EFFECT OF SEDIMENT CHARACTERISTICS ON SCOUR AROUND SPUR-DIKES IN ALLUVIAL CHANNELS

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DEPARTMENT OF CIVIL ENGINEERING
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Submitted to the University of Roorkee, Roorkee, in partial fulfilment of the requirements for the award of the Degree of Master of Engineering in Dam Design, Irrigation Engineering and Hydraulics.

University of Roorkee
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CERTIFICATE

Certified that the dissertation entitled " Effect of Sediment Characteristics on Scour around Spur-dikes in Alluvial Channels", which is being submitted by Shri K. Divakaran Nambudripad in partial fulfilment for the award of the degree of Master of Engineering in Dam Design, Irrigation Engineering and Hydraulics of University of Roorkee, is a record of Student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation have not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of 13 months from April 1960 to May 1961 for preparing dissertation for Master of Engineering Degree at the University.

Dated 15th May 1961

Signature R. J. Garde

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A B S T R A C T

The results of the investigation regarding the role of sediment characteristics on scour around a spur-dike in an alluvial channel are reported herein. The study is a continuation of the analysis of the problem of scour around spur-dikes, carried out by Garde and Subramanya [11]* in the University of Roorkee. The functional relationship obtained by carrying out dimensional analysis has been verified using experimental data collected in the hydraulics laboratory in a 25-ft. long and 2-ft. wide rectangular flume. Contrary to some of the results of previous investigators, it has been found that the characteristics of bed material affect the maximum scour depth appreciably The importance of the Froude number of flow to represent the effect of flow characteristics on the maximum scour depth has been stressed. The effect of sediment size on various other characteristics of scour has also been studied.

* Numbers in square parenthesis refer to numbers in Bibliography.

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LIST OF SYMBOLS USED

Symbol		Dimensions		
A	-	Dimensionless	-	A dimensionless number.
A_b	-	L^2	-	Area of bed of channel.
A_w	-	L^2	-	Area of side walls.
B	-	L	-	Width of channel.
b	-	L	-	Length of spur-dike.
C	-	Dimensionless	-	A dimensionless number.
C_D	-	"	-	Average drag coefficient of sediment particles.
D	-	L	-	Depth of flow.
D_1	-	L	-	Maximum scour depth below water surface.
d	-	L	-	Median diameter of bed material in mm.
d_t	-	L	-	Scour depth below original bed after time t
d_s	-	L	-	Maximum scour depth below bed.
F_r	-	Dimensionless	-	Froude number of flow.
F_b	-	"	-	Bed-factor proposed by Blench.
f	-	"	-	Lacey's silt factor.
g	-	L/T^2	-	Gravitational acceleration.
K, K'	-	Dimensionless	-	Dimensionless coefficients.
L	-	L	-	Width of scour hole in front of spur-dike.
N	-	L	-	Distance of null point from spur-dike.
n	-	Dimensionless	-	An exponent.
n_w	-	"	-	Manning's 'n' for side walls of channel.

LIST OF SYMBOLS USED ----- contd.

Symbol		Dimensions		
P_b	-	L	-	Wetted parimeter of the bed of channel.
P_w	-	L	-	Wetted perimeter of side walls of channel.
Q	-	L^3/T	-	Discharge in channel.
q	-	L^2/T	-	Discharge per foot width, of un-obstructed channel.
q_1	-	L^2/T	-	Discharge per foot width in the constricted area.
R_b	-	L	-	Hydraulics radius with respect to bed.
R_w	-	L	-	Hydraulic radius w.r.t. side walls.
S_w	-	Dimensionless	-	Slope of water-surface.
S_b	-	"	-	Slope of bed-surface.
S_e	-	"	-	Slope of energy line.
T	-	T	-	Time of attaining equilibrium scour depth after introduction of model.
t	-	T	-	Any time after introduction of model.
V	-	L/T	-	Mean velocity in channel.
w	-	L/T	-	Fall velocity of sediment particles.
α	-	Dimensionless	-	Opening ratio $= \left(1 - \frac{b}{B}\right)$.
β	-	"	-	Angle made by sloping face of scour hole in front of spur-dikes, with horizontal.
γ	-	M/L^2T^2	-	Specific weight of water.
γ_s	-	M/L^2T^2	-	Specific weight of sediment.
$\Delta\gamma$	-	M/L^2T^2	-	Difference of specific weights between water and air.

LIST OF SYMBOLS USED ----- contd.

SYMBOL		DIMENSIONS		
$\Delta\gamma_s$	-	M/L^2T^2	-	Difference of specific weights between sediment and water.
θ	-	Dimensionless	-	Angle of inclination of spur to direction of flow.
μ	-	M/LT	-	Dynamic viscosity of water.
ρ	-	M/L^3	-	Mass density of water.
σ	-	Dimensionless	-	Standard deviation of bed material.
η	-	"	-	Shape factor of sediment particles.

LIST OF FIGURES

CHAPTER I

INTRODUCTION

CHAPTER -1

INTRODUCTION

It is often necessary to partially obstruct the flow of water in alluvial channels by the construction of hydraulic structures across them. Most common among such structures are bridges, guide banks and spur-dikes. During heavy floods the bed of the channel around these structures gets scoured to great depths, sometimes even to the extent of exposing their foundations. One of the considerations in the design of foundation of these structures is the probable maximum depth of scour. Also the loose aprons, laid around guide banks and spur-dikes as a protection against scour, are designed after an estimation of the maximum scour depth likely to occur around them. Therefore, a knowledge about the maximum scour depth around obstructions during floods, is highly essential while designing these structures. At present, no reliable and definite rule is available for predicting the maximum depth of scour around such obstructions except Lacey's empirical equations. An under-estimation of the depth of scour is likely to lead to dangerous consequences. On the other hand, if the scour depth is overestimated, as sometimes worked out from Lacey's constants, the structure might be quite safe even during extra-ordinary floods, but there is every likelihood that it may become too costly and uneconomical.

The phenomenon of scour around an obstruction is very complicated since it is influenced by a variety of conditions, such as the type and geometry of the obstruction, the afflux created, the flow conditions and the nature of the bed material. The process of local scour around obstructions can be explained in the following manner: When the flow in a channel is partly obstructed, the original flow pattern within the channel and around the obstruction is modified. The changed flowpattern leads to a readjustment of the shear distribution on the bed of the channel. It is this changed shear distribution within the channel and around the obstruction which disturbs the normal movement of bed material. Once the process of scouring starts, the flow pattern, and hence the distribution of shear on the bed go on changing. It is believed that after a certain time interval, for all practical purposes, the scour reaches a maximum depth when either 1) shear stress on the boundary of the scour hole is at the critical value or 2) the sediment supplied to the scour hole is equal to the sediment thrown out of the hole. A knowledge of the flow phenomenon around the obstruction is important while studying the scour characteristics around them. However, at present no detailed information is available about the mechanism of scour.

Considerable difficulties are encountered while making field observations of scour during floods. A method adopted in India is to observe, after a flood has receded, the depth to which the stones in a loose apron or a stone pitching are burried during the flood. This is very approximate and cannot always be relied upon. At present, there are not reliable methods or equipments for recording the depth of scour during floods. Hence-reliable prototype data, which can be used for the analysis of the problem of scour, are not available.

Furthermore, it is almost impossible to control the different variables in a prototype and study systematically certain other variables. All these difficulties that are met with in the field can be eliminated by studying the problem in a laboratory, under a systematic control over the pertinent variables, though prototype conditions cannot be completely reproduced in a hydraulic model except for very simple cases.

Many investigations have been carried out to study the characteristics of scour around obstructions and other problems related to scour. However, the aim of most of these investigations was to provide some equations for maximum scour depth, than to investigate the problem from theoretical considerations. Exceptions to these are the works of Laursen [5,6,7,8] and Mushtaq Ahmad [22, 23] .

The earlier works like those of Lacey [19], Inglis [13] and Khosla[18] provide empirical formulae for determining the maximum scour depth around obstructions. These formulae include a factor which takes into account the characteristics of the bed material. Blench [3], Andru [2] are also of the opinion that th maximum scour depth is affected by a change in sediment size. Laursen [5,6,7,8] studied the various aspects of scour around bridge piers and abutments. According to him the maximum scour depth is related to the depth of flow, and is independent of velocity and sediment size. Izzard and Bradley [15] believe that sediment size affects only the rate of development of scour hole and not the scour depth. Opinions of the different investigators, are thus found to contradict each other as regards the effect of sediment size on the maximum scour depth. Uptill now no definite information is available about the role of sediment size in determining scour depths. However, it is felt that the sediment size migl be important in scour studies.

The present study was restricted to scour around a spur-dike. Spur-dikes are solid structures constructed across a channel and extending from one bank into the main flow [21] . These are known by different names, such as transverse dikes; groynes or simply spurs, and are widely used for the training of rivers. They serve the following purposes:-

1. Training the river or channel along a desired course.
2. Protecting the bank by keeping the main flow away from it.
3. Contracting a wide channel for improving the depth for navigation.

Mushtaq Ahmad [22] has done some work to study the behaviour of spur-dikes. Although he used a small range of sediment size, which showed no effect on the maximum scour depth, he suggests that a wider range of size should appreciably affect the scour depth.

THE PROBLEM AND LIMITATIONS:

The problem under consideration is to investigate the role of the size of the bed material in the following aspects of scour around a spur-dike:-

a) the maximum scour depth,
b) the geometry of the scour hole and
c) the rate of development of scour hole.

The limitations which were imposed on the study are given below:-

1. Only a single ideal spur-dike in the form of a thin steel plate, placed at right angles to the flow in a straight rectangular flume, was used.
2. A constant opening ratio (equal to the ratio of the width of the channel at the contracted section

to the normal width of the channel) of 0.835 was used. This limitation was imposed because the role of opening ratio on maximum scour has already been investigated [11] .

3. Four different sizes of non-cohesive sand were used, their median diameters being 0.29 mm, 0.45 mm 1.00 mm and 2.25 mm. Their specific gravities were almost same and the average specific gravity was 2.71. The standard deviation of the various sands however, varied between 1.4 and 2.1.

4. The discharge in the flume varied from 0.18 to 1.5 cusecs.

CHAPTER II

REVIEW OF LITERATURE

CHAPTER -2

REVIEW OF LITERATURE

In spite of several attempts ____ both theoretical and empirical___ to analyse the problem of scour around obstructions placed in alluvial channels, very little is known about this phenomenon as such. This is probably due to a large number of variables influencing the scour phenomenon. It is felt that in this connection a brief review of the available literature on the subject would provide sufficient back ground in order to understand the problem. With this view, a short summary of the significant conclusions of the various investigators is given below:-

Lacey [19] was the first to give certain empirical formulae (obtained by applying the regime theory) for determining the depth of scour at different modifications of an alluvial channel. Observations of a number of alluvial rivers, which had attained stability, led him to conclude that the velocity, V_o (termed as the critical velocity) at which the stability or equilibrium of the river is maintained, depends on the depth of flow and the nature of the bed material. This relationship was expressed as

$$V_o = 1.17 \sqrt{fR}\text{, or } R = 0.7305 \frac{V_o^2}{f}, \qquad (1)$$

in which R is the regime depth in ft and

f is the silt factor, which is approximately equal to $1.76 \sqrt{m}$ for regime conditions, m being the weighted mean diameter of the bed material in mm.

Another expression which related the discharge in the river to the critical velocity was also obtained,

$$Q.\, f^2 = 3.8 \;\; V_o^6 \tag{2}$$

in which Q is the discharge in the river in cusecs.

Combining these two equations, an expression for the regime depth, which is also the scour depth in normal stable channels, was obtained. Thus,

$$R = 0.7305 \frac{V_o^2}{f} \quad = \quad 0.7305 \left(\frac{Q}{3.8.f} \right)^{\frac{1}{3}}$$

$$\text{or} \quad R = D_L = 0.47 \left(\frac{Q}{f} \right)^{\frac{1}{3}} \tag{3}$$

where D_L is the depth of scour below water-surface.

This formula can be used only for regime channels. At channel bends with different curvatures, Lacey suggested the following scour depths (Table -1).

TABLE NO. 1

Nature of bend	Scour depth in terms of D_L
1. Straight reaches -- --	1.27 D_L
2. Moderate bends -- --	1.5 D_L
3. Severe bends -- --	1.75 D_L
4. Right angled bends -- --	2.0 D_L

However, it is to be remembered that these scour depths are only approximate and the choice of the coefficients can be made only with considerable experience in the field.

Using Lacey's regime formula, Khosla [18] derived an expression for the scour depth, relating it to the discharge intensity in the river, in the following manner. The minimum stable waterway, P_w, according to Lacey, is given by,

$$P_W = 2.67 \quad Q^{\frac{1}{2}} \tag{4}$$

The discharge intensity, q_1 in the waterway will then be,

$$q_1 = \frac{Q}{P_W} = \frac{Q}{2.67 \; Q^{\frac{1}{2}}} = \frac{Q^{\frac{1}{2}}}{2.67}$$

$$\text{or} \qquad Q = (2.67 \quad q_1)^2$$

Substitution of this relationship in equation (3) gives

$$D_L = 0.47 \left(\frac{Q}{f}\right)^{\frac{1}{3}} = 0.47 \quad \frac{(2.67 \; q_1)^{\frac{2}{3}}}{f^{\frac{1}{3}}}$$

$$= 0.90 \left(\frac{q_1^2}{f}\right)^{\frac{1}{3}} \tag{5}$$

Equation (5) is widely used in the design of loose aprons below weirs and barrages. With certain coefficients applied to it, equation (5) is used in the case of guide banks also. These coefficients, as proposed by Khosla, are given in table 2 below:-

TABLE NO. 2

Location	Range of scour depth	Mean depth to be adopted
Nose of guide bank --	$2 D_L$ to $2.5 D_L$	$2.5 \; D_L$
Transition from nose to straight portion --	$1.25 D_L$ to $1.75 D_L$	$1.5 \; D_L$
Straight portion of guide bank --	$1 D_L$ to $1.5 D_L$	$1.25 D_L$

Khosla's formulae also suffer from the same drawbacks as those of Lacey's in that the coefficients to be applied to different parts of the guide bank are only arbitrary and are found to vary considerably in actual practice.

Inglis [13] refers to the work done in the Central Waterpower, Irrigation and Navigation Research Station at Poona, where certain experiments were carried out with regard to the protection of bridge piers against scour. Model tests, usirg a single bridge pier model placed in a bed of sand of median diameter 0.29 mm. in a rectangular channel, gave the relationship,

$$\frac{D_1}{b} = 1.70 \left[\frac{q_c^{\frac{2}{3}}}{b} \right]^{0.78} \qquad (6)$$

in which D_1 = depth of scour below watr surface,

b = width of pier in ft. and

q_c = discharge per foot width in the centre of the channel i.e. upstream of the pier.

However, this was not found to agree with the observations made at the actual bridge site. Later Joglekar [9] pointed out that the reason for this deviation was that the horizontal extent of scour in/a vertically exaggerated model was always relatively greater than that in its prototype, the angle of repose of the bed material in both cases being the same. Furthermore, the discharge intensity, q_c, being dependent on the curvature of the channel upstream of the pier, was difficult to be determined. Therefore, the available prototype data was analysed and the scour depth was found to be of the order of twice the depth obtained from Lacey's formula (equation 3).

Inglis [13] has suggested the following scour depths downstream of bridges and at noses of guide banks and spur dikes. These are in terms of Lacey's scour depth:-

a) Maximum scour depth downstream of bridges is of the order of 4 D_L.

b) Scour at straight spur-dikes, facing upstream with steeply sloping heads ($1\frac{1}{2}:1$) is of the order of 3.8 D_L; and with long sloping heads (1 in 20), 2.25 D_L.

c) Scour at noses of guide banks with large radius is of the order of 2.7 D_L and

d) Scour at spur-dikes along river banks is 1.7 D_L to 3.8 D_L, depending on the severety of attack, which varies according to conditions such as length of projection, sharpness of curvature, angle and position relative to embayment etc.

Blench [3] has proposed certain coefficients to be applied to Lacey's regime depth for determining the scour depth around different types of obstructions, as given in Table 3 below:-

TABLE NO. 3

	Location	Coefficient
1.	Noses of spur dikes and guide banks	2.0 - 2.75
2.	Flow impinging at right angles to bank	2.25
3.	Between and around bridge-piers	2.0
4.	Downstream of barrages with Hydraulic jump on floor	1.75 - 2.25

These figures were based on the findings of the previous investigators like Lacey, Inglis and others and on his own experience in the field work.

More recently Mushtaq Ahmad [22] carried out laboratory investigations to study the behaviour of spur-dikes. Two sizes of bed materials of 0.354 mm and 0.695 mm mean diameters were used in his experiments. The maximum scour depth was found to be unaffected by this change in the sediment size. However, he believed that a wider range of size should somehow show an effect on the maximum scour depth. For determining the scour depth at the nose of a spur-dike he has suggested an expression of the form,

$$D_1 = K' \cdot q_1^{\frac{2}{3}}, \qquad (7)$$

in which the factor K' depends on angle of inclination of the spur-dike, flow concentration and angle of attack. For various locations and angles of the spur-dike and different flow conditions, he has proposed certain ranges of the value of K'.

It was found that the rate of development of the scour hole could be expressed by exponential functions of the form,

$$\frac{D_t}{D_1} = (1 - b\ e^{-at}) \qquad (8)$$

in which D_t = Depth of scour below water-surface after time t,

D_1 = maximum scour depth below water-surface;

t = time elapsed after placing the model

and a and b are constants.

The coefficient 'b' and the exponent 'a' were found to depend on the sand diameter. The data with the two sands showed that the value of 'a' varied approximately in the ratio of the sand diameters. Also according to him the rate of development of scour is much more rapid for a finer sand than for a coarser one, though the maximum scour depth is almost the same. In other words a coarser sand would take much longer time to attain the same depth of scour than the finer one.

Later, he [23] carried out experiments in order to find optimum spacing and lengths of spur-dikes for effective protection of the bank. T-head spur-dikes were used for this study instead of simple straight ones. It was observed that a single T-head spur-dike could protect the bank to a length of 3 to 5 times the projection of the spur-dikes. Further, he has shown that, if two spur-dikes are used, the optimum spacing should be approximately five times the projection of the spur-dikes. It was also suggested that if the bank to be protected is considerably long, more spur-dikes with the above mentioned spacing could be used. However, these conclusions have not been verified by field data.

<u>Laursen</u> [5,6,7] carried out laboratory investigations in order to study the scour characteristics around bridge piers and abutments. The investigation was done under four phases: 1) Geometry of piers and abutments 2) hydraulic characteristics, 3) sediment characteristics and 4) geometry of the channel cross - section and alignment. The shape and details of the abutments and piers were found to have only minor effects on the maximum scour depth. According to him, there exists a limiting depth of scour which will be approached asymptotically

with time. His significant inferece was that for given geometry of obstruction, the maximum depth of scour around bridge piers and abutments is directly related to the depth of flow in the channel and the width of the obstruction, provided there is appreciable sediment supply. The velocity of flow and the sediment size were found to have little influence on the equilibrium scour depth. Four sizes of sediment in the range of 0.48 mm and 2.20 mm median diameters were used in his investigation.

Recently, Laursen [8] has considered bridge crossings asa case of long contraction foreshortened to an extreme limit. He has obtained relationships from a combination of theoretical considerations and analysis of experimental data for predicting the scour depth around piers and abutments, for the case in which sediment was supplied to the scour hole. Manning's formulaw was used for describing the uniform flow conditions in the normal and contracted channel sections, and an approximate form of total sediment load relationship was used to describe the sediment concentration. Thus, relationships for determining the depth of scour in the contracted section were obtained. These relationship were further solved for the case of an encroaching abutment. The final design relationship for an encoraching abutment was of the form,

$$\frac{ds}{D} = f\left(\frac{b}{B}, \frac{V}{W}\right), \qquad (9)$$

in which ds = depth of scour below original bed,

d = depth of flow,

b = length of abutment

V = shear velocity = $\sqrt{gDS}$

and w = fall velocity of sediment particles.

For small variations in the ratio of shear velocity to fall velocity the depth of scour was found to depend mainly on the geometry of the obstruction and the depth of flow for a given mode of sediment movement.

For the case of scour around bridge piers a design curve of $\frac{d_s}{b}$ against $\frac{D}{b}$ based on the experimental data, has been proposed.

In the discussions on Laursen's paper Tison [9] stated that scour was found to occur even in the case of insignificant degree of contraction and attributes the cause to the curvature of the stream lines around the pier. By applying Bernoulli theorem to points on the curved streamline and on the relatively straight ones near the bank, he has shown that the flow dives dow around the upstream face of the pier resulting in scour. Ryland Thomas [9] analysed the data of model experiments on bridge pier which were carried out in CWINRS, Poona, in the light of Laursen' design curve for bridge piers. It was observed that these data did not agree with the design curve and fell much below it. The reason for this could not, however, be explained.

Andru [2] collected all the available data on scour depths from Laboratory experiments and prototype observations, obtained from various sources. With an aim of providing a practi cal rule for determining scour-depths around obstructions, he plotted all the data on a single graph after changing the dischar into discharge intensity. No attempt was made to separate the data according to the type of obstruction. The best-fit line by eye could be expressed as,

$$D_1 \cdot F_b^{\frac{1}{3}} = 1.35 \quad q_1^{0.74} \qquad (20)$$

in which F_b is the bed factor proposed by Blench and equals $1.9\sqrt{}$

where d is the mean diameter of the bed-material in mm. Another line was drawn with a slope of 2/3 and passing through the field data. This gave an expression,

$$D_1 \cdot F_b^{\frac{1}{3}} = 1.8 \; q_1^{\frac{2}{3}} \tag{11}$$

He has suggested that this equation could be as plausible as the best fit line. Because, for the model tests, he believed that the maximum scour depths were not attained in most cases, and hence model data fell lower than where they should be. Also the model data could be expected to have shifted towards the right because, while the river gave an average discharge intensi of the whole river width, the flume data gave q_1 actually attacking the obstructions.

Further, the data were grouped according to the type of obstruction and the following relationships have been suggested:-

1. For scour around bridge piers,

   $$D_1 \; F_b^{\frac{1}{3}} = 1.7 q_1^{\frac{2}{3}} \tag{12}$$

   in which q_1 is the mean discharge per foot width upstream of the bridge waterway.

2. For severe scour at obstructions like guide banks and spur-dikes,

   $$D_1 \cdot F_b^{\frac{1}{3}} = 2.05 \; q_1^{\frac{2}{3}} \tag{13}$$

   in which q_1 is the discharge per foot width of the contracted section in the case of spur-dikes and it is the percentage of total discharge attacking per foot width of attack in the case of guide banks.

Izzard and Bradley [15] also collected available model and prototype data from different sources and correlated the maximum scour depth to the discharge intensity in the contracted section. The relationship could be expressed as,

$$D_1 = 1.40 \ q1^{\frac{2}{3}}. \qquad (14)$$

They believe that the size of the bed material does not affect the maximum scour depth. According to them only the rate of scour was affected by the size and gradation of the material, the scour in finer sands reaching the equilibrium conditions sooner than scour in sands coarser ones. Further, they observed that the angle made by the sloping face of the scour hole to the horizontal (β in Fig. 1) varied from 20^{o} to 30^{o}. In other words the ratio $\frac{L}{d_s}$ varied approximately between 1.73 and 2.75, L being the horizontal extent of scour along the spur-dike (See Fig. 1). This variation, according to them, depends on the characteristics of the sediment and geometry of abutments.

Liu and Skinner [20] studied the scour around bridge abutments qualitatively. As a result of observations of the scouring process, they concluded that an equilibrium scour depth was obtained only in the case where there was appreciable sediment movement from upstream. In the case of no sediment motion the scour depth was found to increase indefinitely, though even in such a case, the coarser materials filling the scour hole helped to check the scouring. Mention has been made to the works of Keutner, Ishihara and Tison, who have attempted an analytical solution of the problem of scour. Reference was also made to Straub's analysis of equilibrium conditions in a contracted section in which he had expressed the regime depth in the contracted section as a function of the approach depth of flow and the degree of contraction.

Iwagaki and others [14] have also stressed the importance of the effect of sediment size in scour studies. They have suggested that the parameter which takes into account the characteristics of the bed material and of the fluid, is the average drag coefficient of the sediment particles.

Recently Garde and Subramanya [11] carried out investigations to study the role of the different variables which affect the scour around a spur-dike. Dimensional analysis was carried out in order to find the various non-dimensional parameters which influenced the phenomenon. The final form of the functional relationship was,

$$\frac{D_1}{R_b} = f\left(\frac{V}{\sqrt{gR_b}}\ ,\ C_D\ ,\ \theta\ ,\alpha\right) \qquad (15)$$

in which R_b = the hydraulic radius with respect to the bed,

$\frac{V}{\sqrt{gR_b}} = F_r$ = Froude number of flow,

α = opening ratio $= \frac{\text{width of opening}}{\text{width of channel}}$

C_D = average drag coefficient of the sediment particles

and θ = angle of spur-dike to direction of flow

Experiments conducted in the laboratory showed that for given

θ and size of bed material, the dimensionless maximum scour depth could be expressed as a function of the opening ratio and the Froude number.

The present study is based on the above analysis to determine the role of C_D on the scour characteristics around spur-dikes.

SUMMARY:

The review of works of the various investigators shows that many of them provide certain practical rules for determining scour deths. Considerable differenece exists in considering the role of the different variables, such as the degree of contraction and the sediment size. Thus Lacey, Khosla and Andru include in their formulae certain factors, which take into account the size of the bed material. On the other hand, some of the investigators like Izzard and Bradley, and Laursen maintain that the equilibrium scour depth is unaffected by changes in the sediment size. Considering the importance of the problem of scour, it is felt that a thorough knowledge of the effect of sediment size on scour characteristics is highly essential. This can be obtained only by a systematic experimental investigation in the laboratory.

CHAPTER III

DIMENSIONAL ANALYSIS

CHAPTER - 3

DIMENSIONAL ANALYSIS

It was pointed out in the previous chapter that, due to the complex nature of the phenomenon, it is almost impossible to solve the problem of scour around obstructions by purely theoretical analysis. Therefore, experimental investigation has to be adopted in order to determine the laws governing the phenomenon. However, before starting the experimental programme, it is necessary to determine the important parameters which are involved. These parameters can be deduced logically by subjecting all the pertinent variables to dimension analysis. This analysis need to be verified by experimental data.

DIMENSIONAL CONSIDERATIONS:

The maximum depth of scour below the water surface, D_1 (see Fig. 1) is considered as the dependent variable in order to study the effect of the different variables on it. The independent variables which influence the phenomenon can be classified into the following groups:

1. Variables describing the geometry of the channel and of the spur-dike,
2. variables describing the flow,
3. variables pertaining to the fluid, and
4. variables which describe the characteristics of the bed material.

The geometry of the channel was considerably simplifie by using a straight rectangular flume. The width, B, of the flume (see Fig.1) is the vairable which describes the geometry of the channel. The flow pattern around spur-dike will be different for various lengths of the spur-dike, b, and also for various angles or inclination, θ, of the spur-dike to the direction of flow. In the present series of experiments, a simple form of a spur-dike of very small thickness was used, thus simplifying its geometry. Hence b and θ adequately represent the geometry of spur-dike. The variables describing the flow characteristics are the mean velocity in the channel, V, the depth of flow, D, and the slope, S, of the energy line. However, the slope, S, being a function of V, D and sediment and fluid characteristics, cannot be considered as an independent variable. The mass density of water, ρ, and its dynamic viscosity, μ, are important variables in the study of fluid flow problems. Also the existence of a free surface in open channel flow necessitates the inclusion of the gravitational force. The gravitational action depends on the difference between the specific weights of the two fluids in contact. Therefore, the difference in specific weights between water and air, $\Delta\gamma$, is also included as an importance variable. However, since the specific weight of air is comparatively negligible, $\Delta\gamma$, is approximately equal to the specific weight of water, γ. For the sediment the median size, d, can be taken as the representative size. The relative motion of sediment and water depends also on the difference in specific weights of sediment and water, $\Delta\gamma_s$. It is reasonable to believe that the standard deviation of the bed material, σ is important in problems related to scour. The standard deviation, σ is defined as

$$\sigma = \frac{1}{2}\left[\frac{d50}{d16} + \frac{d84}{d50}\right] \qquad (16)$$

in which d_{50}, d_{16} and d_{84} are the particle sizes than which 50%, 16% and 84% respectively of the material are smaller. The effect of the shape of the particles cannot be ignored since it affects the fall velocity of the sediment particles and hence the sediment movement. Mc-Nown and Malaika [16] and Albertson [1] have shown how the fall velocity is affected by the shape of the particles. They have suggested that $\eta = \frac{c}{\sqrt{ab}}$ in which a, b and c are respectively semi-major, semi-intermediate and semi-minor axis lengths, is the best way of representing the shape parameter.

Thus the different variablescan be written in the form of a functional relationship as given below:

$$D_1 = f\left(B, b, \theta, V, D, \rho, \mu, \Delta\gamma, d, \Delta\gamma_s, \sigma, \eta\right) \qquad (17)$$

The fall velocity of the sediment particles, w, is a function of d, η, ρ, μ and $\Delta\gamma_s$. Therefore the viscosity, μ can be replaced by w. Hence equation (17) becomes,

$$D_1 = f\left(B, b, \theta, V, D, \rho, w, \Delta\gamma, d, \Delta\gamma_s, \sigma, \eta\right) \qquad (18)$$

Choosing V, D and ρ as the repeating variables and applying the π theorem, the following relationship can be obtained:

$$\frac{D_1}{D} = f\left(\frac{B}{D}, \frac{b}{D}, \theta, \frac{V}{\sqrt{\frac{\Delta\gamma}{\rho}D}}, \frac{V}{w}, \frac{d}{D}, \frac{V}{\sqrt{\frac{\Delta\gamma_s}{\rho}D}}, \sigma, \eta\right) \qquad (19)$$

Equation (19) shows that the non-dimensional scour depth $\frac{D_1}{D}$ depends on nine dimensionless terms. Some of the terms in the above relationship can be modified in order to have better significance from fluid mechanics point of view. Thus,

$$\frac{V^2\rho}{\Delta\gamma_s D} = \frac{V^2 \rho\, g}{g . D . \Delta\gamma_s} = \frac{V^2}{gD}\ \frac{\gamma}{\Delta\gamma_s} = f\left(\frac{V}{\sqrt{gD}}\ ,\ \frac{\gamma_s}{\gamma}\right), \tag{20}$$

and $$\frac{V^2}{w^2} = \frac{V^2\rho}{w^2\rho}\ \frac{\Delta\gamma_s d}{\Delta\gamma_s D}\ \frac{D}{d} = \left(\frac{\Delta\gamma_s d}{w^2\rho}\right)\left(\frac{V^2\rho}{\Delta\gamma_s D}\right)\left(\frac{D}{d}\right) .$$

But the average drag coefficient of the sediment particles, C_D, is equal to $\frac{4}{3}\ \frac{\Delta\gamma_s d}{w^2\rho}$ and hence,

$$\frac{V^2}{w^2} = f\left(C_D\ ,\ \frac{V}{\sqrt{gD}}\ ,\ \frac{\gamma_s}{\gamma}\ ,\ \frac{d}{D}\right). \tag{21}$$

As mentioned earlier, $\Delta\gamma$ can be replaced by γ and hence

$$\frac{V}{\sqrt{\frac{\Delta\gamma}{\rho}\ D}} = \frac{V}{\sqrt{gD}} .$$

Also $$\frac{b}{D} . \frac{D}{B} = \frac{b}{B} .$$

Substituting these relationships in equation (19) the following relationships ~~in-equation~~ is obtained:

$$\frac{D_1}{D} = f\left(\frac{B}{D},\ \frac{b}{B},\ \theta\ ,\ \frac{V}{\sqrt{gD}},\ \frac{d}{D}\ ,\ C_D\ ,\ \frac{\gamma_s}{\gamma}\ ,\ \sigma,\ \eta\right) \tag{22}$$

However, it is not possible to analyse the experimental data with such a large number of dimensionless groups. Hence, certain simplifying assumptions need to be made before equation (22) can be conveniently used to analyse experimental data.

It is believed that the standard deviatkon, σ , is an important factor which affects the scour around obstructions So far its effect has not been fully studied. Rouse [24] observed that a wide variatkon in the size of the bed material caused the coarser particles to remain in the scour hole while the finer materials were scoured out. Thus the scour hole became gradually paved with the coarser material, thereby reducing the rate of scour. The layer of coarser material which gradually covers the scour hole acts as an armour plating and checks further scouring. The limiting depth of scour could therefore be different for two sands having the same diameter but with different standard deviations. However, if the value of σ of the various sands is chosen to be approximately same as that of the natural bed material, then as a first approximation σ can be omitted.

Secondly, it is known, that the shape factor, η of natural materials does not vary widely and that it has a value between 0.7 and 0.75. Therefore, η can be omitted. Thirdly, the specific gravity of the various materials was almost same in the present investigation. Also, it can be assumed that, rather than the ratio of the specific gravities of sediment and water, the problem involves the difference between the two which has been already taken into consideration in the parameter C_D. Hence $\frac{\gamma_s}{\gamma}$ can also be omitted. Fourthly, the ratio $\frac{d}{D}$ in open channel flow is comparable to the samd grain roughness parameter in pipe flow problems, the size of sediment, d corresponding to the height of the roughness. In most of the runs in the present investigation, the ripples and dunes had developed on the bed of the flume. The height of the ripples and dunes was much greater when compared to the diameter of the particles. For such cases it can be assumed that $\frac{d}{D}$ is not significant. Lastly, the breadth to depth ratio, $\frac{B}{D}$ is important only for the case of three - dimensional flow problems. The flow could be considered to be two - dimensional (which occurs when the channel is either rectangular or very wide) since a rectangular flume was used in the present series of experiments. Moreover, the side wall effect was eliminated by using the hydraulic radius with respect to the bed, R_b, instead of D in the analysis. For these reasons $\frac{B}{D}$ could be omitted. Thus, equation (22) reduces to

$$\frac{D_1}{R_b} = f\left(\frac{V}{\sqrt{gR_b}},\ \frac{b}{B},\ \theta,\ C_D\right). \qquad (23)$$

The opening ratio, $\alpha = (1-\frac{b}{B})$ is used instead of $\frac{b}{B}$.

Hence,

$$\frac{D_1}{R_b} = f\left(\frac{V}{\sqrt{gR_b}},\ \alpha,\ C_D,\ \theta\right). \qquad (24)$$

Thus the non-dimensional depth of scour $\frac{D_1}{R_b}$ seems to depend mainly on four dimensionless parameters, namely the Froude number of the flow, F_r ($= \frac{V}{\sqrt{gR_b}}$) the opening ratio, the angle of inclination of the spur-dike, θ and the average drag coefficient of the sediment particles. Equation (24) provides a simplified relationship which can be used for the analysis of the experimental data.

The inclusion of the average drag coefficient of the sediment particles, C_D, in equation (24) indicates the importance of the role of sediment characteristics on the maximum scour depth. The geometry of the channel and the spur-dike is represented by α and θ. The importance of Froude number as the governing flow parameter can be explained in the following manner.

In the case of open channel flow a free surface exists and therefore the gravitational effects are important. The froude number of the flow is a measure of the influence of the gravitational action on the flow phenomenon. The relative effect of gravity is greater for smaller values of Froude number and the effect decreases with increasing Fr. the various characteristics of flow in open channel, such as the surface configuration, the flow pattern and the pressure distribution are directly related tothe Froude number (See p. 54 of Ref. 24). Considering two geometrically similar channels, the flow pattern will be similar if the Froude number is same in both the channels. This is true also for the case of flow in open channel with lateral constriction. The scour around the obstruction is caused by changes in the flow pattern which modifies the shear distribution on the bed. Due to these reasons Froude number should be an important parameter in scour studies. Furthermore, it is well known that even in the case of unobstructed alluvial channels the Froude number is an important parameter. Garde [12] has shown that the various characteristics of dunes on the bed of the channel are functions of the Froude number and the dimensionless bottom shear.

In the present investigation, a constant opening ratio $\alpha = 0.835$ was used. Also the spur-dike was kept at right angles to the flow (i.e. $\theta = 90^{\circ}$). Therefore the equation (24) reduces to the final form,

$$\frac{D_1}{R_b} = f \quad (F_r \, , \, C_D) \qquad (25)$$

In order to verify this functional relationship, experiments were carried out in the laboratory using different sizes of sand and varying the Froude number of the flow. The experimental data were analysed in order to find the exact from of the relation between the three parameters.

CHAPTER IV

EXPERIMETAL EQUIPMENT AND PROCEDURE

CHAPTER - 4

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The dimensional analysis has shown that the dimensionless maximum scour depth, $\frac{D_1}{R_b}$ depends on the Froude number of flow and the average drag coefficient of the sediment particles, provided the rest of the variables are held constant. This functional relationship was verified by carrying out experiments in the laboratory and analysing the data. A detailed description of the experimental equipment and the procedure adopted in carrying out the experiments are given below:

EQUIPMENT:

The experiments were conducted in a straight rectangular flume (see fig. 2) with glass side walls. The flume was 8-ft wide and 25-ft. long and was of the non-recirculating type. A 12-ft. long head-box, upstream of the flume was fitted with brick baffles and wooden screens. A radial tail gate, which could be operated by a rack and pinion arrangement, was provided at the downstream end of the flume. At the upstream and downstream ends of the flume, cross walls 9" in height were provided and sand was filled between these walls. Angle irons running along the top of the side-walls served as rails along which a point-gauge could be moved.

Water was supplied to the flume from a constant head tank through a 6" supply line. A 6" x 3" venturimeter fitted in the pipe line was used for measuring the discharge passing through the flume. The venturimeter was calibrated before the experiment were started. The discharge into the flume was controlled by the operation of a valve located in the supply line. The water then passed through the baffles and screens in the head box. The baffles and screens helped to destroy the excess energy of the flow and to distribute the flow uniformly across the width of the flume. The water then entered the flume and flowed over the sand bed which was 9" in thickness and discharged over the tail gate into the sump. The water was constantly pumped from the sump to the overhead tank.

A point-gauge mounted on a wooden frame was used for taking the bed-surface and water-surface readings. A plastic shoe about ½" in diameter, was attached to the tip of the point-gauge, in order to make the measurement of the bed-surface elevation easier. The point-gauge could be slided across the flume on a frame work which had a graduated scale fixed to its side. The frame-work along with the point gauge could in turn be moved throughout the length of the flume along the horizontal rails at the top of the side walls. Thus, the point-gauge could be brought to any desired position in the flume. It was possible to measure a difference of 0.001 ft in the elevation with the help of this point-gauge.

The spur-dike model used for the experiments was a thin vertical steel plate, 4" broad and approximately 2 ft high This gave an opening ratio, α = 0.835. The temperature of the water was measured with a thermometer.

SEDIMENT:

Four different sizes of sand of median diameters 0.29 mm, 0.45 mm, 1.00 mm and 2.25 mm were used for the experiment

The sizes of these sands were determined by sieving them through a number of sieves and plotting the size distribution curves (fig. 3). Specific gravities of the various sands were determined with the help of a pyknometer. The characteristics of the various sands are given in Table 4 below:

TABLE 4

SAND	d mm	σ	Sp. gr.	Remarks
A	0.29	1.66	2.69	Natural sand (Ranipur)
B	1.00	1.38	2.75	Sieved
C	2.25	2.08	2.72	Sieved
D	0.45	1.77	2.71	Sands A and B were sieved and mixed in certain proportions.

PROCEDURE:

Before the beginning of each run the sand bed was screeded by means of a wooden template, to give an approximate predetermined slope. A desired discharge was then allowed to flow through the flume by opening the valve slowly so that the sand bed was not disturbed. The tail-gate was carefully lowered and adjusted in such a way as to make the water-surface slope fairly the same as the bed-surface slope. The water was allowed to flow in this condition for two to three hours during which time the bed of the flume adjusted itself to the conditions of flow. When a uniform and stable flow condition was attained, readings of the water-surface and bed-surface elevations were taken at every 1 f along the flume. Fig. 4 shows typical water-surface and bed-surface profiles.

When equilibrium conditions of flow were attained, the spur model was introduced in the flume at 9'-9" downstream of the entrance to the flume. It was believed that the entrance effects did not extend upto this distance. A stop watch was started at the instant when the spur model was introduced. Bed readings were taken at the nose of the spur model at regular ½ hour intervals except in the initial stages, when readings were taken at closer intervals, because of the higher rate of scour. The scouring around the spur model was thus allowed to develop to a stage when the increase in the scour depth was at a very slow rate and could not be detected with the point-gauge. This equilibrium condition of scour was obtained in 1½ to 6 hours or more after the introduction of the model. The temperature of water was taken at various stages during the run in order to get the average temperature of water.

When scour reached equilibrium conditions, the distance N, from the model along the side wall to a point downstream, where a jet of water flowing through the contracted area hit the side wall, was measured. This point, which was termed as the Null point, was located by dropping potassium permanganate solution at different points along the side wall. At a certain point the coloured solution neither moved upstream nor downstream. However, this point was fluctuating and it was very difficult to locate it accurately.

The flow was then slowly stopped and the tail-gate was lowered to drain the water in the flume. Care was taken to see that the scour pattern was not disturbed. Point-gauge readings of the bed around the spur-dike were then taken at regular 3" intervals along and across the flume. With the help of these readings contour maps of the scoured bed around the spur-dike could be plotted. In order to get a correct cross section of the bed at the spur-dike, bed readings were taken at 1", intervals along the model.

The bed of the flume was rescreeded to give a different slope and a similar procedure was adopted with the same discharge as before, but with a different depth of flow. After 4 or 5 runs with this discharge, another set of experiments were conducted with a different discharge. In the case of sands, A, B and C the discharge was maintained at 0.40 and 0.80 cusecs, and for the sand D a wider range was used. The aim was to get as wide a range of Froude number as possible. The data collected by Garde and Subramanya for $\alpha = 0.835$, using 0.29 mm sand were also used for the present analysis.

After the completion of the experiments with one size of the sand, the sand in the flume was removed and a different size of sand was placed in it. A new set of experiments were conducted. Approximately 8 runs were made with each of the four sands. In all 35 runs were made.

The clear water flowing over the sand bed near the upstream end of the flume carried some sediment from the upstream end and provided the necessary sediment supply to the downstream portion of the flume. For the runs in which the rate of sediment movement was large, the sand collected in the tail-gage was occasionally taken out and was fed near the upstream en in small quantities at regular intervals of time.

Inorder to study the applicability of the present analysis to the case of scour around bridge piers, a pier model (length to breadth ratio 3:1) with cylindrical ends and giving opening ratio, $\alpha = 0.835$ was used. The pier model was introduced in the sand bed at a distance downstream of the spur-dike far enough that the scour around the pier was not affected by the spur-dike. At the end of each run the bed reading was recorded at the point of maximum scour. The data for the pier model was collected only for 0.45 mm sand along with the first five runs of that series.

For studying the present problem a recirculating flume would have given better results. However, it was thought that sufficient information could be obtained with the available non-recirculating system.

CHAPTER V

PRESENTATION AND ANALYSIS OF DATA

CHAPTER - 5

PRESENTATION AND ANALYSIS OF DATA

The data collected in the Hydraulics Laboratory were used for verifying the functional relationship# obtained through dimensional analysis. The relationships proposed by the various investigators for the determination of the maximum scour depth were also verified with the help of these data. The role of the sediment size in determining the various scour characteristics-namely, the rate of development of the scour hole, the geometry of the scour hole and the maximum scour depth-was also studied. Before proceeding to the actual analysis, it is thought necessary to mention the methods adopted for calculating the various hydraulic and other parameters used for the analysis.

COMPUTATION OF BASIC PARAMETERS:

The discharge flowing through the system was obtained by finding the average of several observations taken during each run. The depth of water at one foot interval along the flume was obtained from the water-surface and bed-surface readings. The mean value of these depths was taken as the depth of flow, D. Using the relationship, Q = V.D.B., the mean velocity of flow was calculated.

The side wall effect was eliminated by using the hydraulic radius with respect to the bed, R_b, instead of the actual depth of flow. Johnson's method [17] , used for this computation of R_b, is given below:

The area of flow is divided into two parts, the area of the side walls, A_w and the area of the bed A_b. Manning's formula as applied to the glass side walls can be written as,

$$V = \frac{1.486}{n_w} \cdot R_w^{\frac{2}{3}} \; S^{\frac{1}{2}},$$

in which n_w = Manning's 'n' for the walls, which was assumed to be 0.01 for glass.

and R_w = Hydraulic radius with respect to the walls.

Hence,

$$R_w = \left(\frac{V \cdot n_w}{1.486 \; S^{\frac{1}{2}}} \right)^{3/2} = \frac{A_w}{P_w},$$

where P_w is the wetted perimeter of the side walls = 2D. The area of the bed will then be,

$$A_b = A - A_w = B.D - 2\,D.\;R_w \;.$$

Also $\quad R_b = \frac{A_b}{P_b} = \frac{A_b}{B} = \frac{B.D. - 2\,D.R_w}{B} = D - \frac{2D}{B}.\;R_w\;,$

$$\text{or} \quad R_b = D - \frac{2\,D}{B}\,R_w\;. \qquad (26)$$

Thus, knowing the values of R_w, B and D, R_b can be calculated.

In most of the runs, both water-surface slope and bed-surface slope were fairly the same. Hence the slope of the water-surface was taken as the slope of the total energy line. For those runs, in which the two slopes differed appreciably, the slope of the energy line was calculated using the following formula proposed by Einstein and Ning Chien:

$$S_e = S_w - (S_w - S_b)\;\frac{V^2}{2g} \qquad (27)$$

in which S_e, S_w and S_b are the slopes of the energy line, water-surface and bed-surface respectively.

The width of the scour hole in front of the spur dike, L (see Fig. 1) was obtained from the cross section of the scoured bed at the spur-dike.

The average drag coefficient of the various materials was calculated from the formula,

$$C_D = \frac{4}{3} \frac{\Delta \gamma_s d}{w^2 \rho} ,$$

the fall velocity w being taken for an average temperature for each sediment size. This is permissible, since the variation of temperature for each set of data was only about 4° C.

ANALYSIS OF DATA:

Since a constant opening ratio, $\alpha = 0.835$ was used for the investigation, all the results and conclusions given in the following pages hold only for a constant value of α. However, Garde and Subramanya [11] have already suggested procedure for considering the effect of variation of α on maximum scour depth. With this information it is thought that the results of the present investigation can be applied for different values of α also.

1. RATE OF SCOUR:

Whether the scouring process around an obstruction attains equilibrium conditions after a certain time, is controversial. According to Liu and Skinner [20] the scour depth reaches a limiting value only for the case in which sediment is supplied into the scour hole from the upstream. If there is no sediment supply, the scour depth increases indefinitely. Laursen [7] has also demonstrated experimentally that equilibrium conditions of scour exist for the case of sediment supply. In the case of bed scour due to vertical non-submerged jets, Doddiah and others [4] have shown that the depth of scour increase with time in a geometric progression without reaching a limiting value. In almost all the runs of the present series of experiments the scouring process reached a stage when changes in the scour depth with time were difficult to be measured with the available point-gauge. Thus, for all practical purposes, the scour depth attained a limiting value, though it may be increasing very slowly with time. This limiting value is taken as the maximum scour depth, D_1 for all the further calculations. Fig. 5 shows typical cases of development of scour hole for the different sizes of sand. The time taken for attaining the stable scour depth varied widely. In many of the runs this time ranged from 4 to 6 hours. In certain cases it took only about $1\frac{1}{2}$ hours, whereas in frew others even 8 hours time was not quite sufficient to reach equilibrium state.

In the initial stages of the run, the scour hole developed at a very high rate. Thereafter, the depth of scour increased at a much slower rate untill it reached the limiting value. Since the actual rate of scour thus varied with time for a particular run, it was difficult to compare the rates of scour for different sizes of sand as also for various flow conditions. Garde [10] has shown that the dimensionless form of the scour depth $\frac{dt}{ds}$ after any time t can be expressed as a function of the ratio of t to the time, T of attaining equilibrium. The equation thus developed is of the form,

$$\frac{d_t}{d_s} = A \operatorname{Log}_{10} \frac{t}{T} + 1 \qquad (28)$$

in which the variation of the coefficient A was suggested to be dependent on the flow conditions for a particular size of the sediment and for given values of α and θ. Fig. 6 shows a typical plot of $\frac{d_t}{d_s}$ against $\frac{t}{T}$. For measurable values of $\frac{t}{T}$ the correlation seems to be quite satisfactory. Values of A were obtained for various flow conditions with different sediment sizes and its relation with Froude number was studied. Fig. 7 shows the variation of A with F_r for various values of C_D. They show a definite trend although there is some scatter of the points. The value of A is found to decrease gradually with increasing Froude number for a given C_D. This indicates that for constant values of C_D and $\frac{t}{T}$, as F_r is increased the value of $\frac{d_t}{d_s}$ increases correspondingly. However, the time taken for attaining equilibrium scour depth is found to be independent of the flow characteristics. It is again seen from fig. 7 that A has smaller values for the coarser materials than those for finer ones, for the same flow conditions. These qualitative results give a better physical picture of the rate of scour. According to Mushtaq Ahmad [22] and Izzard and Bradley [15] scour in finer material reaches equilibrium conditions sooner than scour in coarser material. However, the results of the present analysis do not show such a condition to exist. On the other hand, in most of the runs with the coarser sediment equilibrium conditions were attained in comparatively much shorter time.

2. GEOMETRY OF SCOUR HOLE:

The point gauge readings of the scoured bed taken after the completion of each run were used for preparing contour maps of the scour hole. Fig. 2 is typical of such a map. Certain general features of the scour pattern are common for all the runs. In most of the runs maximum scouring occurred at the nose of the spur-dikes. In few of the runs with high Froude numbers, there was considerable disturbance to the flow and formation of vortices near the upstream face of the spur-dike. Due to these disturbances the scour depth along the upstream face of the spur-dike was a little more than that at the nose. The location of the maximum scour depth for the various runs is given in Table No. 1 of appendix.

Upstream of the spur-dike the scour hole has an approximate shape of an inverted cone with its apex at the spur-nose. The scour hole flattens out towards the downstream side. Most of the scoured material deposits in the immediate downstream of the spur-dike along the side wall. A bar is thus formed downstream of the spur-dike. This deposition of the material near the wall is of practical importance, as it helps to protect the bank from erosion. A study of the bars formed for the various runs indicates that their relative position is governed mainly by the velocity of flow. Fig. 9 shows the positions of the bars for the various runs with 0.29 mm. 1.0 mm and 2.25 mm sands. With low velocitie the deposition is effected in the immediate downstream of the spur-dike and the bar thus formed is inclined towards the centre of the channel. With higher velocities the bar has a tendency to move a little downstream and to become fairly parallel to the side wall. This can be noticed in Fig. 9. It can be believed that the effective length of the bank which can be protected by the spur-dike depends on the position and length of the bar and therefore on the velocity in the channel. With the four sands tested, there were no noticeable differences in the geometry of the scour hole due to changes in sediment size. Therefore the size of the bed material appears to have no appreciable influence on the qualitative appearances of the scour hole.

The width of the scour hole in front of the spur dike, L (see Fig. 1) is important especially in view of the navigability of channels in erodible material. When spur-dikes are used for the improvement of the depth of navigation, the horizontal extent of the scour-hole has also to be taken into consideration. In order to study the variations in L, it was expressed in the dimensionless form $\frac{L}{d_s}$. Values of L/d_s were computed for those runs in which scour did not reach the opposite wall of the flume. In fig. 10 are plotted the values of L/d_s for various values of Fr for the four sediment sizes. The value of L/d_s is found to have almost a constant value of approximately 2.0 for the finer sands. In other words, the angle β (see Fig. 1) made by the sloping face of the scour hole with horizontal has an average value of 27° and ranges between 24° and 30°. Izzard and Bradley [15] obtained similar results and in their case angle β ranged between 20° and 30°. Laursen [8] has suggested a value of 2.75 for L/d_s ($\beta = 20^\circ$) for determining the scour depth around bridge abutments. However the results of this analysis do not fully agree with the constant value proposed by Laursen. There is a tendency for increase in $\frac{L}{d_s}$ values with decrease in Fr. However, there is appreciable scatter, as can be seen from Fig. 10.

The coarser sediment of 2.25 mm diameter behaves slightly different from the others in this respect. The $\frac{L}{d_s}$ values are slightly higher than those for the other three sizes of sand, for which fairly similar values are obtained The values for the coarser sediment range between 2.75 and 3.25 (or $\beta = 17^{\circ}$ to 20°).

3. NULL POINT:

In the chapter 'Equipment and Procedure' (p. 29) the null point was defined as the point where the jet of water flowing through the contracted area hit the side wall on the spur-dike side. When water strikes the bank there is the possibility of the bank being eroded. The positions of the null point, therefore, is of considerable practical importance in the protection of the bank from erosion. This position will also throw some light on the desirable and safe distance between two spur-dikes.

It was then mentioned that the distance, N of the null point from the spur model was measured for the various runs. These data are shown in Fig. 11 for various values of Froude number with different sizes of sand, after converting N into the dimensionless form of $\frac{N}{b}$, where b is the length of the spur dike. It is seen from fig. 11 that in most of the runs the $\frac{N}{b}$ values like between 2 and 5. However, with low Froude numbers exceptionally high values for $\frac{N}{b}$ of the order of 10 are obtained.

In general there is a tendency for $\frac{N}{b}$ values to decrease with increase in Fr. This can be seen from the data for 0.29 mm, 1.0 mm and 2.25 mm sediments. However, the scatter for sediment of 0.45 mm is too great to even draw a qualitative conclusion. There seems to be no reason why 0.45 mm sand should not behave similar to the other sizes of sand. The reason for the scatter can be attributed to the difficulty in measuring N accurately. In practice the distance N can be obtained only by conducting model tests.

4. MAXIMUM SCOUR DEPTH:

a. VERIFICATION OF DIMENSIONAL ANALYSIS

According to dimensional analysis, under the limitations imposed on the investigation the non-dimensional depth of scour is a function of the Froude number and the average drag coefficient; or,

$$\frac{D_1}{R_b} = f \quad (Fr , C_D) . \qquad \text{(Equation 25)}$$

The experimental data were analysed in order to verify this relationship. In Fig. 12 are plotted the values of $\frac{D_1}{R_b}$ against Fr for all the four values of C_D. The correlation appears to be very satisfactory. The slope of the line in Fig. 12 is found to vary for changes in C_D. For constant drag coefficient the line can be expressed by the equation:

$$\frac{D_1}{R_b} = C \cdot Fr^n \qquad (29)$$

in which n is the slope of the line and C is a dimensionless number. Garde and Subramanya [11] have shown that the value of

C depends on the opening ratio, α, for given size of the bed material. The relationship could be expressed as:

$$C = \frac{K}{\alpha} \qquad (30)$$

in which K is another coefficient. Hence equation (29) becomes,

$$\frac{D_1}{R_b} = K \frac{1}{\alpha} F_r^{\,n} \qquad (31)$$

For an average drag coefficient of 2.85 (equivalent to a median diameter of 0.29 mm) Garde and Subramanya obtained a value of 2/3 for the exponent n. In Fig. 12, for $C_D = 2.85$, the additional data collected during the present series of experiments are plotted. It includes also data from two runs of the previous investigation by Garde and Subramanya for the same openi[ng] ratio of 0.835. The slope of the line is again 2/3. For $C_D = 1.$[8] (d = 0.45 mm) the exponent n is found to be equal to 0.75. It can be seen from Fig. 12 that with the four values of C_D used for the investigaion, the steepest slope of the ~~wal~~ line occurs when $C_D = 0.80$ (d = 1.0 mm) giving n a value of 0.90. When $C_D = 0.45$ (d = 2.85 mm), the value of n is smaller and equal[s] 0.80 . Fig. 13 shows variation of n for various values of C_D. The data collected for the four values of C_D used for the investigation indicate that the exponent n increases for decreasing values of C_D (i.e. for increasing size of sediment). The value of n appears to reach a maximum of 0.90 for a C_D approximatly equal to 0.80 (d = 1.0 mm). Thereafter for further decrease in C_D the value of n decreases correspondingly.

The coefficient K in equation (31) is also found to va[ry] with the drag coefficient. The variation of K with C_D is also plotted on Fig. 13. It is remarkable that the variation in the value of K with C_D is comparable to that of n. The value of K is also found to attain a maximum of approximately 5.0 when the drag coefficient is 0.80. For C_D values larger than 0.80, K decreases gradually. The decrease in K value is much more rapid for C_D less than 0.80. The variations in the values of the exponent n and the coefficient K with drag coefficient clearly indicates that the maximum scour depth is considerably influenced by the bed material size.

The data collected for the bridge pier model with 0.45 mm sediment is also plotted in Fig. 12. These data also follow the same trend as the spur-dike data. This shows that the present analysis is applicable to the case of scour around bridge piers also.

b. VERIFICATION OF RESULTS OBTAINED BY OTHER INVESTIGATORS:

(1) MAXIMUM SCOUR DEPTH AS A FUNCTION OF DISCHARGE INTENSITY:

It would be of interest to see how the formulae proposed by the various investigators behave in the light of the present analysis. These formulae have been discussed at leng in the chapter of 'Review of Literature'. Below is given a table of the various formulae and the name of the investigators:

TABLE NO. 5

Sl.No.	Name of the investigator	Reference	Formula
1	Lacey	[19]	$D_L=0.47\left(\frac{Q}{f}\right)^{\frac{1}{3}}$
2	Khosla	[18]	$D_L=0.90\left(\frac{q_1^2}{f}\right)^{\frac{1}{3}}$

Sl.No.	Name of the Investigator	Reference	Formula
3	CWINRS	[13]	$\frac{D_I}{b} = 1.70\left[\frac{q_c}{b}^{\frac{2}{3}}\right]^{0.78}$
4	Mushtaq Ahmad	[22]	$D_I = K'.q_1^{\frac{2}{3}}$
5	Andru	[2]	$D_I\ F_b^{\frac{1}{3}} = 2.05\ q_1^{\frac{2}{3}}$
6	Izzard & Bradley	[15]	$D_I = 1.40\ q_1^{\frac{2}{3}}$

It can be observed from the above table that most of the expressions relate the maximum scour depth D_1 to the discharge intensity q_1 in the contracted section. In some of the formulae, factor which takes into account the sediment size is also included. Fig. 14 shows the variation of D_1 with the discharge intensity q_1 for the various materials. The correlation appears to be quite satisfactory for the two finer sands of 0.29 mm and 0.45 mm median diameter. For 0.29 mm sand the relationship can be expressed as,

$$D_1 = 1.37\ q_1^{\frac{2}{3}} \tag{32}$$

which agrees well with the formula (equation 14) suggested by Izzard and Bradley. For 0.45 mm sand the coefficient is slightly lower and is found to be 1.25. The discharge used for the coarser sand in the present experiments was not varied and therefore data are not sufficient to show any definite correlation. The few points with 2.25 mm sand, however, fall much below the data for the other sands. Equation of this type thus appears to be inferior to the equation (31) for accurately predicting scour depths around spur-dike.

In the formula proposed by Andru (equation 13) a Bed-Factor, F_b, which is a function of the sediment size, is included. The values of F_b for the various materials used in the present investigation were calculated using the formula, $F_b = 1.9\sqrt{d}$. Values of $D_1 \cdot F_b^{\frac{2}{3}}$ were then plotted against q_1. Fig. 15 shows such a plot in which the equation proposed by Andru is also plotted. A comparison of this plot with Fig. 14 shows that the data for the various sizes of sand are brought closer, giving a better correlation. But the scatter of the data for the same sand remains essentially unaltered. Further, the constant ~~as~~ coefficient 2.05 in his relationship appears to be a little too high with respect to the author's data. An average line through the points, as shown in Fig. 15 gives the constant, a value of approximately 1.40. However, if the data are plotted on a much smaller scale as in the case of Andru's plot, the scatter of the points can be expected to become unimportant compared to the scatter of other points on his plot. Points on his plot scatter considerably, especially his own experimental data. It is, therefore, believed that the expression in which the maximum scour depth is related to the discharge intensity, is not very accurate.

It is possible, by slight manipulations, to convert the Froude number relationships that were obtained for the various sizes of sand, into discharge intensity relationships. For example, with 0.29 mm sand the relationship can be expressed as,

$$\frac{D_1}{R_b} = 4.0\ \frac{1}{\alpha}\ Fr^{\frac{2}{3}} \qquad (34)$$

Hence $D_1 = 4.0\ \frac{1}{\alpha}\ R_b \left(\frac{V}{\sqrt{gR_b}}\right)^{\frac{2}{3}} = \frac{4.0}{g^{\frac{1}{3}}}\ \frac{1}{\alpha}\ V^{\frac{2}{3}}\ R_b^{\frac{2}{3}}$

$$= 1.26 \quad q_1^{\frac{2}{3}} \left(\frac{1}{\alpha^{1/3}}\right) \tag{35}$$

because, R_b is approximately equal to D. Similary for 0.45 mm sand the following expression can be obtained:

$$D_1 = 1.30 \; q_1^{\frac{2}{3}} \left(\frac{V^2}{R_b}\right)^{\frac{1}{24}} \left(\frac{1}{\alpha^{1/3}}\right) \tag{36}$$

Similar expressions can be obtained for the other sediment sizes also. These expressions include certain powers of α, V and R_b other than the discharge intensity, q_1. It appears, therefore, that q_1 does not adequately represent the flow conditions for determining scour depths. It might be due to this reason that in the Fig. 14, even the points for the same size scatter considerably.

(2) APPLICATION TO LAURSEN'S ANALYSIS:

According to Laursen [8], for a given opening ratio, the maximum scour depth is directly related to the depth of flow and is independent of velocity of flow and size of bed material. The present experimental data are analysed in order to verify his conclusions. The depth of scour below the original bed, d_s is plotted against the depth of flow for the 0.45 mm sand in Fig.1 With this sediment a wider range of discharge was used. The data scatter considerably and no correlation is apparent. Furthe the scour depth is found to have remarkable correlation with the velocity of flow. This can be observed in Fig. 17, which shows the variation of d_s with V for 0.45 mm sand. Similar results are obtained for the other sediment sizes also. The author's data, thus do not agree with the relationships proposed by Laurse for the case of bridge abutments.

5. CONCLUDING REMARKS:

Thus it is seen from the foregoing discussions that the size of the bed material plays an important role in the law governing the maximum scour depth around a spur-dike. It is believed that a plot of the type shown in Fig. 13 would make it possible, for all practical purposes, to predict the law for any value of the average drag coefficient. The range of C_D in the present investigation was between 0.45 and 2.85 (or d between 0.29 mm and 2.25 mm).

CHAPTER VI

SUMMARY, CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

CHAPTER - 6

SUMMARY, CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

SUMMARY AND CONCLUSIONS:

Analysis of the maximum scour depth occuring aroun a spur-dike placed in an alluvial channel is carried out by the principle of dimensional analysis. This is done in view of the complex nature of the problem of scour and the difficulties in solving it analytically. Dimensional analysis has revealed that, other factors remaining the same, the dimensionless expression for maximum scour depth is a function of Froude number of flow and the average drag coefficient of the sediment particles. This relationship is verified with the help of the experimental data collected in a 25-ft long and 2-ft wide rectangular non-recirculating flume for various values of the Froude number and different sizes of the bed material. Under the limitations imposed on the investigation, the following significant conclusions can be drawn:

1) The size of the bed material affects the maximum scour depth to an appreciable extent. This is contrary to the results obtained by some of the investigators.

2) The Froude number of flow, $F_r = \frac{V}{\sqrt{gR_b}}$ is a better criterion than the usual discharge intensity for representing the effect of the flow characteristics on the maximum scour depth.

3) The drag coefficient of the sediment particles, C_D, adequately takes into consideration the effe

of characteristics of the sediment and the fluid. However, $\Delta\gamma_s$, in the formulation of $C_D = \frac{4}{3}\frac{\Delta\gamma_s d}{w^2 \rho}$ was not varied.

4) The dimensionless equation (29),

$$\frac{D_1}{R_b} = K. \frac{1}{\alpha} F_r^n$$

in which K and n are functions of C_D, can be used fc determining the maximum scour depth around spur-dikes.

5) For practical purposes, the equation

$$D_1 = K' \quad q_1^{\frac{2}{3}}$$

with K' varying between 1.2 and 1.4 for median size sands can be used for approximate determination of maximu scour depths.

6) The present analysis is applicable to the case of scour . around bridge piers also.

SUGGESTIONS FOR FURTHER STUDY:

Many phases of the problem of scour at obstructions are yet to be investigated. The fact that the bed material size is an important consideration in scour studies opens a new avenue for further research on the problem. In this connection, it is felt that the following suggestions for further work with regard to the bed material characteristics will be valuable for a better understanding of the phenomenon of scour at obstructions:-

1) The exact form of the variation in the values of the ex- ponent n and the coefficient K in the equation (31

$$\frac{D_1}{R_b} = K \frac{1}{\alpha} F_r^n$$

for a wide range in the value of C_D has to be establi hed

2) The role of the various other sediment characteristics, namely its standard deviation, specific gravity and sha factor, on the maximum scour depth has to be investigat

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FIGURES

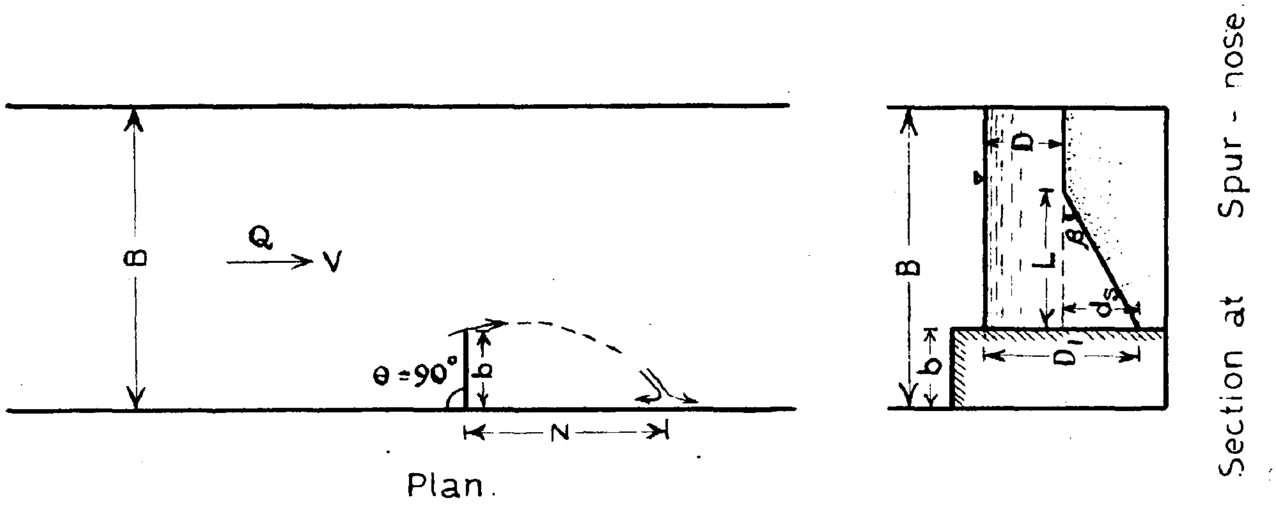


FIG. 1. DEFINITION SKETCH.

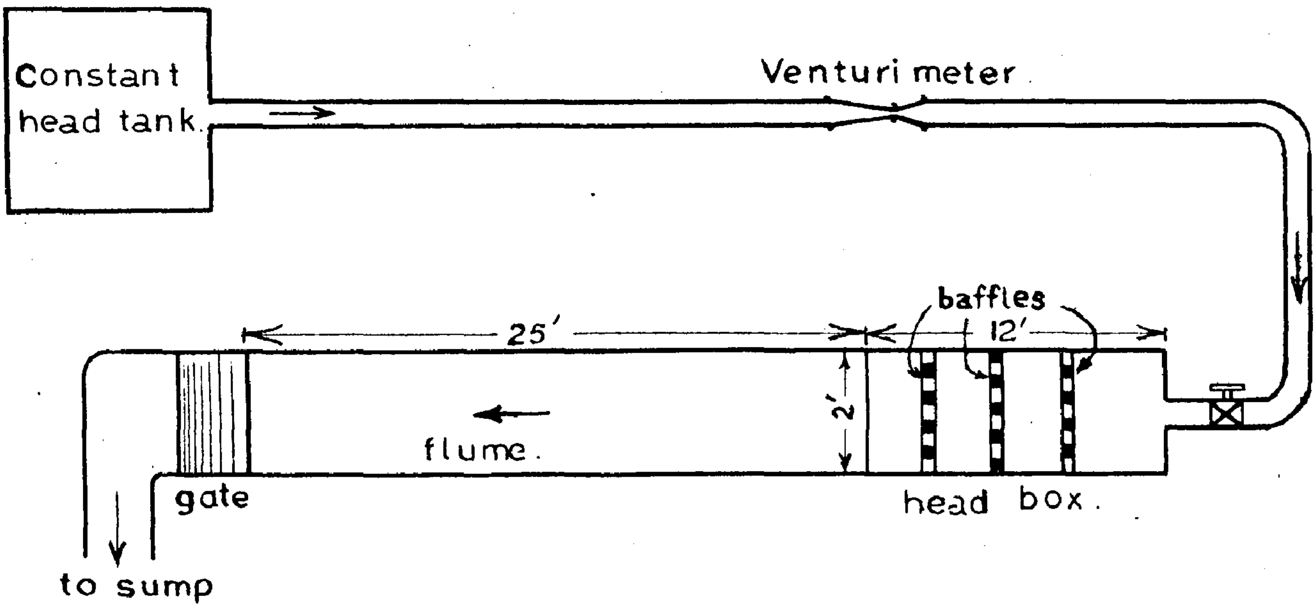


FIG. 2. EXPERIMENTAL SET - UP.

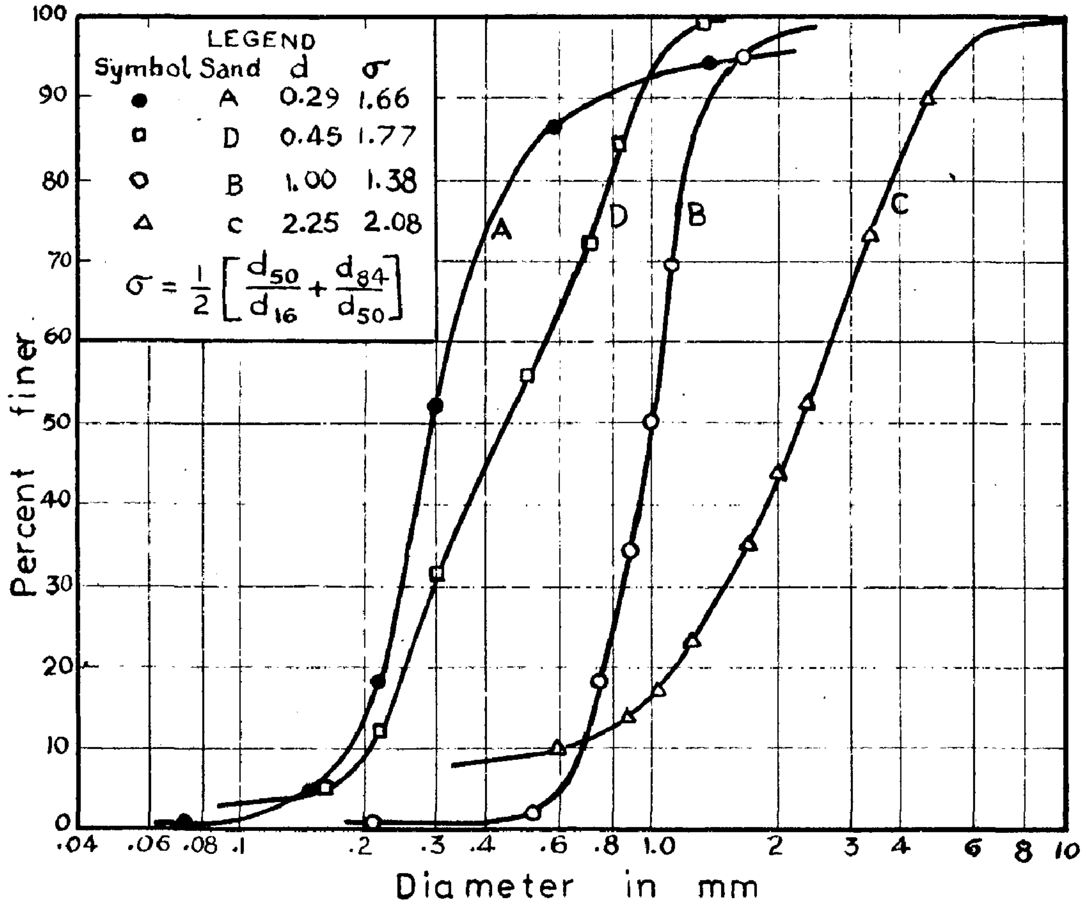


FIG. 3. SIZE DISTRIBUTION CURVES.

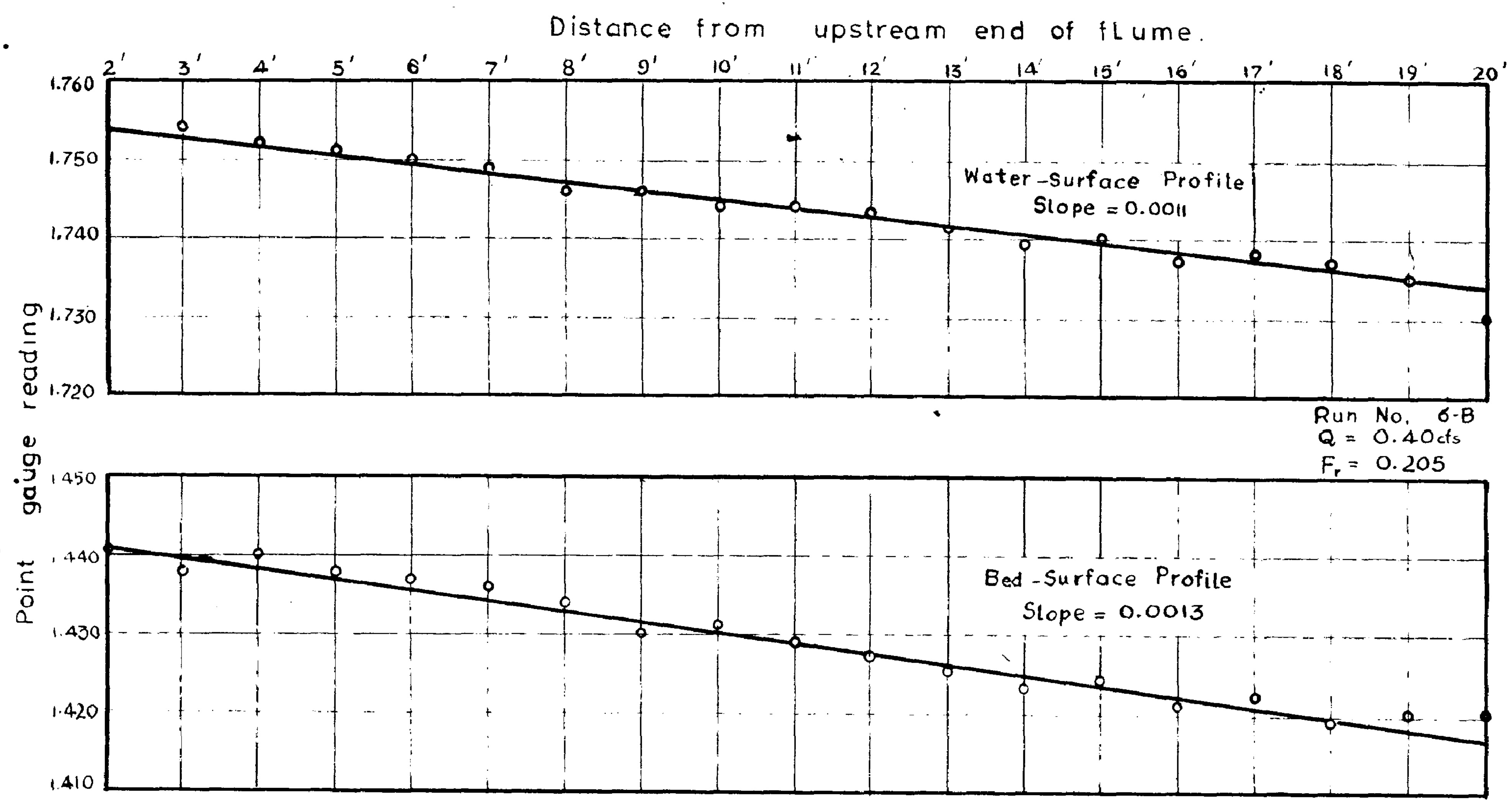


FIG. 4. TYPICAL WATER — SURFACE & BED - SURFACE PROFILES.

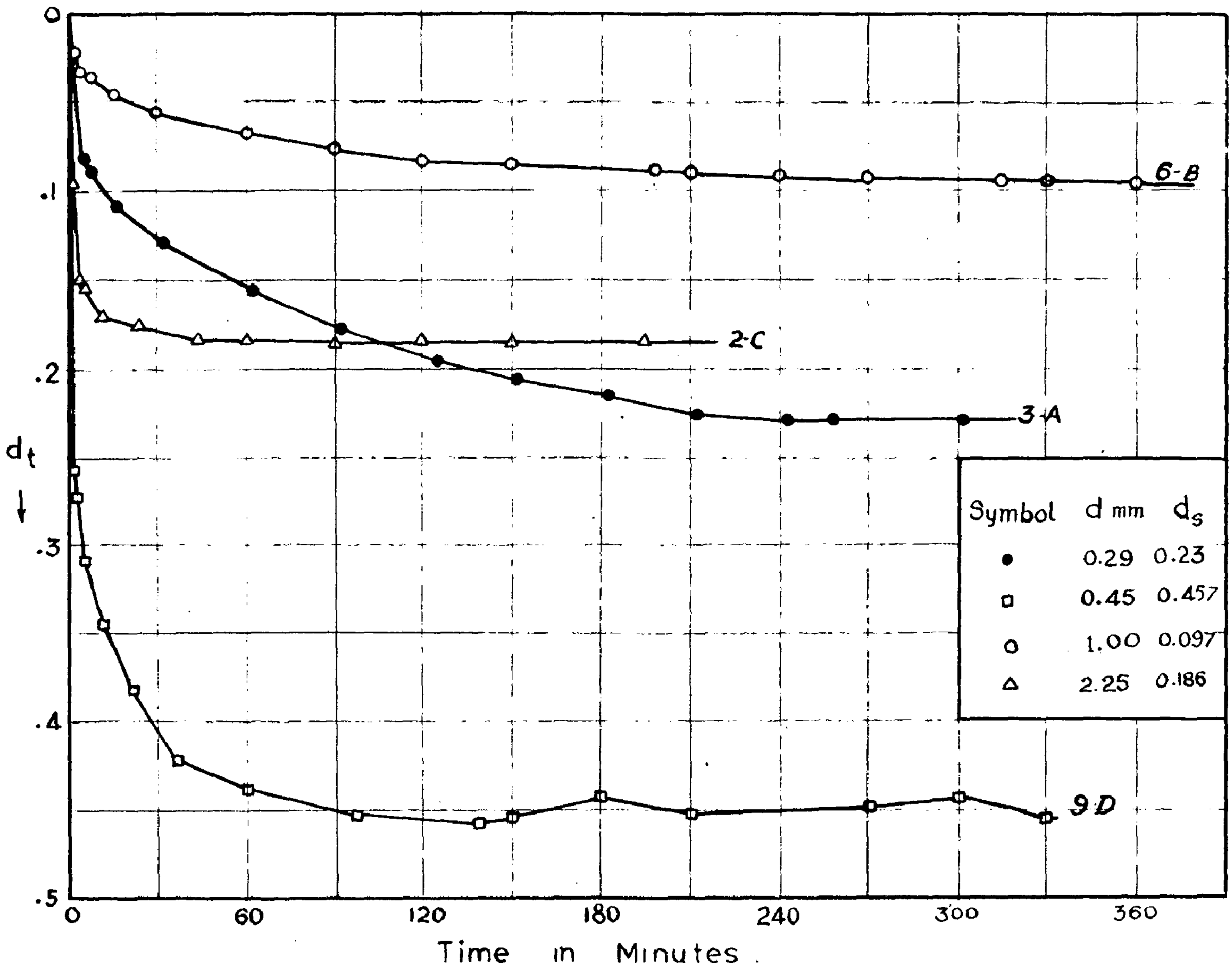


FIG. 5. DEVELOPMENT OF SCOUR HOLE

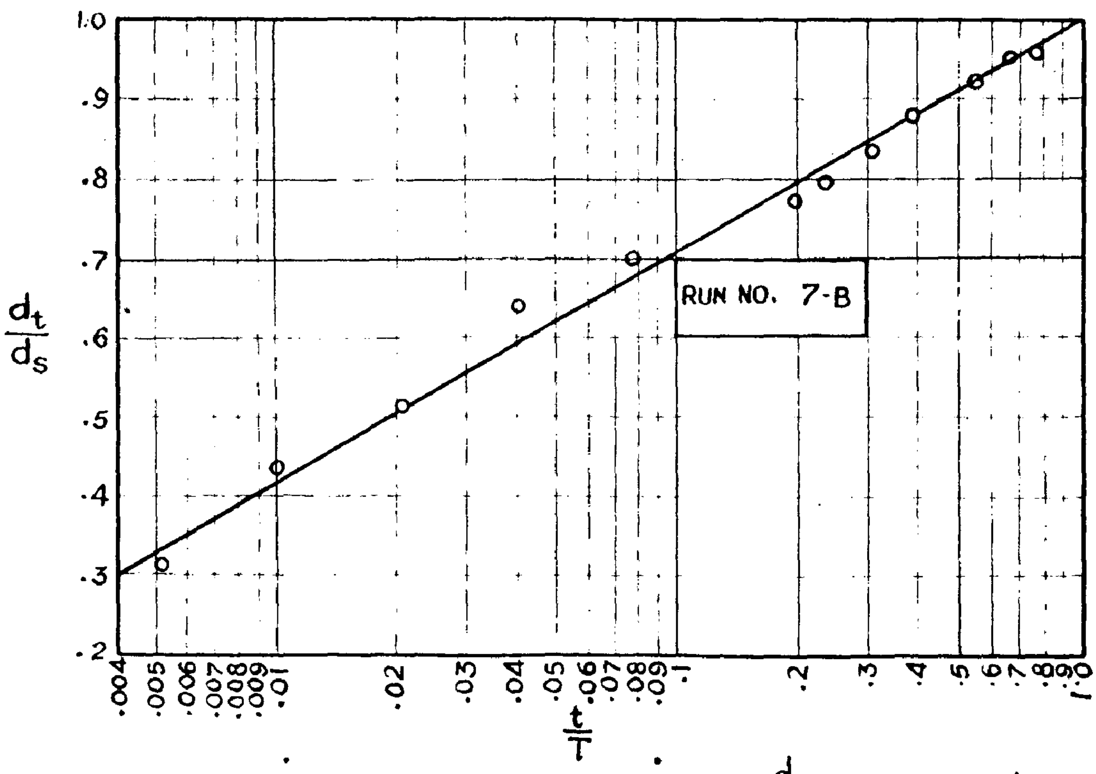


FIG. 6. VARIATION OF $\frac{d_t}{d_s}$ WITH $\frac{t}{T}$

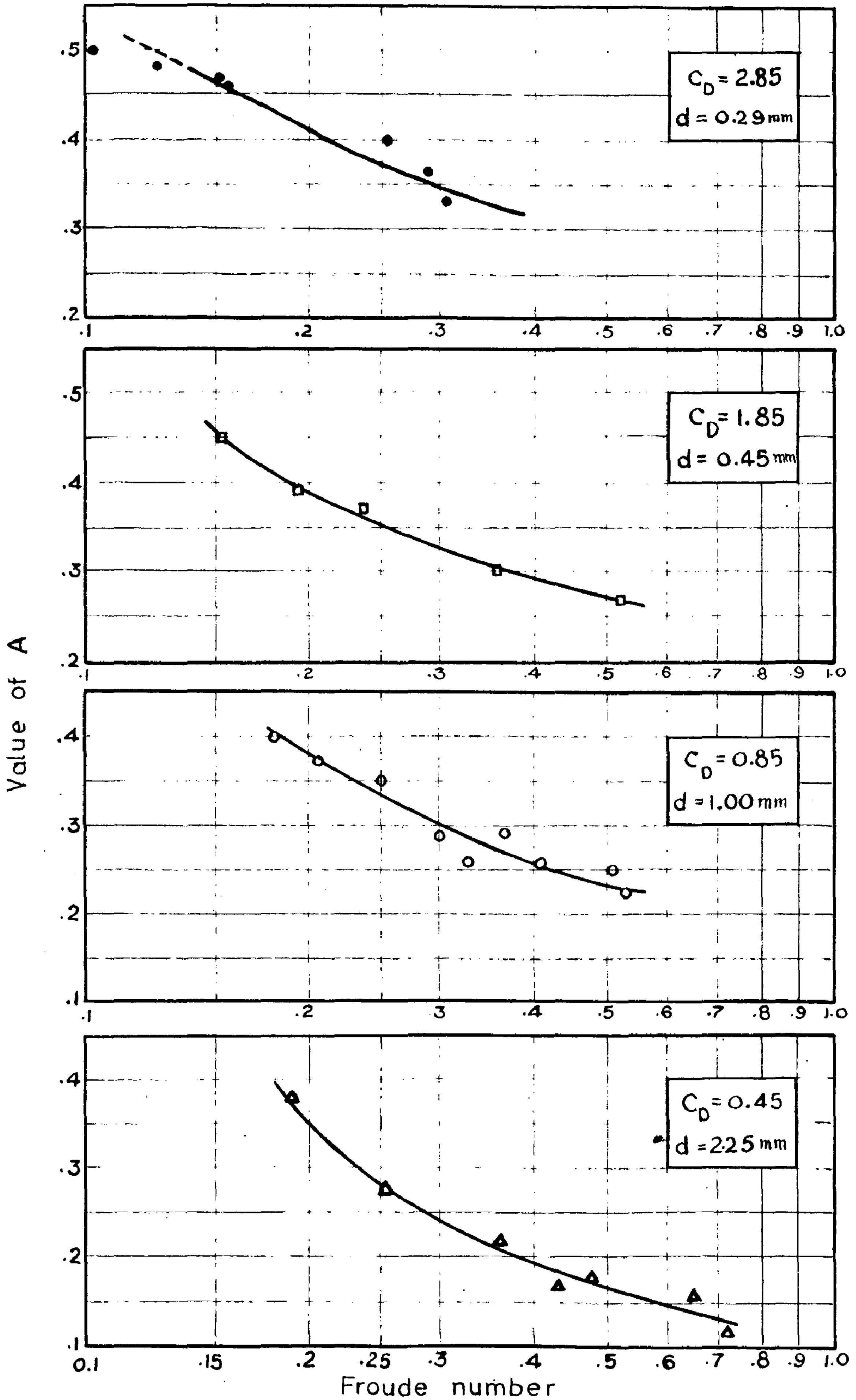


FIG. 7. VARIATION OF A WITH F_r AND C_D

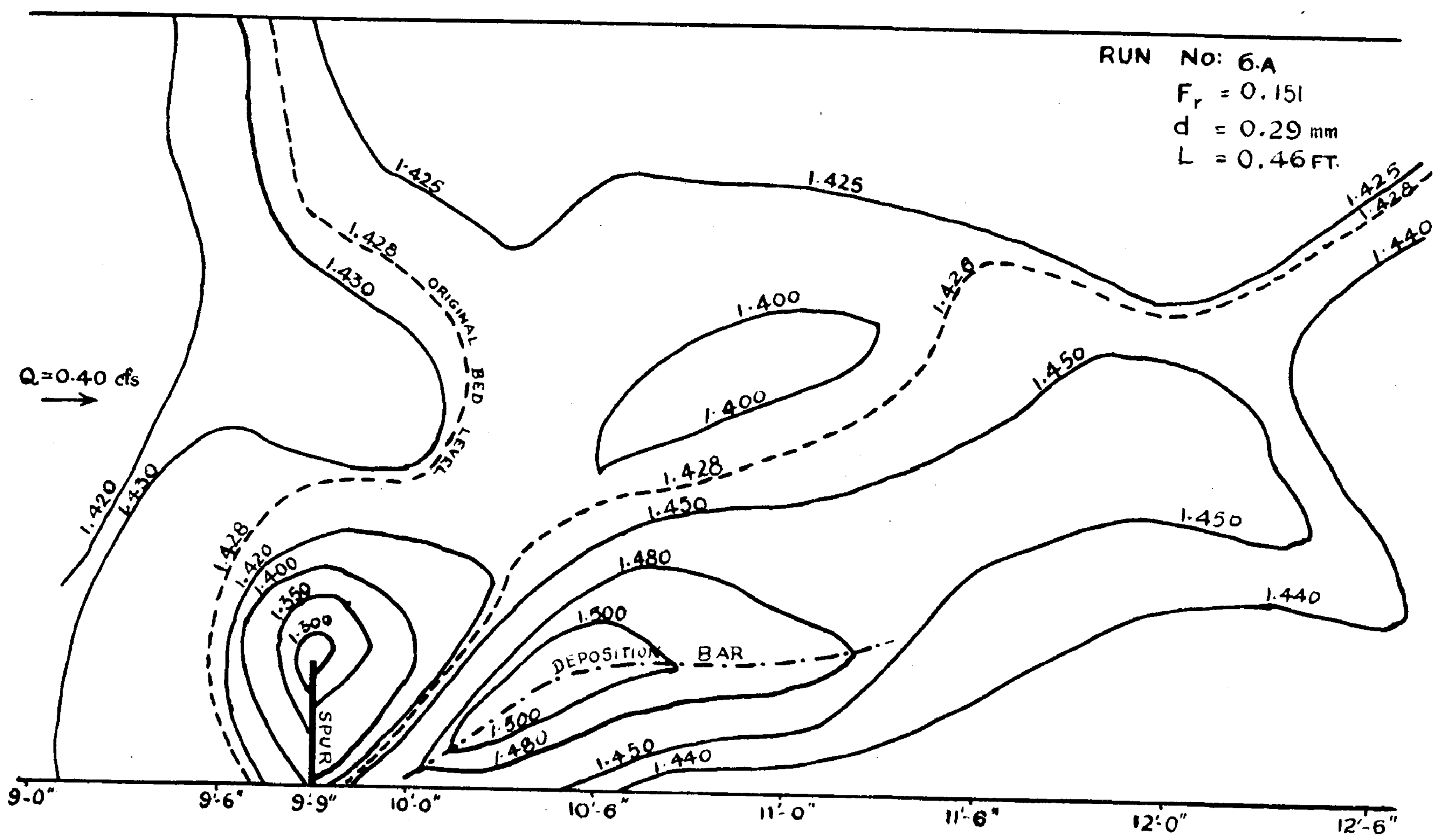


FIG. 8. TYPICAL CONTOUR MAP OF SCOURED BED

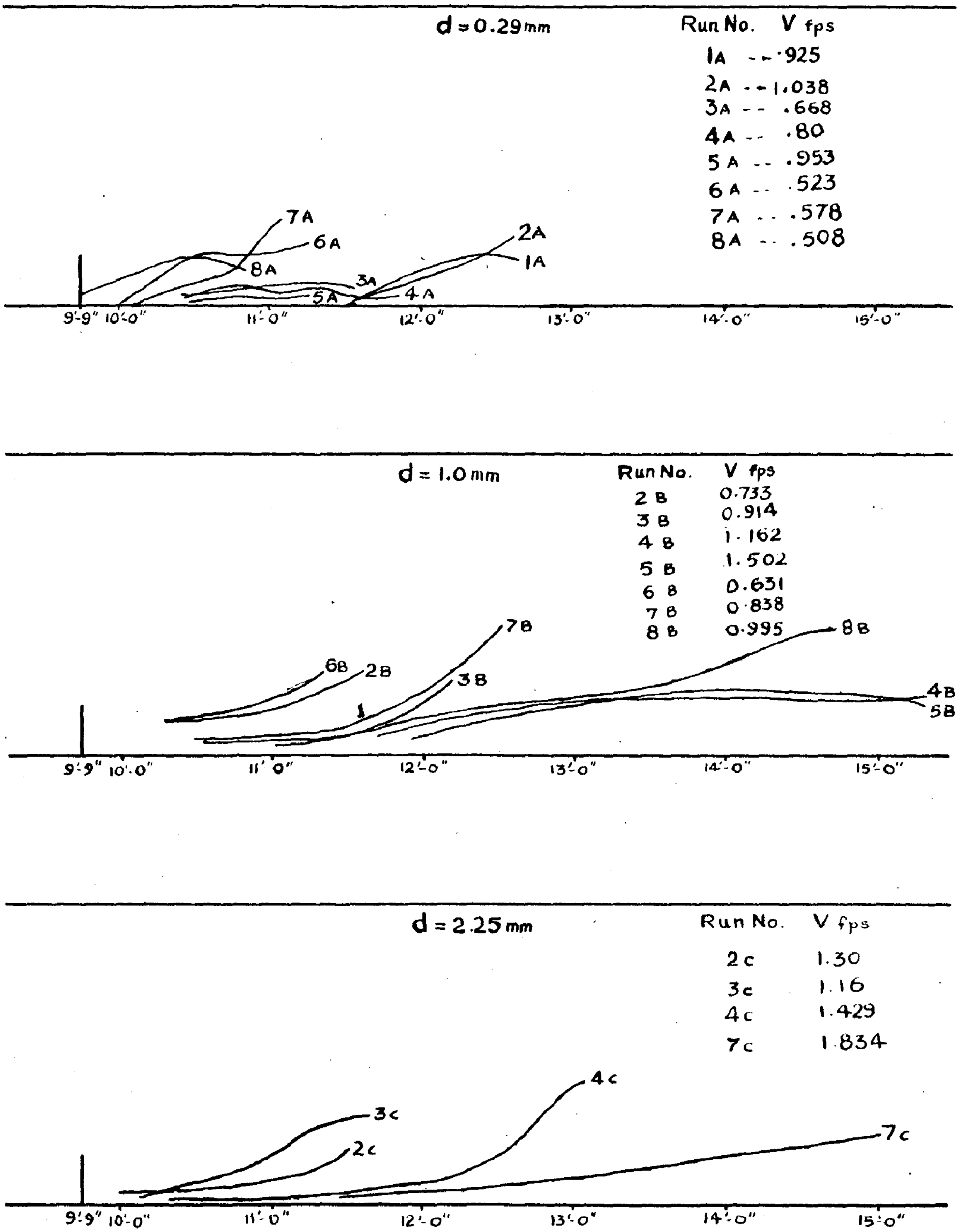


FIG. 9. POSITIONS OF DEPOSITION BARS.

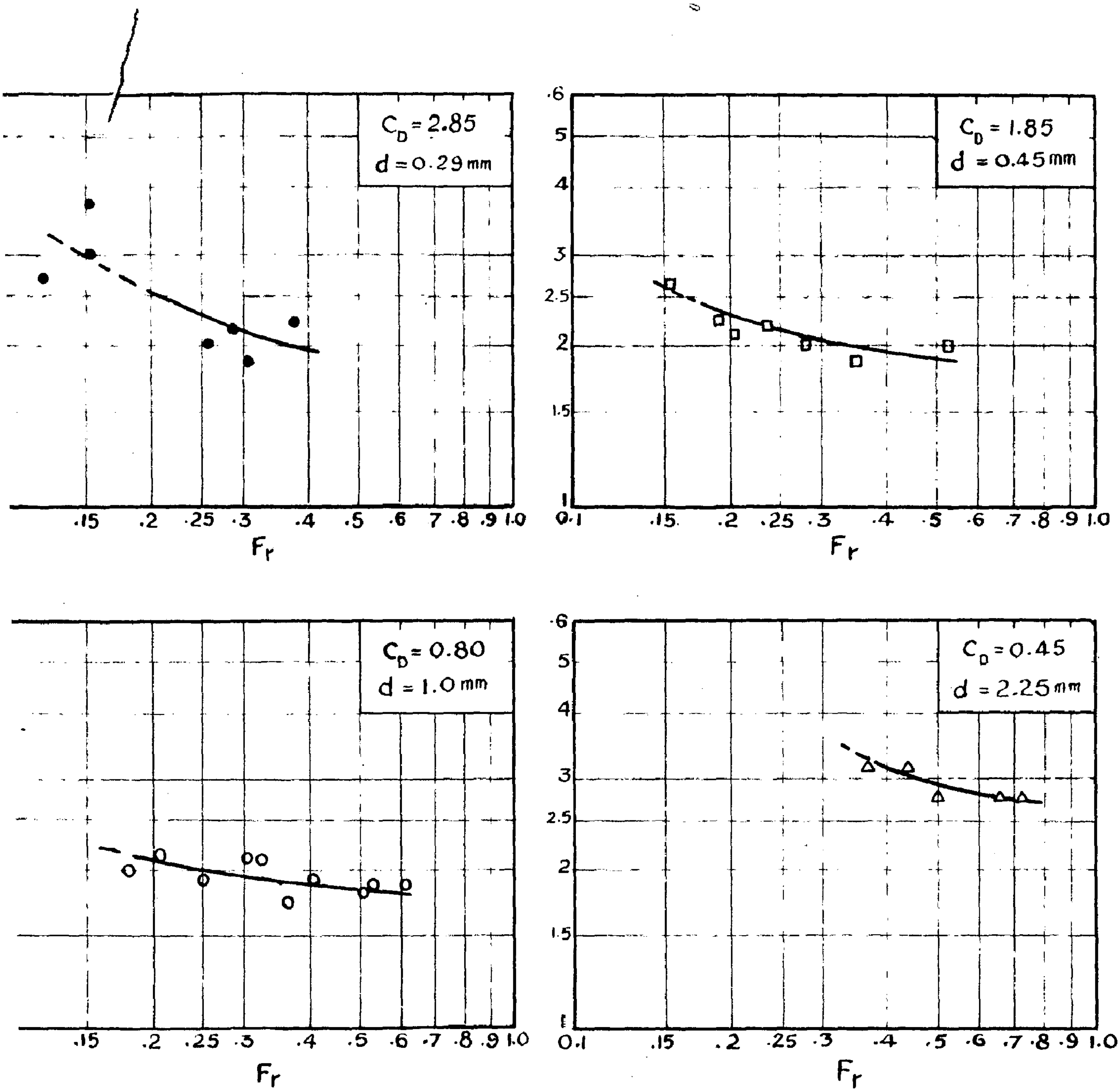


FIG. 10. VARIATION OF $\frac{L}{d_s}$ WITH F_r AND C_D.

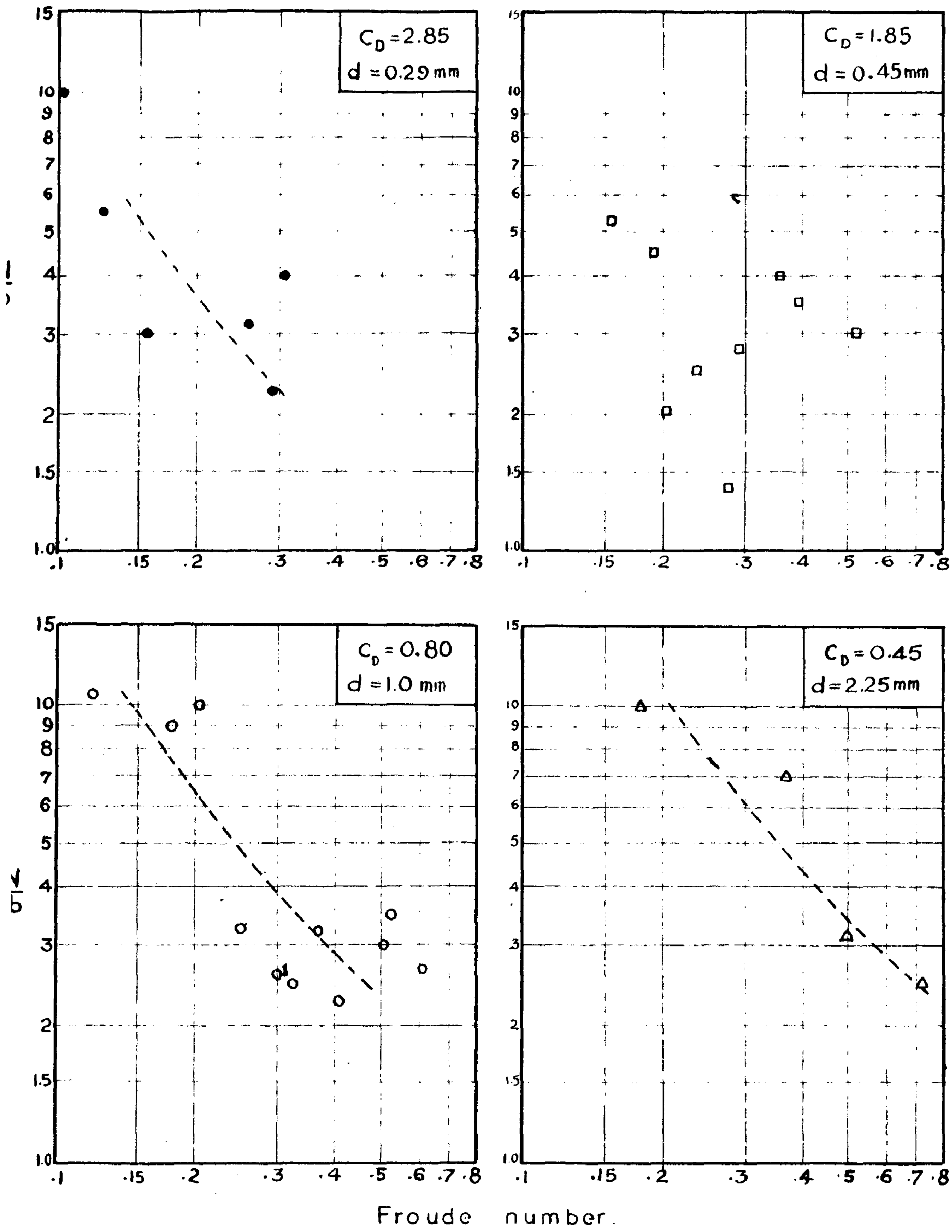


FIG. 11 VARIATION OF $\frac{N}{b}$ WITH F_r AND C_D

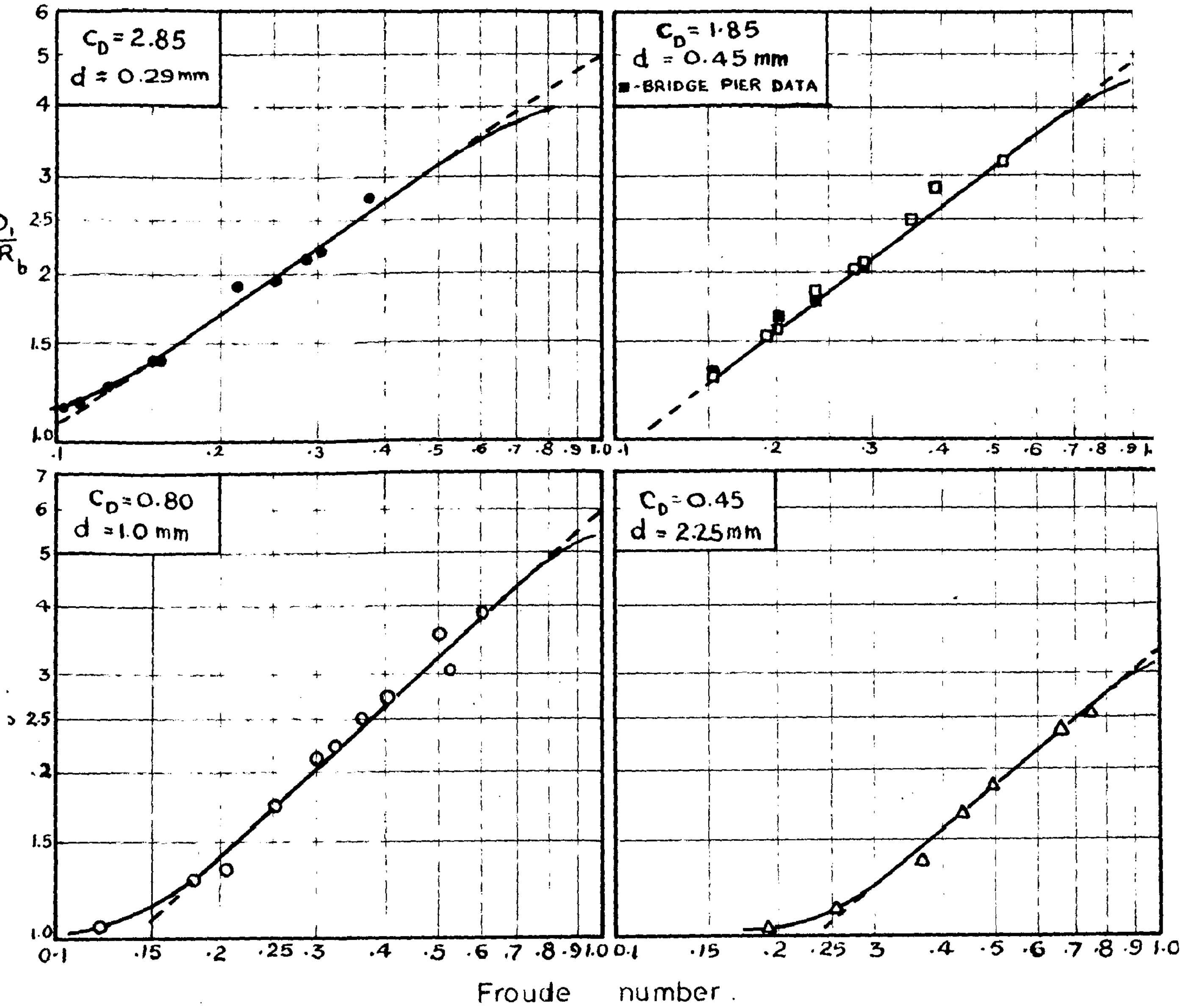


FIG. 12. VARIATION OF $\frac{D_1}{R_b}$ WITH F_r AND C_D.

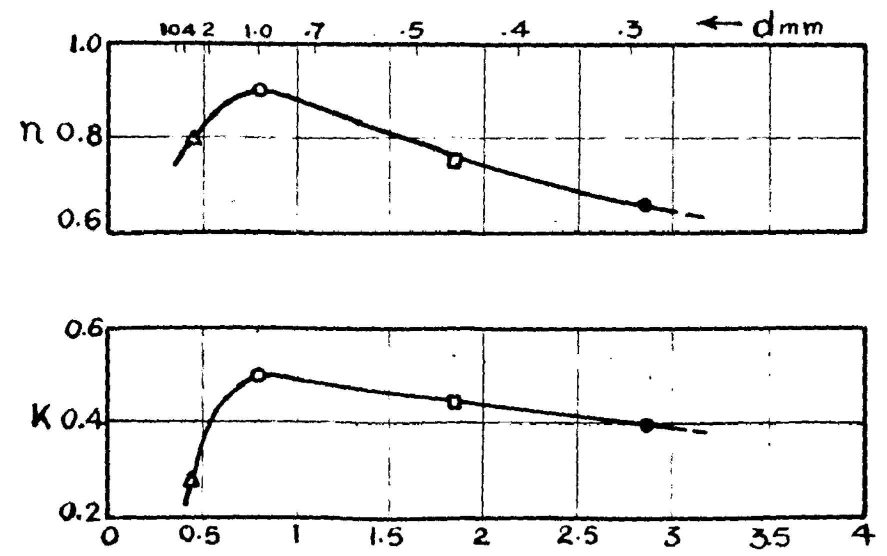


FIG. 13. VARIATION OF n' AND K WITH C_D.

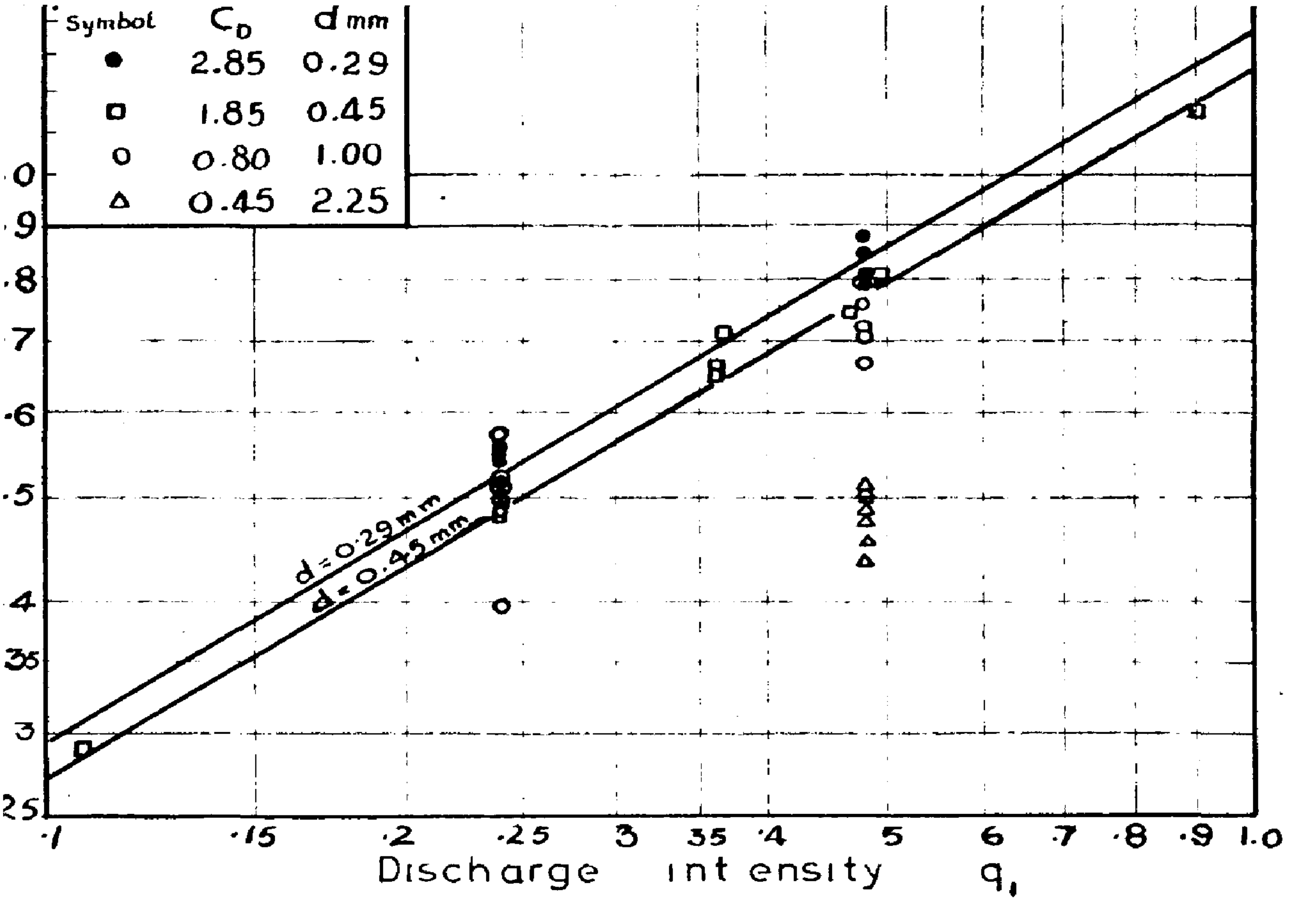
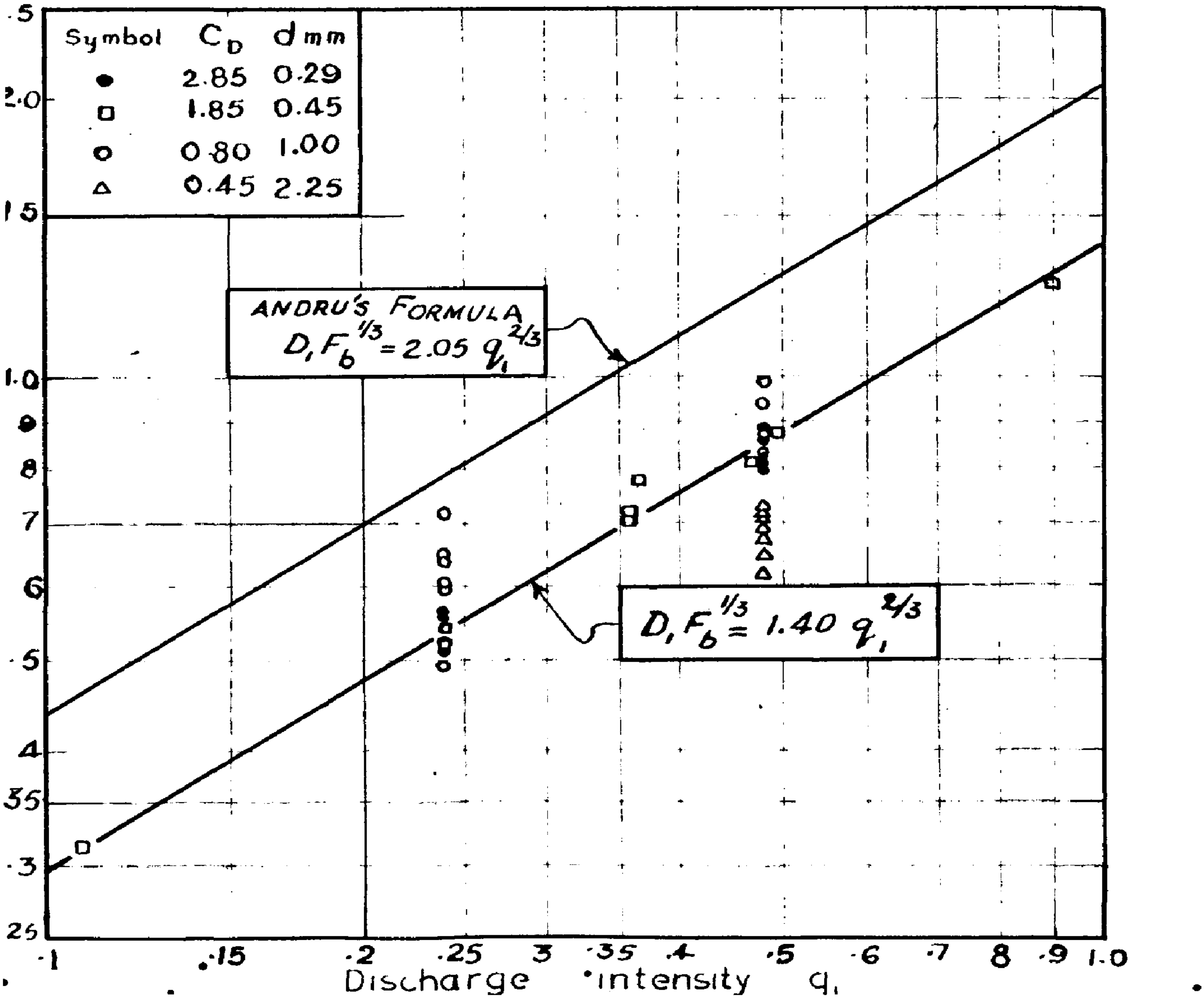


FIG. 14. VARIATION OF D_1 WITH q_1 AND C_D



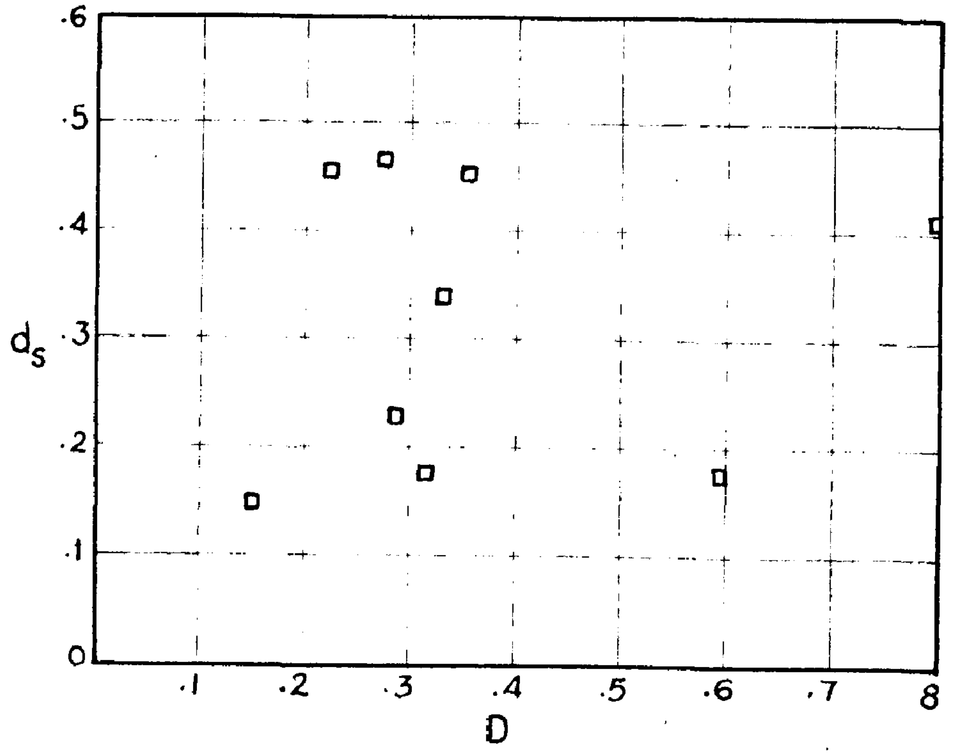


FIG. 16. VARIATION OF d_s WITH D

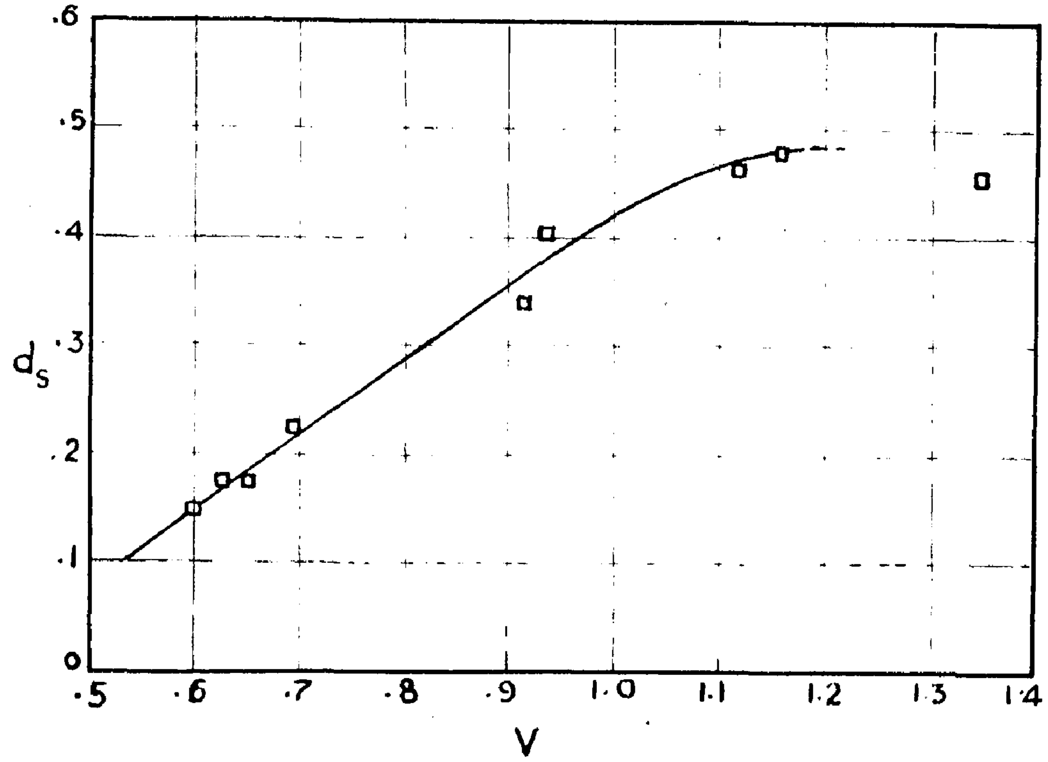


FIG. 17. VARIATION OF d_s WITH V.

APPENDIX

TABLE -1

SUMMARY OF EXPERIMENTAL DATA

$$\alpha = (1 - \frac{b}{B}) = 0.835$$

Q cfs	D ft	S	V fps	ds ft	N ft	Temp. °C	Location of Max. Scour--depth	Sediment movement
0.80	0.432	.00215	0.925	0.391	1.04	29	U/s Face	Fairly good
0.80	0.385	.0019	1.038	0.431	1.33	30.5	Wall	Very high*
0.80	0.599	.0021	0.668	0.230	1.00	31	Nose	Very slight
0.40	0.250	.0017	0.80	0.269	0.75	30.5	Wall	Fairly good
0.40	0.210	.0023	0.953	0.355	-	29.5	Wall	High
0.40	0.383	.0011	0.5225	0.150	1.00	33	Nose	Nil
0.80	0.693	.0011	0.5775	0.184	1.83	33.3	Nose	Nil
0.80	0.789	.00094	0.5075	0.123	3.33	33.3	Nose	Nil
			DATA COLLECTED BY GARDE AND SUBRAMANYA					
0.40	0.470	.0015	0.426	0.082	3.17	-	Nose	Slight
0.40	0.304	.0022	0.658	0.267	1.0	-	Nose	Fairly good
0.80	0.708	.0017	0.565	0.021	3.5	32	Nose	Nil
0.80	0.546	.0015	0.733	0.146	3.0	33	Nose	Nil
0.80	0.438	.0017	0.914	0.302	1.08	33	Nose	Just starti
0.80	0.344	.002	1.162	0.478	1.08	31.7	Nose	Very slight
0.80	0.266	.0044	1.502	0.507	1.167	32	Wall	High
0.40	0.314	.0011	0.637	0.097	3.33	31.7	Nose	Nil
0.40	0.241	.0016	0.830	0.254	0.83	30.6	Nose	Nil
0.40	0.201	.0017	0.995	0.326	0.75	31.4	Wall	Nil
0.40	0.173	.00236	1.156	0.415	1.0	30	Wall	Slight
0.40	0.231	.0019	0.866	0.268	0.83	30.6	Nose	Nil
0.40	0.158	.0018	1.768	0.387	0.875	30.6	Wall	Very high*
0.80	0.527	.0014	0.759	0.012	3.33	-	Nose	Nil
0.80	0.308	.00256	1.30	0.186	-	29	Nose	Nil
0.80	0.345	.002	1.16	0.115	2.33	29	Nose	Nil
0.80	0.280	.0029	1.429	0.226	1.04	30	Nose	Nil
0.80	0.437	.00155	0.915	0.043	-	29.4	Nose	Nil
0.80	0.231	.005	1.732	0.285	-	30	Wall	Very slight
0.80	0.218	.005	1.834	0.304	0.83	29	Wall	Slight
0.78	0.596	.00125	0.655	0.177	1.75	20.5	Nose	Nil
0.82	0.354	.00191	1.158	0.483	1.33	19	Nose	High
0.40	0.2875	.00105	0.696	0.229	0.83	19	Nose	Nil
0.40	0.318	.00107	0.629	0.178	0.67	19	Nose	Nil
0.60	0.328	.0017	0.915	0.340	0.92	18.3	Nose	Fairly good
0.61	0.273	.00174	1.118	0.466	1.167	18.3	Wall	Very high*
0.18	0.150	.00151	0.60	0.146	0.46	18.3	Nose	Nil
1.50	0.802	.00145	0.935	0.409	1.5	18	Nose	Very slight
0.60	0.223	.00283	1.345	0.457	1.0	16.5	Wall	Very high*

Sediment was fed from U/s end of flume at regular intervals.

APPENDIX – Contd.

TABLE- II

TABLE OF COMPUTED PARAMETERS

R_b	C_D	$Fr=\frac{V}{gR_b}$	$\frac{D_1}{R_b}$	q_1	$\frac{L}{d_s}$	$\frac{N}{b}$	A
.411		0.254	1.95	0.479	2.02	3.12	0.40
.360		0.305	2.20	0.479	1.89	4.0	0.33
.577		0.155	1.40	0.479	3.80	3.0	0.46
.238		0.289	2.13	0.24	2.17	2.25	0.365
.200		0.375	2.775	0.24	2.23	-	0.30
.370		0.151	1.405	0.24	3.05	3.0	0.47
.665	2.85	0.125	1.277	0.479	2.72	5.5	0.48
.760		0.1025	1.162	0.479	2.03	10.0	0.5
.460		DATA OF GARDE AND SUBRAMANYA					
.295		0.11	1.178	0.24	-	9.51	-
		0.213	1.905	0.24	-	3.0	-
.570		0.153	1.31	0.467	2.64	5.25	0.45
.327		0.356	2.475	0.491	1.86	4.0	0.30
.272		0.235	1.84	0.24	2.18	2.49	0.37
.303		0.201	1.586	0.24	2.11	2.01	
.309	1.85	0.290	2.097	0.36	-	2.76	
.252		0.392	2.84	0.366	-	3.50	
.145		0.278	2.01	0.108	2.0	1.38	
.748		0.1905	1.55	0.90	2.24	4.5	0.39
.207		0.521	3.2	0.36	2.01	3.0	0.27
.688		0.12	1.0305	0.479	-	10.5	-
.521		0.178	1.28	0.479	2.0	9.0	0.4
.413		0.25	1.732	0.479	1.93	3.24	0.35
.319		0.363	2.50	0.479	1.74	3.24	0.29
.250		0.528	3.03	0.479	1.89	3.5	0.225
.299	0.80	0.205	1.325	0.24	2.15	10.0	0.375
.228		0.30	2.113	0.24	2.13	2.49	0.29
.188		0.405	2.732	0.24	1.92	2.25	0.26
.162		0.505	3.56	0.24	1.805	3.0	0.25
.220		0.325	2.22	0.24	2.1	2.49	0.26
.135		0.608	3.87	0.24	1.88	2.625	-
.502		0.189	1.024	0.479	-	10.0	0.38
.286		0.432	1.651	0.479	3.14	-	0.17
.320		0.362	1.36	0.479	3.26	7.0	0.22
.259	0.45	0.495	1.873	0.479	2.76	3.12	0.18
.410		0.252	1.105	0.479	-	-	0.28
.215		0.658	2.325	0.479	2.77	-	0.16
.202		0.72	2.505	0.479	2.75	2.49	0.12