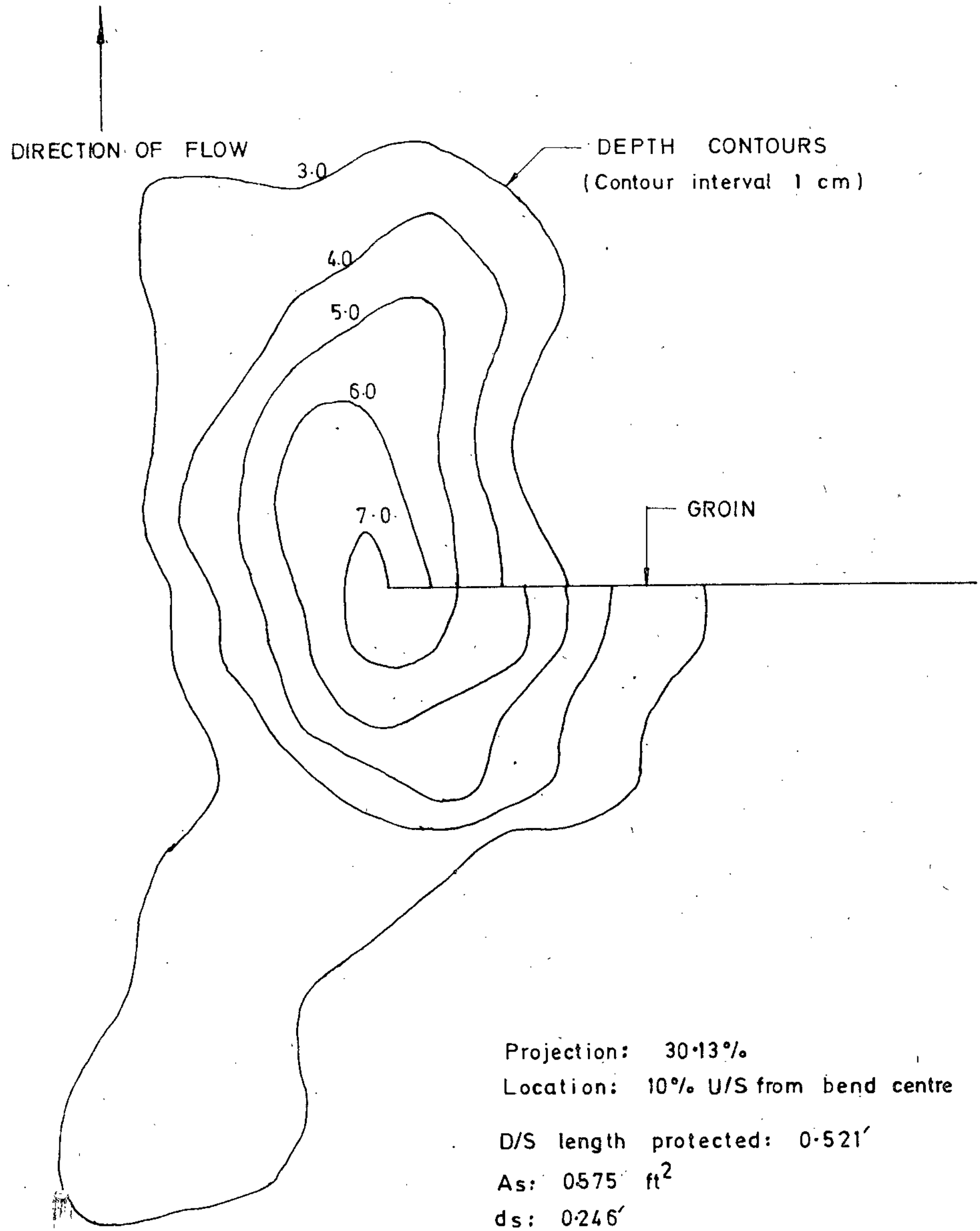


FIG. 4.23 SCOUR PATTERN AROUND GROIN, SET 6
SCALE: 1:2, (Q = 0·0322 cfs)



Projection: 30·13%
Location: 10% U/S from bend centre
D/S length protected: 0·521′
As: 0·575 ft^2
ds: 0·246′

FIG. 4.24 SCOUR PATTERN AROUND GROIN, SET 6
SCALE: 1:2 (Q = 0·03222 cfs)

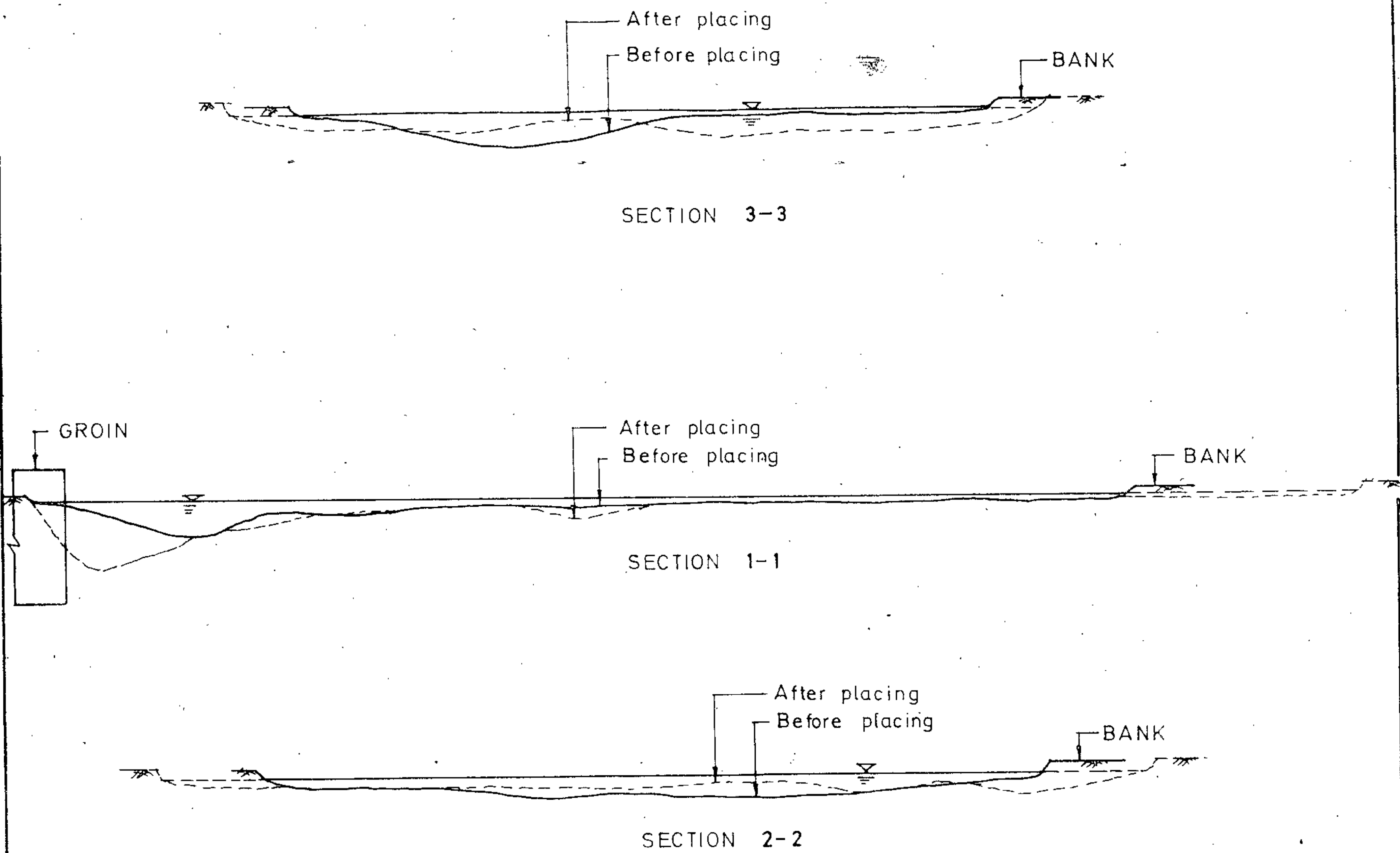


FIG. 4·25 VARIATION OF CROSS SECTION BEFORE AND AFTER PLACEMENT OF GROIN, SETUP 1
(SCALE: 1:5) (Q - 0·03222 cfs)

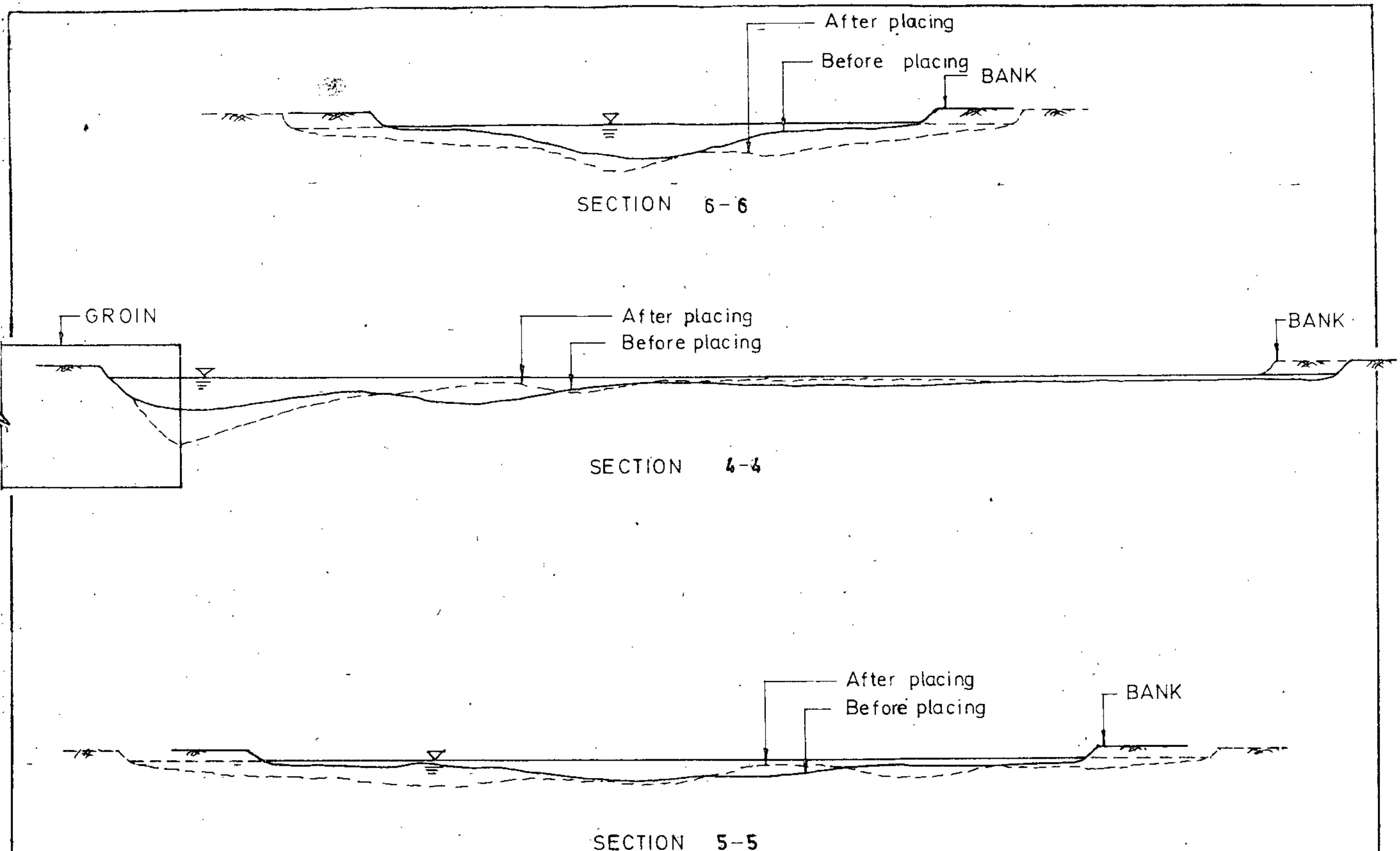


FIG. 4.26 VARIATION OF CROSS-SECTION BEFORE AND AFTER PLACEMENT OF GROIN, SET UP 1
(SCALE: 1:5) (Q = 0·03222 cfs)

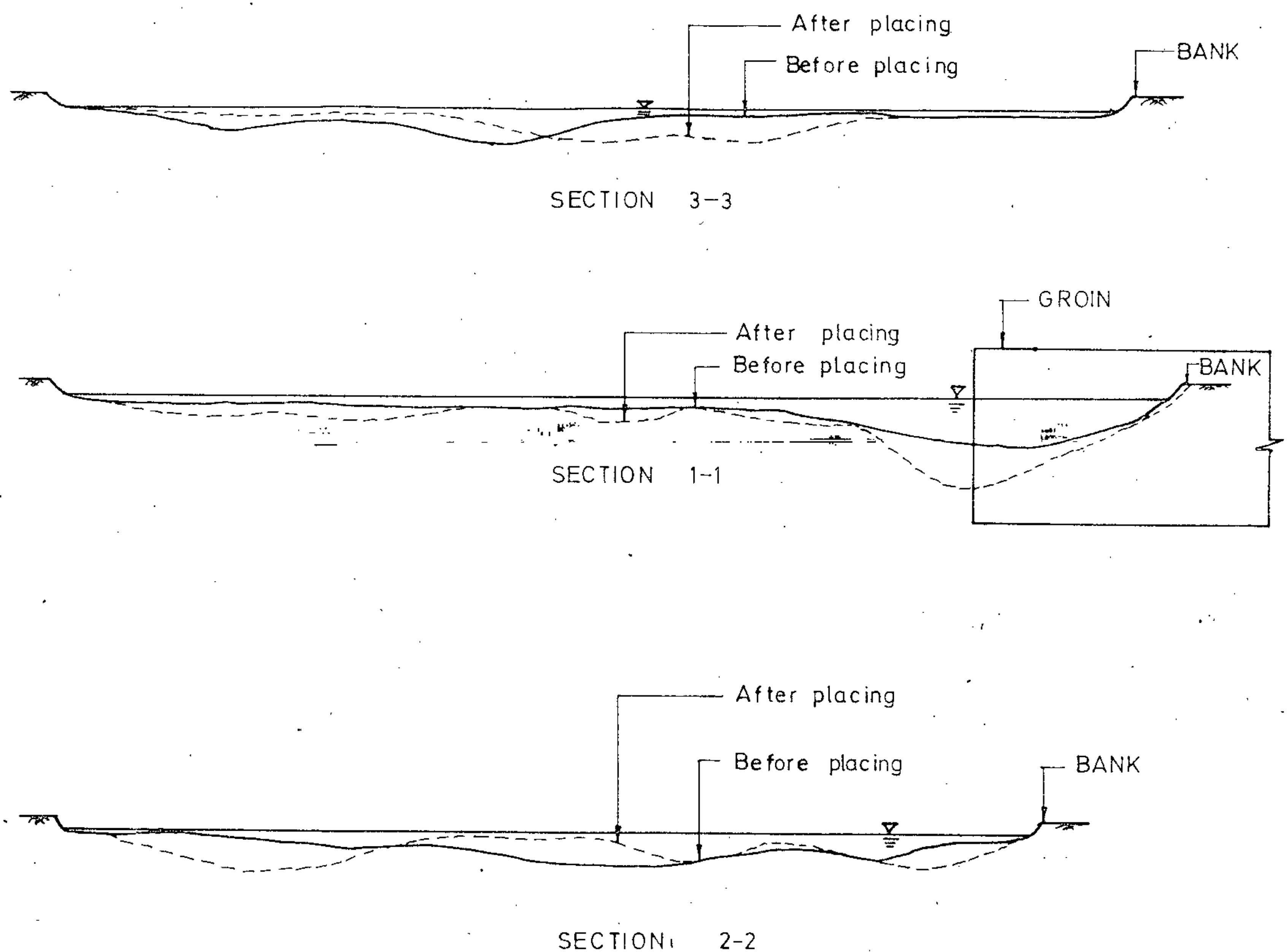


FIG. 4.27 VARIATION OF CROSS-SECTION BEFORE AND AFTER PLACEMENT OF GROIN, SETUP 2 (SCALE: 1:5) (Q = 0·03222 cfs)

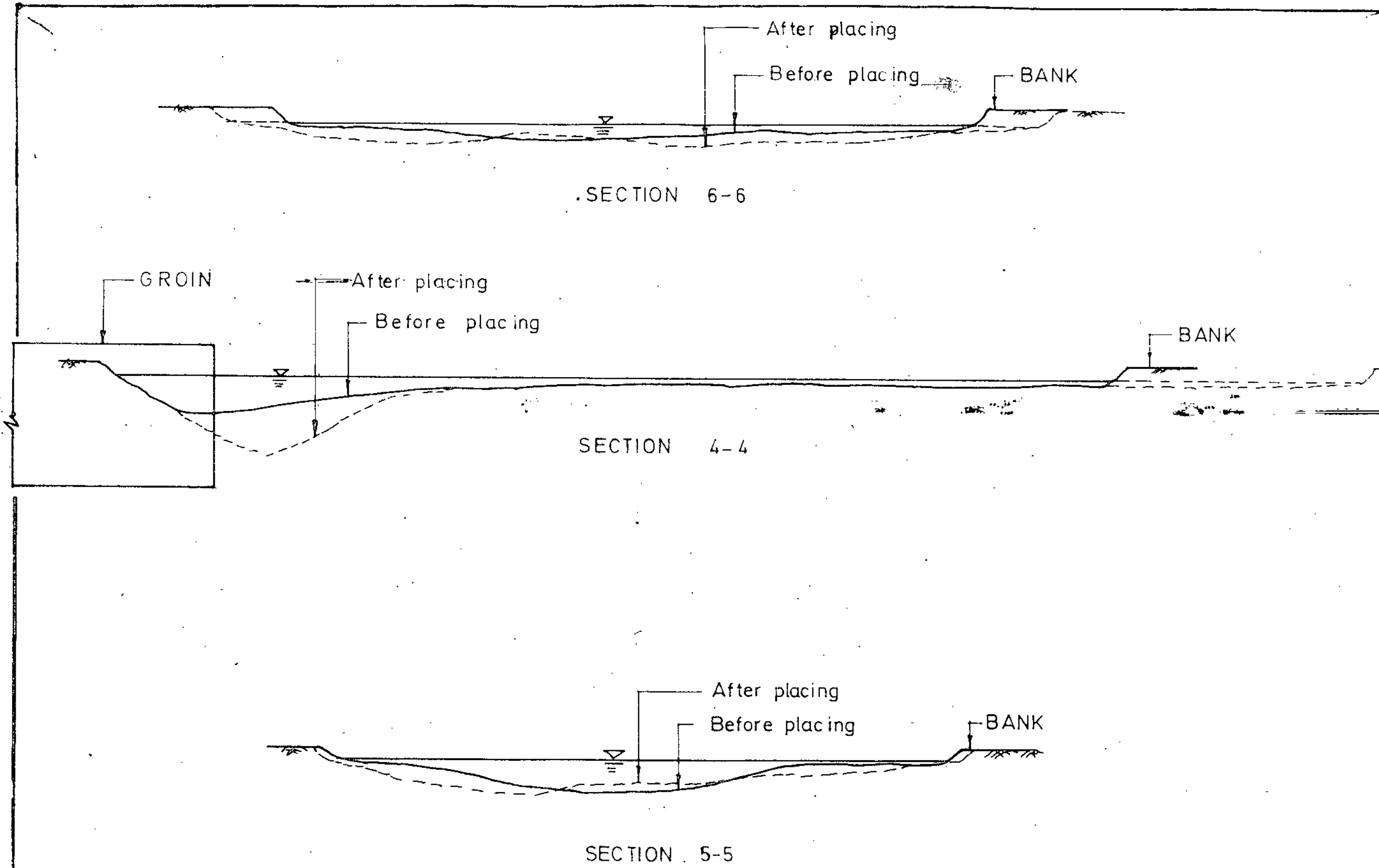


FIG. 4.28 VARIATION OF CROSS SECTION BEFORE AND AFTER PLACEMENT OF GROIN, SETUP 2

(SCALE: 1:5) (Q = 0·03222 cfs)

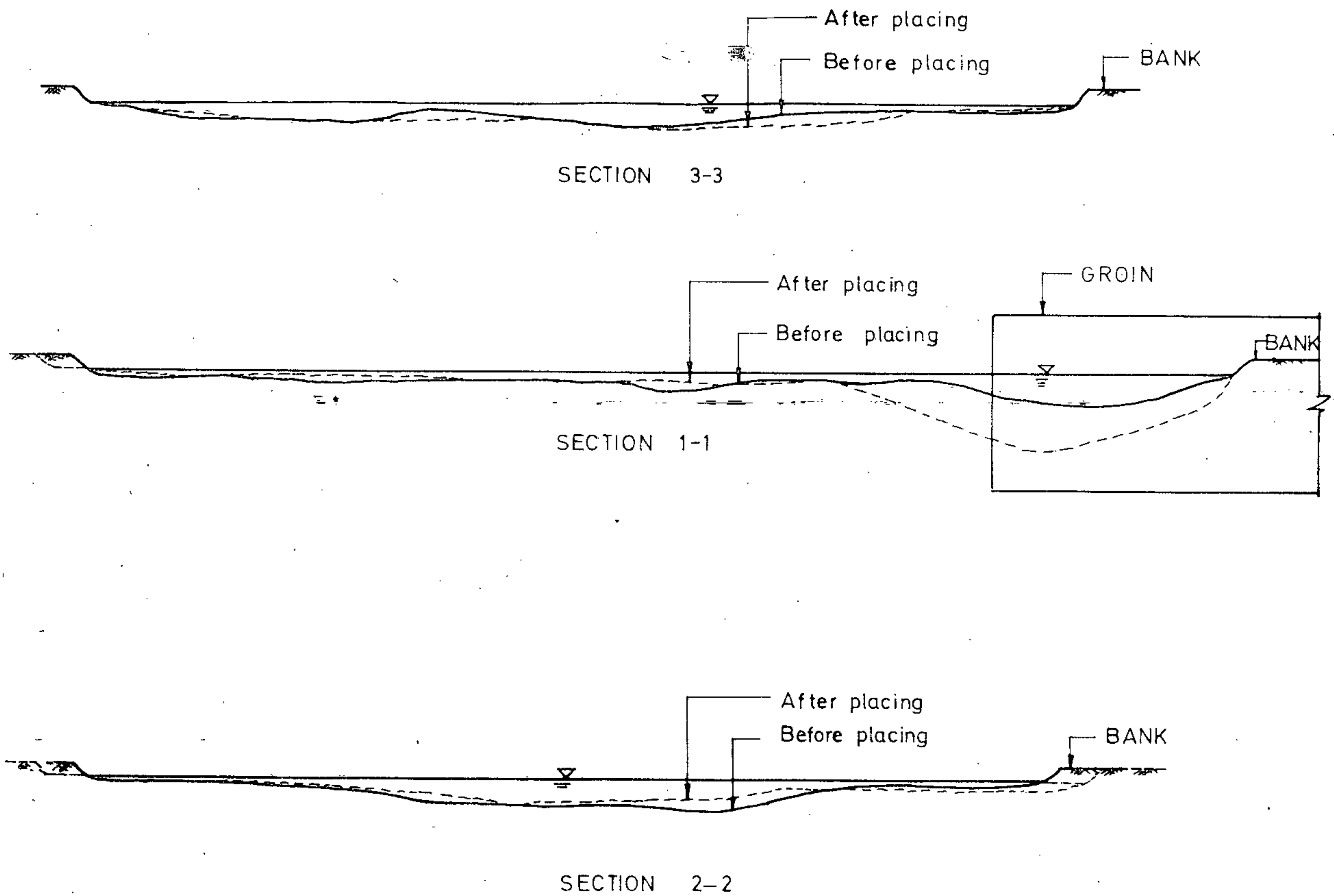


FIG. 4.29 VARIATION OF CROSS SECTION BEFORF AND AFTER PLACEMENT OF GROIN, SETUP 3 (SCALE: 1:5) (Q= 0·03222 cfs)

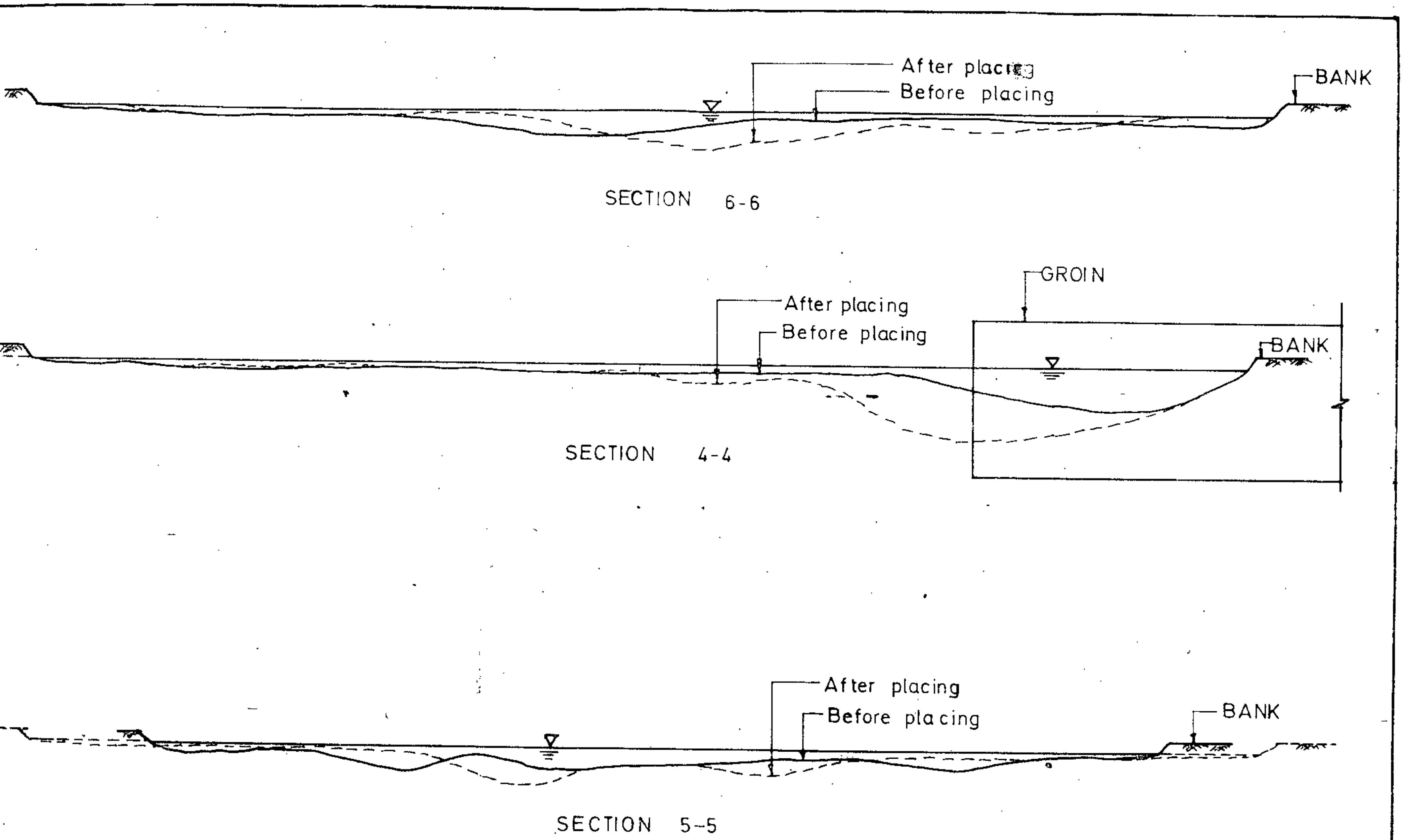


FIG. 4·30 VARIATION OF CROSS-SECTION BEFORE AND AFTER PLACEMENT OF GROIN SETUP 3
(SCALE: 1:5) (Q = 0·03222 cfs)

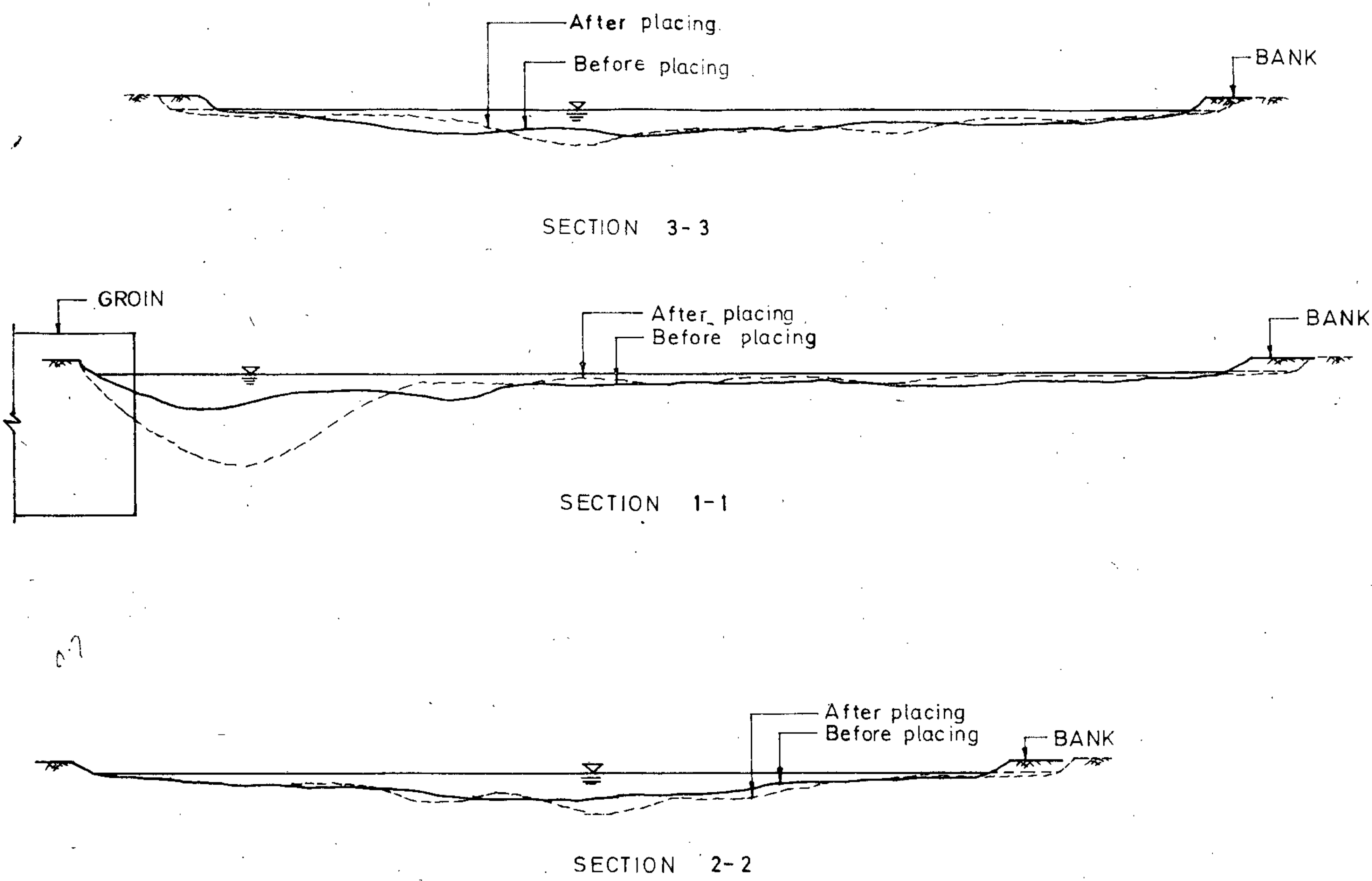


FIG. 4.31 VARIATION OF CROSS-SECTION BEFORE AND AFTER PLACEMENT OF GROIN, SETUP 4
(SCALE: 1:5) (Q = 0·03222 cfs)

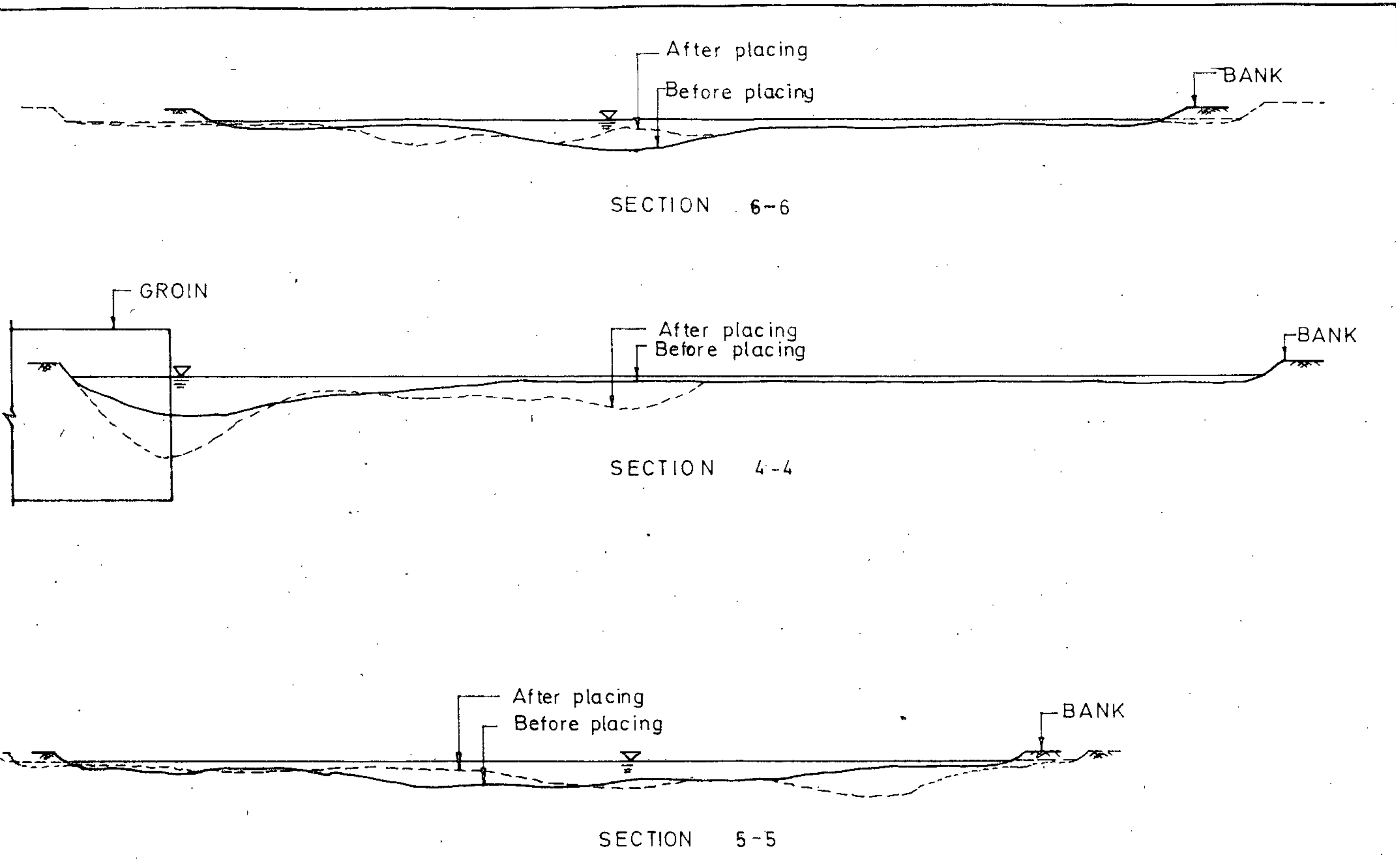


FIG. 4.32 VARIATION OF CROSS-SECTION BEFORE AND AFTER PLACEMENT OF GROIN, SET UP 4
(SCALE: 1:5) (Q = 0.03222 cfs)

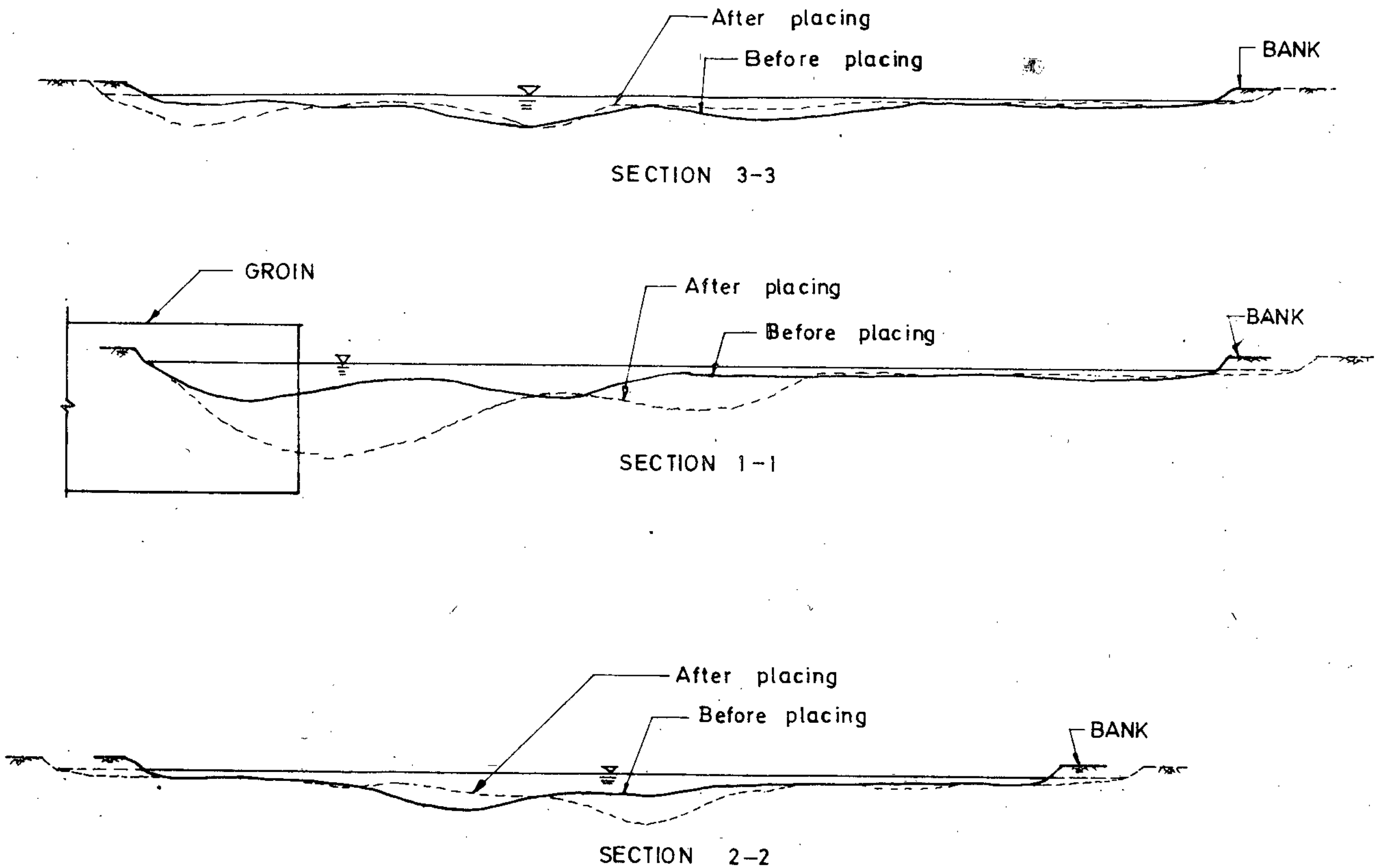


FIG. 4.33 VARIATION OF CROSS-SECTION BEFORE AND AFTER PLACEMENT OF GROIN, SETUP 5
(SCALE: 1:5) (Q = 0·03222 cfs)

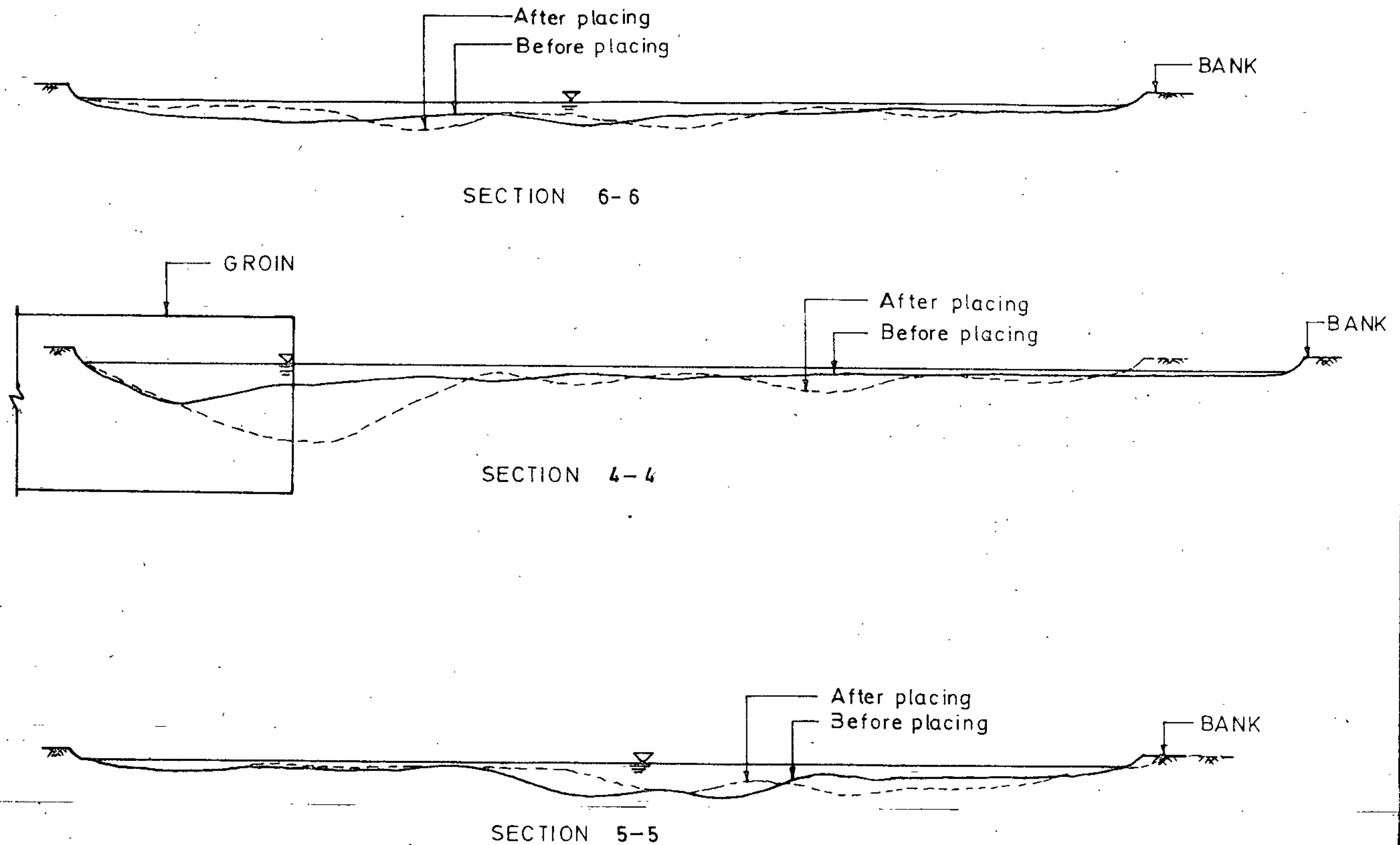


FIG. 4.34 VARIATION OF CROSS-SECTION BEFORE AND AFTER PLACEMENT OF GROIN, SETUP 5
(SCALE: 1:5) (Q = 0·03222 cfs)

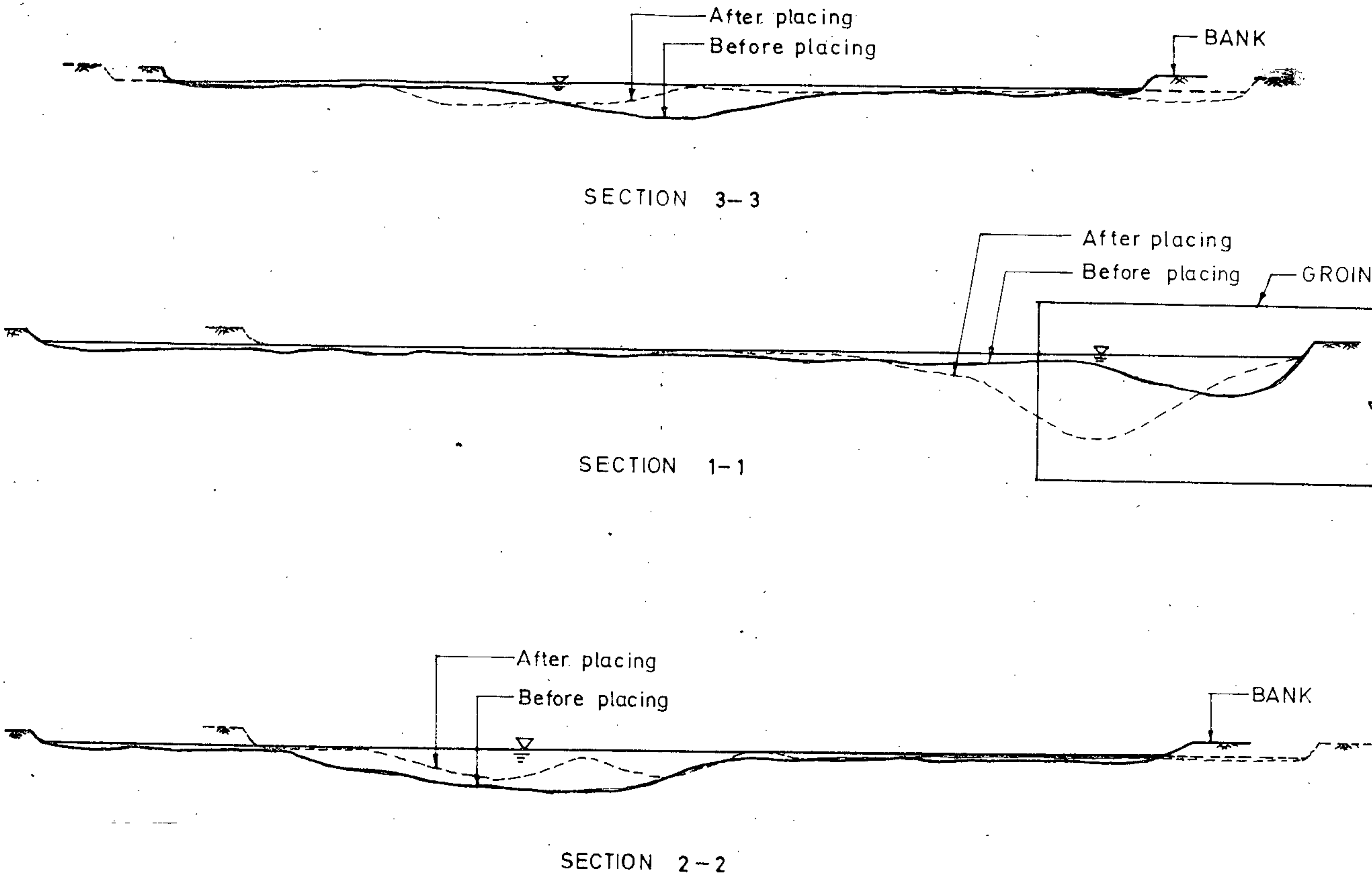


FIG. 4.35 VARIATION OF CROSS SECTION BEFORE AND AFTER PLACEMENT OF GROIN, SETUP 6
(SCALE: 1:5) (Q= 0·03222 cfs)

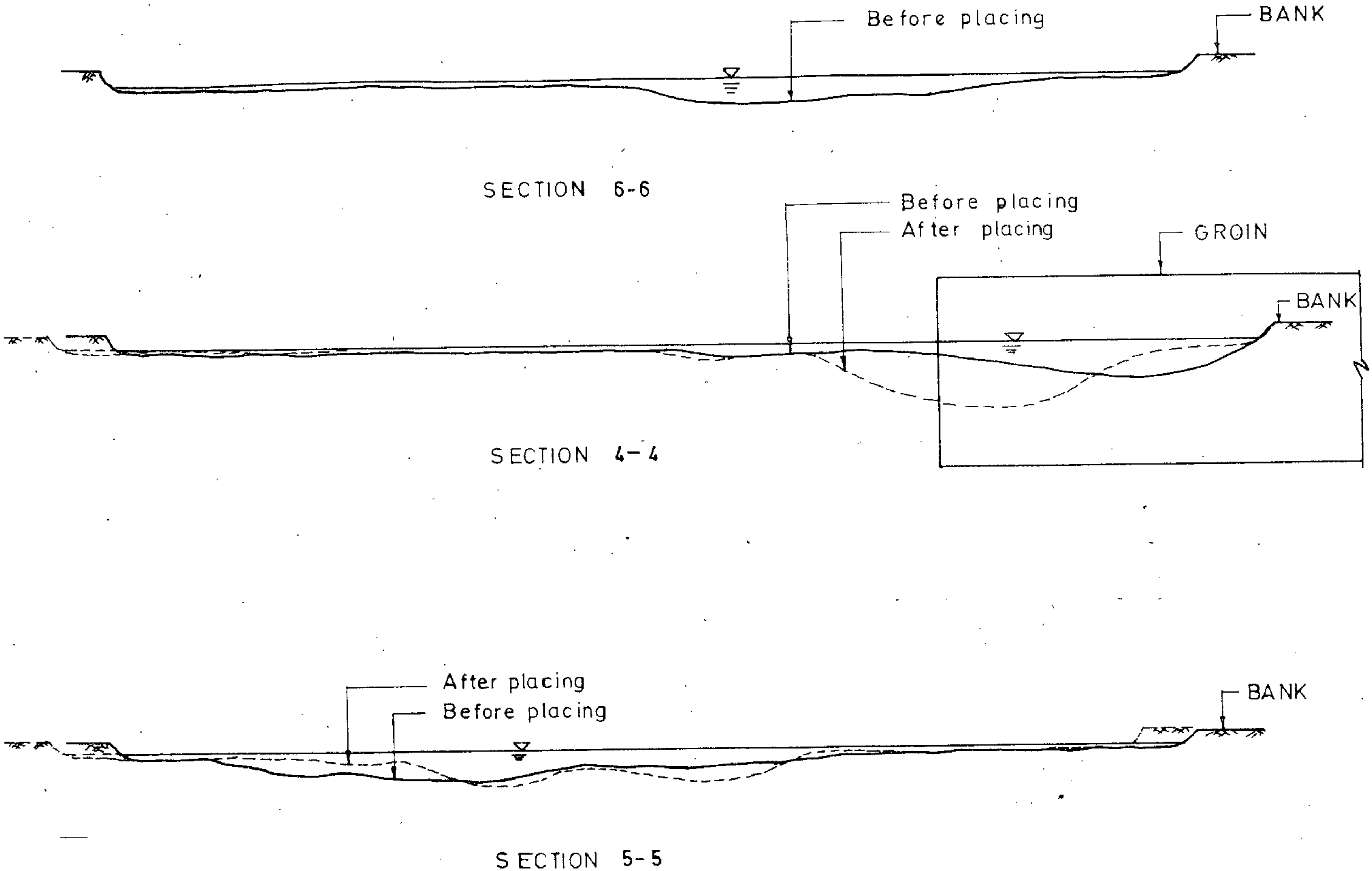


FIG. 4.36 VARIATION OF CROSS-SECTION BEFORE AND AFTER PLACEMENT OF GROIN, SETUP 6
(SCALE: 1:5) (Q = 0·03222 cfs)

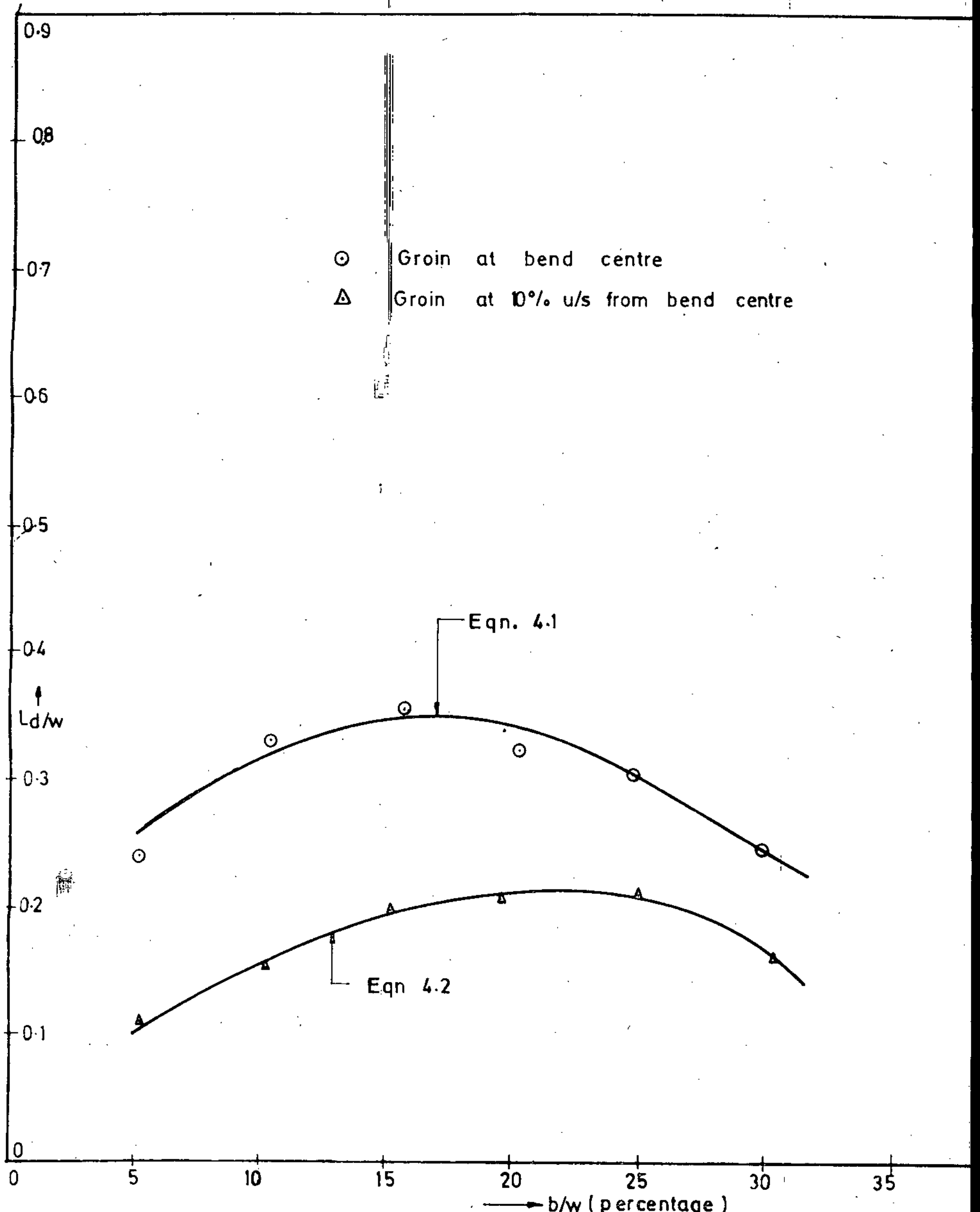


FIG. 4·37 RELATIONSHIP BETWEEN GROIN PROJECTION AND DOWN STREAM LENGTH PROTECTED

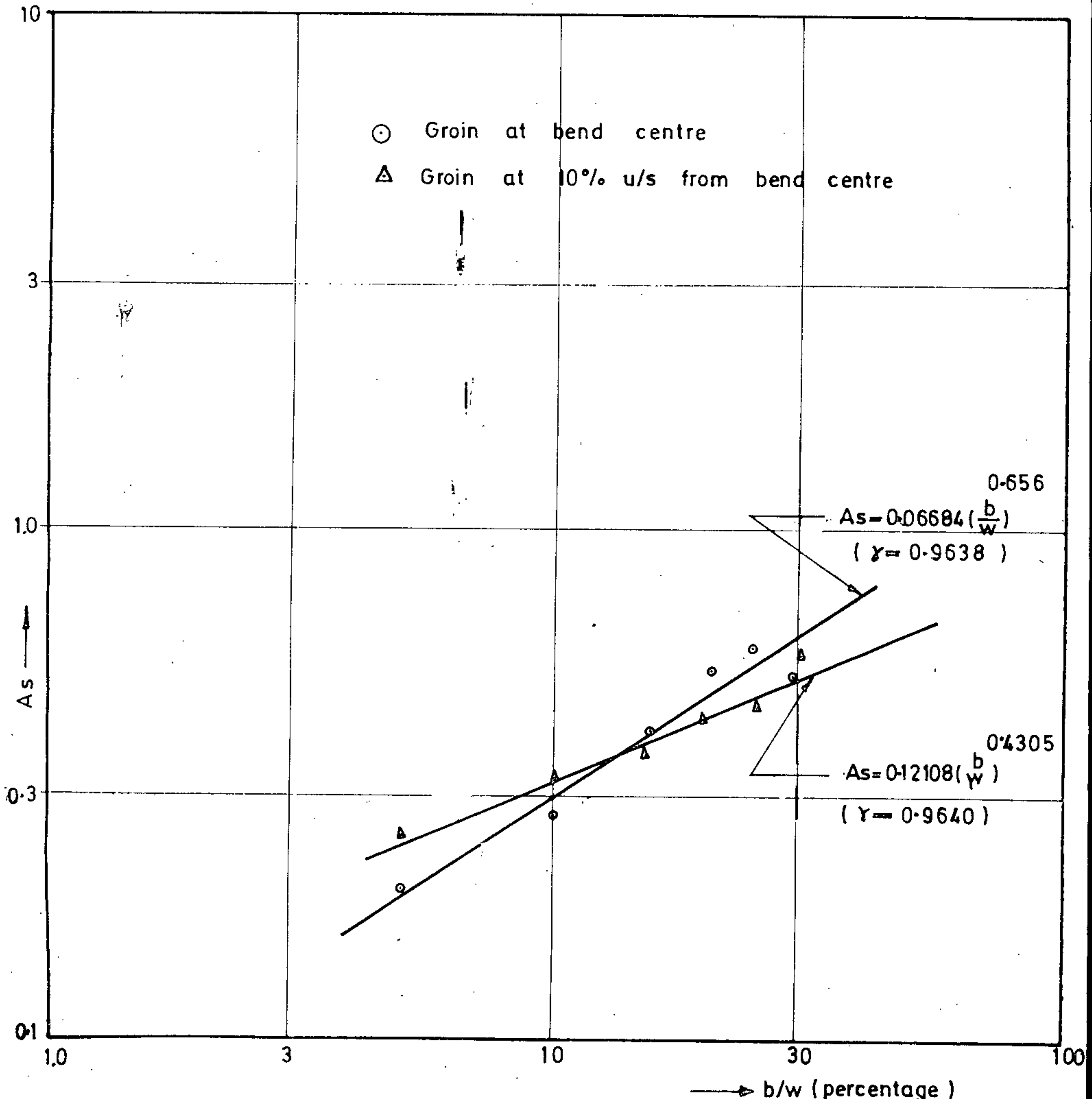


FIG. 4.38 RELATIONSHIP BETWEEN GROIN PROJECTION AND SCOUR AREA

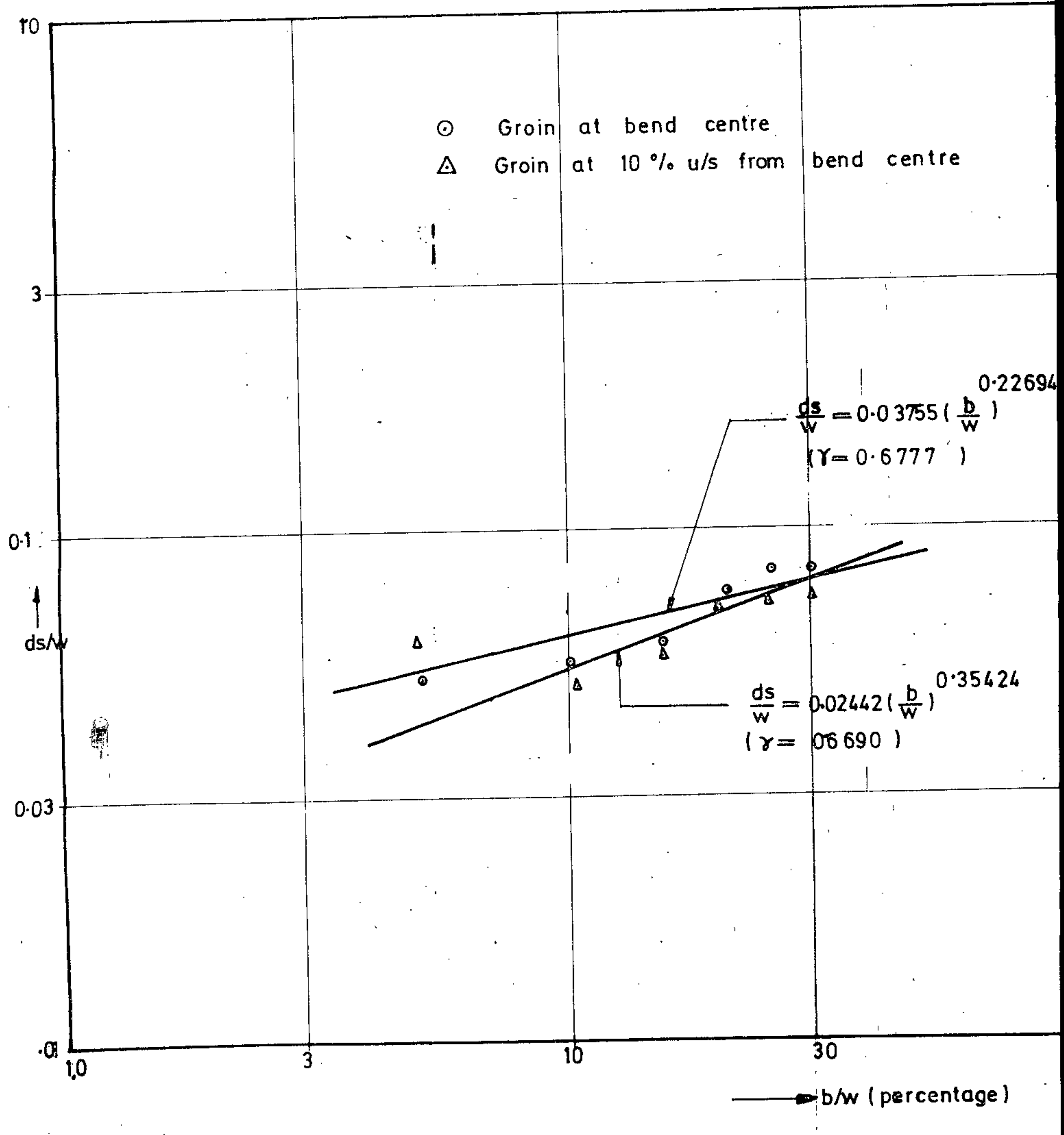


FIG. 4.39 RELATIONSHIP BETWEEN SCOUR AND GROIN PROJECTION
(Q = 0·03222 cfs)

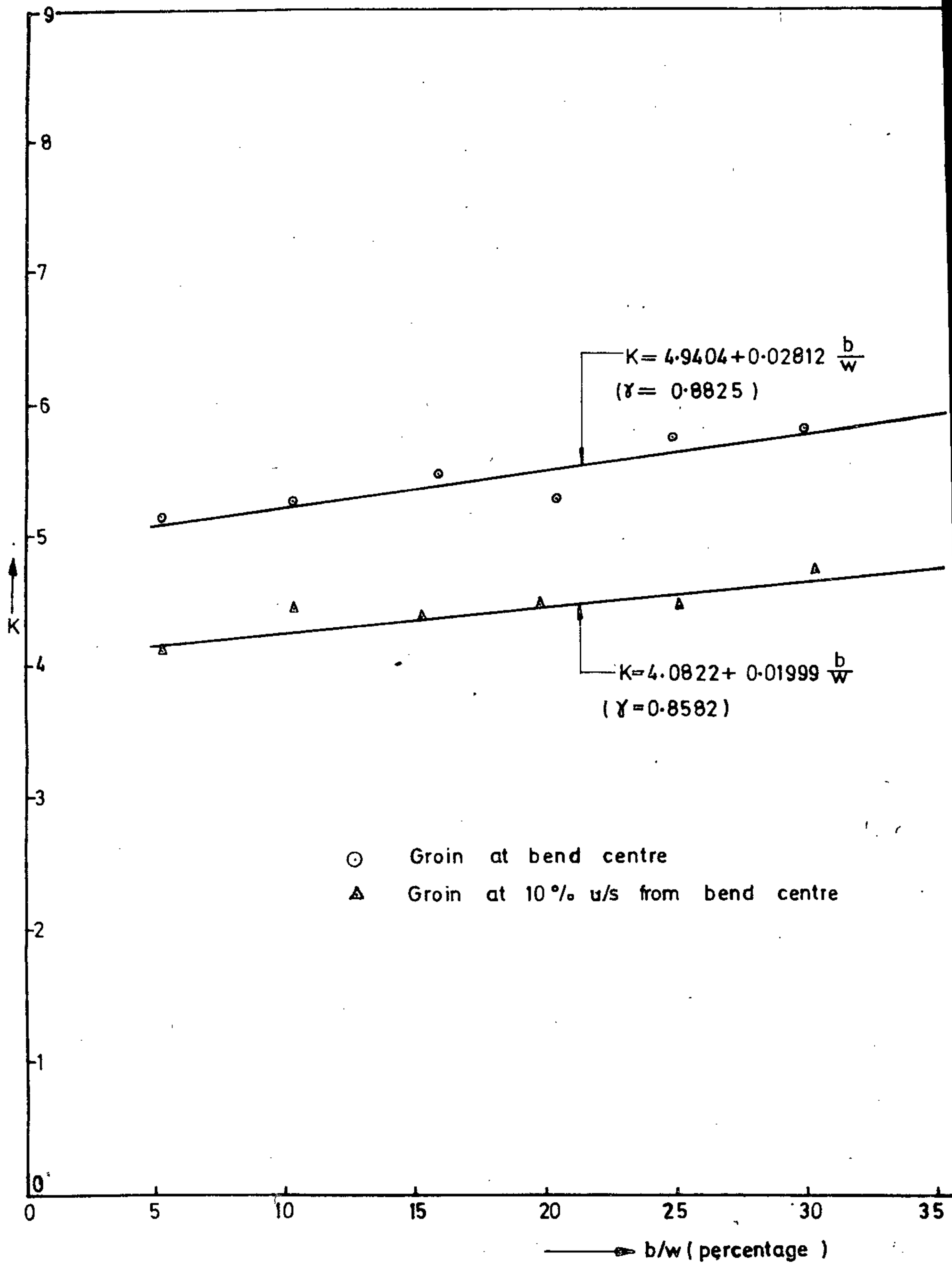


FIG. 4.40 RELATIONSHIP BETWEEN GROIN PROJECTION AND SCOUR CONSTANT (Q = 0·03222 cfs)

Table - 1

Set up : 1
Section : 1-1

Initial channel slope :0.00333
Discharge :0.0322 cfs

Groin projection : 5.27%
Groin Location : Bend centre

	Before groin placing	After groin placing
1. Slope	0.00101	0.00167
2. Projection,ft.	0.12500	-
3. Channel width, ft.	3.50000	4.25000
4. Area of cross-section,sft.	0.07639	0.11806
5. Maximum depth of flow,ft.	0.24166	0.41666
6. Average depth of flow,ft.	0.02183	0.02778
7. Average velocity of flow,fps.	0.42178	0.27291
8. Wetted perimeter,ft.	3.52690	4.42913
9. Hydraulic radius,ft.	0.02166	0.02666
10. Meander length,ft.	15.74803	14. 76378
11. Meander thalweg length,ft.	19.68504	20. 66929
12. Chan el length,ft.	13.50000	12.500000
13. Channel sinuosity	1.16652	1.18110
14. Thalweg sinuosity	1.45815	1.65354
15. Shear stress, pound/sft.	0.00137	0.00278
16. Stream power,ft-lb/sec.ft.	0.00203	0.00336
17. Maximum depth to width ratio	0.03333	0.04902
18. Froude Number	0.50307	0.28855
19. Relative radius of curvature	1.78571	1.47059
20. Mannings roughness co-efficient	0.00859	0.01962
21. Maximum scour depth, ft.	-	0.22310

Table 1 (Contd.)

Set up : 1 Initial channel slope: 0.00333

Section: 1-1 Discharge : 0.0322 cfs

Groin projection : 5.27% Groin Location : Bend centre	Before groin placing	After groin placing
22. Plan area of scour, sft.	-	0.19800
23. Downstream length protected, ft.	-	1.00000
24. Upstream bank caving	-	0.08333
25. Scour constant, K	-	5.15956
26. Downstream length protected/projection	-	8.00000
27. Upstream bank/projection	-	0.66667
28. Downstream length protected/width	-	0.23529
29. Maximum scour depth/width		0.05245

Table - 2

Set up 1
Section: 4-4

Initi l channel slop : 0.00333
Discharge : 0.03222 cfs

Groin projection : 10.3%
Groin Location : Bend centre

	Before groin placing	After groin placing
1. Slope	0.00101	0.00167
2. Projection, ft.	0.22917	-
3. Channel width, ft.	4.00000	3.75000
4. Area of cross-section, sft.	0.11111	0.14410
5. Maximum depth of flow, ft.	0.10500	0.19667
6. Average depth of flow, ft.	0.02778	0.03843
7. Average velocity of flow, fps.	0.28998	0.22359
8. Wetted perimeter, ft.	4.10105	3.95341
9. Hydraulic radius, ft.	0.02709	0.03645
10. Meander length, ft.	14.76278	14.76378
11. Meander thalweg length, ft.	18.70079	19.68504
12. Channel length, ft.	12.00000	12.50000
13. Channel sinuosity	1.23032	1.18110
14. Thalweg sinuosity	1.55840	1.57480
15. Shear stress, pound/sft.	0.00171	0.00380
16. Stream power, ft-lb/sec.ft.	0.00203	0.00336
17. Maximum depth to width ratio	0.02625	0.05245
18. Froude Number	0.30660	0.20100
19. Relative radius of curvature	1.06250	1.13333
20. Mannings roughness co-efficient	0.01451	0.01987
21. Maximum scour depth, ft.	-	0.20609
22. Plan area of scour, sft.	-	0.27800

Table - 2 (Contd.)

Set up : 1 — Initial channel slope : 0.00333

Section: 4-4 — Discharge : 0.03222 cfs

Groin projection: 10.3%

Groin Location : Bend centre	Before groin placing	After groin placing
23. Downstream length protected, ft.	-	1.25000
24. Upstream bank caving	-	0.08333
25. Scour constant, K	-	5.21186
26. Downstream protected/ projection	-	5.45455
27. Upstream bank caving/ projection	-	0.36364
28. Downstream length protected/width	-	0.33333
29. Maximum scour depth/width	-	0.05496

Table - 3

Set up : 2 Initial channel slope: 0.00333

Section: 1-1 Discharge : 0.03222 cfs

Groin projection: 15.69% Groin Location : Bend centre	Before groin placing	After groin placing
1. Slope	0.00101	0.00167
2. Projection, ft.	0.33333	-
3. Channel width, ft.	3.25000	4.08333
4. Area of cross-section, sft.	0.10938	0.18264
5. Maximum depth of flow, ft.	0.10499	0.24934
6. Average depth of flow, ft.	0.03366	0.04473
7. Average velocity of flow, fps.	0.29457	0.17641
8. Wetted perimeter, ft.	3.31365	4.26509
9. Hydraulic radius, ft.	0.03301	0.03282
10. Meander length, ft.	12.79528	15.05906
11. Meander thalweg length, ft.	16.73228	19.68504
12. Channel length, ft.	12.00000	13.25000
13. Channel sinuosity	1.06627	1.13653
14. Thalweg sinuosity	1.39436	1.48566
15. Shear stress, pound/sft.	0.00208	0.00446
16. Stream power, ft-lb/sec.ft.	0.00203	0.00336
17. Maximum depth to width ratio	0.03230	0.06106
18. Froude Number	0.28295	0.14699
19. Relative radius of curvature	1.53846	1.22449
20. Mannings roughness co-efficient	0.01631	0.03169
21. Maximum scour depth, ft.	-	0.24606

Table - 3 (Contd.)

Set up : 2 | Initial channel slope: 0.00333
Section: 1-1 | Discharge : 0.03222 cfs.

Groin projection : 15.69% Groin Location : Bend centre	Before groin placing	After groin placing
22. Plan area of scour, sft.	-	0.45800
23. Downstream length protected, ft.	-	1.43333
24. Upstream bank caving	-	5.41451
25. Scour constant, K	-	5.41451
26. Downstream length protected/projection	-	5.50005
27. Upstream bank caving/ projection	-	0.12501
28. Downstream length projected/ width	-	0.35102
29. Maximum scour depth/width		0.06206

Table - 4

Set up : 2
Section: 4-4

Initial channel slope: 0.00333
Discharge : 0.03222 cfs

Groin projection : 20.29% Groin Location : Bend centre	Before groin placing	After groin placing
1. Slope	0.00236	0.00203
2. Projection, ft.	0.58333	-
3. Channel width, ft.	3.16667	3.16667
4. Area of cross-section, sft.	0.12674	0.23958
5. Maximum depth of flow, ft.	0.10302	0.24278
6. Average depth of flow, ft.	0.04002	0.07566
7. Average velocity of flow, fps.	0.25422	0.13449
8. Wetted perimeter, ft.	3.28084	3.31365
9. Hydraulic radius, ft.	0.03863	0.07230
10. Meander length, ft.	9.84252	10.82677
11. Meander thalweg length, ft.	12.30315	13.28740
12. Channel length, ft.	8.50000	9.25000
13. Channel sinuosity	1.15974	1.17046
14. Thalweg sinuosity	1.44743	1.43648
15. Shear stress, pound/sft.	0.00569	0.00916
16. Stream power, ft-lb/sec.ft.	0.00474	0.00408
17. Maximum depth to width ratio	0.03253	0.07667
18. Froude Number	0.22395	0.08616
19. Relative radius of curvature	1.10526	1.10526
20. Mannings roughness co-efficient	0.03210	0.08564
21. Maximum scour depth, ft.	-	0.24278

Table - 4 (Contd.)

Set up : 2 Initial channel slope: 0.00333
Section: 4-4 Discharge : 0.03222 cfs

Groin projection : 20.29%

Groin Location : Bend centre	Before groin placing	After groin placing
22. Plan area of scour, sft.	-	0.54250
23. Downstream length protected, ft.	-	0.91667
24. Upstream bank caving	-	0.04167
25. Scour constant, K	-	5.25016
26. Downstream length protected/ projection	-	1.57144
27. Upstream bank caving/project	-	0.07143
28. Downstream length protected/width	-	0.20745
29. Maximum scour depth/width		0.07571

Table - 5

Set up : 3   Initial channel slope : 0.00333

Section: 1-1   Discharge : 0.03222 cfs

Groin projection : 24.65% Groin Location : Bend centre	Before groin placing	After groin placing
1. Slope	0.00236	0.00203
2. Projection,ft.	0.72917	-
3. Channel width,ft.	3.50000	3.58333
4. Area of cross-section,sft.	0.09722	0.20660
5. Maximum depth of flow,ft.	0.08202	0.22310
6. Average depth of flow,ft.	0.02778	0.05766
7. Average velocity of flow,fps.	0.33141	0.15595
8. Wetted perimeter,ft.	3.58842	3.77297
9. Hydraulic radius,ft.	0.02709	0.05476
10. Meander length,ft.	10.33465	9.84252
11. Meander thalweg length,ft.	12.30315	12.30315
12. Channel length,ft.	9.00000	1.12486
13. Channel sinuosity	1.14829	1.40607
14. Thalweg sinuosity	1.36702	1.40607
15. Shear stress,pound/sft.	0.00399	0.00694
16. Stream power, ft-lb/sec.ft.	0.00474	0.00408
17. Maximum depth to width ratio	0.02343	0.06226
18. Froude Number	0.35041	0.11445
19. Relative radius of curvature	1.28571	1.25582
20. Mannings roughness co-efficient	0.01941	0.06131
21. Maximum scour depth,ft.	-	0.24934

Table - 5 (Contd.)

Set up : 3 Initial channel slope: 0.00333
Section: 1-1 Discharge : 0.03222 cfs

Groin projection : 24.65%
Groin Location : Bend centre

	Before groin placing	After groin placing
22. Plan area of scour, sft.	-	0.58140
23. Downstream length protected, ft.	-	1.08333
24. Upstream bank caving	-	0.12500
25. Scour constant, K	-	5.76622
26. Downstream length protected/ projection	-	1.48570
27. Upstream bank caving/projection	-	0.17143
28. Downstream length projected/width	-	0.30232
29. Maximum scour depth/width		0.08428

Table - 6

Set up : 3
Sectio..: 4-4

Initial channel slope: 0.00333
Discharge : 0.03222 cfs

Groin projection : 29.89%
Groin Location : Bend centre

	Before groin placing	After groin placing
1. Slope	0.00236	0.00203
2. Projection, ft.	1.08333	-
3. Channel width, ft.	3.91667	4.12500
4. Area of cross-section, sft.	0.14236	0.28646
5. Maximum depth of flow, ft.	0.12467	0.21982
6. Average depth of flow, ft.	0.03635	0.06944
7. Average velocity of flow, fps.	0.22633	0.11248
8. Wetted perimeter, ft.	4.10105	4.26509
9. Hydraulic radius, ft.	0.03471	0.06716
10. Meander length, ft.	9.59646	10.43307
11. Meander thalweg length, ft.	13.53346	14.76378
12. Channel length, ft.	8.25000	9.50000
13. Channel sinuosity	1.16321	1.09822
14. Thalweg sinuosity	1.64042	1.55408
15. Shear stress, pound/sft.	0.00511	0.00851
16. Stream power, ft-lb/sec.ft.	0.00474	0.00408
17. Maximum depth to width ratio	0.03183	0.05329
18. Froude Number	0.20920	0.07522
19. Relative radius of curvature	1.19149	1.13131
20. Mannings roughness co-efficient	0.03356	0.09747

Table - 6 (Contd.)

Set up : 3		Initial channel slope:	0.00333
Section: 4-4		Discharge :	0.03222 cfs

Groin projection : 29.89% Groin Location : Bend centre	Before groin placing	After groin placing
21. Maximum scour depth, ft.	-	0.24606
22. Plan area of scour, sft.	-	0.52030
23. Downstream length protected, ft.	-	1.00000
24. Upstream bank caving	-	0.04167
25. Scour constant, K	-	5.82555
26. Downstream length protected/ Projection	-	0.92308
27. Upstream bank caving/projection	-	0.03846
28. Downstream length protected/ width	-	2424200
29. Maximum scour depth/width		0.08559

Table - 7

Set up : 4 | Initial channel slope: 0.00333
Section: 1-1 | Discharge : 0.03222 cfs

Groin projection : 5.07%

Groin Position : 10% Upstream from bed centre

	Before groin placing	After groin placing
1. Slope	0.00201	0.00216
2. Projection, ft.	0.14583	-
3. Channel width, ft.	3.50000	3.75000
4. Area of cross-section, sft.	0.10764	0.20313
5. Maximum depth of flow, ft.	0.06562	0.27887
6. Average depth of flow, ft.	0.03075	0.05417
7. Average velocity of flow, fps.	0.29933	0.15862
8. Wetted perimeter, ft.	3.60892	4.01903
9. Hydraulic radius, ft.	0.02983	0.05054
10. Meander length, ft.	10.03937	10.62992
11. Meander thalweg length, ft.	13.38583	13.81890
12. Channel length, ft.	9.00000	8.00000
13. Channel sinuosity	1.11549	1.32874
14. Thalweg sinuosity	1.48731	1.72736
15. Shear stress, pound/sft.	0.00374	0.00681
16. Stream power, ft-lb/sec.ft.	0.00404	0.00434
17. Maximum depth to width ratio	0.01875	0.07437
18. Froude Number	0.30082	0.12010
19. Relative radius of curvature	1.57143	1.46667
20. Mannings roughness co-efficient	0.02116	0.05893

Table - 7 (Contd.)

Set up : 4 — Initial channel slope: 0.00333

Section: 1-1 — Discharge : 0.03222 cfs

Groin projection : 5.07%

Groin Position : 10% Upstream from bed centre

	Before groin placing	After groin placing
21. Maximum scour depth, ft.	-	0.23622
22. Plan area of scour, sft.	-	0.25417
23. Downstream length protected, ft.	-	0.41667
24. Upstream bank caving	-	0.45833
25. Scour constant, K	-	4.12570
26. Downstream length protected/projection	-	2.85723
27. Upstream bank caving/ projection	-	3.14633
28. Downstream length projected/ width	-	0.11111
29. Maximum scour depth/width	-	0.06299

Table - 8

Set up : 4 Initial channel slope: 0.00333
Section: 4-4 Discharge : 0.03222 cfs

Groin projection : 10.42%
Groin position : 10% Upstream from bend centre

	Before groin placing	After groin placing
1. Slope	0.00201	0.00216
2. Projection, ft.	0.31250	-
3. Channel width, ft.	3.83333	3.75000
4. Area of cross-section, sft.	0.11458	0.21354
5. Maximum depth of flow, ft.	0.10827	0.23950
6. Average depth of flow, ft.	0.02989	0.05694
7. Average velocity of flow, fps.	0.28120	0.15089
8. Wetted perimeter, ft.	3.93701	3.93701
9. Hydraulic radius, ft.	0.02910	0.05424
10. Meander length, ft.	8.07087	9.48819
11. Meander thalweg length, ft.	11.25984	13.38583
12. Channel length, ft.	7.00000	8.00000
13. Channel sinuosity	1.15298	1.18602
14. Thalweg sinuosity	1.60855	1.67323
15. Shear stress, pound/sft.	0.00365	0.00731
16. Stream power, ft-lb/sec.ft.	0.00404	0.00434
17. Maximum depth to width ratio	0.02824	0.06387
18. Froude Number	0.28663	0.11144
19. Relative radius of curvature	1.21739	1.24444
20. Mannings roughness co-efficient	0.02215	0.06495

Table - 8 (Contd.)

Set up : 4
Section: 4-4

Initial channel slope: 0.00333
Discharge : 0.03222 cfs

Groin projection : 10.42%
Groin position : 10% Upstream from bend centre

	Before groin placing	After groin placing
21. Maximum scour depth, ft.	-	0.19357
22. Plan area of scour, sft.	-	0.32222
23. Downstream length protected, ft.	-	0.57500
24. Upstream bank caving	-	0.08333
25. Scour constant, K	-	4.42259
26. Downstream length protected/ projection	-	2.40000
27. Upstream bank caving/projection	-	0.26666
28. Downstream length protected/width	-	0.15333
29. Maximum scour depth/width		0.05162

Table - 9

Set up : 5 — Initial channel slope: 0.00333

Section: 1-1 — Discharge : 0.03222 cfs

Groin projection : 15.28%

Groin position : 10% Upstream from bend centre

	Before groin placing	After groin placing
1. Slope	0.00201	0.00216
2. Projection, ft.	0.45833	-
3. Channel width, ft.	3.25000	3.50000
4. Area of cross-section, sft.	0.12326	0.30382
5. Maximum depth of flow, ft.	0.08530	0.26247
6. Average depth of flow, ft.	0.03793	0.08681
7. Average velocity of flow, fps.	0.26140	0.10605
8. Wetted perimeter, ft.	3.28084	3.60892
9. Hydraulic radius, ft.	0.03757	0.08419
10. Meander length, ft.	9.84252	10.43307
11. Meander thalweg length, ft.	12.75591	13.68110
12. Channel length, ft.	9.00000	9.00000
13. Channel sinuosity	1.09361	1.15923
14. Thalweg sinuosity	1.41732	1.52012
15. Shear stress, pound/sft.	0.00471	0.01135
16. Stream power, ft-lb/sec.ft.	0.00404	0.00434
17. Maximum depth to width ratio	0.02625	0.07499
18. Froude Number	0.23653	0.06343
19. Relative radius of curvature	1.64103	1.52381
20. Mannings roughness co-efficient	0.02828	0.12407

Table 9 (Contd.)

Set up : 5
Section: 1-1

Initial channel slop : 0.00333
Discharge : 0.03222 cfs

Groin projection : 15.28%
Groin position : 10% Upstream from bend centre

	Before groin placing	After groin placing
21. Maximum scour depth, ft.	-	0.20669
22. Plan area of scour, sft.	-	0.37417
23. Downstream length protected, ft.	-	0.58333
24. Upstream bank caving	-	0.18750
25. Scour constant, K	-	4.35071
26. Downstream length protected/ projection	-	1.27273
27. Upstream bank caving/ project	-	0.40909
28. Downstream length protected/ width	-	0.19444
29. Maximum scour depth/width	-	0.05905

Table - 10

Set up : 5
Section: 4-4
Initial channel slop : 0.00333
Discharge : 0.03222 cfs

Groin projection : 19.87%
Groin position : 10% Upstream of bend centre

	Before groin placing	After groin placing
1. Slope	0.00201	0.00216
2. Projection, ft.	0.64583	-
3. Channel width, ft.	3.75000	3.25000
4. Area of cross-section, sft.	0.11632	0.22917
5. Maximum depth of flow, ft.	0.10171	0.23622
6. Average depth of flow, ft.	0.03102	0.07051
7. Average velocity of flow, fps.	0.27699	0.14060
8. Wetted perimeter, ft.	3.85499	3.36286
9. Hydraulic radius, ft.	0.03017	0.06815
10. Meander length, ft.	7.87402	7.48031
11. Meander thalweg length, ft.	11.02361	12.20472
12. Channel length, ft.	7.00000	6.50000
13. Channel sinuosity	1.12486	1.15082
14. Thalweg sinuosity	1.57480	1.87765
15. Shear stress, pound/sft.	0.00378	0.00919
16. Stream power, ft-lb/sec.ft.	0.00404	0.00434
17. Maximum depth to width ratio	0.02712	0.07268
18. Froude Number	0.27715	0.09331
19. Relative radius of curvature	1.42222	1.64102
20. Mannings roughness co-efficient	0.02304	0.08122

Table - 10 (Contd.)

Set up : 5 Initial channel slope: 0.00333

Section: 4-4 Discharge : 0.03222 cfs

Groin projection : 19.87%

Groin position : 10% Upstream of bend centre

	Before groin placing	After groin placing
21. Maximum scour depth, ft.	-	0.23622
22. Plan area of scour, sft.	-	0.43417
23. Downstream length protected, ft.	-	0.66667
24. Upstream bank caving	-	0.04167
25. Scour constant, K	-	4.48096
26. Downstream length protected/ projection	-	1.03227
27. Upstream bank caving/ projection	-	0.06452
28. Downstream length protected/ width	-	0.20513
29. Maximum scour depth/width	-	0.07268

Table - 11

Set up : 6
Section: 1-1

Initial channel slope: 0.00333
Discharge : 0.03222 cfs

Groin projection : 25%
Groin position : 10% Upstream from bend centre

	Before groin placing	After groin placing
1. Slope	0.00232	0.00231
2. Projection, ft.	0.81250	-
3. Channel width, ft.	3.91667	3.25000
4. Area of cross-section, sft.	0.09722	0.18750
5. Maximum depth of flow, ft.	0.09514	0.23950
6. Average depth of flow, ft.	0.02482	0.05769
7. Average velocity of flow, fps.	0.33866	0.17184
8. Wetted perimeter, ft.	3.96982	3.33005
9. Hydraulic radius, ft.	0.02449	0.05630
10. Meander length, ft.	9.35039	9.35039
11. Meander thalweg length ft.	12.79520	12.89370
12. Channel length, ft.	8.37500	8.50000
13. Channel sinuosity	1.11646	1.10005
14. Thalweg sinuosity	1.52779	1.51691
15. Shear stress, pound/sft.	0.00355	0.00812
16. Stream power, ft-lb/sec.ft.	0.00466	0.00464
17. Maximum depth to width ratio	0.02429	0.07369
18. Froude Number	0.37882	0.12608
19. Relative radius of curvature	1.34042	1.61538
20. Mannings roughness co-efficient	0.01760	0.06047

Table - 11 (Contd.)

Set up : 6
Section: 1-1

Initial channel slope: 0.00333
Discharge : 0.03222 cfs

Groin projection : 25%
Groin position : 10% Upstream from bend centre

	Before groin placing	After groin placing
21. Maximum scour depth, ft.	-	0.24606
22. Plan area of scour, sft.	-	0.46056
23. Downstream length protected, ft.	-	0.81250
24. Upstream bank ecaving	-	-
25. Scour constant, K	-	4.46529
26. Downstream length protected/ projection	-	1.00000
27. Downstream length protected/ width	-	0.20745
28. Maximum scour depth/width		0.07571

Table - 12

Set up : 6
Section: 4-4

Initial channel slope: 0.00333
Discharge : 0.03222 cfs

Groin projection : 30.13%
Groin position : 10% Upstream from bend centre

	Before groin placing	After groin placing
1. Slope	0.00232	0.00231
2. Projection, ft.	0.97917	-
3. Channel width, ft.	3.50000	3.66667
4. Area of cross-section, sft.	0.09896	0.19097
5. Maximum depth of flow, ft.	0.08530	0.20013
6. Average depth of flow, ft.	0.02827	0.05208
7. Average velocity of flow, fps.	0.32559	0.16872
8. Wetted perimenter, ft.	3.60892	3.77297
9. Hydraulic radius, ft.	0.02742	0.05062
10. Meander length, ft.	8.85827	9.84252
11. Meander thalweg length, ft.	12.00781	13.28740
12. Channel length, ft.	8.00000	9.50000
13. Channel sinuosity	1.10728	1.03605
14. Thalweg sinuosity	1.50098	1.39867
15. Shear stress, pound/sft.	0.00397	0.00730
16. Stream power, ft-lb/sec.ft.	0.00466	0.00464
17. Maximum depth to width ratio	0.02437	0.05458
18. Froude Number	0.34126	0.13029
19. Relative radius of curvature	1.57143	1.50000
20. Mannings roughness coefficient	0.01975	0.05735

Table - 12 (Contd.)

Set up : 6
Section: 4-4

Initial channel slope: 0.00333
Discharge : 0.03222 cfs

Groin projection : 30.13%
Groin position : 10% Upstream from bend centre

	Before groin placing	After groin placing
21. Maximum scour depth, ft.	-	0.24606
22. Plan area of scour, sft.	-	0.57528
23. Downstream length protected, ft.	-	0.522083
24. Upstream bank caving	-	-
25. Scour constant, K	-	4.76717
26. Downstream length protected/ projection	-	0.53191
27. Upstream bank caving/ projection	-	-
28. Downstream length protected/ width	-	0.16026
29. Maximum scour depth/width	-	0.07571