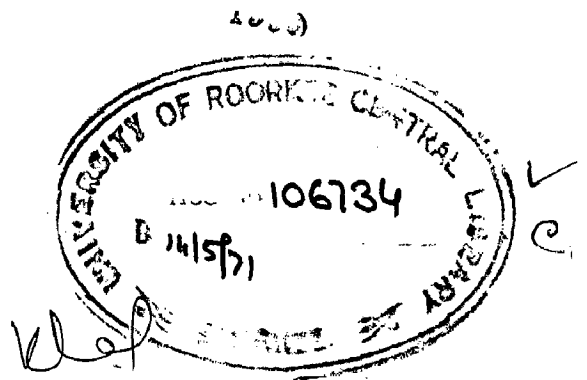# FLUME STUDIES ON RESISTANCE
# OF TWO - DIMENSIONAL
# STRIP ROUGHNESSES

*A Dissertation*
*submitted in partial fulfilment*
*of the requirements for the Degree*
*of*

MASTER OF ENGINEERING

*in*

HYDRAULICS AND IRRIGATION ENGINEERING

*By*
SUSHIL CHANDRA

DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE
August 1970

CERTIFICATE

Certified that the dissertation entitled
"FLUME STUDIES ON RESISTANCE OF TWO-DIMENSIONAL STRIP ROUGHNESSES"
which is being submitted by Sri Sushil Chandra in partial fulfil-
ment of the requirements for the award of the Degree of Master
of Engineering in Hydraulics and Irrigation Engineering of the
Roorkee University is a record of the student's own work carried
out by him under my supervision and guidance. The matter
embodied in this dissertation has 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 seven and a half months from January 1970 to
August 15, 1970 for preparing this dissertation for the Master
of Engineering Degree at this University.

Rangaraju

(K.G. Rangaraju)
Reader in Civil Engineering
University of Roorkee,
Roorkee, U.P.

Roorkee

Dated: August 25, 1970

1

# ABSTRACT

This thesis presents the results of an experimental investigation on the mechanism of resistance to flow over artificial roughness elements. The studies were carried out on two-dimensional sharp-edged strips of negligible thickness placed on the bed of an open channel. The various aspects of the problem covered by the experiments included the resistance characteristics of a single roughness element as well as those of series of roughness elements placed on a smooth boundary. In case of elements in series, using two-dimensional strips having relative spacings of 60 and 80, the total resistance of the boundary, as well as the skin friction of the plane boundary were measured; the latter was measured using a Preston tube. Experiments were also performed to verify the hypothesis of Rangaraju and Garde that for roughness elements in series on a plane boundary, upto a relative spacing of 40, the negative friction in the standing eddy cancels with the positive friction further downstream and thus the net skin friction is zero. For this purpose experiments were made using two-dimensional strips placed on a boundary to which gravel particles were glued.

As a result of the present investigation it was proved that the above hypothesis is true upto a relative spacing of 40. In addition, information has also been presented about the form resistance of the strips and the skin friction of the plane boundary at relative spacings exceeding 40. Analysis of data on the drag of a single element has indicated a unique relation between the drag coefficient and the relative depth of flow.

## ACKNOWLEDGEMENTS

The author wishes to express his deep sense of gratitude to his guide, Dr. K.G. Rangaraju, Reader in Civil Engineering, University of Roorkee whose expert guidance, invaluable suggestions, constant encouragement and keen interest thoroughly stimulated him in his work.

The author also takes this opportunity to thank the staff of Hydraulics Laboratory, University of Roorkee particularly Mr. B.R. Sethi and Mr. J.P. Jain for their wholehearted assistance and cooperation during the experimental work linked with the present investigation.

Last but not the least, the assistance of my colleague Mr. Ihsan Ahmad during the various stages of the work is gratefully acknowledged and appreciated.

# CONTENTS

# LIST OF SYMBOLS

| Symbol | | Meaning | Units | Dimension |
|---|---|---|---|---|
| A | = | Projected area of a body on a plane normal to direction of flow | $m^2$ | $L^2$ |
| $B_1$ | = | Constant in the resistance equation | Dimensionless | - |
| B | = | Width of the channel | metres | L |
| $C_D$ | = | Drag coefficient with respect to Average velocity. | Dimensionless | - |
| $C_{D_o}$ | = | Drag coefficient based on the average velocity but for infinite stream conditions | " | - |
| $C_{D_1}$ | = | Drag coefficient based on the free stream velocity | " | - |
| $C_{D_h}$ | = | Drag coefficient based on the velocity at the crest level of the element. | " | - |
| $C_1, C_2$ | = | Constants in Resistance equation and function of L/h | " | - |
| $C_f$ | = | Local skin friction coefficient | " | - |
| $C_{f_1}$ | = | Average friction coefficient assuming zero shear within standing eddy | " | - |
| $C_{f_2}$ | = | Average friction coefficient for shear over a length $L_2$ and defined by $C_{f_2} = C_{f_1} \cdot L_2/L$ | " | - |
| $C_{f_3}$ | = | Average friction coefficient assuming skin friction to be effective in a length $L_3$ | " | - |
| $C_w$ | = | Constant used by Morris | " | - |
| D | = | Depth of flow in the flume measured from the bottom. | cms or m | L |

| Symbol | | Meaning | Units | Dimensions |
|---|---|---|---|---|
| d | = | grain size | cms or m | L |
| d' | = | Diameter of the Preston Tube | " | L |
| $\delta$ | = | Thickness of the boundary layer defined so that the velocity at the edge of boundary is equal to 99% of the free stream velocity | cms | L |
| $\rho$ | = | Mass density of the flowing fluid | metric sluga/m³ | $ML^{-3}$ |
| $F_s$ | = | Total positive skin friction between two roughness elements per unit width. | Kgm/metre | $MT^{-2}$ |
| $F_s'$ | = | Total positive skin friction per unit width between 35 h and total length, L, between two roughness elements. | Kgm/m | $MT^{-2}$ |
| $F_r$ | = | Froude's number of flow | dimensionless | - |
| f | = | Darcy-Weisbach Resistance coefficient | " | - |
| $f_s$ | = | Darcy-Weisbach Resistance coefficient for smooth bed. | " | - |
| g | = | Acceleration due to gravity | Metre/sec² | $LT^{-2}$ |
| h | = | height of the roughness element | cms | L |
| j | = | Width of groove in a bed with roughness elements | metres | L |
| K | = | Karman's constant | dimensionless | - |
| $K_s$ | = | Equivalent sand grain roughness of the bed | metres | L |
| $K_s'$ | = | Resistance parameter and a function of roughness geometry | metres | L |
| L | = | Spacing between the roughness elements | " | L |
| $L_1$ | = | length of the standing eddy | cms. | L |
| $L_2$ | = | $L - L_1$ | cms. | L |
| $L_3$ | = | L - 35 h (h in metres) | metres | L |

| Symbol | Meaning | Units | Dimensions |
|---|---|---|---|
| $\lambda$ = | Roughness concentration, defined as the ratio of projected area of the roughness elements to the area of the bed. | dimensionless | M |
| $\mu$ = | Dynamic viscosity of the flowing fluid | $\dfrac{kgm\text{-}sec}{metre^2}$ | $ML^{-1}T^{-1}$ |
| N = | No. of elements in periphery | dimensionless | - |
| n = | Manning's coefficient | metre/sec$^{-1/3}$ | $TL^{-1/3}$ |
| $\nu$ = | Kinematic viscosity of the flowing fluid | m²/sec. | $L^2T^{-1}$ |
| $P_u$ = | Pressure on the upstream face of the roughness element at a height y from the floor | Kgn/m² | $ML^{-1}T^{-2}$ |
| $P_d$ = | Constant pressure on the down stream face of the element | " | " |
| P = | Wetted Perimeter of the channel | metres | L |
| $R_b$ = | Hydraulic Radius of the bed of the channel | " | " |
| Q = | Discharge flowing | m²/sec | $L^3T^{-1}$ |
| $R_e$ = | Reynolds No. of flow | Dimensionless | - |
| $R_h$ = | Reynolds No. with respect to the velocity at the crest of the element | " | - |
| $R_x$ = | Reynolds number of flow at a distance x from the edge of the plate | " | - |
| $\gamma$ = | Unit weight of the flowing fluid | Kgn/m² | $ML^{-2}T^{-2}$ |
| $r_o$ = | Radius of the conduit | metres | L |
| $\Delta p_p$ = | Preston tube reading (difference between static pressure and Pitot pressure) | cms. | L |
| $\Delta F$ = | Force per unit width on the element | Kg/m | $ML^{-1}$ |
| S = | Water surface slope | Dimensionless | - |

| Symbol | | Meaning | Units | Dimensions |
|---|---|---|---|---|
| $S_1$ | = | Peripheral spacing between roughness elements | metres | L |
| $t$ | = | thickness of roughness element | cms | L |
| $T_0$ | = | Total shear stress on the bed of the channel | Kgm/m² | $ML^{-1}T^{-2}$ |
| $T_0'$ | = | Skin friction at a distance x from the element | " | " |
| $T_{0_1}'$ | = | Average shear stress due to the skin friction of the plane boundary when the shear in standing eddy is neglected. | " | " |
| $T_{0_1}''$ | = | $T_0 - T_{0_1}'$ | " | " |
| $T_e'$ | = | net positive friction of the plane boundary which is equal to the friction between 33 h and L. | " | " |
| $T_0''$ | = | $T_0 - T_0'$ | " | " |
| $V_e$ | = | free stream velocity | metres/sec | $LT^{-1}$ |
| $U_h$ | = | Velocity of height 'h' from the floor | " | " |
| $U$ | = | velocity at a height 'y' from the floor | " | " |
| $V$ | = | Average velocity in the vertical centre line of the channel | " | " |
| $\bar{V}$ | = | Average velocity over the cross-section of the channel | " | " |
| $V_*$ | = | Shear velocity $=\sqrt{T_0/\rho}$ | " | " |
| $x$ | = | distance along the flow | cms | L |
| $X^*, Y^*$ | = | Parameters used by Patel | Dimensionless | - |
| $y$ | = | Height measured from the floor | metres | L |

## LIST OF FIGURES

# CHAPTER - 1

# INTRODUCTION

## 1.1 Preliminary Remarks:

Tho problem of resistance to flow in open channols has rocolvod tho attention of hydraulic engineers for a long timo bocauso of its importanco in several practical problems. Knowlodgo of the rosistanco to flow is important in tho dosign of channols, preparation of stage - dischargo curvos and in tho computation of sediment transport rato in alluvial channols. Howovor, in spito of the vast amount of work dono on tho problem, tho rosistance for differont roughnossos under differont flow conditions is not accurately known at present. Consoquontly correct solution of tho problems montionod earlior is also not possiblo.

Tho commonly used rosistanco rolations aro thoso of Chozy and Manning. In both of theso equations the rosistanco cooffiolent is takon constant for a particular typo of roughnoos, rogardloss of fluid and flow conditions. Howovor this is soldom truo in caso of natural channels and, thereforo, thoso oquations aro inadoquato in describing tho behaviour of such channols ovor a wide rango of flow conditions.

## 1.2 Studios on Artificial Roughnossos:

With tho objoct of providing a roughnoss standard for

upon channels similiar to Nikuradso's sand-grain concept for commercial pipes, several studies have been carried out using artificial roughness elements. Contributions of Powell (16), Johnson (8), Sayre - Albertson (24), and Adachi (1) are worth mentioning in this connection. Those investigators studied the total resistance of a boundary with various types and concentrations of roughness elements. However these studies have not led to an acceptable roughness standard for open channels.

Einstein and Banks (4), by a rational analysis based on flume studies with various patterns of roughness elements, concluded that the total resistance of the boundary having a series of roughness elements on it can be taken as sum of the resistance of individual roughness elements. In other words presence of a roughness element has no significant effect on the resistance of other roughness elements and the total resistance can be obtained as the sum of form resistance of individual roughness elements and the boundary friction over the whole area. Based on this concept Einstein and Barbarossa (5), proposed a method for prediction of resistance to flow in alluvial channels. However because of infinite arrangements and spacings of roughnesses that are encountered in natural channels the interference effect may become important and needs to be investigated properly.

Ranqaraju and Gardo (19), made a thorough investigation

of the effect of interference on the resistance of artificial roughness elements by conducting extensive experiments in a flume as well as in wind tunnels. They used sharp-edged two-dimensional strips of negligible thickness as the roughness elements on a smooth plane boundary. Their conclusions were that the total resistance of a plane boundary with roughness elements having relative spacing between 2.5 and 40 can be estimated on the assumption that the total resistance is equal to the form resistance of the roughness elements; the form resistance of the strips is strongly dependent on the relative spacing and the ratio of depth of flow to height of element. This means that, in the range of their experiments, the skin friction is practically zero. One can arrive at such a conclusion if the skin friction of the plane boundary is a very small fraction of the total resistance; because of the smoothness of the boundary in such a case the total resistance would prove equal, within range of experimental accuracy, to the measured form drag as found by Rangaraju and Garde. The net skin friction can also be nearly zero ( for L/h less than 40) if the positive friction beyond the standing eddy downstream of the roughness cancels out with the negative friction within the eddy. Such an assumption has been made by Rangaraju and Garde in their studies. However in the absence of measurements of skin friction for the runs conducted by Rangaraju and Garde, it is not possible to say which of the above hypotheses

is correct. The foregoing point can be settled convincingly
if the plane boundary between the roughness elements is made
quite rough. If the hypothesis of Rangaraju and Gardo that
the net skin friction is zero for L/h < 40 (where L is spacing
between roughness elements and h is the height of elements)
is true the total resistance of the roughened plane bed on
which roughness elements are placed should prove equal to the
total resistance of the smooth plane bed with the same roughness
geometry provided L/h < 40. On the other hand, if the resis-
tance in the former case exceeds that in the latter, the
conclusion of Rangaraju and Gardo that the total resistance is
equal to the form resistance of the strips (for L/h < 40) may
not be acceptable.

## 1.3 Scope of Present Investigation:

The present investigation was, therefore, carried out to
test the validity of the assumption discussed above and also
to extend the results of Rangaraju and Garde to larger spacings
of roughness elements. For the former purpose resistance
studies were made using two-dimensional strips placed on a
plane boundary on which were glued gravel particles of 2 mm
size. These studies were performed for two values of L/h viz.
20 and 40 - the latter being the limit upto which there is no
net skin friction, according to Rangaraju and Garde.

At L/h values greater than 40, the net skin friction of the plane boundary is expected to be significant. Hence studies were carried out for L/h values greater than 40, using two-dimensional strips placed on a smooth boundary. These studies included the measurement of skin friction by a Preston Tube.

For the case of a single two-dimensional sharp-edged roughness element placed on a plane boundary the available information is based mainly on the wind tunnel studies made by Plate (13), Good and Joubert (6) and Rangaraju and Garde (18). An attempt at extending these results to open channel flow (18) proved unsuccessful, probably because of the influence of the free surface. Hence one aspect of the study was to provide information on the resistance of a single element placed on a plane boundary. It may be noted that this forms a limiting case of a series of elements placed on the boundary.

1.4 **Limitations of Study:**

The experiments were performed on two-dimensional sharp-edged roughness elements of negligible thickness placed on the bottom of the flume and extending across the entire width.

The work was carried out in three parts:

(a) To study the resistance of a single isolated roughness element placed on the boundary. Two sizes of element viz 3 cm and 4 cm were used to cover a range of D/h from 2.0 to 12.0.

(b)   To study the resistance characterstics for a series
      of roughness elements placed on a smooth boundary
      for large spacings viz L/h = 60 and L/h = 80. The
      height of roughness in this case was kept as 1 cm.

(c)   To study the resistance to flow over strip roughnesses
      placed on a plane gravel bed. Using a roughness of
      4 cm height, two different spacings (L/h = 40 and
      L/h = 20) were used in this part of the study.

      The experiments were, in all cases, restricted to low
froude numbers.

C H A P T E R - 2

## REVIEW OF LITERATURE

### 2.1    Preliminary Remarks:

Considerable work has been done during the last three
decades concerning the resistance to flow in rigid boundary open
channels. Using artificial roughnesses on the channel boundary.
These studies have been performed using different types and
arrangements of roughness elements. The salient features of
some of these investigations are discussed in the following para-
graphs. For the present study the review of literature has been
divided into two parts:

(a)    Studies on resistance of single roughness element kept
       either on the bottom of an open channel or on the wind
       tunnel floor.

(b)    Studies on resistance of series of roughness elements
       placed on the bed of an open channel.

### 2.2    Studies on Single Roughness Element:

Plate (13), 1964, studied the problem of drag on a smooth
boundary having a two-dimensional sharp-edged normal plate
immersed in its turbulent boundary layer. The experiments were
performed in a wind tunnel having a 1.83 m square section. The
height of plate was varied from 1.25 cm to 5.00 cm and variation
of the drag coefficient with $\delta/h$ was studied. ($\delta$ being thickness

of the boundary layer). The main conclusions obtained as a
result of his investigation were:

(a)      drag coefficient $C_{D_1}$ of the roughness element was related
         to $\delta/h$ by the equation,

$$C_{D_1} = 1.03 \ (h/\delta)^{2/7} \tag{2.1}$$

where, $C_{D_1}$ = Drag coefficient of the plate with respect to
                  free stream velocity.

(b)      The negative friction in the standing eddy zone cancels
         the positive friction downstream of reattachment point
         over a distance 33 times the height of roughness element.
         Beyond this point, theory of undisturbed boundary layer
         is applicable.

Adachi (1), 1964, conducted open channel studies using a two-
dimensional wooden bar 3 mm high and 6.4 mm thick placed on the
channel bed. He measured the form drag of the strip under
various depths of flow. The tests were carried out in a 20 cm
wide, 30 cm deep and 14.40 meters long steel flume having a
slope of 1/500. He argued that in case of roughness element
placed on the channel bed, the velocity gradient over the element
height is marked and accordingly the average velocity needs to
be taken as the characteristic velocity. The relative depth D/h,
was found to be a significant parameter and to affect the drag
coefficient defined with respect to average velocity.

Consoquently ho plottod $C_D$ against D/h and tho curvo propoood by Adochi hao boen shown in Figuro (S.3).

Good and Joubort (5), 1968, modo an oxporimontal study on tho drag cooofficiont of a two-dimonsional normal plato immorood in a turbulont boundary layor. Tho oxporimontal brood plato forming tho smooth boundary wag 6" wido and 3 ft 7" long. Tho hoight of normal plato was variod from 1" to $4\frac{1}{2}$" by firmly clomping it to a 6" wido panol. Tho results showad that tho drag coofficiont of tho plato is rolatod to dimonsionloos paramotor $V_*/V_0$ oxcopt possibly whon h/δ < 1, in accordanco with the rolation,

$$C_{D_1} = f (h/\delta, V_*/V_0) \qquad (2.2)$$

whoro, $V_0$ = froo stroam voloci ty

and $V_*$ = shoar voloci ty

It was furthor found that ovor a considorable rango of plato hoighto $C_{D_1}$ varios logarithmically with h/δ, tho slopo of oomi-log plot boing difforont for difforont $V_*/V_0$. Thoy aloo comparod thoir data with Plato'a data and found tho ogroomont good.

Chong (3), 1970, corriod out dotailed invostigationo of tho rolationohip botwoon friction factor of flow ovor ripplo bodo and goomotric proportioo of ripploo such oo shapo and concontrotion. During this otudy, ho studiod tho longth of otanding oddy bohind a two-dimonsional normal plato placod on tho channol bod. Ho found that $L_1/h$ is a function of $\overline{VD}/\nu$ Fig.(S.19) shows tho variation of $L_1/h$ with $\overline{VD}/\nu$ for runo

In the range of experiments, performed by them the resistance could be predicted by using standard values (22) of drag coefficient.

This concept implied that the interference effect is not significant. However while dealing with small spacings and various types of roughnesses one can still expect the interference effect and this aspect needs further investigation.

Morris (11), 1955, presented a new concept of flow over rough pipe and channel surfaces based on the effect of longitudenal spacing of roughness elements. He expressed the opinion that longitudenal spacing of the elements is a roughness dimension of paramount importance in rough conduits. He classified the flow over rough surfaces into three categories:

(a)    Isolated roughness flow: In this type of flow wake zone at each element is fully developed and dissipated before the next element is reached. For this zone equation of friction factor was given as,

$$f = f_s \left[ 1 + \frac{67.2 \, C_D}{L/h} \left( 1 - \frac{N S_1}{P} \right) \right] \qquad (2.4)$$

where, $f_s$ = friction factor for plane boundary at Reynold's No. of flow

N = no. of elements in periphery

$S_1$ = clear peripheral spacing between elements

and    P = wetted perimeter.

(b)    Wake interference flow:  In this case spacing of
elements is such that the wake zones behind each element
are not fully dissipated before the next element is
reached.  For this type of flow he found that,

$$\frac{1}{\sqrt{f}} = 2 \log_{10} \frac{D}{L} + 1.75 \tag{2.5}$$

(c)    Quasi-Smooth flow:  When roughness elements are so
close that the flow skims over the crest of each element
and stable vortices exist between various elements the
flow was termed as quasi-smooth.  For this type of flow
Morris gave the following equation for the friction
factor,

$$f = f_s + (\frac{C_w \, U_h}{V})^* / \frac{L}{h,j} \tag{2.6}$$

where, $U_h$ is the velocity at the crest level of element

$C_w$ = constant (taken as 0.5)

j = width of groove

In the equation (2.6) either h or j, whichever is smaller is
to be used.

Sayre and Albertson (21), 1961, carried out flume
studies on discontinuous angle iron roughness elements with
different spacings and studied the variation of $K_s'$ (roughness
parameter) with pattern of roughness.  They suggested the
resistance equation as

$$\frac{\bar{V}}{V_*} = 6.06 \log_{10} \frac{D}{K_s'} \tag{2.7}$$

The above equation yield a value of Karman's constant (K) as 0.38, however analysis of velocity profiles revealed that K changes appreciably with roughness concentration. Nevertheless, they recommended K is equal to 0.38 for wake interference flow.

From the study of variation of $K'_s$ with the roughness pattern they found that for different arrangement and type of roughness elements maximum resistance could occur at various concentrations.

O' Loughlin and Macdonald, 1964, performed open channel experiments and investigated the effect of roughness pattern and concentration on the resistance coefficient. They found that shape and pattern of roughness elements has no significant effect on the resistance coefficient below a concentration of 0.10. But above this value of concentration resistance coefficient is affected considerably by the concentration.

O'Loughlin (26), 1965 assumed that the departure from the logarithmic profile can be expressed by defining a momentum diffusion coefficient $\epsilon'$, such that,

$$\epsilon' = \epsilon_{log} + \epsilon_w \tag{a}$$

The velocity profile is a combination of a logarithmic field and a mixing effect in the wake layer.

$$\text{Here } \epsilon_{log} = \frac{\tau}{(\frac{du}{dy})_{log}} \tag{b}$$

$$= \frac{\tau y}{\rho A V_*} \tag{c}$$

$\epsilon'$ was assumed constant between the boundary and a level
$y = 0.2D$ which is comparable to roughness height i.e. $\epsilon_w$ will
be negligible above this level and $\epsilon'$ will be equal to $\epsilon_{log}$.
Assuming such a distribution of $\epsilon'$, he obtained the velocity
distribution for flow over a boundary with cubes placed at a
regular spacing. He found that the actual profiles showed
qualitative agreement with the theoretical profiles.

He also studied the variation of $T_{o_1}'/T_o$ with $D/h$
and roughness concentration as predicted by his mathematical
model.

Here $T_{o_1}'$ = Average shear stress of the boundary between
the roughness elements.

and $T_o$ = Total shear stress.

The experimental values were found to be lower than this.
For cubes with concentration $y = 1/256$, $1/128$, and $1/64$, the
values of $T_{o_1}'/T_o$ were found to be 0.60, 0.50 and 0.42 respectively,
for the $D/h$ value used by him.

Rangaraju and Garde (19), 1970, carried out investi-
gations of the interference effect on the resistance of two-
dimensional strip roughness at different spacings. They found
that the total resistance of a plane boundary having series of
roughness elements with L/h between 2.5 and 40 can be assumed
equal to form resistance of the roughness elements. Based on
flume and tunnel data, an empirical equation for computing the
drag was given as

$$\frac{1}{\sqrt{C_D}} = C_1 \log_{10} \frac{D}{h} + C_2 \qquad (2.8)$$

where $C_1$ and $C_2$ are constants and functions of L/h. The
variations of $C_1$ and $C_2$ with L/h are shown in Fig.(2.2) and (2.3)
respectively.

Rangaraju and Garde also showed by plotting of data
that the method given by Morris (11) does not yield satisfactory
results over a wide range of data.

Roberson and Chen (20), 1970, investigated the flow in
conduits with low concentration with regularly spaced cubes and
spheres so as to obtain functional relationship between con-
centration of given type of roughness and resistance produced
by this roughness. They developed a procedure for obtaining
transition functions for flow in conduits roughened with dis-
crete elements, assuming a logarithmic velocity distribution with
a suitable correction for the 'wake effect'. The drag charac-
teristics of roughness elements, viscous resistance of the

smooth wall and velocity distribution conduit were considered separately and equations relating these were solved to obtain a resistance relation. The plots of transition functions for different concentration ranging from 0.0001 to 0.123 as well as curves of coefficient of drag against Reynolds number were also plotted. These curves for cubical roughnesses are shown in Figures (2.4) and (2.5).

A comparison was also made of the data of this analysis with the experimental results of Koloseus and O'Loughlin as shown in Figure (2.4). This indicates reasonably good agreement between theory and experiments.

Drag coefficient values computed with respect to an velocity over the height of the roughness element (cube or sphere) were found to be independent of the nature of velocity distribution.

Besides these investigations discussed above, several other investigations have been carried out by Koloseus (9), Peterson and Mohanty (14), Rouse, Koloseus and Davidian (23), Horbich and Shulits (7) using artificial roughness elements. These have not been reviewed here, since they are not directly related to the work planned in this study.

<u>Summary:</u>

Among the various investigations on the subject of artificial roughness, the studies of Rangaraju- Garde and Roberson and Chen are the only ones dealing with the individual roughness

effects and may be said to be based on the ideas put forward
by Einstein and Banks. It is interesting to note that the
studies of Rangaraju and Garde were performed at fairly high
concentrations using two-dimensional strips. As such they were
concerned with the variation of the form drag coefficient of
the strips with their geometry; the skin friction of the plane
boundary was found to be practically nil. On the other hand,
Roberson and Chen performed their experiments using cubes at
low concentration. Therefore, the skin friction of the plane
boundary was found to be a significant part of the total resis-
tance and the premise that $C_{D_h}$ is independent of velocity dis-
tribution was found to be valid for the low concentrations
studied by them. In a general case, one would possibly be required
to consider the skin friction of the plane boundary as well as
the variation of the form drag coefficient of the roughnesses
with the relative spacing. Such an approach is planned during
this investigation.

CHAPTER - 3

## ANALYTICAL CONSIDERATIONS

### 3.1 Preliminary Remarks:

Having considered the work of past investigators on
the problem of resistance, some basic aspects of the problem
are discussed in this Chapter. This would serve as a
guideline for the subsequent analysis of the data of the
present investigation.

### 3.2 Drag Coefficient:

It is well known that a body placed in a fluid flowing
at uniform velocity past it experiences a force in the direc-
tion of flow which is termed as drag force. The body, in
turn, exerts a force equal in magnitude but opposite in
direction. This is commonly known as resistance. The total
drag on the body is the sum of deformation drag, friction
drag and form drag. Deformation drag is due to wide spread
deformation and occurs only at low Reynold numbers. Friction
drag is caused by the shear stress due to the velocity
gradient near the body and is a function of Reynold's number.
The form drag, on the other hand is due to pressure
difference between the front and rear of the body caused as
a result of seperation of flow. In case of two-dimensional
sharp-edged strips kept in a fluid where Reynold's number
exceeds $10^0$ only form drag is prevalent, the extent of which

is not known for various goomotries. In the caso of a plano boundary with a regular array of two-dimonsional strips total drag is oqual to the drag on the strip plus the drag of tho plano boundary. Since no thcoretical mothod is available for ostimation of form drag on normal strips placed on tho boundary ot different spacings, experimental investigations aro tho only solution. Also estimation of frictional resistance of tho plano boundary by theoretical methods is complicatod because of the presence of scporntion zono and the ill-defined characterstics of tho redovoloping boundary layer. Honco tho convenient way to tackle tho problom is to resort to experimontation. The present study is, therefore, planned to provide experimontal data on the form drag of strips and tho skin friction of tho plano boundary at various spacings. In this Chaptor dimonsional analysis of the problem has boen corriod out to facilitate analysis of the experimental data. Also some basic ideas resulting from past investigation's havo boon introduced to obtain equations which would form the starting point for analysis of data.

## 3.3   Resistance of a Sinolo Element:

The forco $\Delta F$ on a unit width of a two-dimonsional normal plate kept on tho boundary of an open channel can be doscribod by tho following functional relation:

$$\Delta F = \emptyset \ (h, \ D, \ V, \ P, \ \mu, \ g) \tag{3.1}$$

where $\rho$ is the mass density, $\mu$ - dynamic viscosity of the flowing fluid and $g$ - acceleration due to gravity.

By choosing $V$, $h$ and $\rho$ as repeating variables the above equation can be rewritten in dimensionless form as,

$$\frac{\Delta F}{\rho \frac{V^2}{2} \cdot h} = \Phi_1 \left( D/h, \frac{Vh\rho}{\mu}, \frac{V}{\sqrt{gh}} \right) \qquad (3.2)$$

i.e. $\qquad C_D = \Phi_2 \left( D/h, \frac{Vh\rho}{\mu}, \frac{V}{\sqrt{gh}} \right) \qquad (3.3)$

For sharp - edged roughness elements kept in a uniform stream the drag coefficient is known to be independent of Reynold's number of values of Reynold's number above $10^3$. Assuming that this is valid for elements on the boundary also, Equation (3.3) can be simplified for $R_e > 10^3$ as,

$$C_D = \Phi_3 \left( D/h, \frac{V}{\sqrt{gD}} \right) \qquad (3.4)$$

The Equation (3.4) gives the functional relationship of the drag coefficient of an isolated roughness element placed on the bottom of the flume. The variation of $C_D$ with both these parameters will be studied in the present investigation.

## 3.4 Resistance of a Plane Boundary Glued with Gravel and Two-Dimensional Strips:

The second aspect of the experimental programme is to measure the resistance characterstics of a plane boundary with gravels of 2 mm size glued on it, two-dimensional strips being fixed on this surface at the desired spacing. It is intended to determine the total resistance of the boundary as well as the form drag coefficient of the strips by pressure measurements.

The functional relationship for the total resistance of the boundary can be written as,

$$S' = \phi_4 (V, D, \rho, \mu, g, h, d, L) \tag{3.5}$$

where, d = grain size.

Choosing, $V$, D and $\rho$ as repeating variables,

$$S' = \phi_5 (\frac{V}{\sqrt{gD}}, \frac{VD\rho}{\mu}, D/h, D/d, L/D) \tag{3.6}$$

This can be modified as,

$$\frac{V}{V_*} = \phi_6 (\frac{V}{\sqrt{gD}}, \frac{Vh\rho}{\mu}, D/h, h/D, L/h) \tag{3.7}$$

At low Froude's number resistance coefficient is independent of Froude's number as found by Koloscus (9). Hence $\frac{V}{\sqrt{gD}}$ can be omitted. Further $\frac{Vh\rho}{\mu}$ can also be ignored for $R_0 > 10^5$. h/d remained constant during the study, hence Equation (3.7)

simplifies to,

$$\frac{\bar{V}}{V_*} = \Theta_7 \; (D/h, \; L/h) \tag{3.8}$$

Using tho hydraulic radius with rospoct to tho bod of tho flumo, $R_b$, the foregoing equation becomes,

$$\frac{\bar{V}}{V_*} = \Theta_8 \; (R_b/h, \; L/h) \tag{3.9}$$

Similarly tho drag coefficiont of tho strip can be writton os,

$$C_D = \Theta_9 \; (D/h, \; L/h) \tag{3.10}$$

### 3.9 Resistance of a Smooth Boundary with Two-Dimensional Strips Placed on it:

In this aspect of tho study it is proposod to uso two-dimensional strips of 1 cm hoight placod at tho dosirod spacing along tho length of the flumo. The total rosistenco of tho bod as woll as the skin friction of tho plano boundary would bo moasurod. From those it is proposod to ostimate the form rosistanco of the strips as prossuro measuromont on a otrip of such a small height would bo very difficult.

For tho total rosistanco of the boundary, one can writo tho functional rolation,

$$S' = \Theta_{10}(V, D, \rho, h, \mu, g, L) \tag{3.11}$$

This can be simplified to,

$$\frac{V}{V_*} = \phi_{11} \left( R_b/h, \ L/h, \ \frac{\overline{V} \, R_b \, \rho}{\mu} \right) \tag{3.12}$$

after omission of Froude's number which is very low in the present experiments.

In general the average bed shear stress, $\tau_0$, can be written as sum of the shear due to the roughness elements and the net shear due to the skin friction of the plane boundary. It may be noted that within the separation zone downstream of each element, there is reverse flow at the bed and hence the shear is negative. Downstream of the standing eddy, the shear is once again positive. Hence two approaches are open for analysis of the skin friction data and the computation of the form drag of the roughness elements.

I Approach: When the negative shear in the standing eddy is completely neglected, assuming the reverse velocities to be too low to cause any shear.

II Approach: When it is assumed that the negative shear in the zone of standing eddy cancels with the positive shear over a certain distance from the boundary. Further analysis will be carried out based on both these approaches.

### 3.5.1 I Approach:

If negative friction is completely neglected then,
total shear can be written as,

$$\tau_o = \tau'_{o_1} + \tau''_{o_1} \tag{3.13}$$

where $\tau'_{o_1}$ is the average shear stress due to the skin friction of the plane boundary (See Fig.(3.1)).

and $\tau''_{o_1}$ = shear stress due to form resistance of roughness elements.

$\tau'_{o_1}$ may be written as,

$$\tau'_{o_1} = C_{f_1} \frac{\rho V^2}{2} \tag{3.14}$$

and $\tau''_{o_1}$ may be written as,

$$\tau''_{o_1} = C_{D_1} \frac{h}{L} \frac{\rho V^2}{2} \tag{3.15}$$

Equations (3.13), (3.14) and (3.15) will form the basis of analysis of data using this approach.

### 3.5.2 II Approach:

Plate (15), in his study of a normal plate placed in a turbulent boundary layer, found that the net friction of the plane boundary for a distance of 35 times the height of the plate from the plate is zero. Apparently, within this distance,

tho nogativo friction within tho standing oddy componsatos for tho positive friction downstroam of tho oddy. Similar roqults aro not availablo for fully dovelopod flow in an opon channol on which a sorios of roughnoss olmnents aro placed. Howovor using Plato's critorion for this caso also, as a first approximation, ono can writo

$$\tau_0 = \tau_0' + \tau_0'' \qquad (3.16)$$

whore $\tau_0'$ is the effoctivo or net positive friction of tho plano boundary (Soo Fig.(3.1)).

$\tau_0'$ and $\tau_0''$ may bo writton as

$$\tau_0' = C_{f_3} \; \rho \frac{V^2}{2} \qquad (3.17)$$

and, $$\tau_0'' = C_D \cdot h/L \; \rho \frac{V^2}{2} \qquad (3.18)$$

Equations (3.16), (3.17) and (3.18) will form tho basis for analysis of data using this approach. On tho basis of dimonsionol analysis prescntod oarlior, one can writo

$$C_{f_1}, \; C_{f_3} = \Phi \left( \frac{\mathring{V} R_b \rho}{\mu}, L/h, R_b/h \right) \qquad (3.19)$$

and, $$C_D, \; C_{D_1} = \Phi (D/h, L/h) \qquad (3.20)$$

# CHAPTER - 4

## EXPERIMENTAL SET-UP AND PROCEDURE

### 4.1 Preliminary Remarks:

All the experiments concerning the present investigation
were conducted in the Hydraulics Laboratory of the University
of Roorkee, Roorkeo. The work was programmed and executod as to
provide detailed information regarding the various parametoro
required for further analysis as discussed in the preceding
Chapter. The experiments wore performed in three parts viz.
oxporimonts on the single isolated roughness element placed on
the bottom of the flume, studies on series of roughness clomento
with rough boundary and series of eloments placed on a smooth
boundary. The details of these oxperiments, various equipmont
used and the procedure followed are discussod in various soctions
of this Chaptor.

### 4.2 Details of Equipmant Used:

The experimental work was done in a 47.25 cm wide, 60 cm
doop and 11 meters long tilting flume with glass side walls
and a wooden false bottom. (Photo-1) The flume was of the recirculating
typo with an overhead tank and sump arrangement. It was provided
with adjustable brass rails on the top of each side wall and
these wore maintained parallel to the bod. The pointor gago
was mounted on a wheeled carriago which could be moved on the

rails. A tail gate was provided at the downstream end of the flume for adjusting the depth of flow.

The discharge was measured by a calibrated rectangular sharp-crested weir installed in a tank downstream of the flume. The velocity distribution in the flume during a run was measured by a calibrated prandtl tube. The ensuing heads were read on an inclined manometer.

Pressure measurements in case of single element and elements in rough boundary were made using a sharp-edged element of wood, 0.30 cm thick but chamfered at the top to get a knife edge. Pressure taps were provided approximately 5 mm apart both on upstream and downstream faces of the element, but very close to the centre of its width. Plastic tubes were connected to the pressure taps and led to the limbs of an inclined manometer.

For studies on series of elements angle iron strips of negligible thickness were nailed to flume bottom at the required spacing to form the roughness. The elements spanned over the full width of the flume in all the runs carried out during this study.

4.3 Experimental Procedure(Single Roughness Element):

For the study of the variation of drag on a single normal plate kept on the boundary the two-dimensional wooden strip of

tho roquirod hoight was nailed to tho flume bottom at a distanco
5.5 m from the upstroam ond of tho flume. For any particular
discharge, tho roquirod depth of flow upstroam of tho clomcnt
was obtained by adjusting tho tail gato. Tho prossuros on tho
two facos of the cloment were then moasured.

Velocity profile at tho centre lino of width was takon
50 cm upstream of tho eloment with a calibratod prandtl tubo.
Flow depth for each run was moasured by a point or gago having a
loast count of 0.01 cm. Tho tcmperature of the flowing wator
and tho discharge woro also recorded.

The experiments woro performod using strips of two hdghts,
viz 3 cm and 4 cm. A total of 14 runs covering range of depth
from 7.50 cm to 36.00 cm were mado for this study.

4.4    Exoerimental Procoduro (Sorios of Elements on a Rough Boundary):

In ordor to have a rough boundary gravel of size 2 mm
was gluod uniformly to bottom of the flumo. The roughnoso
elements usod in this part of study woro anglo iron strips of
galvaniood iron 4 cm in height, (see Photo-2) One roughness element noar
tho middlo of length of flume was made of wood and provided with
prossure taps to facilitato prossure moasurcment. The experi-
mcntal work was done on two slopos 1 x $10^{-3}$ & 2 x $10^{-3}$. For
oach slopo two different roughness pattorns, of spacing 80 cm
and 160 cm woro usod. Aftor tho roquirod roughnoss pattorn
was placod on tho flumo at the dosircd slope, uniform flow was

established at pre-determined depth and the discharge and temperature were measured. On each slope three different depths were used for each pughness pattern. For each run two velocity profiles were taken, midway and quarterway between the roughness elements in a reach 5.5 m from upstream end of the flume. The average velocity of flow in the vertical centre line was obtained by integrating the above profiles. The mean of the values given by the above profiles was used as the average velocity in the vertical centre line in calculations. The pressure distribution around a representative element was measured as in the case of studies on single element.

### 4.3 Experimental Procedure(Series of Elements on a Smooth Boundary):

In the studies of roughness placed on smooth boundary, 1 cm high angle iron strips were nailed to the bottom of the flume at the required spacing. Two different spacings, viz 80 cm and 60 cm, yielding L/h = 80 and L/h = 60 were used. The experiments were performed at two slopes, viz 1/1300 and 1/750.

After the required roughness pattern was placed on the bottom of the flume set to the desired slope, uniform flow was established at a predetermined depth. For each value of L/h, three different depths, viz 5 cm, 10 cm and 15 cm were

used for each slope. The discharge and the water temperature
were also noted.

For all the runs the velocity profile was measured over
the element as well as midway between the two elements at
the centre line of width. Skin friction measurements were made
at three sections distant 5 cm, 15 cm and 23.60 cm respectively
from one side of the flume using a Preston tube of dia 0.2096 cm.
The observations were taken at these three sections over the
entire length between two roughness elements. Only the positive
shear values were measured. It may be mentioned that the
velocity and shear measurements were made beyond a distance of
5.5 m from flume entrance to avoid the effect of entrance
disturbances.

From the Preston tube readings, the shear was calculated
using the curve given by Patel (13). The equation given by
Patel (13) are listed below for reference.

For range,   $3.5 < Y^* < 5.3$

$$X^* = Y^* + 2 \log_{10} (1.95 \, Y^* + 4.10)$$   (4.1)

where,   $X^* = \log_{10} \left( \dfrac{\Delta p \, d'^2}{4 \rho \nu^2} \right)$   (4.2)

and

$$Y^* = \log_{10} \left( \dfrac{T'_o \, d'^2}{4 \rho \nu^2} \right)$$   (4.3)

where, $\tau_o'$ is skin friction

and    d' is the diameter of the Preston Tube

and    $\Delta P_p$ is Preston Tube reading

In range,    $1.5 < Y^* < 3.5$

$$Y^* = 0.8287 - 0.1381 \; X^* + 0.1437 \; X^{*2} - 0.006 \; X^{*3} \qquad (4.4)$$

Finally in Range,    $Y^* < 1.5$

$$Y^* = 0.5 \; X^* + 0.037 \qquad (4.5)$$

CHAPTER - 5

## ANALYSIS OF EXPERIMENTAL DATA

### 5.1 Preliminary Remarks:

The experimental data collected on the various aspects of the problem have been analysed in this Chapter. The analysis has been carried out on the basis of the functional relationship developed in Chapter III. Firstly the resistance of a single element placed on the boundary has been studied. The data on strip roughness placed on a gravel bed have been analysed later. Lastly the strip roughness data for case of a smooth boundary have been analysed to extend the results of Rangaraju and Garde (19).

### 5.2 Resistance of a Single Element:

### 5.2.1 Pressure Distribution:

The data concerning pressure distribution around the element placed on the bed, have been analysed first. The pressure measurements for any run indicated a reasonably constant value of pressure on the down stream face. Hence, for the sake of convenience the pressure distribution has been shown in a pressure difference form (vide Fig.5.1). Here $p_u$ is the pressure on the upstream face, $p_d$ is the pressure on the downstream face and y is the height measured from the bottom of the flume.

It has been pointed out earlier (15) that such a form

of plotting does reflect all the charactoriatics of variationo
of upstream prosouro. Fig. (5.1) shows that the prossuro on the
upstream face is also more or loss constant over the height,
oxcept for a small height noar the top. Tho variation of $p_u$
along tho height for largo D/h valuoo con be soon to bo smallor
than that for small D/h valuos.

3.2.2 <u>Variation of Drag Coofficient with D/h:</u>

Tho drag coefficient, $C_D$, for each run was obtainod by
intogration of tho prossuro difference diagrams similar to
Fig. 5.1. As shown in Chaptor 3, $C_D$ is expectod to be a
function of D/h and $F_r$ . Figuro (5.3) shows the variation of
drag cooffici ent with D/h. It is soen that drag coofficiont
decroasos continually with incroaso in D/h, the decrooso boing
pronouncod in the rango of D/h betwoon 2.0 and 4.0.

The values of $V/\sqrt{gD}$ aro markod opposite oach point on
Figuro (5.3) and Fr doos not soom to havo any offect on $C_D$.
Howovor the rango of Fr covorod in this study is very small and
moro data are required to ascertain the influenco of Fr on $C_D$.

Tho curvo proposod by Adachi on a 6.4 cm thick strip of
hoight 5 mm placod on the bod of the flumo is also plottod in
tho Figuro (5.3). It con bo soon that at low valuos of D/h
Adachi's curvo agroos with that proposod in this study for
strips of zoro thicknoss; at high valuos of D/h Adachi's curvo
falls abovo tho ono proposod horo. It is not knwon whothor

Adachi has used the average velocity in the vertical center line as indeed it should be with the center line pressure measurements. Obviously if the average velocity over the cross-section is used along with center line pressure measurements the computed $C_D$ would be higher. Further, studies by Vijaya Singh (25) on two-dimensional normal plates with various values of t/h have shown $C_D$ to increase with t/h in the range of 0 to 1. Since t/h was 1.08 for strips used by Adachi, the higher values of $C_D$ obtained by Adachi may not be inexplicable.

The drag coefficient for a plate on the bed of an open channel can be predicted using the $C_{D_0}$ V/s δ/h curve proposed by Rangaraju - Garde (See Figure 2.1) along with the equation for blockage, namely

$$C_D = C_{D_0} (1 - h/D)^{-2.85} \qquad (2.3)$$

Obviously in fully developed flow in an open channel, D = δ and hence $C_{D_0}$ can be read from Figure (2.1) for the required value of D/h and then equation (2.3) used to find $C_D$. Such a procedure has been used to obtain a relation between $C_D$ and D/h. (see Figure 3.3). It is seen that the author's curve falls well above the curve predicted from wind tunnel studies. The difference may be due to the fact that in case of wind tunnel the top boundary was smooth and parallel to flow while in flume water depth decreased just downstream of the element.

This decrease in depth results in higher acceleration of flow which may lead to higher drag coefficient values.

Experimental data have also been plotted in the form $1/\sqrt{C_D}$ V/s log D/h in Figure (5.2). It is seen that the following relationship fits the data reasonably well:

$$\frac{1}{\sqrt{C_D}} = 0.85 \log_{10} D/h + 0.13 \qquad (5.1)$$

## 5.3 SERIES OF ELEMENTS ON A ROUGH BOUNDARY:

### 5.3.1 Preliminary Remarks:

It was mentioned earlier that the studies on the rough boundary are performed to test the arguments of Rangaraju-Garde that for L/h $\leq$ 40 the net skin friction is zero and the total resistance of the boundary is equal to form resistance of the roughness elements. If these findings are true then the total resistance of the roughened plate bed (with two-dimensional strips placed on it) should be equal to the total resistance of smooth plane bed with the same arrangement of strips. The data collected on the resistance of the gravel bed with strips placed on it has been analysed in this section to check these premises.

### 5.3.2 Pressure Distribution:

The pressures measured on the two faces of the roughness

olcmcnt placed on tho bod of tho flumo indicated that for a
givon volocity and dcpth of flow, tho pressuro over tho down-
stroam foco was constont. Advantago was takcn of this fact
in plotting tho prossuro distribution diagram, on the Figuro
5.4, whoro prossuro distribution is shown in form of prossuro
difforence botwoon upstroam and downstroam faco of the olcmont
plottcd against y/h. Thoso diagrams indicate that oxcopt for a
small height near the top tho pressuro on the upstroam faco also
remains constant ovor tho height of the element. The drag
cooffici ent valuos for each run woro computed by tho intogration
of corrosponding prossuro distribution diagrams. Tho $C_D$ valuos
woro obtainod with rospoct to center line volocity. It con
bo notcd that tho avorage abcissa on the plottcd curvos of Fig.
5.4 ylolds the form drag coofficient for tho corrosponding run.
Tho naturo of variation of form drag cooffici ent with relovent
paramotor will be studiod in Soc. 5.3.4.

5.3.3 Comparison of Form Rosistanco with tho total Rosistraco:

From tho moasurod valuos of tho drag coofficicnt, tho
valuos of $T_0^n$ woro computod from tho following oquation:

$$T_0^n = C_D \cdot h/L \cdot P \cdot V^2/2 \qquad (5.2)$$

Tho valuos of $T_0^n$ aro plottcd against $T_0$ ($T_0 = Y R_b S$), for
all tho twolvo runs corried out using strips on a gravel bod,
in Figuro (55). Tho agroomont botwoon $T_0$ and $T_0^n$ is fairly

good except for three runs. It may be mentioned here that $C_D$ values determined in the flume are usually liable to some error. The drag coefficient was determined from center line pressure and velocity measurements and the average velocity in the center line was obtained by integration of velocity profiles taken at two different cross-sections. In case of a rough boundary with large strips placed over it, the readings of the conventional Prandtl tube could be affected by the curvature of the flow, thus introducing some error into the measured velocity. It should be noted that any errors in the velocity will introduce larger errors in the computed value of $C_D$. As such the agreement or the scatter on figure may not provide adequate basis to prove or disprove the contention that for $L/h \leqslant 40$, the total resistance would be equal to the form resistance of the strips. Comparison of the total resistance in case of smooth and rough boundaries (with the same roughness pattern on them) as done in section 5.3.3.- may be the only logical basis to test the foregoing contention.

### 5.3.4 Variation of Drag Coefficient:

The dimensional analysis in Chapter 3 has shown that drag coefficient $C_D$ can be expressed as

$$C_D = \phi \ (D/h, \ L/h)$$

Rangaraju and Garde ( 19 ) found that for their data the relation between the above parameters can be put in the form

$$\frac{1}{\sqrt{C_D}} = C_1 \log D/h + C_2 \qquad\qquad (2.8)$$

whore, $C_1$ and $C_2$ aro functions of $L/h$.

Accordingly in this caso also tho drag coofficient valuoo computod from maaouromonto on rough boundary are plottod on

$$\frac{1}{\sqrt{C_D}} \text{ vs. } \log_{10} D/h \text{ ploto for both tho spacingo (Soo Fig.5.6)}$$

The values of $C_D$ detormined indirectly (i.o. by taking totol rosistanco oquol to form rosistanco) for the smooth boundary dato of Rangaraju-Gardo aro also plottod on this figuro. Whilo a majority of tho rough boundary dato show agroomont with tho data for smooth boundary, somo points indicato a lovor valuo of $C_D$ than for the smooth boundary at corrosponding D/h valuos. Tho probable reasono for this scattor havo boon discussod previously. From Fig.(5.6) one may conclude that tho drag coofficiont of tho strip (for a givon arrangomont) is not oignificantly affoctod by tho roughnoss of tho plane boundary.

5.3.3 <u>Annlysis of Total Rosistance:</u>

It has been shown in Chaptor 3, that the total resistanco of tho rough boundary can be oxprossod by tho Equation 3.9 i.o.

$$\frac{V}{V_*} = \phi \left( R_b/h, L/h \right)$$

Accordingly tho data on rough boundary for the two difforont L/h values aro plottod on a graph of $V/V_*$ vs $\log_{10} R_b/h$ (Soo Fig.5.7).

The data of Rangaraju and Garde on a smooth boundary for these two spacings are also plotted on Figure 5.7. It is interesting to note that data for rough boundary show good agreement with the data obtained from experiments on smooth boundary for both the spacings. Since the skin friction would be otherwise significant in case of the rough boundary the agreement of rough boundary data with those of the smooth boundary may be taken to substantiate the premise of Rangaraju and Garde that the net skin friction is zero for L/h $\leq$ 40.

For strips spaced at L $\leq$ 40 h, analysis has been carried out on the assumption that the net friction over a distance of 35 h downstream of the element is zero. The distance 35 h was used on the basis of Plate's results.

5.3.6 Analysis of Velocity Profiles:

Typical velocity profiles for both L/h = 20 and 40 are shown in dimensionless form in Fig.5.8 and 5.9 respectively. The profiles have been shown for two different depths in each case. These profiles were taken at two different sections along the length, as indicated on the figures. The data for both the spacings show a break in the profile and the inapplicability of a single velocity distribution law over the whole depth. The break in velocity profile has been previously reported by Morris(11) Adachi(1), O'Loughlin (12). It has also been reported by some

of these investigators that the velocity distribution over the element differs appreciably from that between elements. But it is interesting to note from Fig.5.9 that the velocity distribution one quarterway and midway between elements is practically the same for L/h = 40. Similiarly for L/h = 20, velocity profiles tend to coalesce. It is quite likely that the velocity profile over the element may differ from the profiles taken between the roughness elements. But no profile was taken over the element in this series of tests.

A comparison of the velocity profiles has also been made with the velocity profiles for the smooth boundary with roughness elements obtained by Rangaraju (17). The curves on the Figures 5.8 and 5.9 represent the smooth boundary velocity profiles. Three of the four typical profiles presented here show these curves. In case of the fourth (i.e. for L/h = 40 and D = 32.0 cms) no velocity profile was available for smooth boundary, hence no comparison has been made in this plot. It is seen that velocity profiles for rough boundary and those for smooth boundary are similar which indicates that the frictional resistance of the boundary has no appreciable effect on the velocity distribution in the channel and it remain practically unaltered.

## 5.4 Series of Elements on a Smooth Boundary:

### 5.4.1 Preliminary Remarks:

In this section, the data concerning the resistance of two-dimensional strips placed on a smooth boundary have been analysed. Firstly the total resistance of boundary has been studied; this is followed by an analysis of the data concerning skin friction. These results have been used subsequently to determine the relation between form drag of strips and their geometry. Firstly the approach evolved here is used to predict the resistance for Basha's runs (2), and the predicted values are compared with the observed values.

### 5.4.2 Analysis of Total Resistance:

It was shown in Chapter 3 that the total resistance can be expressed as

$$\frac{\bar{V}}{V_*} = \Phi \ (R_b/h, \ L/h)$$

The conventional resistance equation is,

$$\frac{\bar{V}}{V_*} = \frac{2.30}{K} \log_{10} \frac{R_b}{h} + A_1 \tag{5.3}$$

where K is the Karman's constant and $A_1$ is a constant dependent on the type and arrangement of roughness elements.

The above equation predicts a linear relationship between $\bar{V}/V_*$ and $\log_{10} \frac{R_b}{h}$. On the basis of above equation on effort was made to study the variation of $\bar{V}/V_*$ with $\log_{10} \frac{R_b}{h}$.

Fig.(5.10) shows this plot for the two spacings tested during the study. It shows that a unique relation exists between these parameters for a particular spacing. The equations governing the resistance can be written as

$$\frac{V}{V_*} = \frac{2.30}{K} \log_{10} \frac{R_b}{h} + 5.95 \text{ for } L/h = 60 \qquad (5.4)$$

and, $$\frac{\bar{V}}{V_*} = \frac{2.30}{K} \log_{10} \frac{R_b}{h} + 6.90 \text{ for } L/h = 80 \qquad (5.5)$$

This indicates that $K = 0.396$ for this type of roughness and the resistance for $L/h = 80$ is greater than for $L/h = 60$.

### 5.4.3 Variation and Local Skin Friction Coefficient

The local skin friction coefficient $C_f$ could be defined as

$$C_f = \frac{T'_o}{\rho \bar{V}^2/2} \qquad (5.6)$$

where $T'_o$ is the shear stress at a distance x from the element (see Fig. 3.1). As mentioned earlier, the skin friction measurements were made along three rows parallel to the flow - at a distance of 5 cm, 15 cm and 23.6 cm from the side wall. It was noticed that, in gneral, the shear stress (at any distance x from the element) close to the wall tended to be about higher then that on the centre line. However, one would expect the shear on the centre line to be highest. Nevertheless the average value of $T'_o$ along the width was used in the

computation of $C_f$.

Figures (5.11) and (5.12) show the variation of local skin friction coefficient $C_f$ with $x/L$, $x/h$ and $\bar{V}x/\nu$ . Data for both $L/h = 80$ and $60$ have been plotted on these figures. All the figures indicate a similiar trend - i.e. $C_f$ values increase with of the above parameters. However there is no unique relation between $C_f$ and any of these parameters. No third parameter, which would systematise the scatter on these figures, could be found.

The local friction coefficient for the developing turbulent boundary layer is given by,

$$C_f = \frac{0.059}{R_x^{1/5}} \tag{5.7}$$

This relationship has been plotted in Figure     for comparison and shows a marked variation from the nature of variation obtained in the present investigation. In case of normal turbulent boundary layer $C_f$ values decrease with increase of Reynold's number whereas in the present study a completely different trend is indicated. This may be because of the fact that the boundary layer downstream of the standing eddy is a redeveloping boundary layer.

5.4.4 <u>Variation of Average Skin Friction Coefficient</u>:

It was shown in Chapter 3 that for computing average skin friction coefficient two approaches are possible. In the I approach the shear in the standing eddy is assumed to be

zoro whilo in II cpproach it io ocsumed thot tho not skin friction for o longth of 33 h from tho olcmont is zoro. Obviouoly tho friction eooffleicnt voluos obtained from thooo two cpproachoo would bo differcnt. Tho variation of thooo friction eoofficiont voluos with tho portincnt porsmotoro will bo discussed in tho following sectiono.

### 5.4.3 I Appxonch (Aroumino Zoro Shoar within Eddy):

Roforring to Figuro 3.1 (of Chaptor 3) tho avorago drag eoofficiont $C_{f_1}$ was dofinod ao,

$$C_{f_1} = \frac{Aron\ ABC}{L\ \rho\frac{V^2}{2}} \tag{3.8}$$

$$= \frac{F_9}{L\ \rho\frac{V^2}{2}} \tag{5.9}$$

whoro $F_9$ is tho total pooitive skin friction botwoon two roughnoos olomonto por unit width.

Anothor drag coofficiont $C_{f_2}$ can bo dofined oo

$$C_{f_2} = \frac{F_9}{L_2\ \rho\frac{V^2}{2}} \tag{5.10}$$

$$= C_{f_1} \cdot L/L_2 \tag{5.11}$$

Tho variation of $C_{f_1}$ ond $C_{f_2}$ with tho rolovont poromotoro may now bo studiod.

Variation of $C_{f_1}$ and $C_{f_2}$ with $\dfrac{\bar{V}R_b}{\nu}$ :

It is expected that $C_{f_1}$ and $C_{f_2}$ would be functions of Reynolds number. The Reynolds numbers that can be considered significant are $\bar{V}R_b/\nu$ and $\bar{V}L/\nu$ . Figures 5.13 and 5.14 show variation of $C_{f_1}$ and $C_{f_2}$ with $\bar{V}R_b/\nu$ respectively. It is seen that $C_{f_1}$ and $C_{f_2}$ decrease with increase in Reynolds number of main flow. In both the figures data for the relative spacings tested viz. L/h = 60 and L/h = 80, fall together yielding a unique relationship.

The equation of the experimental line in Fig. 5.13 is,

$$C_{f_1} = \frac{0.323}{\left(\dfrac{\bar{V}R_b}{\nu}\right)^{0.423}}$$

(5.12)

Similarly the straight line of the Fig. 5.14 could be given by the equation,

$$C_{f_2} = \frac{0.689}{\left(\bar{V}R_b/\nu\right)^{0.48}}$$

(5.13)

Variation of $C_{f_1}$ and $C_{f_2}$ with $\bar{V}L/\nu$ :

The plots of $C_{f_1}$ and $C_{f_2}$ against the parameter $\bar{V}L/\nu$ are shown in Fig.(5.15) and (5.16) respectively. These figures indicate that skin friction coefficient decreases with increase of $\bar{V}L/\nu$ . Again in both cases experimental points for

different spacings fall in such a way that seperate lines could be drawn for each spacing.

## 5.4.6 II Approach (Considering Skin Friction Beyond 35h):

As pointed out in Chapter 3, the net skin friction of the plane boundary could be supposed to be the skin friction beyond a distance equal to 35h from the element, on the basis of Plate's results (13). Accordingly net skin friction would be effective over the area BCDE (See Fig.3.1). Hence $C_{f_3}$ could be defined as

$$C_{f_3} = \frac{Area \ BCDE}{L \ \rho \ V^2/2} \tag{5.14}$$

$$= \frac{F_s{}'}{L \ \rho \ V^2/2} \tag{5.15}$$

where $F_s{}'$ is the positive skin friction per unit width between 35h and total length L between two elements, downstream of an element. The variation of $C_{f_3}$ with the pertinent parameters has been studied below.

Figure 5.17 shows a plot of $C_{f_3}$ with $VR_b/\nu$ for all the smooth boundary data. It is seen that $C_{f_3}$ decreases with increase in Reynolds number of the main flow. The data for both the series (L/h = 60 and L/h = 80) fall together. The equation of line fitting the data is

$$C_{f_3} = \frac{(0.256)}{(VR_b/\nu)^{0.435}} \tag{5.16}$$

The Karman - Prandtl equation for a smooth boundary can be written as

$$\frac{1}{\sqrt{f_s}} = 2\log_{10} R_e \sqrt{f_s} - 0.8 \tag{5.17}$$

This is usually expressed in graphical form - $R_e$ vs $f_s$ to facilitate direct solution. For an open channel Reynolds number can be written as $4\bar{V}R_b/\nu$ and since the average shear stress (of the smooth boundary) can be written as $\frac{f_s}{4} \cdot P \cdot \frac{V^2}{2}$, hence $C_{f_3}$ becomes, equal to $f_s/4$. Accordingly Equation (5.17) has been modified to show the variation of $C_{f_3}$ with $(4\bar{V}R_b/\nu)$ according to Karman - Prandtl equation. This equation predicts higher $C_{f_3}$ values than those obtained from the straight line of the data of the present investigation (See Fig.5.17). The difference is because of the fact that Karman - Prandtl equation is valid for a boundary where friction remains constant. In the present case frictional resistance of the smooth boundary is constantly varying because of the redeveloping boundary layer.

Fig. 5.18 shows plot of $C_{f_3}$ vs. $VL/\nu$ . The friction coefficient decreases with increase of $VL/\nu$ . As in Fig. 5.15 and 5.16 different lines are obtained for the two different values of L/h on which the investigation was carried out. It may be seen that the scatter in case of individual spacings in this plot is much smaller than the scatter in either Fig. 5.15 or 5.16.

5.4.7 Variation of $L_1/h$ vs. $V_{R_b}/\nu$ :

The length of standing oddy for different roughness pattorns usod in this study was computed from tho shor distribution diagrams. Tho curvoo of moaoured skin friction vo x woro oxtrcpolatod to find tho point at which the skin friction is zoro. This was takon as tho limit of the standing oddy. Tho longth of tho standing oddy has boon plottod in a dimonsionloss form in Fig. 5.19 which is a plot of $L_1/h$ against $V_{R_b}/\nu$ . Tho data rovoal difforont curvos for tho two difforont roughnoss pattorns viz L/h = 60 ond L/h = 80. It may bo soon that tho longth of standing oddy incroasos with tho incroaso of $V_{R_b}/\nu$ in both casos. Tho rosulting curvos from tho prosont invostigation indicato a similiar trond to that obtainod by Chang (3) for a singlo olomont which incidontally is tho limiting caso of olomonts in sries. Tho rosults of tho oxporimontal runs conductod by Chang aro also plottod on tho Fig.5.19.

A plot was also mado botwoon $L_1/h$ and D/h but no rolation could bo ostablishod botwoon thoso paromotors. Honco this plot has boon omittod from prosontation.

5.4.8. Variation of Form Drag Coofficiont of Strips:

It woo shown in Chaptor 3, that tho form drag cooffciont for tho strips could bo dotorminod in two ways on the baois of two difforont aooumptions. Tho first ono is to nogloct tho nogativo friction within tho oddy and ascribo tho difforonco

of total shear and measured positive friction to the resistance
of strips. The second approach is to assume the net skin fric-
tion to be the measured skin friction values beyond 3h from
the element and find $T_o''$ accordingly. The latter procedure has
been used here since the rough boundary studies have lent
support to the assumptions involved in the second approach.

As shown earlier on the basis of dimensional analysis,
the drag coefficient of a roughness element in series can be
written as

$$C_D = \emptyset \ (D/h, \ L/h)$$

The drag coefficient for each run was computed using Equations
(3.16), (3.17) and (3.18). Assuming a similarity with the
semi-logarithmic relation for friction in pipes, plots of
$1/\sqrt{C_D}$ vs. $log_{10} D/h$ were plotted for different spacings. These
are shown in Fig.3.20 which indicates a linear relationship
between $\dfrac{1}{\sqrt{C_D}}$ and $log_{10} D/h$ for two different L/h values used
in this study. Such a relationship was also found by Rangaraju
and Garde in their studies covering a range of L/h from 2.3
to 40.0. It may be seen that there is a tendency for data of
different slopes to fall on different lines. No explanation
could be given for this tendency and hence average lines are
drawn.

5.4.9  Variation of $T_o'/T_o$ vs L/h :

It was mentioned earlier that the experiments of Rangaraju

and Garde (17) on a smooth boundary having series of roughness
elements showed that the total resistance of the boundary could
be taken as equal to form resistance of the roughness elements
upto a value of L/h = 40. In other words upto L/h = 40, the
frictional resistance of the boundary may be taken as zero.
However for larger spacings skin friction of the plane boundary
would be important. Fig. shows the values of $T_o'/T_o$ (i.e. the
ratio of net skin friction to total shear) plotted against
L/h. $T_o'/T_o$ has been shown to be zero for L/h    40 on the basis
of studies by Rangaraju and Garde. The author's data shows
considerable scatter but the parameter $T_o'/T_o$ can distinctly be
seen to increase with increase in L/h.

### 8.4.10  Prediction of Shear For Basha's Data

In order to check the validity of the method developed
here, use is made of Basha's (2) data on two-dimensional strips
of negligible thickness for a relative spacing of 48. This is
done as follows. The total resistance is given by

$$T_o = T_o' + T_o''$$

$$= C_{f_3} \cdot L \cdot P \cdot \overline{V}^2/2 + C_D \cdot \frac{h}{L} \cdot \frac{\overline{V}^2}{2} \qquad (5.18)$$

In case of Basha's data for L/h = 48, the $C_{f_3}$ values for different
runs were computed from the Equation (5.13). The values of $C_D$
were computed from the equation (2.3) using the $C_1$ and $C_2$ values
for a relative spacing of 48 from Figs. 5.21 and 5.22 respectively.

The total resistance $T_o$ was then computed from the Equation
(5.18). The observed and the computed values of $T_o$ are compared in Fig.5.24. The values of slope for each run are marked against the corresponding point on the figure.

In general the computed values are within $\pm$ 15 % of the observed values, though the computed values tend to be smaller for data with larger values of slope. This may be due to the presence of surface waves, the resistance of which has not been taken into account in the present method.

5.4.11 Analysis of Velocity Profiles:

The conventional resistance equation cab be written as

$$\frac{V}{V_*} = \frac{2.30}{K} \log_{10} \frac{D}{K_s} + B_1 \tag{5.19}$$

where $B_1$ = function of roughness geometry
Since $\overline{V}/V_*$ is constant for a given value of D/h and $L/h_e$
hence $K_o$ would also be constant for given values of $D_o h$ and
L. Accordingly the velocity distribution law could be written as

$$U/V_* = \emptyset \ (\log_{10} y/h) \qquad \text{for given values}$$

of $D_o h$ and L. On this basis typical data on the velocity
distribution for flow over roughness elements in series has
been plotted in Figures 5.23 and 5.26. The velocity profiles
taken midway between the elements and those over the element
are plotted together for each value of L/h.

It is distinct that tho velocity over tho element at
any given elevation from tho bed is always greater than tho
velocity between the roughness elements at the corresponding
elevation. This may probably bo on account of the increase in
mean velocity over tho element.

The difference in velocity profile over the element and
midway between the elements, noticed in Figures 5.25 and 5.26,
have been previously pointed out by Adachi (1) and Rangaraju
and Garde (17). It is seen from tho Figures 5.25 & 5.26 that the
difference between velocity profiles over tho roughness element
and midway between elements is larger in case of larger spacing.
Another point to note is that a break in velocity profile occurs
in case of both tho spacings used here. This fact has also been
pointed out by previous investigators (1,9,10,13).

## C H A P T E R - 6

# CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

The present investigation has thrown additional light on the mechanism of resistance to flow over two-dimensional sharp edged artificial roughness elements in an open channel. The main aspects of the problem investigated were form resistance of roughness elements and skin friction of the plane boundary having regular arrangement of roughness elements in series. As a result of the analysis of the data collected during the present investigations the following conclusions are derived:

1.  The drag coefficient of a single normal plate kept on the bed of an open channel decreases continuously with increase of D/h.

2.  The equation

    $C_D = C_{D_0}(1 - h/D)^{-2.85}$ and the curve of $C_{D_0}$ vs $\delta/h$ proposed by Rangaraju and Garde from wind tunnel studies is inadequate for the determination of drag coefficient of a roughness element placed on the bed of an open channel.

3.  In case of a plane boundary having roughness elements placed on the boundary in series the total resistance may be taken equal to the form resistance of the strips for $L/h \leqslant 40$.

4.  The total resistance of a plane boundary with roughness

elements having $L/h > 40$ can be determined by adding the form resistance of the strips to the skin friction between 33h and L downstream of the element. Equations ( 2.8 ) and (3.18) along with figures (3.21) and (3.22) enable calculation of the form resistance while equations (3.16) and (3.17) along with figure (3.17) can be used for the calculation of the above frictional resistance.

## Suggestions for Further Study:

It is desirable to continue the study of the problem presented herein in order to get a better understanding of the phenomenon of resistance. In this context the following suggestions can be made for further research on the problem:

1. The present investigations used only sharp edged roughness elements spanning the whole width of the flume. Further studies should be carried out with different types of roughness elements.

2. Studies concerning the skin friction of the boundary as well as the total resistance of the boundary should be made with larger spacings.

3. In case of resistance of single element more studies should be made on effect of Froude's number on drag coefficients.

## REFERENCES

1. Adachi, S., "On the Artificial Strib Roughness" Bulletin No. 69, Disaster Prevention Research Institute, Kyoto University, March 1964, pp 1-20.

2. Basha, M.A., "Resistance Characterstics of Artificially Roughened Open Channels in Relation to those of Alluvial Channels", M.E. Dissertation, University of Roorkee, May 1961.

3. Chang, Fred F.M., "Ripple Concentration and Friction Factor", Journal of Hydraulic Division, ASCE, vol. 96, No. HY 2, Proc. Paper 7067, February, 1970, pp 417-430.

4. Einstein, H.A., and Banks, R.B., "Fluid Resistance of Composite Roughness", Rans. A.G.U., Vol. 31, No.4, August, 1950, pp 603 - 610.

5. Einstein, H.A., and Barbarossa, N.L.,"River Channel Roughness" Transactions, A.S.C.E., vol 107, 1942, pp 1121-1146.

6. Good, M.C. and Joubert, P.N. "The Form Drag of Two-Dimensional Bluff Plates Immersed in Turbulent Boundary-Layers", Journal of Fluid Mechanics, vol 31, Part 3, 1968, pp 547 - 582.

7. Herbich, J.B. and Shulits, S., "Large Scale Roughness in Open Channel Flow", Journal of Hydraulic Division, Proc., A.S.C.E., vol 90, November 1964, pp 203 - 210.

8. Johnson, J.W., "Rectangular Artificial Roughness in Open Channels",Trans.A.G.U., vol 25, Part VI, 1944 pp 906-914.

9. Koloseus, H.J., "The Effect of Free-Surface Instability on Channel Resistance", Ph.D. Dissertation, State University of Iowa, August, 1958.

10. Koloseus, H.J., and Davidian J., "Free Surface Instability correlations and Roughness Concentration Effects on Flow over Hydrodynamically Rough surfaces" Geological Survey Water Supply Paper 1592- C.D., U.S. Govt. Printing Office, 1966.

11. Morris, H.M., "Flow in Rough Conduits", Trans. A.S.C.E., vol. 120, 1955, pp 373 - 410.

12. O'Loughlin, E.M. and Macdonald, E.G., "Some Roughness Concentration effects on Boundary Resistance", La Houille Blanche, No.7/1964, pp 773 - 783.

13. Patel, V.C. "Calibration of Preston Tube and Limitations on its use in pressure gradients", Journal of Fluid Mechanics, vol. 23, 1965.

14. Peterson, Dean F. and Mohanty, P.K. "Flume Studies of Flow in Steep Rough Open Channels", Proc., A.S.C.E., vol. 86, November, 1960, pp 55-76.

15. Plate, E.J., "The Drag on a smooth Flat Plate with a Fence immersed in its Turbulent Boundary Layer", Presented at the Fluids Engg. Conference, Philadelphia, A.S.M.E., May, 1964.

16. Powell, R.W., "Flow in a Channel of Definite Roughness", Trans. A.S.C.E., vol. 111, 1946, pp 531-566.

17. Rengaraju, K.G.,"Mechanism of Resistance to Flow Over Artificial Roughness Elements", Ph.D. Dissertation, University of Roorkee,Roorkee, May 1967.

18. Rangaraju, K.G. and Garde, R.J., "Resistance of an inclined plate placed on a Plane Boundary in Two-Dimensional Flow", Journal of Basic Engineering, Trans. A.S.M.E., Ppaer No. 69-FE-3,March, 1970, pp 21-31.

19. Rangaraju, K.G. and Garde, R.J., "Resistance to Flow over Two-Dimensional Strip Roughness", Journal of Hydraulics Division, ASCE, Vol. 96, No. HY3, Proc. paper 7181, March, 1970, pp 815- 834.

20. Roberson, John A. and Chen, C.K., "Flow in Conduits with Low Roughness Concentration", Journal of Hydraulics Division, ASCE, vol. 96, No. HY4, Proc. Paper 7224, April, 1970, pp 941-957.

21. Robinson, A.R. and Albertson, M.L., "Artificial Roughness Standard for Open Channels", Trans. A.G.U., vol 33, No.6, December, 1952, pp 881 - 888.

22. Rouse, H., "Fluid Mechanics for Hydraulic Engineers" Dover Publications, Inc., New York, 1961, p 217, p 228.

23. Rouse, H., Koloseus, H.J. and Davidian, J., "The Role of Froude number in Open-Channel Resistance", Journal of Hydraulic Research, I.A.H.R., vol. 1, 1963, pp 14-19.

24. Sayre, W.W. and Albertson, M.L., "Roughness spacing in Rigid Open Channels", Trans.ASCE, vol.128,'63, pp 343-427.

25. Singh, V.,"Wind Tunnel Studies of Form Drag on Two-Dimensional Square Normal Plates, M.E. Dissertation, Univ. of Roorkee, Roorkee, Dec. 1969, Fig. 4.5.

26.    O' Loughlin, E.M., "Resistance to flow over boundaries
with small roughness concentration" Ph.D. Thesis, State
University of Iowa, 1965.

**F I G U R E S**
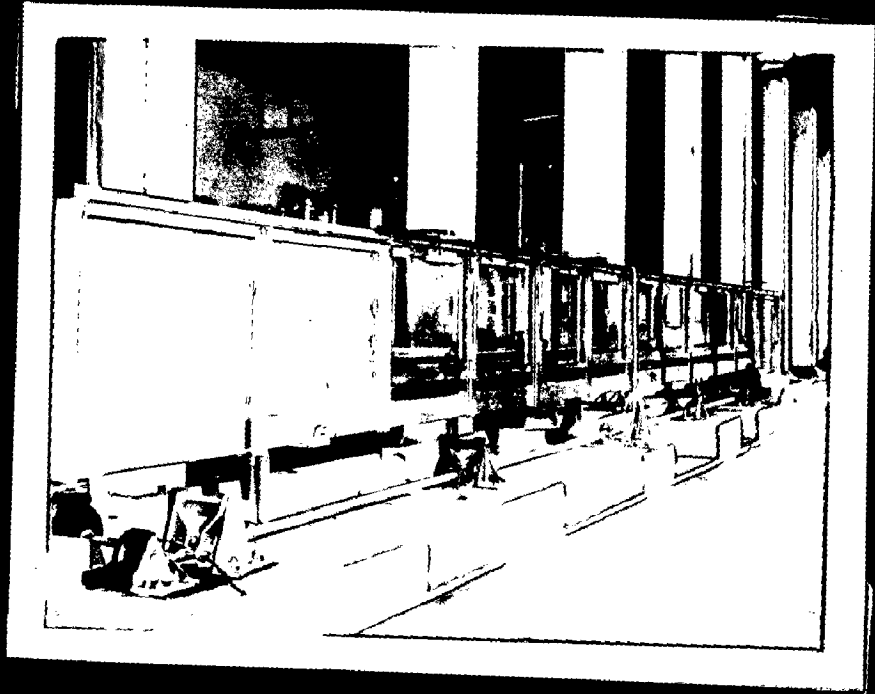
Photograph 1 - General View of the Experimental Flume



Photograph 2 - Roughness elements in position
on the bottom of the flume
glued with gravel.
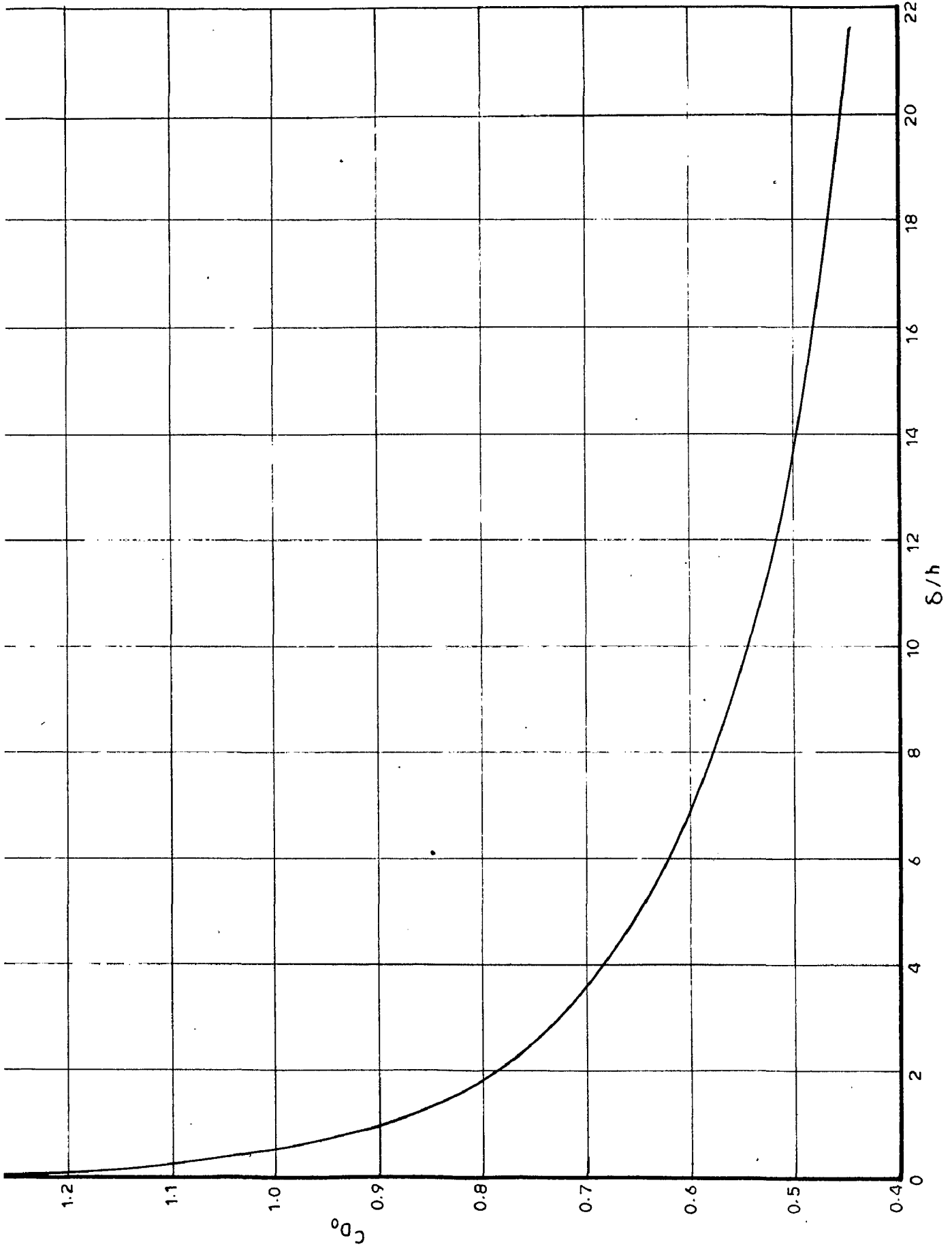
FIG. 2.1 _ VARIATION OF $C_{D_O}$ WITH $\delta/h$ FOR NORMAL PLATES IN BOUNDARY LAYER (REF. 18)

77
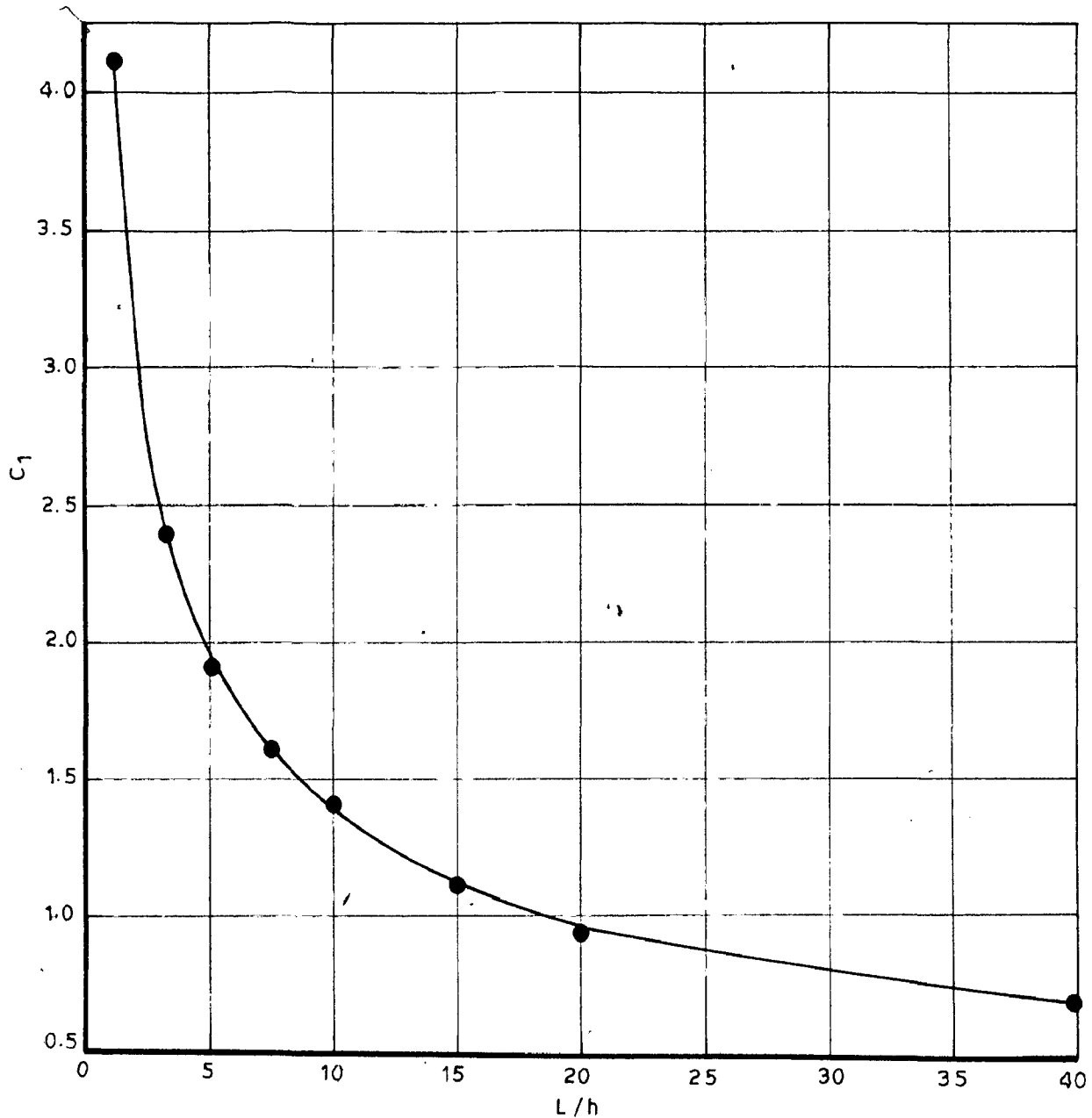
FIG.2.2 _ VARIATION OF $C_1$ WITH L/h FOR TWO-DIMENSIONAL
ELEMENTS IN SERIES (REF. 19)
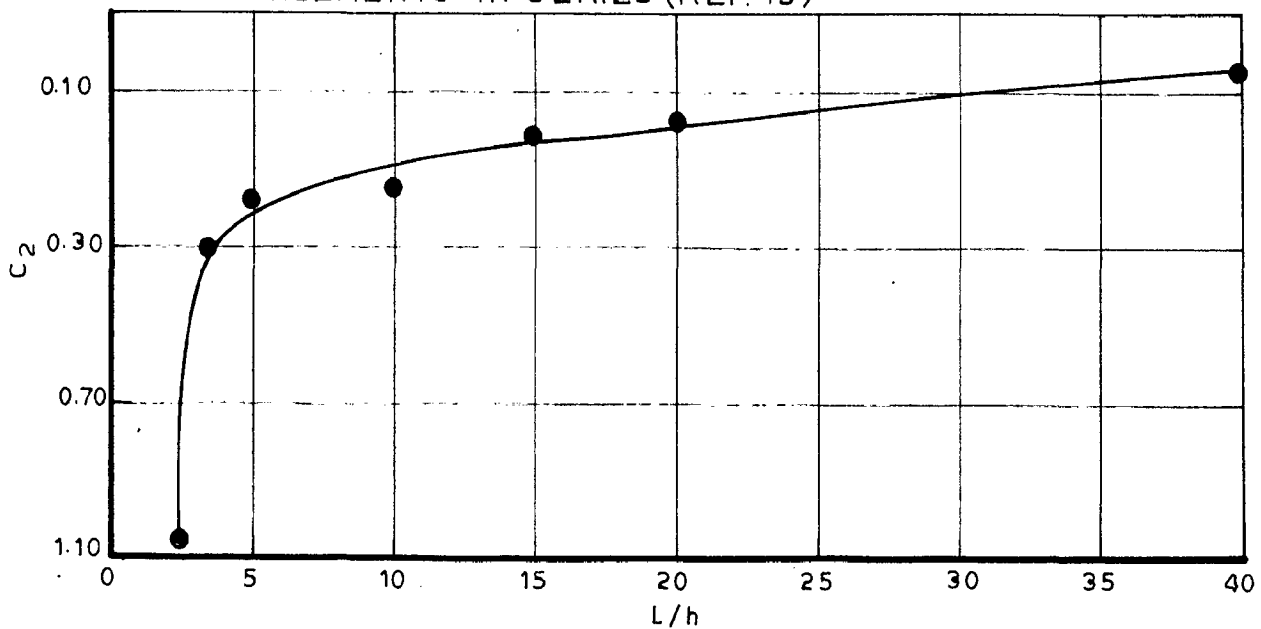


FIG.2.3 _ VARIATION OF $C_2$ WITH L/h FOR TWO DIMENSIONAL ELEMENTS
IN SERIES (REF. 19)
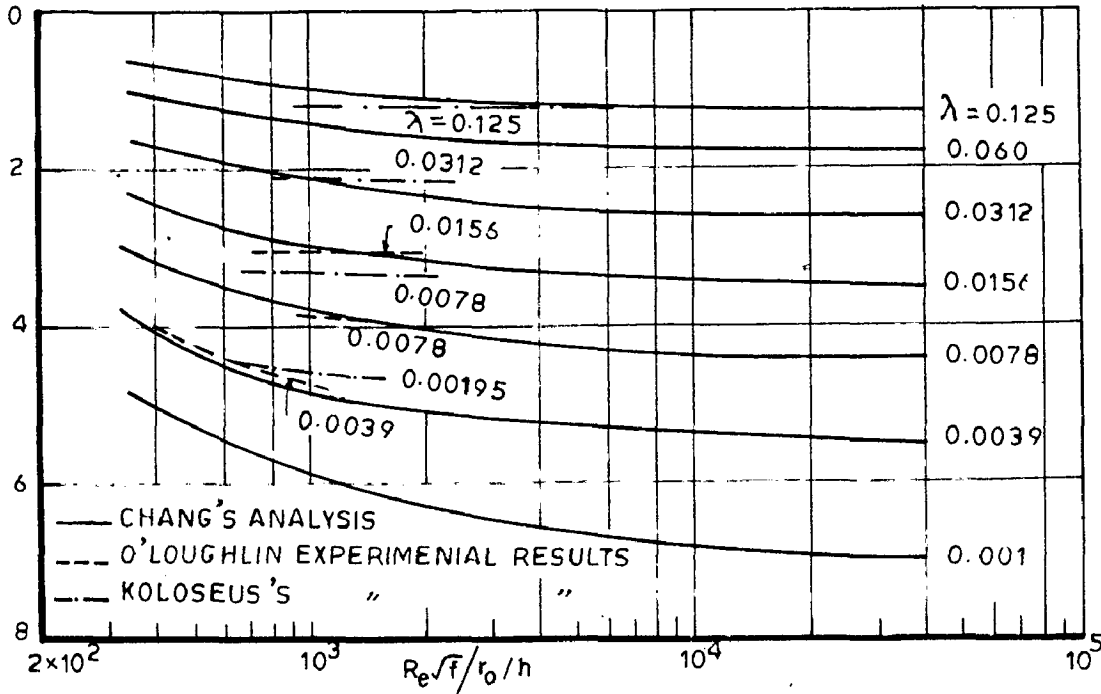
FIG. 2.4_ TRANSITION FUNCTIONS FOR CONDUIT ROUGHENED WITH CUBES (REF. 3 )
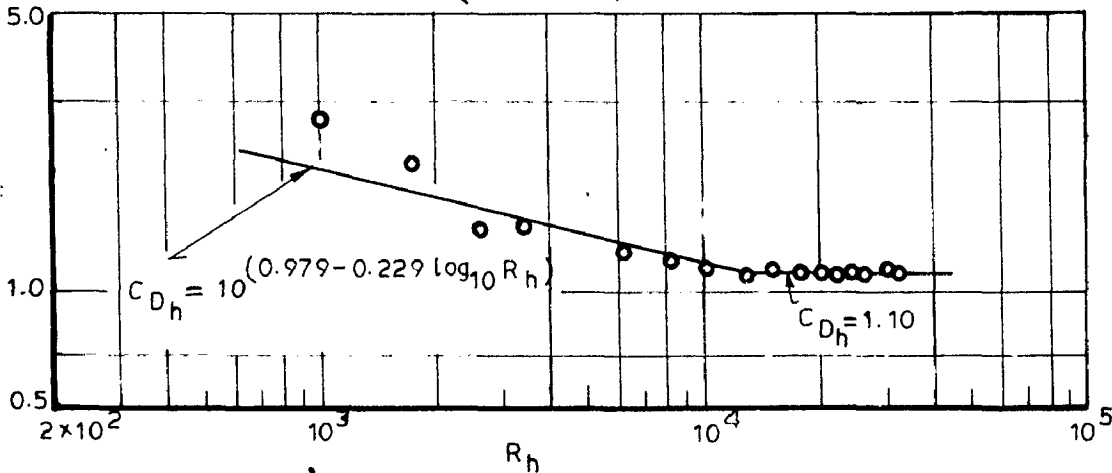


FIG. 2.5_ PLOT OF COEFFICIENT OF DRAG VS REYNOLDS NUMBER FOR CUBE (REF. 3 )
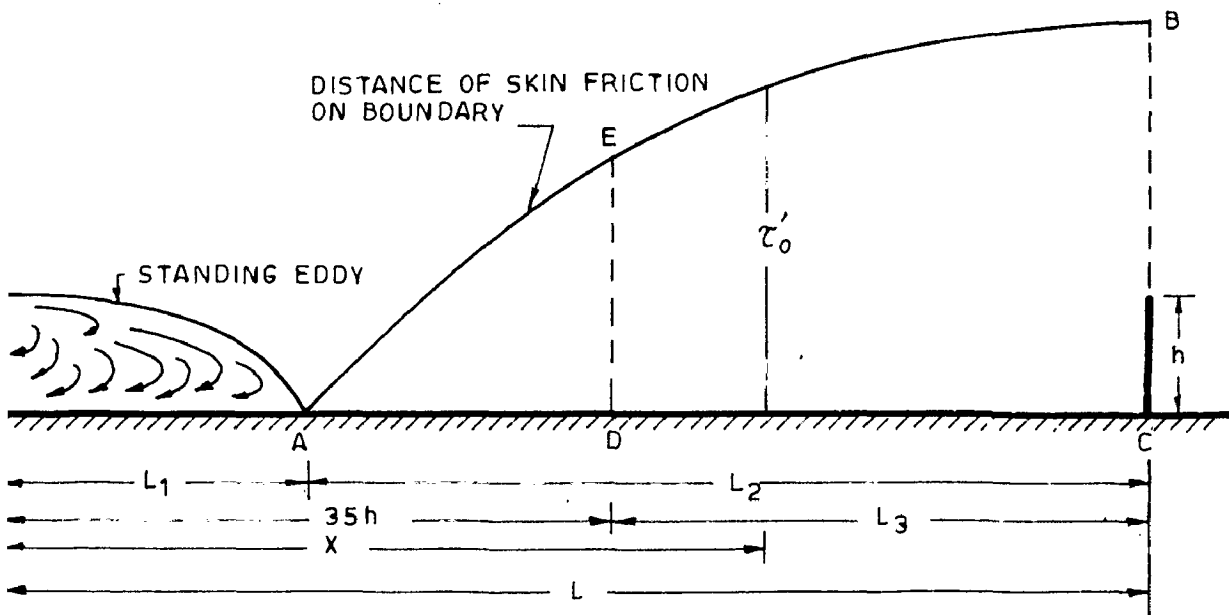


3.3.1 _ SCHEMATIC DIAGRAM OF SHEAR STRESS DISTIBUTION

FIG. 4.1 — SCHEMATIC DIAGRAM OF EXPERIMENTAL FLUME

NOT TO SCALE

FROM OVERHEAD TANK

TO SUMP
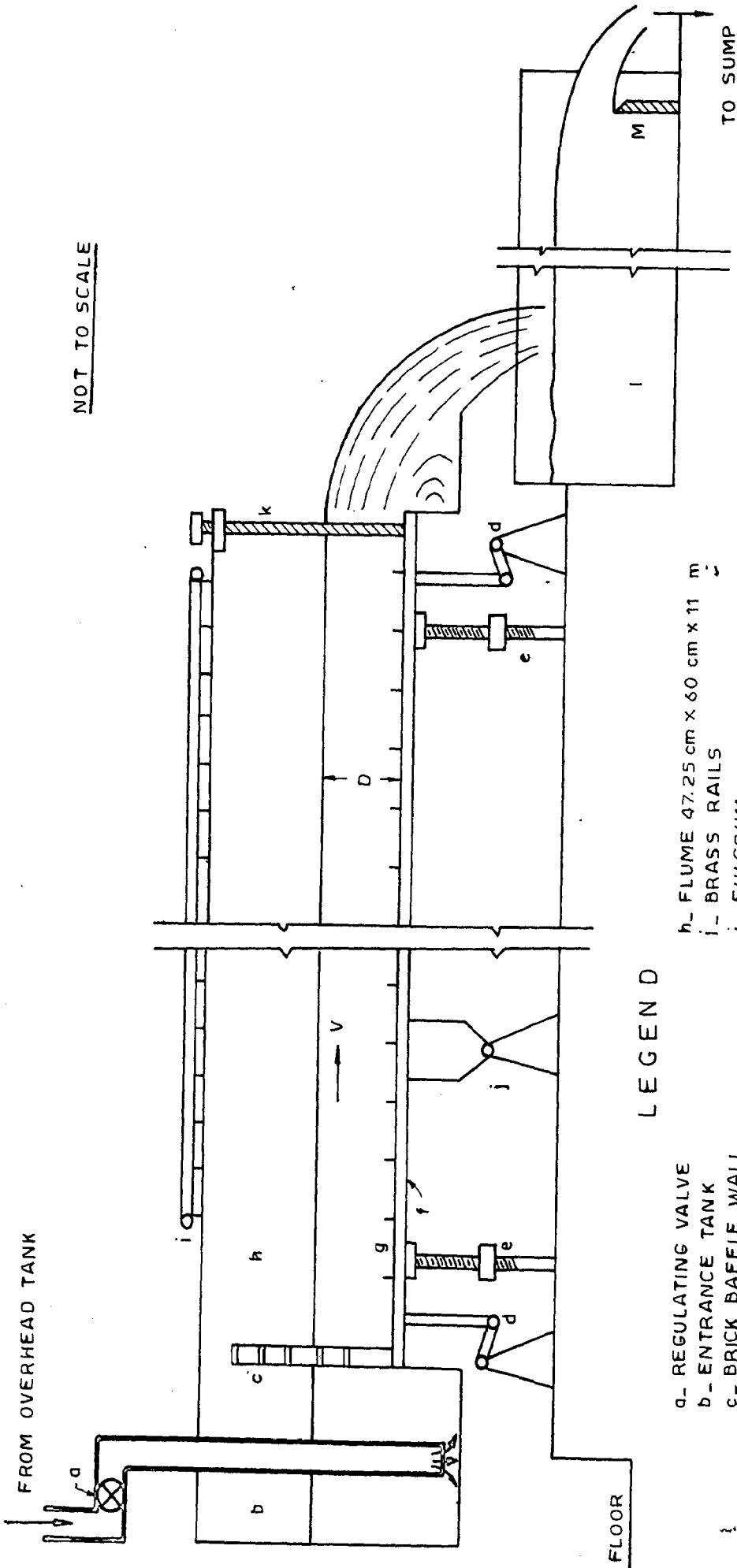
LEGEND

a — REGULATING VALVE
b — ENTRANCE TANK
c — BRICK BAFFLE WALL
d — JACKS
e — LOCKING ARRANGEMENT
f — WOODEN FALSE BOTTOM
g — ROUGHNESS STRIP

h — FLUME 47.25 cm × 60 cm × 11 m
i — BRASS RAILS
j — FULCRUM
k — TAIL GATE
l — TANK
m — RECTANGULAR SHARP-CRESTED WEIR

FLOOR
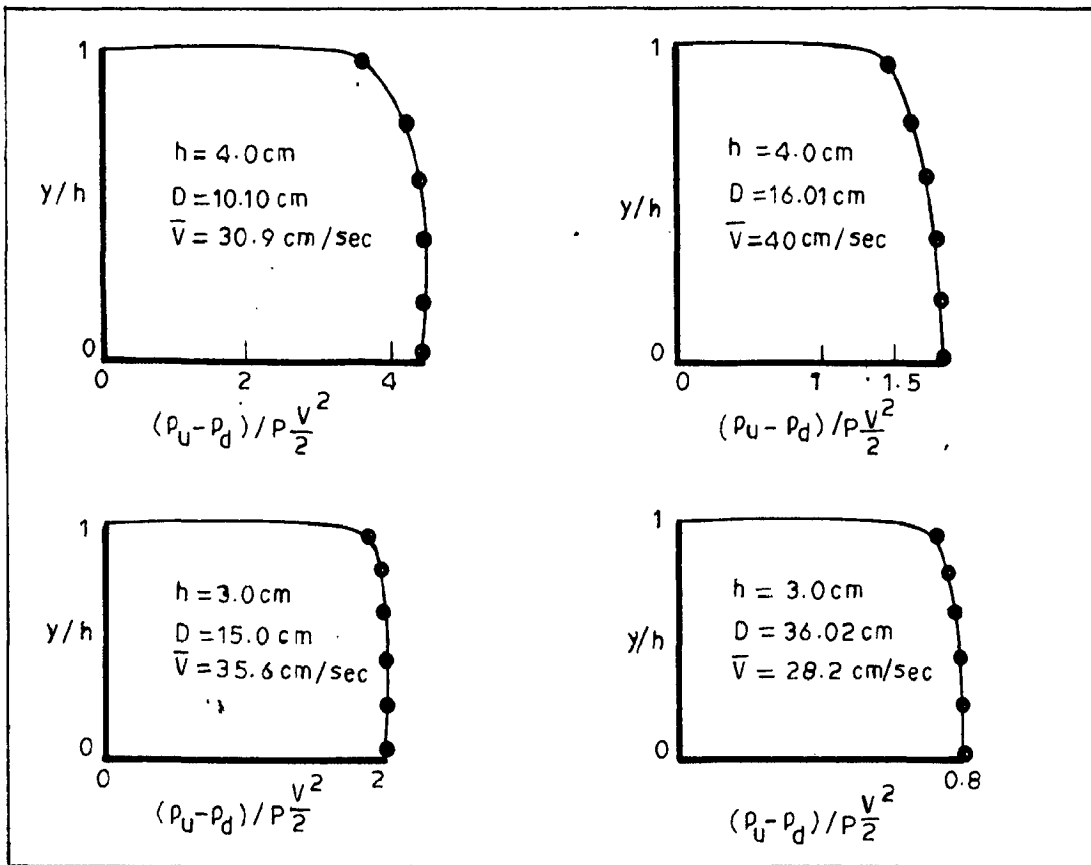
FIG.5.1 _ PLOT OF PRESSURE DIFFERENCE AROUND
SINGLE ELEMENT
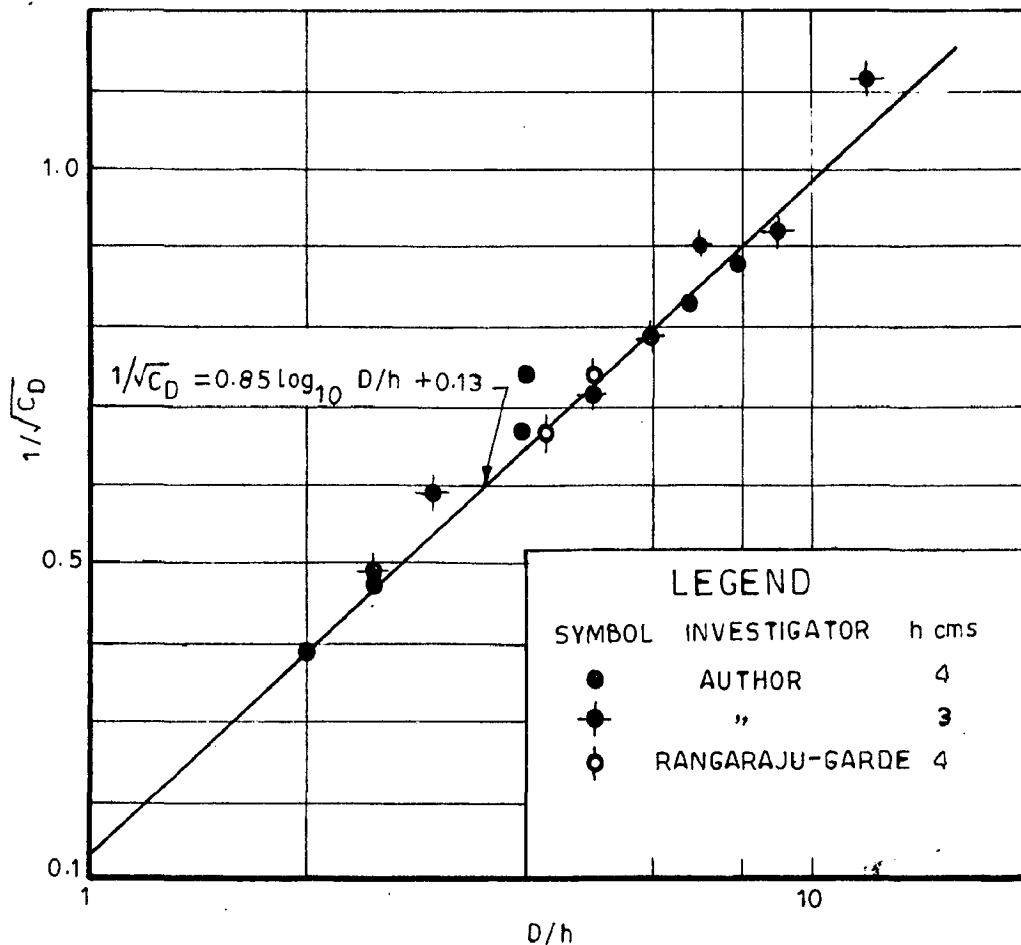


FIG.5.2 _ VARIATION OF $1/\sqrt{C_D}$ WITH D/h FOR SINGLE
ELEMENT
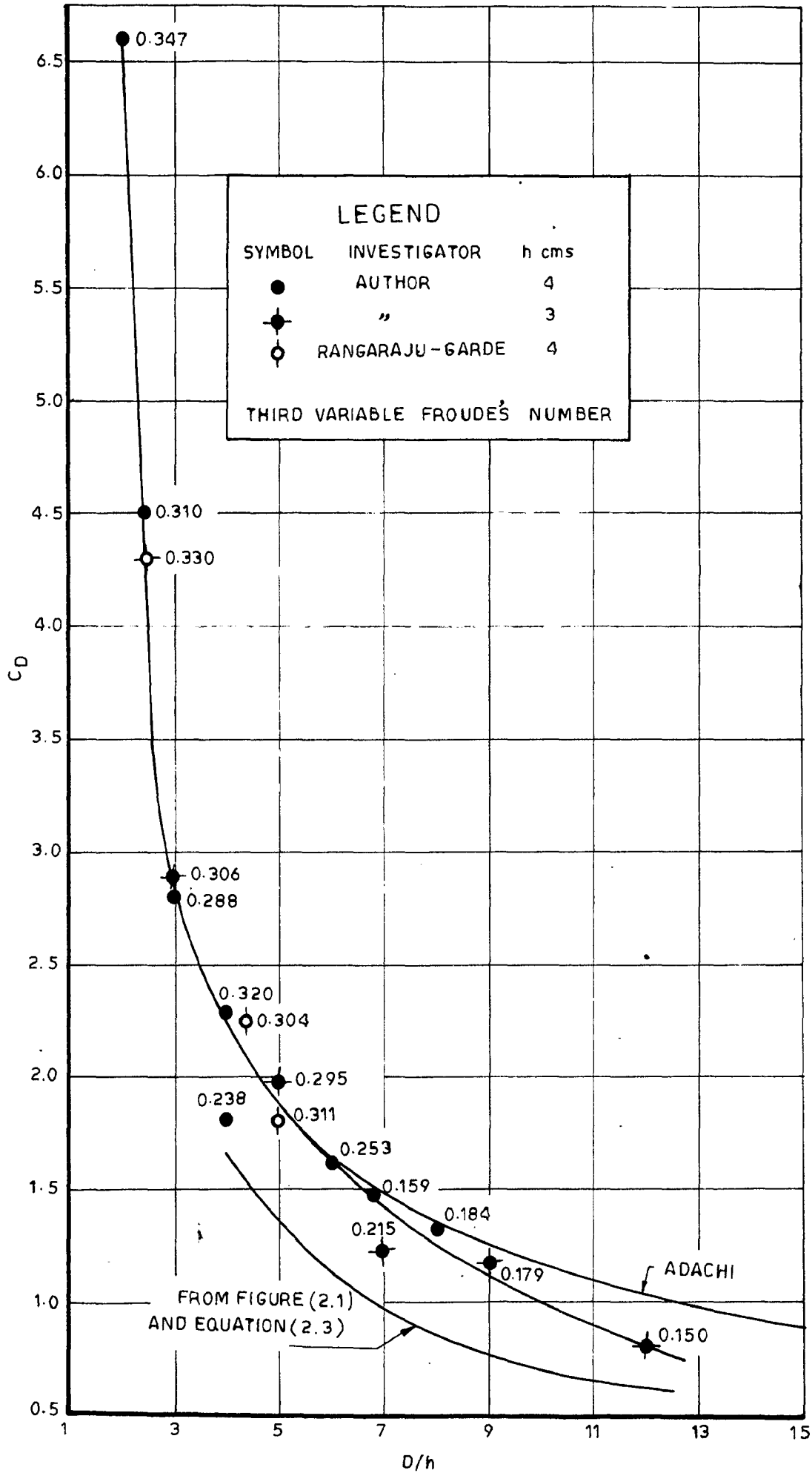
FIG.5.3 _VARIATION OF $C_D$ WITH D/h FOR SINGLE ELEMENT
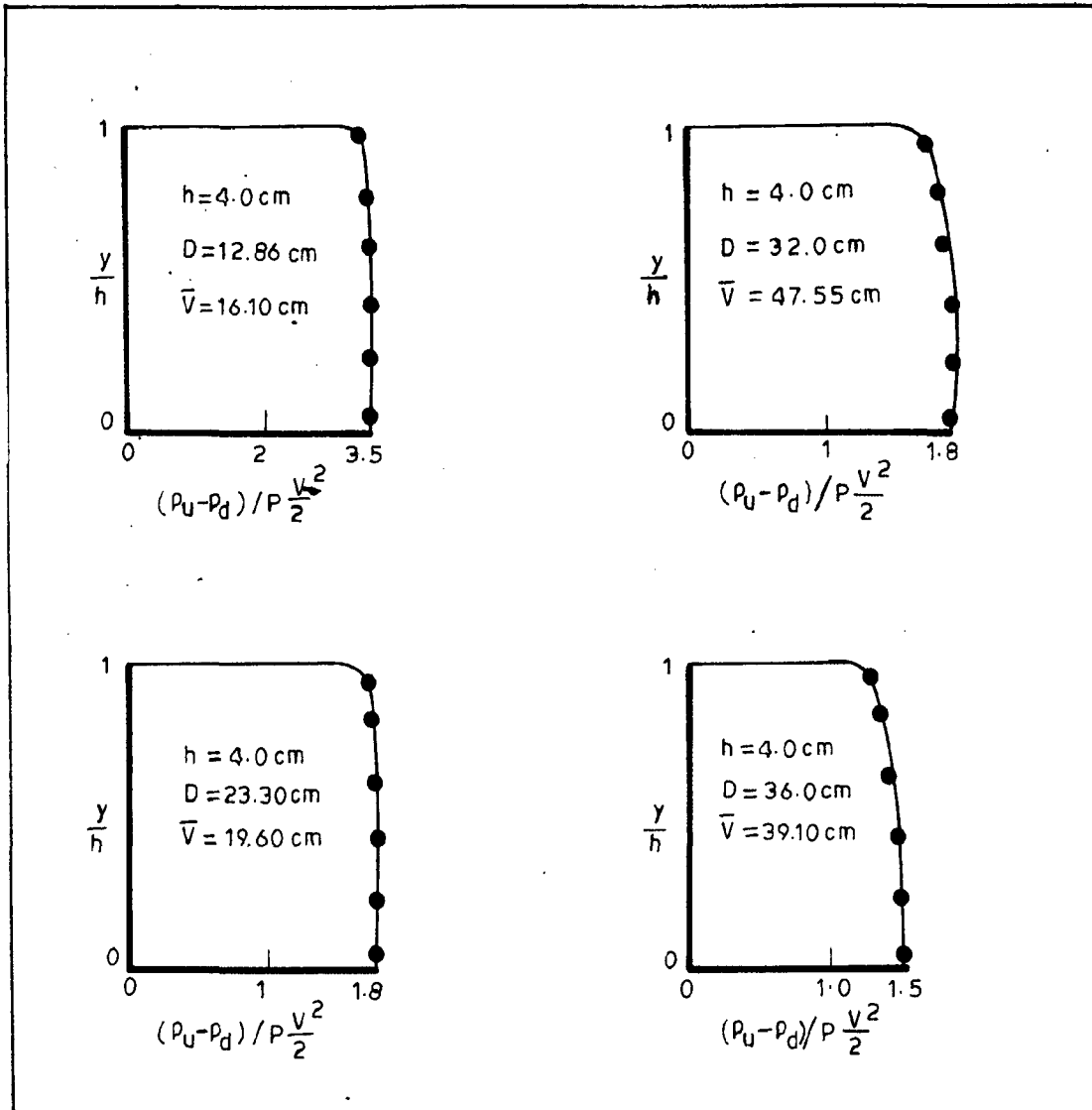
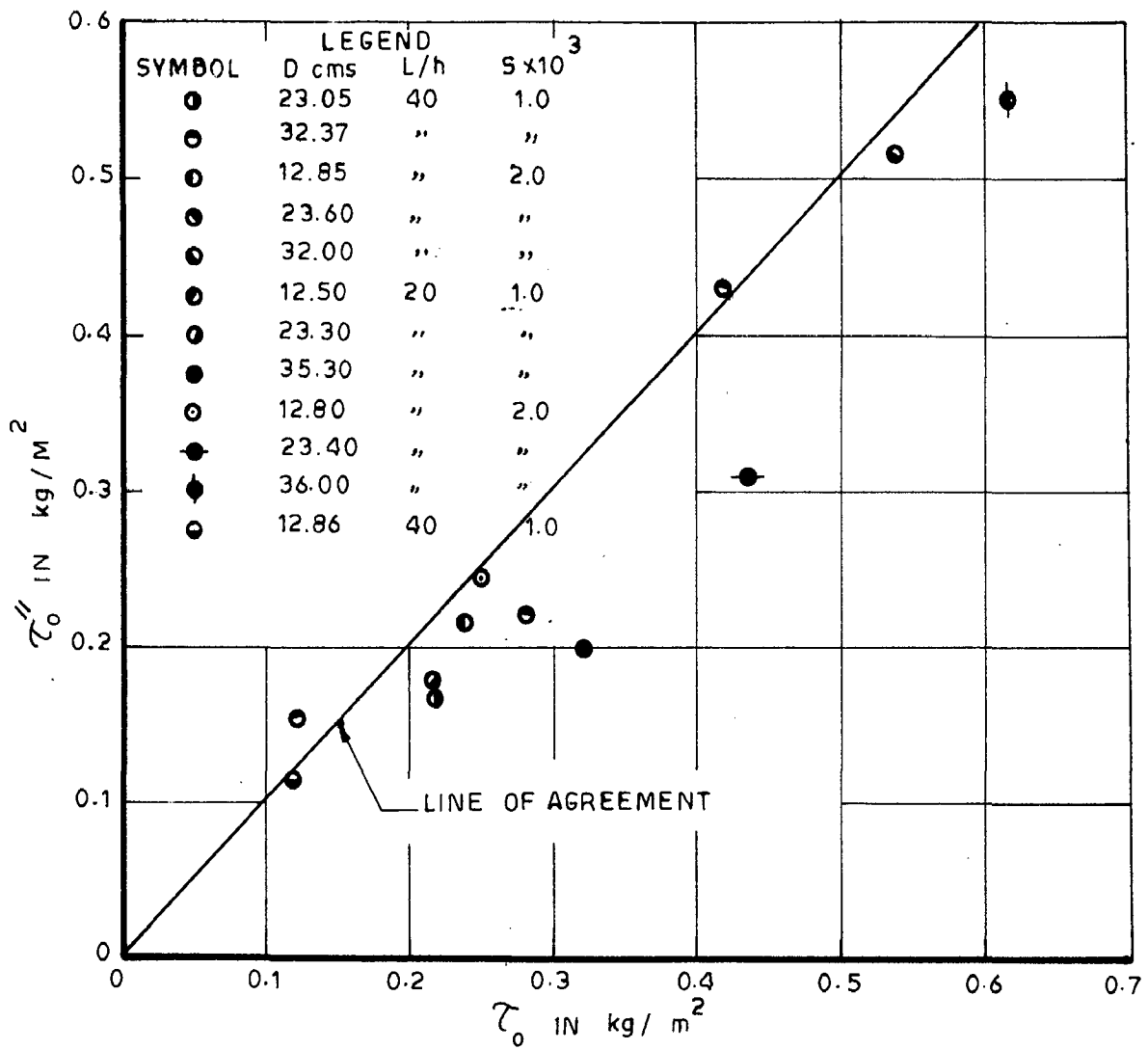FIG.5.4 _ PLOT OF PRESSURE DIFFERENCE AROUND ELEMENTS IN ROUGH BOUNDARY

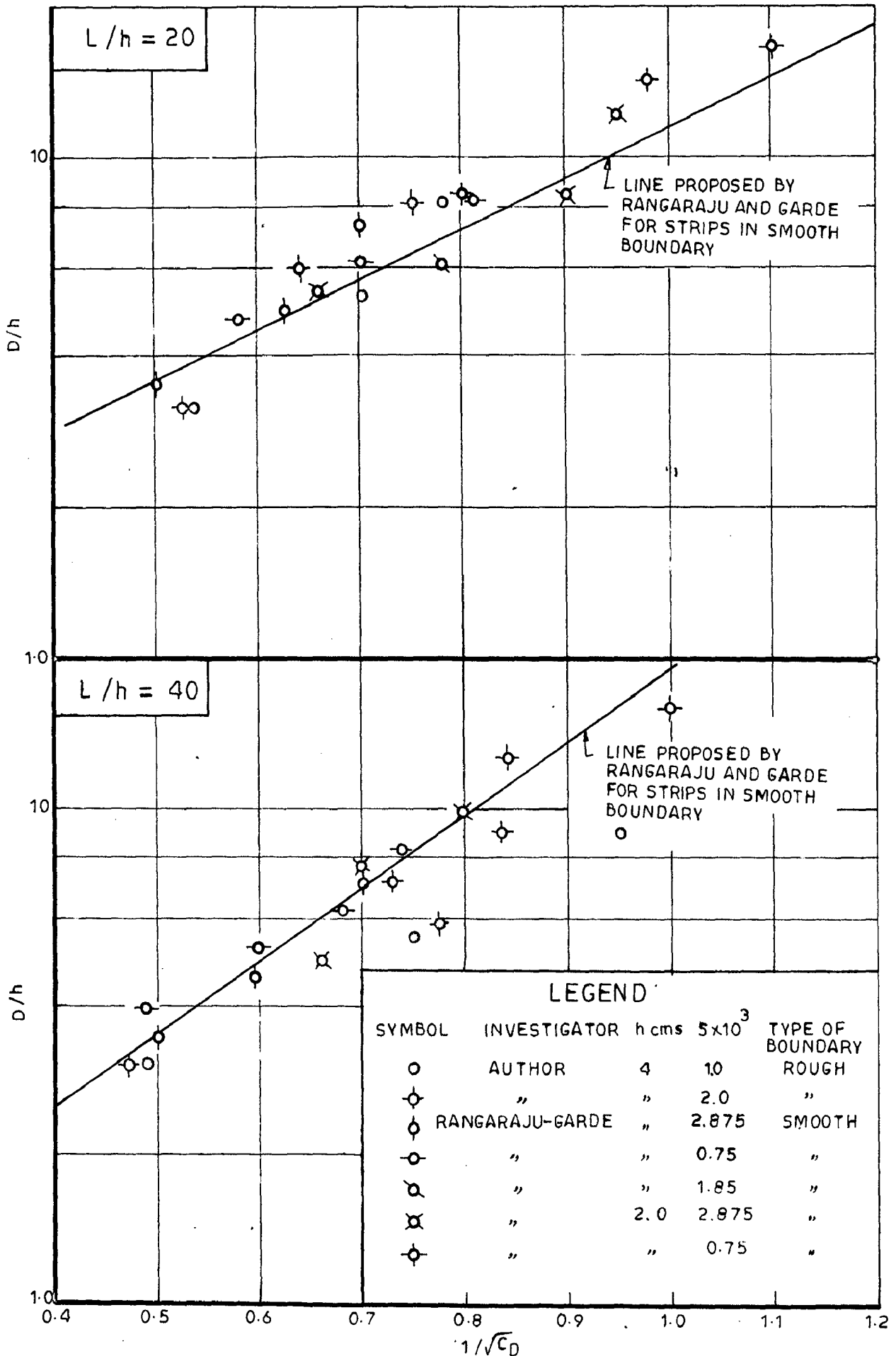FIG. 5.5 _ COMPARISON BETWEEN $\tau_0$ AND $\tau_0''$ FOR ROUGH BOUNDARY WITH STRIPS

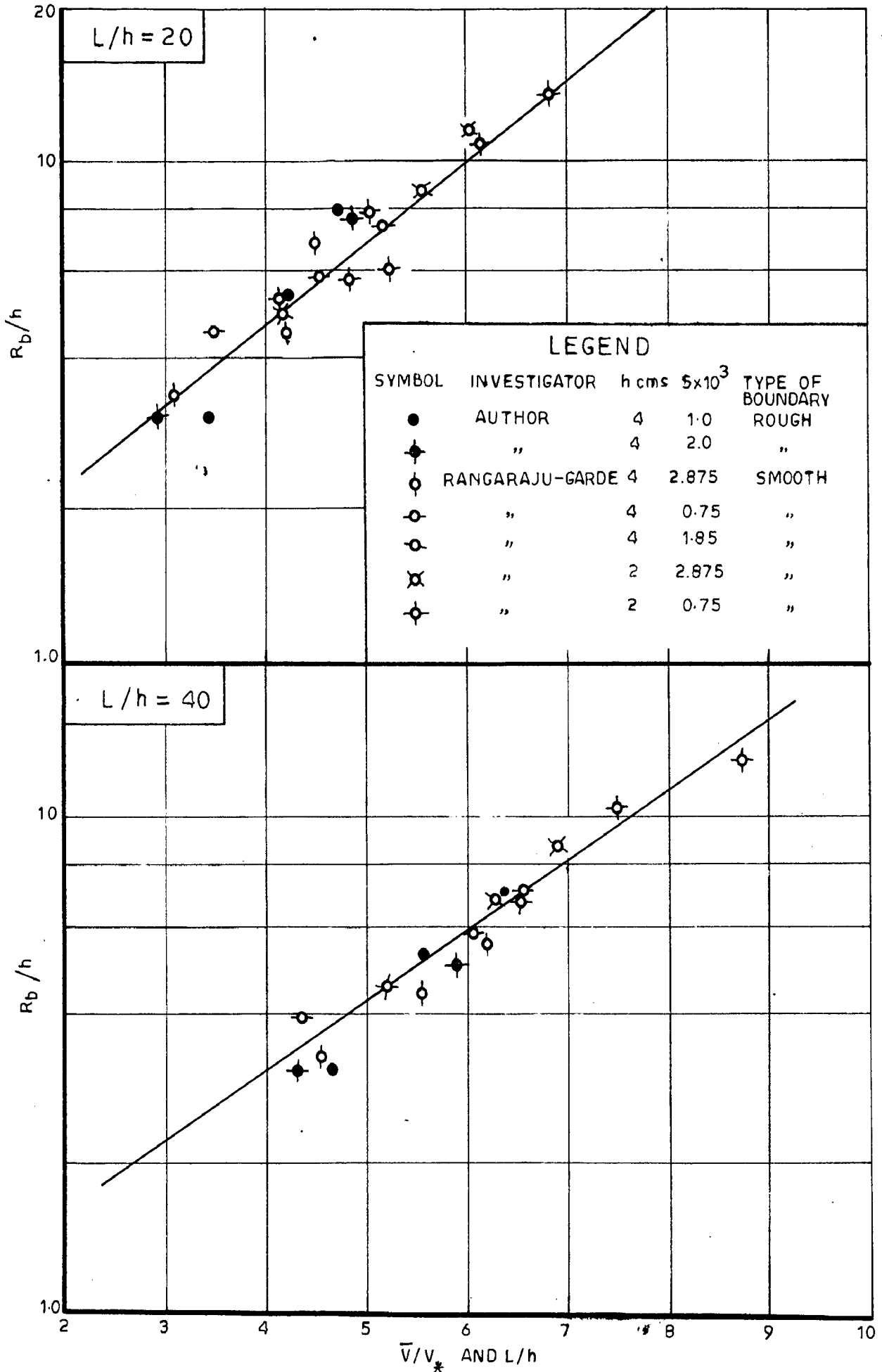FIG. 5.6 _ VARIATION OF $1/\sqrt{C_D}$ WITH D/h AND L/h FOR ELEMENTS IN SERIES

L/h = 20

20

10

$R_b/h$

1.0

LEGEND

| SYMBOL | INVESTIGATOR | h cms | $S \times 10^3$ | TYPE OF BOUNDARY |
|---|---|---|---|---|
| ● | AUTHOR | 4 | 1·0 | ROUGH |
| | ,, | 4 | 2.0 | ,, |
| ○ | RANGARAJU-GARDE | 4 | 2.875 | SMOOTH |
| -○- | ,, | 4 | 0·75 | ,, |
| -○- | ,, | 4 | 1·85 | ,, |
| ✕ | ,, | 2 | 2.875 | ,, |
| ○ | ,, | 2 | 0·75 | ,, |

L/h = 40

10

$R_b/h$

1·0

2    3    4    5    6    7    8    9    10

$\bar{V}/V_*$  AND L/h

FIG. 5.7 – VARIATION OF $\bar{V}/V_*$ VS $R_b/h$ AND L/h  FOR ELEMENTS
IN SERIES

LEGEND

| SYMBOL | POSITION | $S \times 10^3$ |
|---|---|---|
| ◊ | 40cm D/S OF THE ELEMENT | 1·0 |
| ◊ | ,, ,, ,, ,, ,, | 2.0 |
| ◉ | 60cm D/S OF THE ELEMENT | 1·0 |
| ○ | ,, ,, ,, ,, ,, | 2.0 |
| ● | MIDWAY BETWEEN ELEMENT | 2.875 |

L/h = 20
D = 12.5 cm

y/h

LINE FOR ROUGHNESS ELEMENTS IN SMOOTH BOUNDARY (17)

L/h = 20
D = 36 cm

U/V$_*$

U/V$_*$

FIG.5.8 _ PLOT OF U/V$_*$ VS LOG$_{10}$ y/h FOR ELEMENTS IN ROUGH BOUNDARY

FIG.5.9_PLOT OF U/V$_*$ VS LOG$_{10}$ $y/h$ FOR ELEMENTS IN ROUGH BOUNDARY
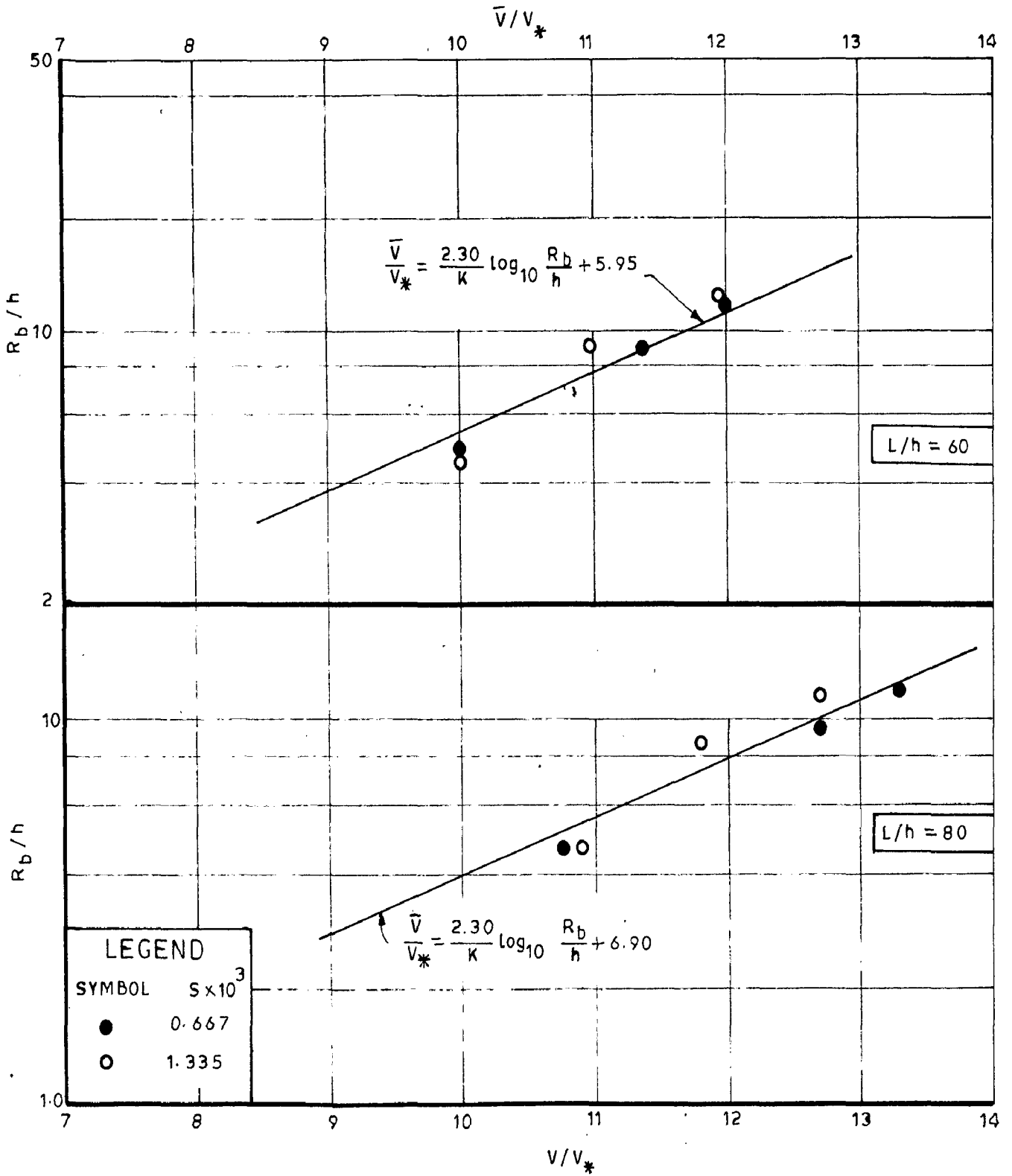
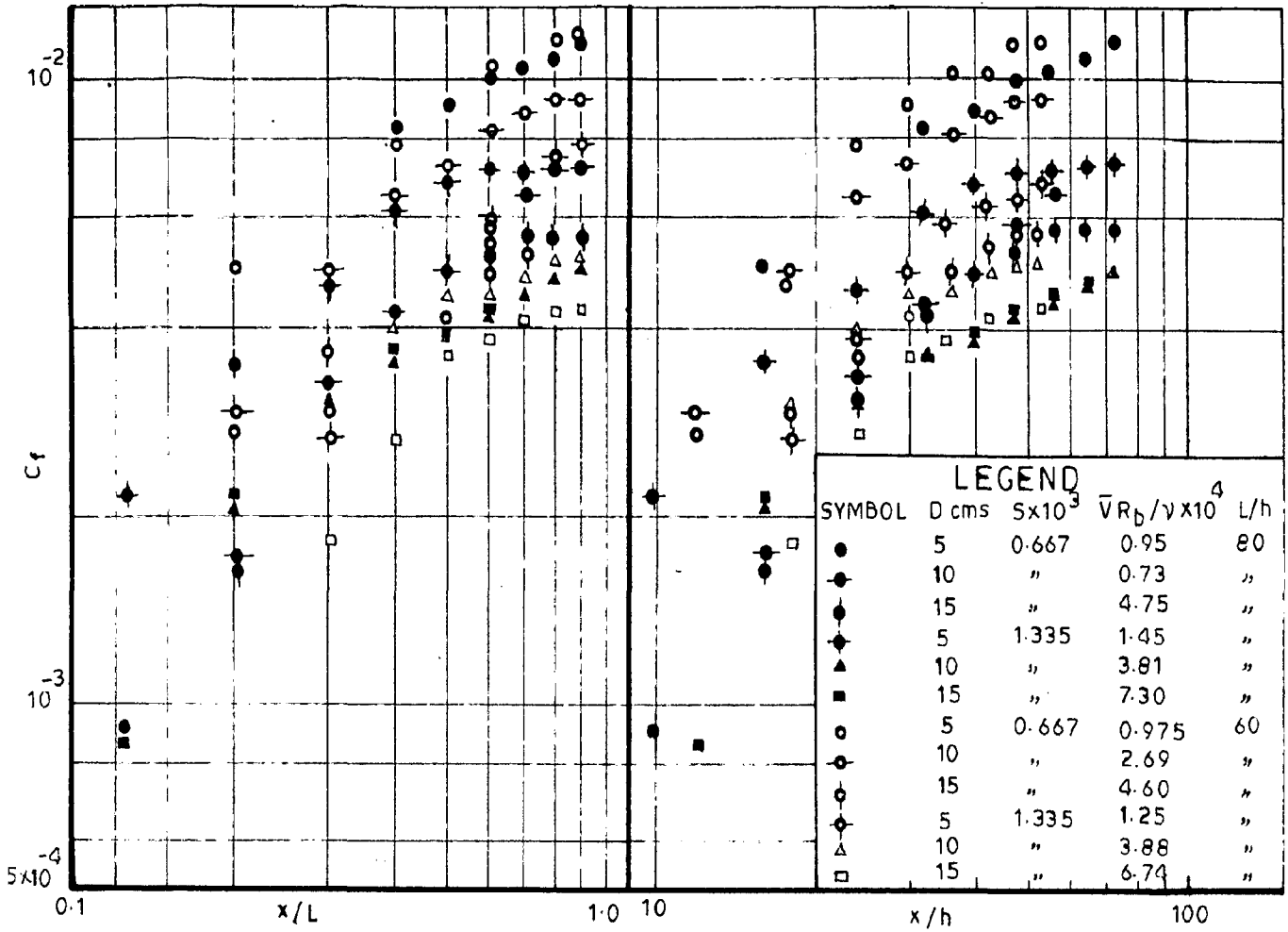FIG. 5.10 _ VARIATION OF $\bar{V}/V_*$ WITH $R_b/h$ AND $L/h$ FOR SMOOTH BOUNDAR

LEGEND

| SYMBOL | D cms | $S \times 10^3$ | $\overline{V}R_b/\nu \times 10^4$ | L/h |
|---|---|---|---|---|
| ● | 5 | 0.667 | 0.95 | 80 |
| ◑ | 10 | " | 0.73 | " |
| ◐ | 15 | " | 4.75 | " |
| ◆ | 5 | 1.335 | 1.45 | " |
| ▲ | 10 | " | 3.81 | " |
| ■ | 15 | " | 7.30 | " |
| ○ | 5 | 0.667 | 0.975 | 60 |
| ◔ | 10 | " | 2.69 | " |
| ◒ | 15 | " | 4.60 | " |
| ◇ | 5 | 1.335 | 1.25 | " |
| △ | 10 | " | 3.88 | " |
| □ | 15 | " | 6.74 | " |

FIG. 5.11 – VARIATION OF $C_f$ WITH x/L AND x/h FOR ELEMENTS ON SMOOTH BOUNDARY



$$C_f = 0.059/R_x^{1/5}$$

LEGEND
SAME AS IN
FIG. 5.11
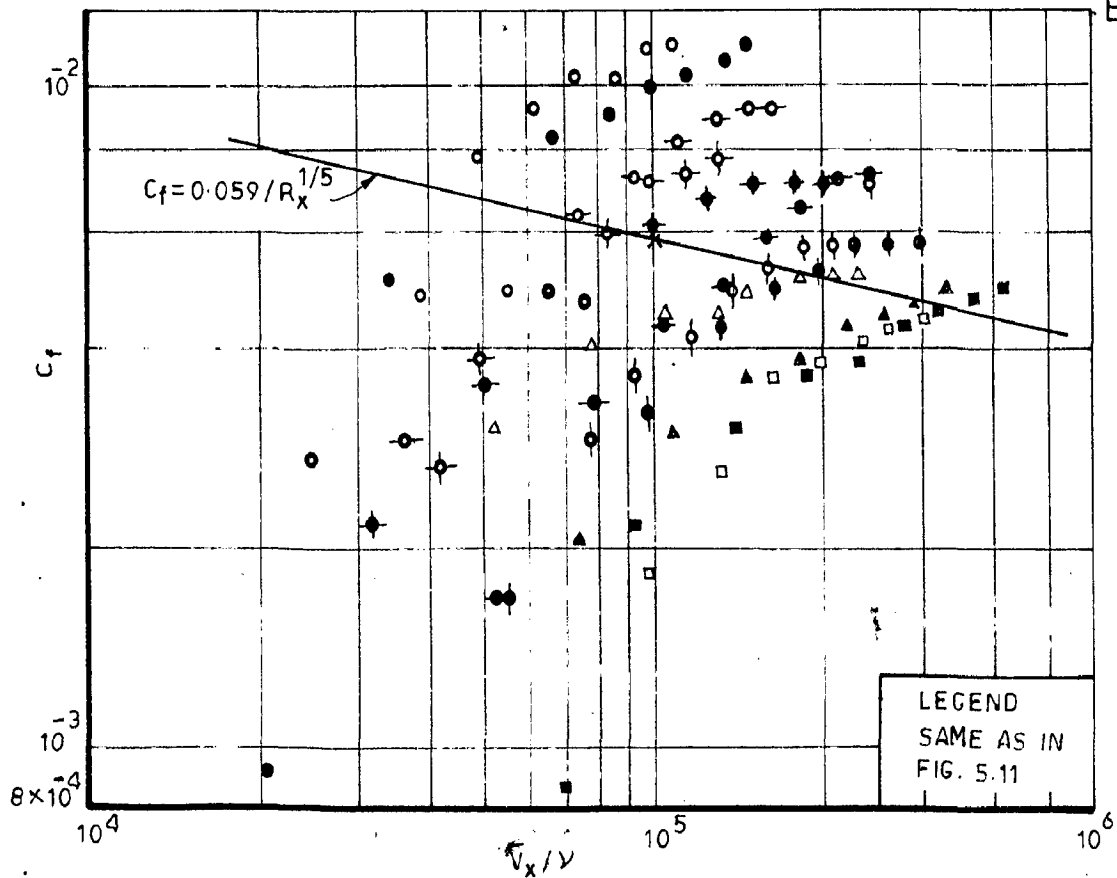
FIG. 5.12 – PLOT OF $C_f$ VS $\overline{V}x/\nu$ FOR ELEMENTS ON SMOOTH BOUNDARY

FIG.5.15 _ VARIATION OF $C_{f_1}$ WITH $\overline{V}L/\nu$ FOR ELEMENTS ON SMOOTH BOUNDARY

LEGEND
SAME AS IN
FIG. 5.13
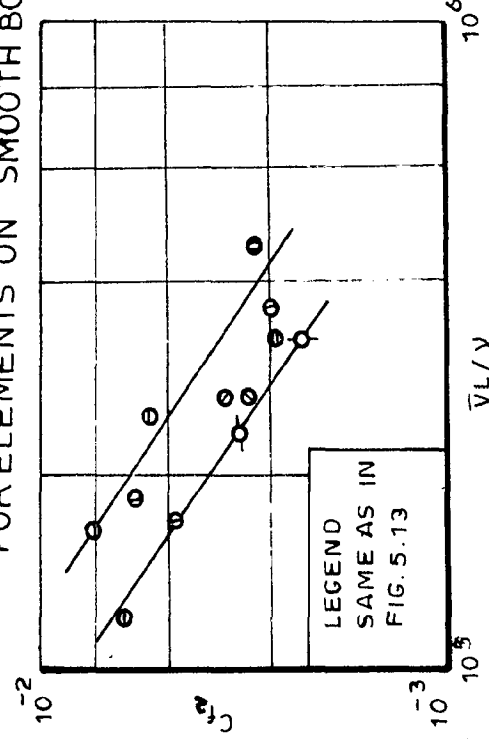
FIG.5.16 _ VARIATION OF $C_{f_2}$ WITH $\overline{V}L/\nu$ FOR ELEMENTS ON SMOOTH BOUNDARY

LEGEND
SAME AS IN
FIG. 5.13

$$C_{f_1} = \frac{0.325}{(\overline{V}R_b/\nu)^{0.425}}$$

FIG.5.13 _ VARIATION OF $C_{f_1}$ WITH $\overline{V}R_b/\nu$ FOR ELEMENTS ON SMOOTH BOUNDARY

$$C_{f_2} = \frac{0.685}{(\overline{V}R_b/\nu)^{0.480}}$$

LEGEND
SAME AS IN
FIG. 5.13

FIG.5.14 _ VARIATION OF $C_{f_2}$ WITH $\overline{V}R_b/\nu$ FOR ELEMENTS ON SMOOTH BOUNDARY

| SYMBOL | D cms | L/h | $S \times 10^3$ |
|---|---|---|---|
|  | 5 | 80 | 0.667 |
|  | 10 | " | " |
|  | 15 | " | " |
|  | 5 | " | 1.335 |
|  | 10 | " | " |
|  | 15 | " | " |
|  | 5 | 60 | 0.667 |
|  | 10 | " | " |
|  | 15 | " | " |
|  | 5 | " | 1.335 |
|  | 10 | " | " |
|  | 15 | " | " |

LEGEND
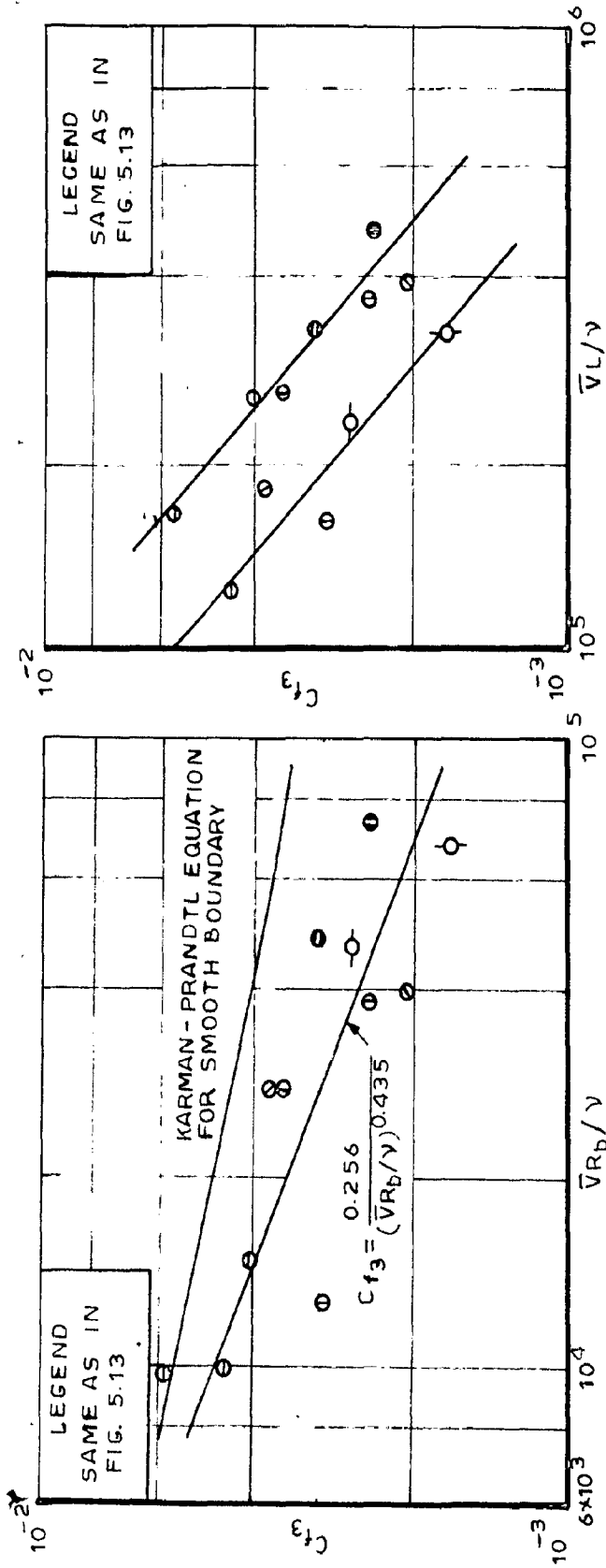
FIG.5.17 _ VARIATION OF $C_{f_3}$ WITH $\overline{V}R_b/\nu$ FOR ELEMENTS ON SMOOTH BOUNDARY

FIG.5.18 _ VARIATION OF $C_{f_3}$ WITH $\overline{V}L/\nu$ FOR ELEMENTS ON SMOOTH BOUNDARY

FIG.5.19 _ VARIATION OF $L_1/h$ WITH $\overline{V}R_b/\nu$ FOR ELEMENTS ON SMOOTH BOUNDARY

LEGEND
SAME AS IN
FIG. 5.13

KARMAN-PRANDTL EQUATION
FOR SMOOTH BOUNDARY

$$C_{f_3} = \frac{0.256}{(\overline{V}R_b/\nu)^{0.435}}$$

$C_{f_3}$

$\overline{V}R_b/\nu$

$10^{-2}$

$6 \times 10^3$

$10^4$

$10^5$

$10^{-3}$

LEGEND
SAME AS IN
FIG.5.13

$C_{f_3}$

$\overline{V}L/\nu$

$10^{-2}$

$10^5$

$10^6$

$10^{-3}$

$L_1/h$

$L/h=60$

$L/h=80$

$L/h=\infty$

$\overline{V}R_b/\nu$

$20$

$15$

$10$

$5$

$0$

$10^3$

$10^4$

$10^5$

LEGEND

| SYMBOL | L/h | h cms | INVESTIGATOR |
|---|---|---|---|
| ⊖ | 60 | 1·0 | AUTHOR |
| ⊖ | 80 | 1·25 | ,, |
| ⊖ | ∞ | 2·54 | CHANG(3) |
| ⊖ | ,, | 3·80 | ,, |
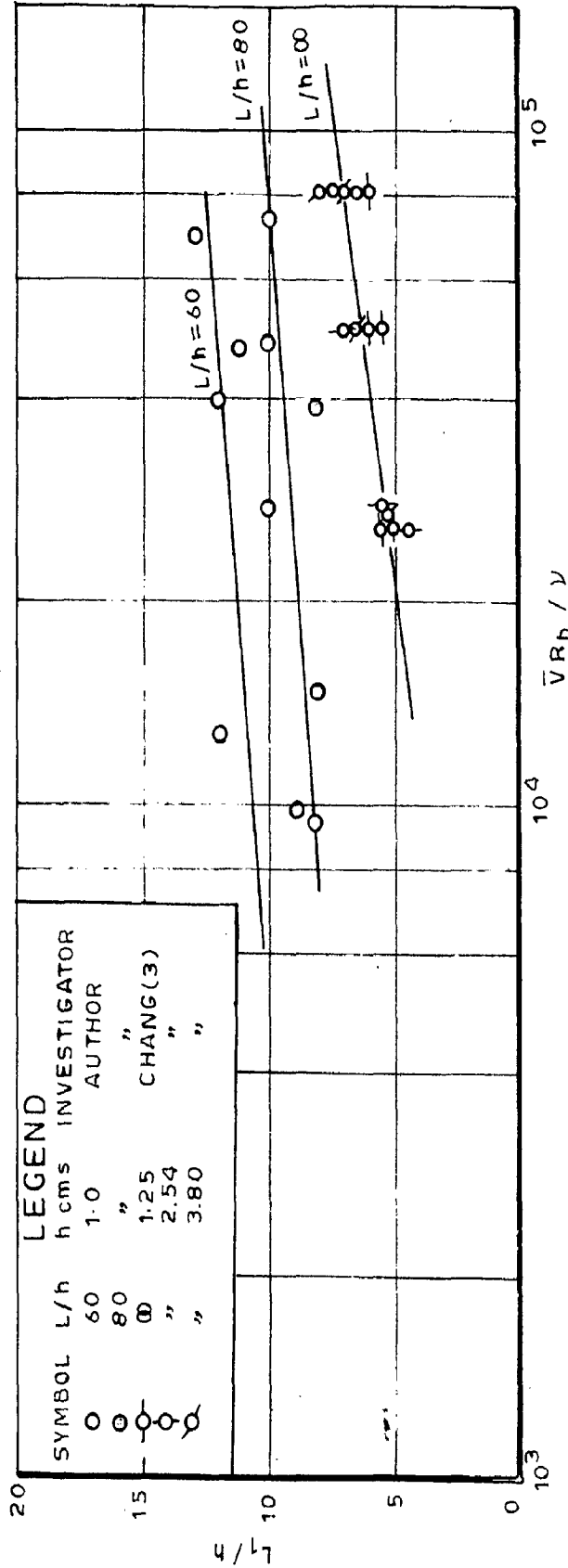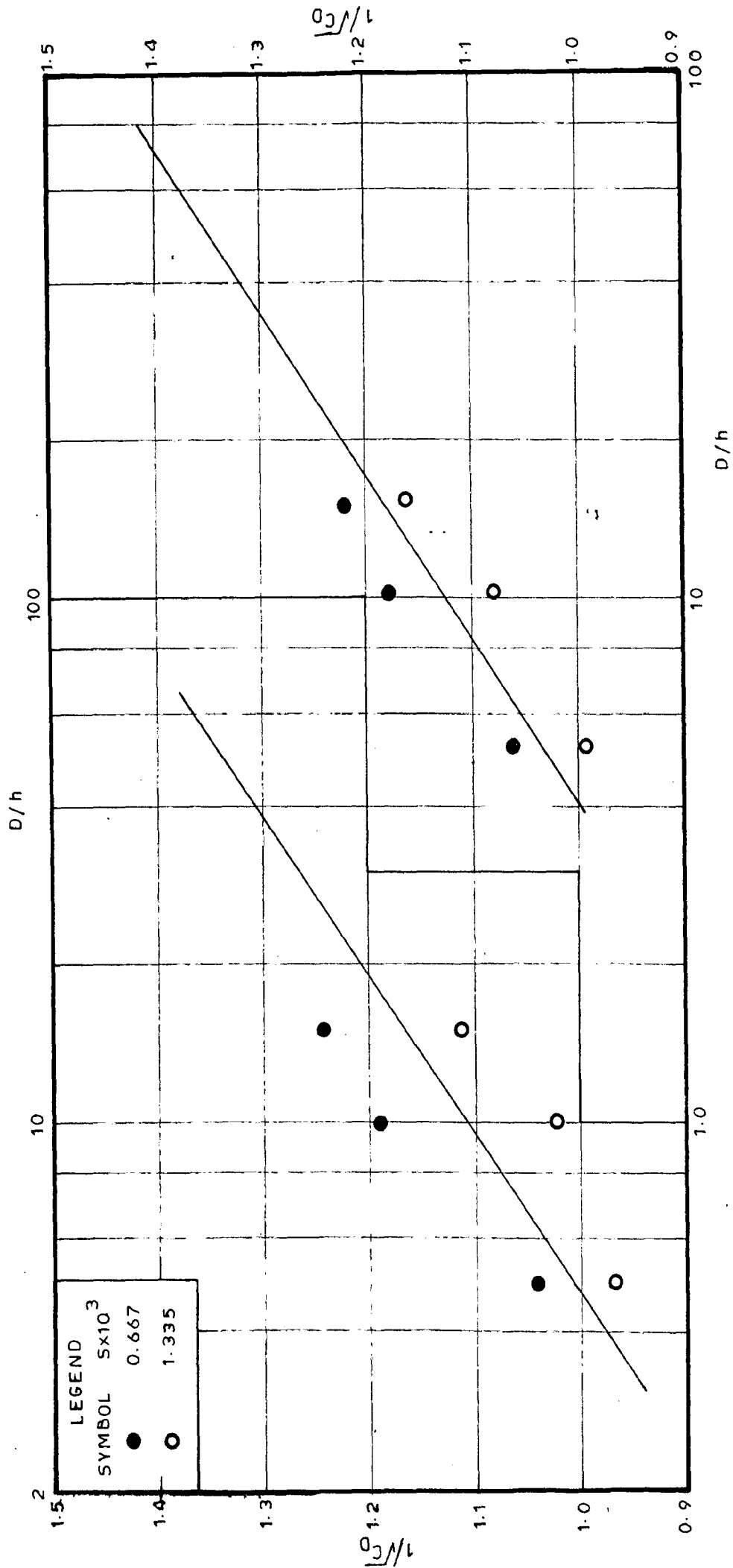
FIG.5.20 _ VARIATION OF $1/\sqrt{C_D}$ WITH $D/h$ AND $L/h$ FOR ELEMENTS ON SMOOTH BOUNDARY

LEGEND

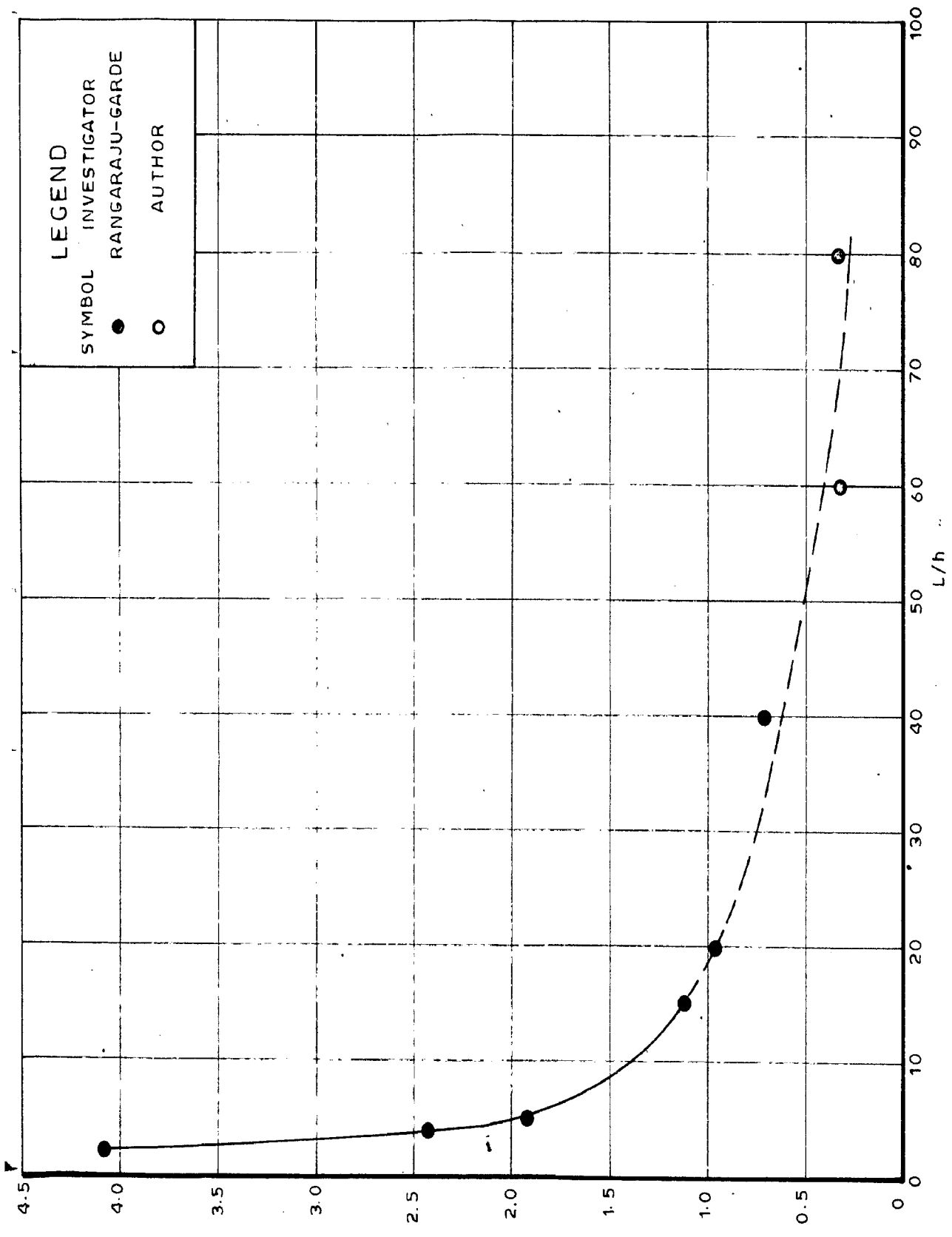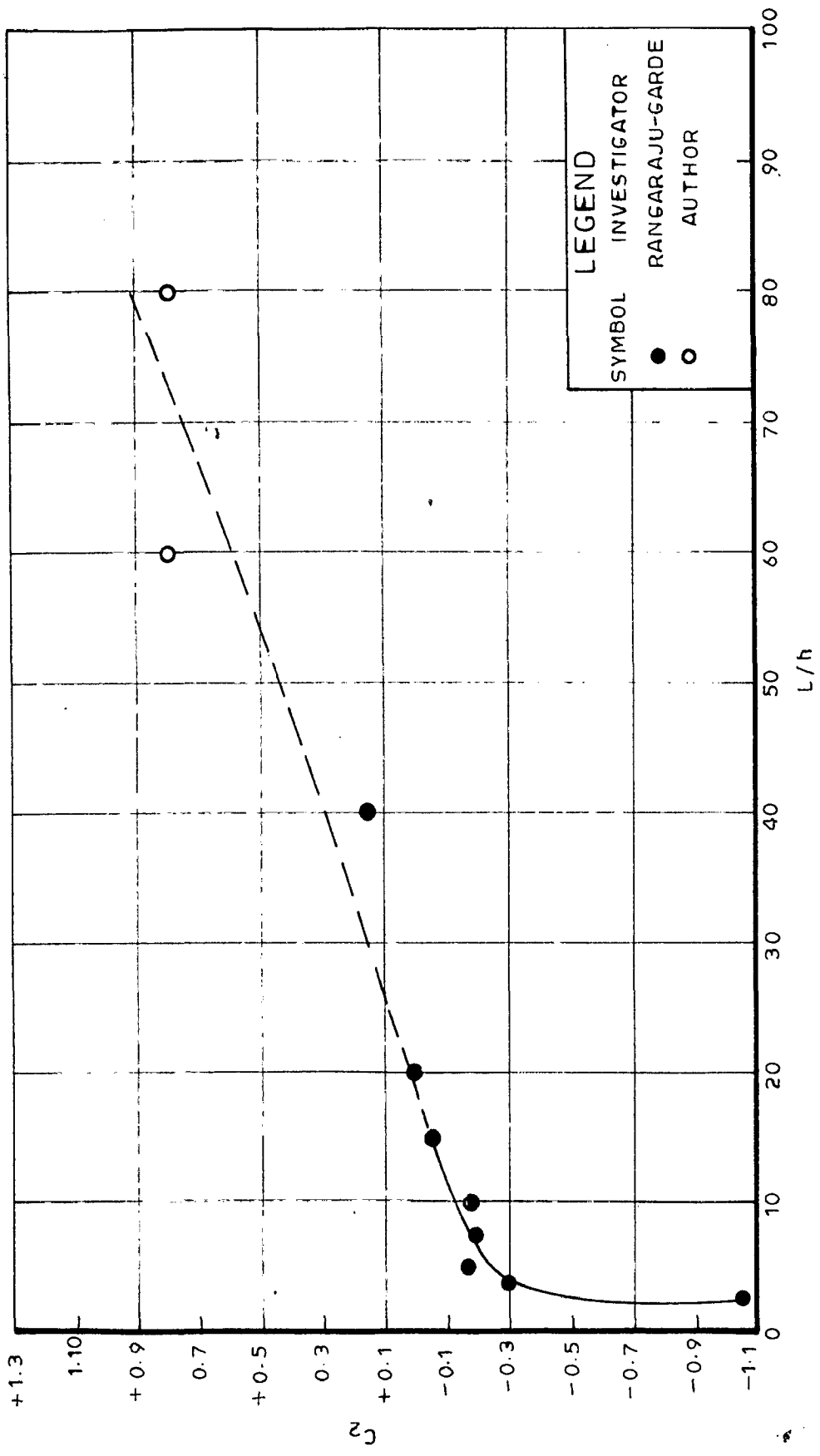| SYMBOL | $S \times 10^3$ |
|--------|------------------|
| ● | 0.667 |
| ○ | 1.335 |

FIG.5.21_VARIATION OF $C_1$ WITH $L/h$ FOR ELEMENTS ON SMOOTH BOUNDARY

FIG.5.22_VARIATION OF $C_2$ WITH L/h FOR ELEMENTS ON SMOOTH BOUNDARY

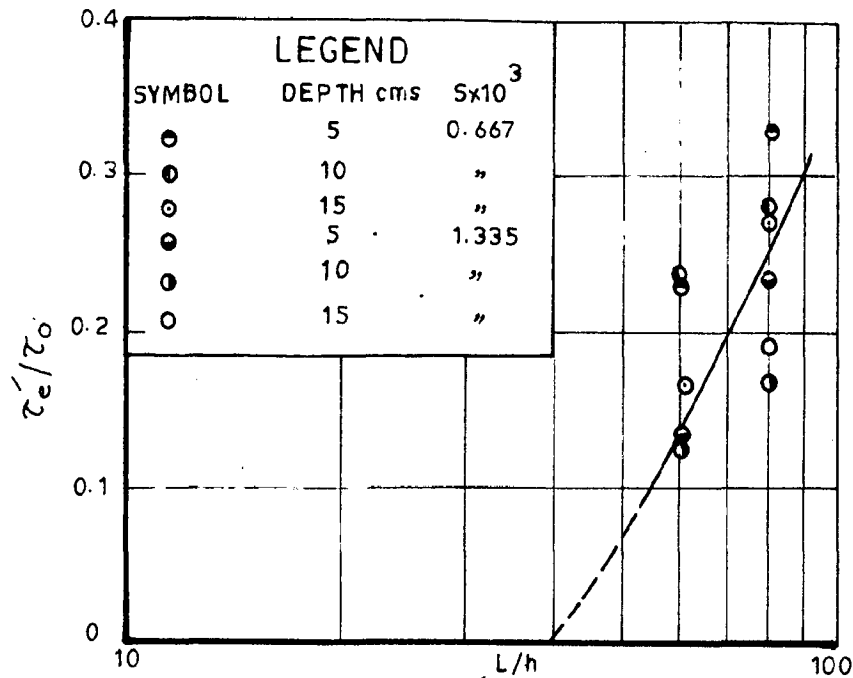FIG.5.23 VARIATION OF $\tau_e'/\tau_o$ WITH L/h FOR ELEMENTS
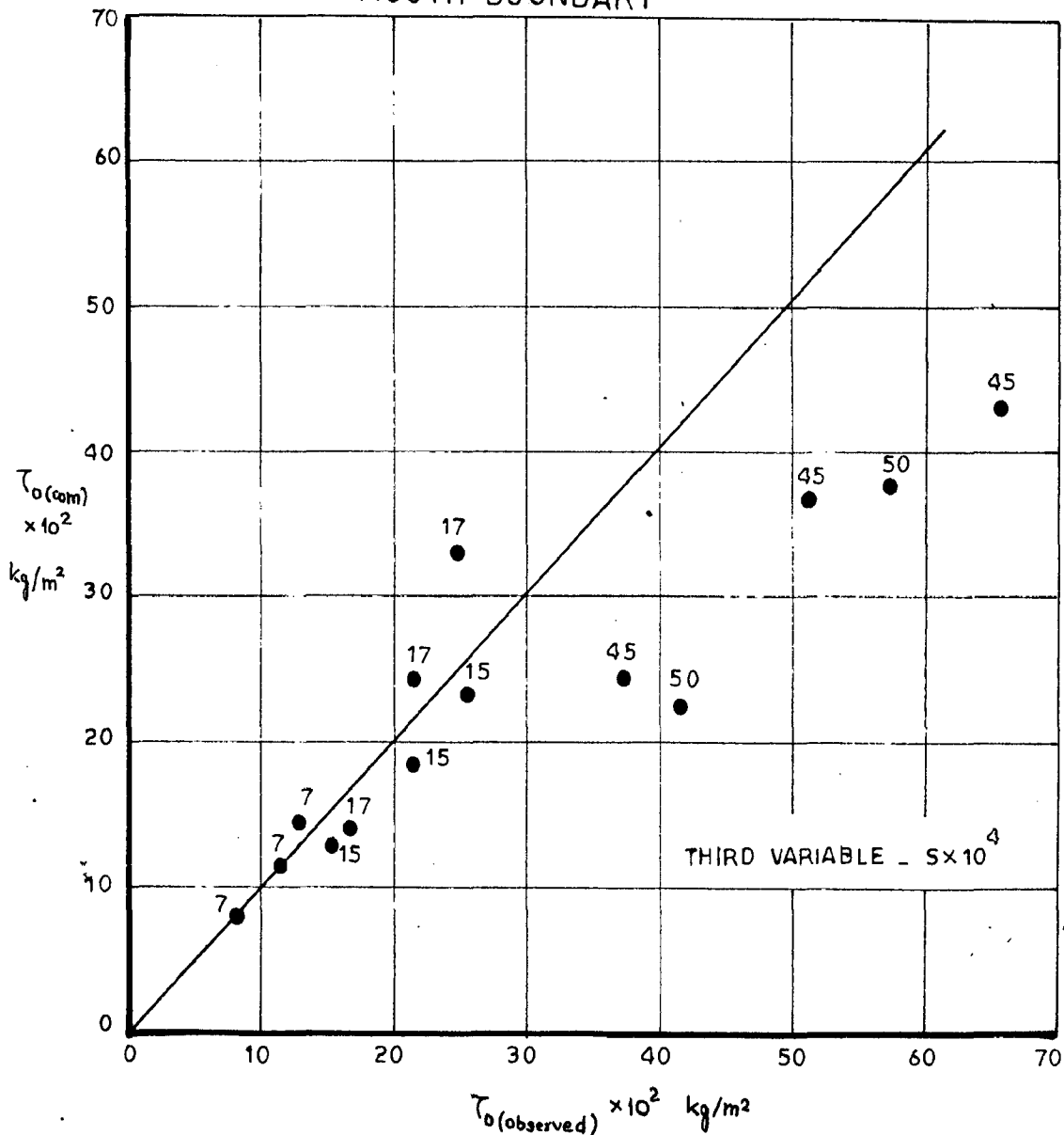ON SMOOTH BOUNDARY



FIG.5.24 PREDICTION OF SHEAR FOR BASHA'S DATA
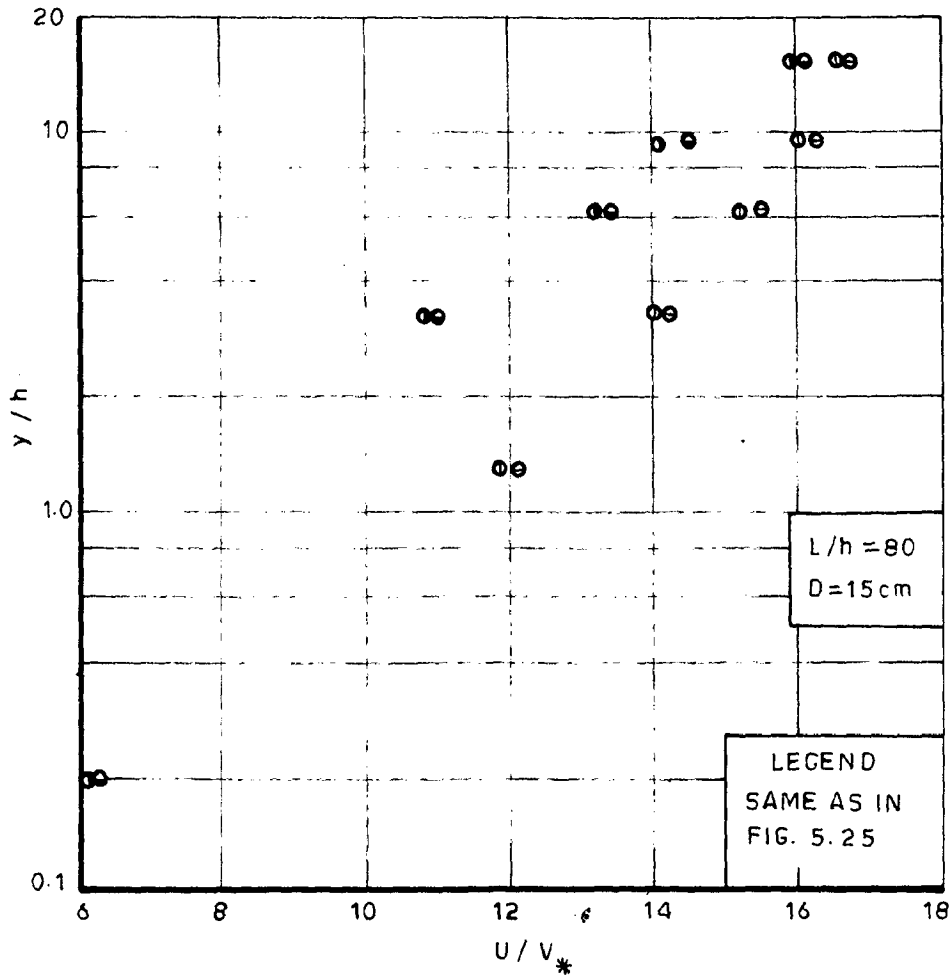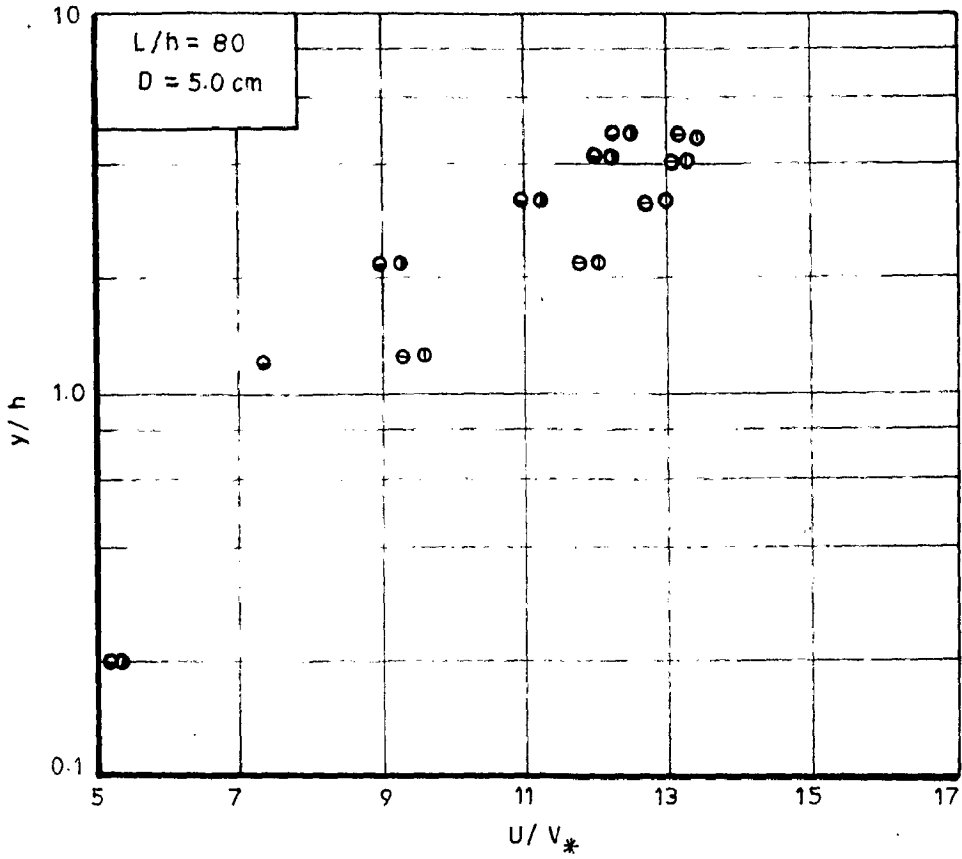USING AUTHOR'S METHOD

FIG. 5.26 PLOT OF U/V∗ VS $\log_{10}$ y/h FOR ELEMENTS
ON SMOOTH BOUNDARY

<u>A P P E N D I X</u>

TABLE - I

SUMMARY OF DATA COLLECTED BY THE AUTHOR ON SINGLE ROUGHNESS ELEMENT

Width of the Flume = 47.25 cms.

| Run No. | Cms h | cms D | Cumecs Q | $T^0C$ | cms/sec V | $C_D$ |
|---------|-------|-------|----------|--------|-----------|-------|
| 1 | 4.0 | 8.30 | 1.20 | 17.5 | 31.30 | 6.60 |
| 2 | 4.0 | 10.10 | 1.50 | 19.5 | 30.90 | 4.50 |
| 3 | 4.0 | 12.00 | 1.70 | 19.0 | 30.11 | 2.81 |
| 4 | 4.0 | 16.01 | 2.25 | 19.0 | 29.82 | 2.26 |
| 5 | 4.0 | 16.01 | 3.00 | 18.0 | 40.00 | 1.81 |
| 6 | 4.0 | 27.27 | 3.35 | 17.5 | 26.05 | 1.47 |
| 7 | 4.0 | 32.00 | 4.80 | 18.0 | 32.21 | 1.32 |
| 8 | 3.0 | 7.50 | 1.00 | 18.0 | 28.25 | 4.27 |
| 9 | 3.0 | 9.00 | 1.25 | 19.0 | 28.80 | 2.91 |
| 10 | 3.0 | 15.01 | 2.50 | 18.5 | 35.60 | 1.98 |
| 11 | 3.0 | 18.00 | 2.85 | 19.5 | 33.73 | 1.63 |
| 12 | 3.0 | 21.10 | 3.14 | 19.5 | 31.40 | 1.23 |
| 13 | 3.0 | 27.03 | 3.70 | 20.0 | 29.20 | 1.18 |
| 14 | 3.0 | 36.02 | 4.70 | 19.5 | 28.21 | 0.814 |

## TABLE - II

SUMMARY OF DATA COLLECTED BY THE AUTHOR USING 2-DIMENSIONAL STRIPS ON ROUGH BOUNDARY

Width of the flume = 47.25 cms.     Manning's 'n' for glass side wall = 0.009

| Run No. | h cms | L cms | $S \times 10^3$ | $Q \times 10^5$ cumecs | D cms | T°C | V cms/sec | $R_b$ Cms | $C_D$ |
|---|---|---|---|---|---|---|---|---|---|
| 15 | 4.0 | 160 | 1.0 | 9.8  | 12.86 | 31.0 | 17.10 | 12.20 | 3.50 |
| 16 | 4.0 | 160 | 1.0 | 27.5 | 23.05 | 31.5 | 25.11 | 21.30 | 2.06 |
| 17 | 4.0 | 160 | 1.0 | 51.5 | 32.37 | 32.0 | 33.53 | 28.20 | 1.63 |
| 18 | 4.0 | 160 | 2.0 | 12.9 | 12.85 | 32.0 | 21.30 | 12.10 | 3.70 |
| 19 | 4.0 | 160 | 2.0 | 42.5 | 23.60 | 32.5 | 39.13 | 21.00 | 2.43 |
| 20 | 4.0 | 160 | 2.0 | 72.0 | 32.00 | 32.0 | 47.65 | 27.30 | 1.79 |
| 21 | 4.0 | 80  | 1.0 | 6.9  | 12.50 | 31.5 | 13.10 | 12.10 | 4.35 |
| 22 | 4.0 | 80  | 1.0 | 21.8 | 23.30 | 33.0 | 20.00 | 21.70 | 1.78 |
| 23 | 4.0 | 80  | 1.0 | 43.5 | 35.30 | 32.5 | 26.00 | 31.80 | 1.16 |
| 24 | 4.0 | 80  | 2.0 | 8.9  | 12.80 | 32.5 | 15.50 | 12.40 | 4.53 |
| 25 | 4.0 | 80  | 2.0 | 30.0 | 23.40 | 31.0 | 26.91 | 21.80 | 1.69 |
| 26 | 4.0 | 80  | 2.0 | 66.5 | 36.00 | 31.5 | 39.01 | 30.8  | 1.41 |

## TABLE - III

### SUMMARY OF DATA COLLECTED BY THE AUTHOR USING 2-DIMENSIONAL STRIPS ON SMOOTH BOUNDARY

Width of the flume = 47.25 cms.    Manning's 'n' for glass side wall = 0.009

| Run No. | $h$ cms | $L$ cms | $L_1$ cms | $S \times 10^3$ | $Q \times 10^3$ Cumecs | $D$ cms | $T°C$ | $V$ cms/sec | $R_b$ Cms | $T'_o \times 10^2$ Kg/m² | $T'_e \times 10^2$ Kg/m² |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27 | 1.0 | 80 | 8.0 | 0.667 | 4.30 | 5.0 | 26.0 | 18.60 | 4.56 | 1.25 | 1.00 |
| 28 | 1.0 | 80 | 10.0 | 0.667 | 15.80 | 10.0 | 26.0 | 29.61 | 8.30 | 1.80 | 1.57 |
| 29 | 1.0 | 80 | 10.0 | 0.667 | 26.00 | 15.0 | 26.0 | 35.70 | 11.65 | 2.31 | 2.06 |
| 30 | 1.0 | 80 | 8.0 | 1.333 | 6.30 | 5.10 | 27.0 | 26.80 | 4.66 | 2.10 | 1.46 |
| 31 | 1.0 | 80 | 8.0 | 1.333 | 18.00 | 10.00 | 27.0 | 39.15 | 8.37 | 2.72 | 1.88 |
| 32 | 1.0 | 80 | 10.0 | 1.333 | 34.50 | 15.0 | 27.0 | 39.40 | 12.70 | 4.66 | 2.97 |
| 33 | 1.0 | 60 | 9.0 | 0.667 | 4.25 | 5.25 | 26.0 | 18.0 | 4.76 | 1.00 | 0.734 |
| 34 | 1.0 | 60 | 11.0 | 0.667 | 13.20 | 10.30 | 26.0 | 26.80 | 8.77 | 2.08 | 1.390 |
| 35 | 1.0 | 60 | 11.5 | 0.667 | 24.00 | 15.10 | 26.0 | 33.70 | 12.00 | 2.05 | 1.330 |
| 36 | 1.0 | 60 | 12.0 | 1.335 | 5.90 | 5.20 | 29.0 | 24.10 | 4.55 | 1.31 | 0.863 |
| 37 | 1.0 | 60 | 12.0 | 1.335 | 18.50 | 10.40 | 28.0 | 38.00 | 9.00 | 2.60 | 1.500 |
| 38 | 1.0 | 60 | 13.0 | 1.335 | 35.00 | 15.50 | 28.0 | 47.80 | 12.40 | 3.14 | 2.035 |