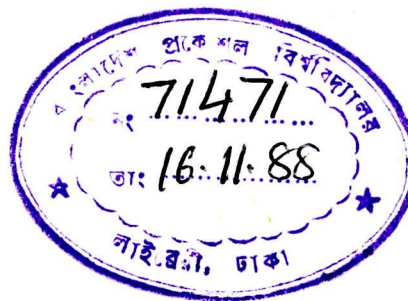


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CORRELATION OF NON-DIMENSIONAL PARAMETERS FOR WATER
COURSES IN ALLUVIUM

Submitted by

Yasmin Begum



In partial fulfilment of the requirements for the degree of
Master of Science in Water Resources Engineering, Bangladesh
University of Engineering and Technology, Dhaka.

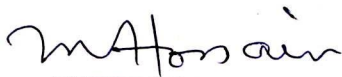


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CERTIFICATE

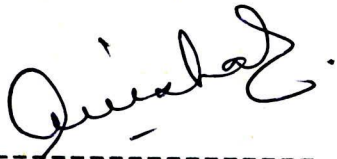
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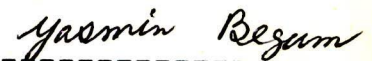
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED BY YASMIN BEGUM
ENTITLED "CORRELATION OF NON-DIMENSIONAL PARAMETERS FOR WATER
COURSES IN ALLUVIUM" BE ACCEPTED AS FULFILLING THIS PART OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENGINEERING
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ABSTRACT

This study involved the examination of the complexity and multiplicity of the relationships among the variables governing alluvial river behaviours. In doing so a set of non-dimensional parameters were formulated, considering the dominant variables which govern the geometry of water courses in alluvium. Principle of dimensional analysis specially the method of synthesis was utilized in obtaining the parameters. The non-dimensional parameters developed and used in this study are

$$(B/H, H/D_{50}, Q^{2/5}/H(Sg)^{1/5}, C, Q^{2/5}/D_{50}(Sg)^{1/5}, V_*/(gD_{50})^{1/2}, V/(gH)^{1/2}) = 0 \quad (1)$$

A considerable body of equilibrium state, data collected from various sources throughout the world containing over 7000 sets of data were available in the department of Water Resources Engineering, BUET. These data sets contained data from both laboratory and field conditions. Laboratory data were initially used for developing the functional equations among the parameters. Correlations thus developed were then verified against the field data. When the continuity of the correlation from laboratory circumstances through to field circumstances were tested, they showed well defined continuity. From among the above mentioned non-dimensional parameters four sets of correlations were obtained both for laboratory data and field data separately as follows.

For laboratory data

$$B/H = 0.347 \left[\frac{Q^{2/5}}{H(Sg)^{1/5}} \right]^{1.746} \quad \text{for } 100 < C < 10,000 \text{ ppm} \quad (2)$$

$$B/H = 0.347 \left[\frac{Q^{2/5}}{H(Sg)^{1/5}} \right]^{1.746} \quad \text{for } 0.2 < Fr.No. < 0.8 \quad (3)$$

$$B/H = 0.347 \left[\frac{Q^{2/5}}{H(Sg)^{1/5}} \right]^{1.7} \quad \text{for } 0.4 < Fr_{*}No. < 1.3 \quad (4)$$

$$H/D_{50} = 0.125 \left[\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}} \right]^{1.027} \quad \text{for } 0.2 < Fr.No. < 0.8 \quad (5)$$

The coefficient of correlation for the above four equation were 0.83, 0.83, 0.803 and 0.985, respectively.

For field data

$$B/H = 0.144 \left[\frac{Q^{2/5}}{H(Sg)^{1/5}} \right]^{2.26} \quad \text{for } 100 < C < 10,000 \text{ ppm} \quad (5)$$

$$B/H = 0.226 \left[\frac{Q^{2/5}}{H(Sg)^{1/5}} \right]^{2.139} \quad \text{for } 0.2 < Fr. No. < 0.8 \quad (6)$$

$$B/H = 0.1200 \left[\frac{Q^{2/5}}{H(Sg)^{1/5}} \right]^{2.352} \quad \text{for } 0.4 < Fr_{*}No. < 1.3 \quad (7)$$

$$H/D_{50} = 0.225 \left[\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}} \right]^{0.89} \quad \text{for } 0.2 < Fr. No. < 0.8 \quad (8)$$

The coefficient of correlation for the above four equation were 0.93, 0.93, 0.94 and 0.93 respectively.

Though the correlation had different coefficient and exponents for the regression equations, based separately on laboratory and field data, the compliance between the laboratory and field situation was satisfactory.

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LIST OF SYMBOLS

a	-	coefficient of the developed equations
A	-	total cross-sectional area
A _b	-	area corresponding to bed
A _w	-	area corresponding to sides
B	-	water surface width
b	-	exponent of the developed equations
C	-	charge in ppm
	-	Chezy's discharge coefficient
D ₅₀	-	Median particle size of the bed material
d ₆₅ , d ₉₀	-	particle sizes, represented as the diameter of percentage finer than
f	-	Darcy - Weisbach friction factor
f', f''	-	friction factor due to grain roughness and bed form respectively
f()	-	function of
f _s	-	seepage force in the bed of the channel
Fr.No	-	Froude number
F	-	thrust of a screw propeller
g	-	acceleration due to gravity
H	-	depth of flow
K	-	wall roughness height

- constant of resistance equation of Garde and Ranga Raju
- K_1, K_2 - function of sediment size, in Resistance equation of Garde - Ranga Raju
- K_s - Sand grain size in gravel bed rivers - d_{90}
- n - Manning's roughness coefficient
- N - revolution of the propeller
- n_w - Manning's coefficient for the side wall
- n - Manning's roughness coefficient for rough plane boundary
- q - discharge per unit width
- q_b - sediment load per unit width
- Q - total water discharge
- Q_b - sediment discharge
- R - hydraulic radius
- R_b - hydraulic radius corresponding to bed to grain and form resistance.
- R'_b, R''_b - hydraulic radius of the bed corresponding to grain and form resistance.
- Re - Reynolds number.
- R_w - Reynolds number of the particle related to fall velocity.
- S - longitudinal slope.
- S' - slope that the flow if bed is plane.

- s'' - additional slope resulting from the drag of bed undulations.
- S_c - shape factor of the channel cross-section
- S_p - shape factor of the particles.
- S_R - shape factor of the channel reach.
- T - side slope, horizontal distance per unit vertical rise
- V - velocity of flow.
- V_* - shear velocity $\sqrt{gRs}$.
- W - fall velocity
- x = non-dimensional parameters $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$
- y = depth of flow
- γ - specific weight of water
- γ_s - specific weight of sand
- γ_f - specific weight of fluid
- ν - kinematic viscosity of fluid
- ρ - mass density of fluid
- ρ_s - density of sediment particles
- ρ_f - density of fluid
- σ - standard deviation of the size distribution of bed material
- τ - shear stress
- τ_0', τ_0'' - shear stresses corresponding to the grain and form resistance respectively to grain and form resistance

CHAPTER 1

INTRODUCTION



1.1 ALLUVIAL CHANNELS

Alluvial channels are those for which the bed and banks are composed of sediment, transported and deposited by the stream itself. The alluvial channels are susceptible to shifts both in channel position and pattern as the alluvium is eroded and deposited. The geometry of an alluvial channel can be altered by the flow towards a configuration which is in dynamic equilibrium with the prevailing flow conditions. Alluvial channels can be subdivided into two major categories, stable and unstable channel. A stable channel can be defined as one with bed and banks that are nearly fixed within a definite span of time. An unstable channel, on the otherhand, is one with bed and banks that are not fixed in position with time. These definitions immediately pose a problem because the natural behaviour of many alluvial channels is such that a change of bank position is natural and expected, for example, when a meander shifts in the downstream direction. Meander shift of alluvial river is a normal channel behaviour and it should not be considered to be an unstable condition. Although to a landowner whose property is being destroyed by the meander shift, it will obviously be considered unstable. If a river maintains its cross-sectional area and shape during the shift, it should be considered stable. Therefore an unstable channel is one that progressively enlarge

its channel or in which the bed elevation changes by aggradation or degradation (Schumm, 1980).

An alluvial river continually changes its position and shape as a consequence of hydraulic forces acting on its bed and banks. In alluvial river system it is the rule rather than the exception that banks will erode, sediments will be deposited and floodplains islands and side channels will undergo modification with time. Changes may be very slow or dramatically rapid depending on the hydraulic forces. Archaeological, botanical, geologic and geomorphic evidence supports the conclusion that most rivers are subject to continuous change as a part of their morphologic evolution. But dramatic changes in morphology of alluvial streams occur due to major climatic and hydrologic changes and diastrophic events of earths.

The nature of the bed material has a considerable influence on the hydraulics of alluvial streams. The size distribution of the material and as well as the variation in size and character along the length are important from a geomorphological viewpoint. The median size of the bed material in a natural stream is found to decrease continually along the length of the stream. This reduction in size is partly due to sorting action and partly due to abrasion. As the stream comes down from mountainous regions to the plains the slope decreases and the stream width increases gradually. Such a decrease in slope reduces the capacity of the stream to transport the coarser particles brought from upstream and the coarser particles are thus deposited on the stream bottom. Sorting takes place depending on the variation of sedi-

ment transport capacity along the length of the stream. Abrasion is the reduction in the size of particles due to rubbing, grinding and crushing of the sediment particles against each other or against the bed. It is evident that if abrasion has to be a major factor in reducing the sediment size, majority of the transported material must travel along or near the bottom, i.e. as bed load. On the otherhand, sorting can be the more important factor in the reduction of sediment size if the material is transported as suspended load.

1.1.1 Variables governing alluvial river geometry and pattern

Prediction of alluvial river geometry and pattern is very difficult due to the fact that rivers carry not only water but also a large quantity of silt. Moreover, a number of variables control the alluvial river geometry and pattern. These are: water discharge, sediment discharge, flow velocity, bed configuration, stream power, bed material size, composition and gradation, turbulence, temperature, density and viscosity of water and acceleration due to gravity. All these variables are interrelated and inter-dependent. Some of them play a more dominating role on shaping the alluvial river geometry (Depth, width, slope, etc.). Among the dominating variables, some are water discharge, sediment discharge, velocity, acceleration due to gravity, viscosity of water and median particle size of the bed material. The effects of these variables have been studied by many investigators and a number of technical papers published. Some of the

notable workers are, Simons (1971), Schumm (1960), Simons and Richardson (1966).

Shapes of streams:

The shape of an alluvial stream includes the cross-sectional shape i.e. geometry and shape in plan. Most of the alluvial stream channels are found to be relatively wide and shallow. If the channel is deep and narrow, the banks become unstable due to higher velocities, and the consequent high shear stresses along the sides. The material that is eroded from the sides drops on the bed and thus a narrow and deep channel tends to widen until the velocities near the sides are too low to cause further erosion. The side slopes is a function of the nature of the material forming the channel, i.e. its sediment size, specific weight and cohesivity. If the slope of the stream is large, it will naturally produce higher velocities and hence the channel would be relatively wide. Since the sediment transport rate increases with increase in slope, a similar statement can be made regarding the dependence of cross-sectional shape on sediment transport (after Schumm 1980).

A thorough understanding of the hydraulics of alluvial streams needs knowledge of their plan form. So the shape of the stream in plan is also important. In general, the plan forms of alluvial streams can be classified as braided, straight and meandering. These forms refer to limited reaches of an alluvial stream and it is quite common to have all these three plan forms occurring in the same stream in different reaches. Furthermore,

there are no well defined lines of demarcation between these forms. Some reaches of an alluvial stream can be classified as braided but the secondary channels may be of meandering type. (after Garde 1985).

1.2 IMPORTANCE OF THE STUDY:

In present time, the need to understand the alluvial channel circumstances is even more pressing. More complicated problems are encountered, more and more rivers are being modified and developed for multipurpose use, flood control, water supply, power generation, irrigation, navigation and recreational facilities for which artificial changes are being made in the water courses of alluvium. These problems have become complicated due to the presence of alluvium in the water courses. In fact if the water courses were to flow through nonerodible material, many of the above problems would not exist. Alluvial water courses with mobile boundary are free to adjust the shape, pattern and slope. So huge expenditures are required for multipurpose use of water courses in the alluvium. These problems are more acute in under-developed and developing countries. An intimate relationship has always existed between development of civilizations and rivers.

Prediction of behaviour of an alluvial river is a major problem in the control and utilization of the surface water of the earth. Basically the engineer, has to correlate the variables which govern alluvial river phenomenon to predict the river

geometry. Too many variables are related to alluvial river flow phenomenon and it is very difficult to incorporate all these variables into mathematical equation. Most theoretical experimental, empirical treatments are based on idealized and simplified assumption involving one or two dominating factors. These dominating factors are selected according to their relative importance in alluvial river geometry. This type of study for alluvial stream is potentially dependent on extensive use of different non-dimensional parameters originating from theoretical analysis.

1.3 SOURCES OF DATA:

Data obtained from various sources throughout the world have been compiled by Peterson and Howells (1973). The data collection of Peterson and Howells is essentially an update of the data collection of Johnson (1943). Again Peterson and Howell (1978) added more data and published an uptodated compendium consisting a total of 6606 sets of data records. Peterson and Howells data compendium later been modified by Brownlie (1981). The data base contains 7027 records in total of which 5263 sets are laboratory data and 1764 sets are field data. This updated compilation of data is available at Water Resources Engineering Department of BUET. This Data base has been used in this study.

1.4 OBJECTIVES OF THE WORK:

The objective of this study are as follows:

- 1) To develop non-dimensional functional equation to represent channel geometry in alluvium taking into consideration the important variables as the principle factors governing the geometry and sediment transport in alluvial water courses.
- 2) To develop the functional equations between the non-dimensional terms using the laboratory data.
- 3) To extend these equations developed by use of laboratory data between the non-dimensional terms to field circumstances by testing the continuity of correlations from laboratory data to field data.

CHAPTER 2

REVIEW ON ALLUVIAL RIVER GEOMETRY, BED FORMS AND RESISTANCE

2.1 INTRODUCTION

Alluvial channel dimensions are largely due to water discharge, whereas channel shape and pattern are related to the type and amount of sediment load moved through the channel. The large channel forms in response to a large water discharge, but the pattern itself and the shape of the channel depends on the proportion of the total sediment load (silt, clay, sand gravel). Geomorphic history is also important because it can determine the slope of the alluvial plain upon which the stream flows. When the proportion of bed load in a channel is small the channel is a narrow, deep, suspended load channel (width depth ratio usually less than 10). When the percentage of bed load is intermediate, the mixed-load channel has a lower width-depth ratio (between 10 and 40) and sinuosity in between about 2.0 and 1.3. This channel may also be relatively straight, but the thalweg or the deepest part of the straight channel may be sinuous. As the proportion of the bed load increases, the width-depth ratio of a bed-load channel increases (greater than 40) and sinuosity is low. There is a tendency for multiple thalwegs to form. The greatest development of channels and bars occurs in the braided channel, when the ratio of bed load to total load is high. (Schumm, 1980).

A channel in regime exists in a state of dynamic equilibrium, self adjusting its geometry, channel pattern, slope and bed forms. A channel is said to be in a state of 'Regime', if the flow is such that 'silting and scouring' need no special attention. Brief review of literature on channel forms, factors affecting alluvial river geometry, bed forms in alluvial channels and resistance to flow.

2.2. CLASSIFICATION OF CHANNEL FORMS:

Alluvial channels can be subdivided into two major categories, stable and unstable channels. A stable channel can be defined as one with bed and banks that are fixed and an unstable channel is one that progressively enlarges its channel or in which the bed elevation changes by aggradation or degradation.

Leopold and Wolman classified broadly all alluvial channels in terms of channel pattern, that is, the configuration of the river as viewed on a map, into three categories:

- 1) Straight
- 2) Meandering
- 3) Braided

It has been argued that this classification is far too simplistic because a braided channel is also straight and at high discharges it may be impossible to distinguish between a braided and a straight channel. However, the bedforms and the morphology of these two channels are different, and it is reasonable to classify streams into these three categories.

2.2.1 Straight channels:

Straight channels are those which follow essentially a straight alinement. They exist generally with either flat slopes, which are inadequate to provide erosive velocities or steep slopes that produce relatively high velocities. In the latter case, it is possible that the straight alinement results primarily from momentum that discourages turning. It is also possible that the alinement might be influenced by a heavy concentration of sediment which required for its transport the full capacity provided by the steep slope. Leopold and Wolman (1957) have pointed out that truly straight channels are rare in nature. Although a stream may have relatively straight banks, the thalweg or path of greatest depths along the channel is sinuous. The best examples of straight channels are man made canals for the purpose of irrigation and drainage.

The sinuosity of a river, the ratio between thalweg length to down valley distance is most often used to distinguish between straight and meandering channel. Sinuosity varies from a value of unity to a value of three or more. Wolman and Miller (1964) took a sinuosity of 1.5 as the division between meandering and straight channels. However, it should be emphasized that any such division between straight and meandering channel is arbitrary and that a meandering stream may be of low sinuosity as low as 1.2 (Schumm, 1977).

2.2.2 Meandering channels:

A meandering channel is one that consists of alternating bends, giving an S - shape appearance to the plan view of the river. More precisely, Lane (1957) concluded that a meandering stream is one whose channel alignment consists principally of pronounced bends. The meandering river consists of a series of deep pools in the bends and shallow crossings in the short straight reach connecting the bends. The thalweg flows from a pool through a crossing to the next pool forming the typical S curve of a single meander loop. Meandering streams are found to occupy valleys of moderate slope expressed by Lane (1957) as between $S=0.0017Q^{1/4}$ and $S=0.10/Q^{1/4}$, Q being the average discharge in cubic feet per second. Angles (1949) stated "Meandering - is nature's way of damping out excess energy during a wide range of flow conditions the pattern depending upon the grade of material, the relation between discharge and charge (sediment concentration) and the rate of charge and discharge. Lane (1957) in his analysis showed that "for the same average discharge and material size, streams in non cohesive material tend to be more nearly straight when they are steeper than the meandering of streams". Later, Shin and Einstein (1964) and Shen and Komura (1968) found that meandering tendencies develop with differences between the shear stresses at the two-sides of the cross section. Other investigators mentioned the effects of secondary currents. Yang (1971) analyzed stream meanders in terms of the least time

rate of energy expenditure. Schumm and Khan (1972) had showed channel patterns as a continuous process (fig. 2.1) and related it with sinuosity and slope.

2.2.3 Braided channels

A braided river is generally wide with poorly defined and unstable banks, and is characterized by a steep, shallow course with multiple channel divisions around alluvial islands Leopold and Wolman (1957) have found that braiding is one of the many patterns which can maintain quasiequilibrium among the variables of discharge, sediment load and transporting ability. Lane (1957) concluded that, generally the two primary causes that may be responsible for the braided condition are (1) over loading, that is, the stream may be supplied with more sediment than it can carry resulting in deposition of part of the load and (2) Steep slopes, which produce a wide shallow channel where bars and islands form readily. Either these factors alone, or both in concert, could be responsible for a braided pattern. Another cause of braiding is easily erodable banks. If the banks are easily eroded, the stream widens at high flow and at low flow bars form which become stabilized forming islands. Braided channels of stream in regimen are seldom found except on relatively steep slopes, indicated by Lane (1957) to be $S = 0.10 \sqrt[4]{Q}$ or greater and by Leopold and Wolman (1957) as $S = 0.06Q^{-0.44}$ or greater, Q in the first instance being the average discharge in cubic feet per second and in the second, the bank full discharge;

S is the slope, in feet per thousand feet. In aggrading streams braiding may occur on either flat, moderate, or steep slopes, but in either balanced or aggrading streams, it is believed to result primarily from random deposition of materials transported during high flows in quantities or size too great for continued transport during moderate or low flows. These deposits frequently form bars upon which vegetation flourishes to discourage further movement by succeeding high discharges, thus intensifying the braiding.

2.3 FACTORS AFFECTING ALLUVIAL RIVER BEHAVIOUR:

Variables affecting alluvial river channels are numerous and interrelated. Their nature is such that unlike rigid boundary hydraulic problems, it is not possible to isolate and study the role of any individual variable.

Major factors affecting alluvial stream channel forms are:

- i) Stream discharge
- ii) Sediment load
- iii) Grain size and grain size distribution
- iv) Longitudinal slope
- v) Bank and bed resistance to flow
- vi) Vegetation
- vii) Geologic factors
- viii) Geomorphology

- ix) Hydrologic factors, including possible changes in flow and runoff and the hydrologic effects of changes in land use.
- x) Climatic changes
- xi) Diastrophic events of earths
- xii) Ecological/biological changes that will result from physical change
- xiii) Sea level fluctuations
- xiv) Works of man.

The fluvial processes involved are extremely complicated and the variables of importance are difficult to isolate. A change in any one of the mentioned variables changes the characteristics of the channel. But dominant discharge is one of the most important dominant variables governing the morphology of alluvial streams. Sediment movement is maximum in, what is known as the dominant stage of river, when most of the changes in the bed configuration take place. Again that constant discharge which is the equivalent, for channel forming purposes, of the variable river flow is known as dominant discharge.

By bank erosion or berm build-up the channel will be enlarged until a stable condition is reached. Stability of channel means, the degree of which bank positions are maintained and whether or not the bed of the channel degrades or aggrades.

2.4 BED FORMS IN ALLUVIAL CHANNELS:

All irregularities larger than the largest size particle forming the bed are called bed configuration. Several synonyms of this term are in common use in the literature and among workers in the field. Some of them are: bed geometry, form of bed roughness, bed forms, bed regime, bed phase, bed irregularities, sand waves, bed material forms, and bed shape. A free surface flow over an erodable sand bed generates a variety of different bed forms and bed configurations. The type of bed configuration and the dimensions of the bed forms are dependent on the properties of the flow, fluid and bed material. Different types of bed forms are associated with a distinct type of flow, which emphasizes the complex nature of the phenomenon and suggests the possibility that it can operate in a number of distinct phases of behaviour each linked by transitions. Descriptions of and definitions for the principal types of bed forms and configurations presented by the USE (1966) Task Force on Bed forms and Alluvial Channels, Committee on Sedimentation are given in table 2.1.

2.4.1 Regimes of flow and bed forms in alluvial channels:- The flow in sand bed channels is divided into two flow regimes with a transition zone between (Sameness and Richardson, 1963). Each of these two flow regimes is characterized by similarities in the shape of the bed configurations, mode of sediment transport, process of energy dissipation, and phase relation between the bed and water surfaces. This classification has been fairly well

accepted by engineers. The two regimes and their associated bed configurations as reported by Simons (1977) are as follows:

- A. Lower flow regime:
 - 1. Ripples
 - 2. Dunes
- B. Transition Zone: Bed configurations range from dunes to plane beds or to antidunes.
- C. Upper flow regime:
 - 1. Plane bed with sediment movement
 - 2. Antidunes
 - a. Standing waves
 - b. Breaking antidunes
 - 3. Chutes and Pools
 - 4. Slug flow

In table 2.2 variation of different variables with flow regimes and bed forms for two sand sizes are presented.

2.4.1 A) Lower flow regime

Lower flow regime begins with the beginning of motion. The resistance to flow is large and sediment transport small. The bed form is either ripples or dunes or some combination of the two. The water surface undulations, if they exist, are out of phase with the bed surface, and there is a relatively large separation zone downstream from the crest of each ripple or dune. Resistance of flow is caused mainly by the form roughness.

B. Upper flow regime:

In the upper regime, resistance to flow is relatively small and sediment transport is large. The usual bed forms are plane bed or antidunes. The water surface is in phase with the bed surface except when an antidune breaks, and normally the fluid does not separate from the boundary. A small separation zone may exist downstream from the crest of an antidune prior to its breaking. Resistance to flow is the result of grain roughness with the grains moving, of sand waves and their subsidence and of energy dissipation when the antidunes break. The mode of sediment transport is for individual grains to roll almost continuously downstream in sheets one to several grain diameters thick. However, when antidunes break, much of the bed material in the region of the breaking wave is briefly suspended, then most sediment movement stops temporarily and there is return of suspended particles to the bed. Various types of bed forms are shown in fig. 2.3.

2.4.1 C) Transitions: The "transition" zone encompasses the bed forms that occur during the passage from lower regime to Upper regime. This transition is not unique in loose boundary hydraulics. The passage from ripples to dunes constitutes two more transitions with very interesting properties.

2.5 RESISTANCE TO FLOW IN ALLUVIAL CHANNELS:

For flow in pipes, conduits and rigid boundary open channels as well as alluvial streams, there is a definite relationship between the mean velocity V , the pipe diameter D , or the hydraulic radius R (or the depth of flow y), the slope S and the characteristics of the channel boundary. Such a relationship is commonly known as resistance equation.

A resistance equation is required in the design of conduits, irrigation channels river improvement works, sediment transport studies etc. Though the forms of resistance equation in rigid boundary channels and pipes are well established, but considerable uncertainties exist over the choice of the proper value of the coefficients and constant involved in the equations for alluvial channel flow. The problem of predicting the resistance to flow in alluvial channels is complicated as the configuration of the bed changes with changes in flow conditions. This changing bed condition (ripples, dunes, transitions, antidunes, bars etc.) makes it extremely difficult to describe the resistance due to these bed forms by a constant resistance coefficient.

2.5.1 Variables describing resistance to flow:

The variables determining the resistance to flow are numerous. A general flow formula that considers the major variables in open channels are as follows (Simons, 1977)

$$(v, y, s, \rho, \mu, g, d, \sigma, \rho_s, S_p, S_R, S_c, f_s) = 0 \quad \dots\dots 2.1$$

where

v = velocity

y = depth

s = slope of energy grade line

ρ = density of water

μ = dynamic viscosity of water

g = gravitational acceleration

d = representative diameter of bed material

σ = standard deviation of the size distribution of bed material

ρ_s = density of sediment

S_p = shape factor of the particles

S_R = shape factor of the channel reach

S_c = shape factor of the channel cross-section

f_s = seepage force in the bed of the channel

The influence of some of these factors on resistance to flow are known but it is difficult to consider them because of their complexity. The effects of others are not known, with knowledge of these circumstances, equation 2.1 can be transformed into

$$\frac{V}{V_*} = (Re, -\frac{d}{y}, -\frac{1}{R_W}, -\frac{\tau}{\sigma_s d}) \quad \dots\dots 2.2$$

where

$$\frac{V}{V_*} = \text{a measure of the resistance} = -\frac{V}{\sqrt{gRS}}$$

$$Re = \text{Reynolds number} = -\frac{VR}{\mu}$$

$$\frac{d}{y} = \text{Relative roughness}$$

$$R_w = \text{Reynolds number of the particle related to fall velocity}$$

$$= \frac{Wd}{\gamma} \text{---, where } w \text{ is fall velocity}$$

$$\frac{\tau}{\delta'_s d} = \text{Froude number related to the particle}$$

$$= \text{Ratio of drag force to the gravitational force,}$$

$$\text{where } \delta'_s = (\delta_s - \delta).$$

With a rigid boundary δ'_s representing the specific weight of a boundary particle and w its fall velocity can be assumed equal to infinity. Then $-\frac{\tau}{d\delta'_s}$ and $-\frac{1}{R_w}$ are both zero, and equation 2.2 reduces to

$$-\frac{V}{V_*} = f(R_e, d/y) \dots\dots\dots 2.3.$$

Then $-\frac{V}{V_*}$ can be transformed to

$$-\frac{V}{V_*} = \frac{V}{\sqrt{gR}} \cdot \frac{1}{\sqrt{S}} = \frac{Fr}{\sqrt{S}} \text{ where } \frac{V}{\sqrt{gR}} = \text{Froude number}$$

Thus equation 2.3 turns into

$$\frac{Fr}{\sqrt{S}} = f(R_e, d/y)$$

$$\text{or, } S = F_r^2 f_2 (Re) \left(-\frac{d}{y}\right)^n \quad \dots\dots\dots (2.4)$$

Many resistance formulas are of this form.

The Darcy - Weisbach formula, applicable for steady uniform flow in pipe can be written as

$$f = \frac{8gRS}{V^2} \quad \dots\dots\dots (2.5)$$

where R is hydraulic radius

& f is the friction factor

By writing $V_*^2 = gRS$, the above equation can be written as

$$\frac{V}{V_*} = \sqrt{\frac{8}{f}} \quad \dots\dots\dots (2.6)$$

It can also be shown from dimensional analysis that

$$f = f_1(Re, K/D) \quad \dots\dots\dots (2.7)$$

where K is the wall roughness height

and $\frac{K}{D}$ is known as relative roughness

f is found to increase with increasing values of K/D, on the other hand, the term R/K when hydraulic radius R is used instead of D then it is called relative smoothness. Equation (2.7) is valid for laminar as well as turbulent flow in pipes. Two most common parameters for describing resistance to steady uniform flow are:

1. The Chezy resistance factor, C.
2. The Manning roughness coefficient, n.

Chezy's equation for uniform flow is

$$V = C\sqrt{RS} \quad \dots\dots\dots (2.8)$$

in which S is the slope of water surface and C is known as Chezy's discharge coefficient. C is variable with bed as well as flow characteristics.

Approximately C may be written as

$$C = 18 \log 12.21 - \frac{R}{K_s} \quad \dots\dots\dots (2.9)$$

In its present form Manning's equation in SI units can be written as

$$V = \frac{1}{n} R^{2/3} S^{1/2} \quad \dots\dots\dots (2.10)$$

In fps units the constant 1 is replaced by 1.49. The values of n for different types of surfaces have been listed by Chow and these remain invariant with respect to the system of units.

By comparing Chezy's equation with Manning's and Darcy Weisbach, the following dimensionless equation can be obtained

$$\frac{V}{V_*} = \frac{C}{\sqrt{g}} = \frac{R^{1/6}}{n\sqrt{g}} = \sqrt{8/f} \quad \dots\dots\dots (2.11)$$

Comparing this equation with Kenlegan's equations of the following forms for smooth and rough boundaries

$$\frac{V}{V_*} = 5.75 \log \left(\frac{V_* R}{\zeta} \right) + 3.25 \quad - \text{ smooth boundaries} \\ \dots\dots\dots (2.12a)$$

$$\frac{V}{V_*} = 5.75 \log \left(\frac{R}{K_s} \right) + 6.25 \quad - \text{ Rough boundaries} \dots\dots (2.12b)$$

The above shows that Manning's and Chezy's equation do not take into account the effects of viscosity on resistance if C and n are made purely functions of the type of surface over which the flow takes place. Hence the equations can be dependable only when viscous effects are negligible or when the boundary is hydrodynamically rough.

Strickler (1923) defined Manning's n as a function of particle size

$$n = \frac{d^{1/6}}{21}$$

where d represent the diameter in m of the uniform sand used in performing the study.

When the channel bottom is made up of non-uniform alluvial material under no motion condition, Meyer-Peter and Muller (1948), recommended that

$$K_s = d_{90}$$

While Einstein (1950) and Irmay (1949) recommended d_{65} and

maximum size of bed material respectively.

For flow in gravel and boulder rivers Manning or Chezy type equations cannot be used for low R/K_s values. Resistance law proposed by Thomson and Cambell (1979) is

$$V/V_* = 5.75 \left(1 - 0.45 \frac{d_{50}}{R}\right) \log \left(\frac{2.67R}{d_{50}}\right) \dots\dots 2.13$$

The total resistance in the general case of alluvial channel can be considered to be the sum of the grain resistance and the form resistance due to the bed undulations, but the size and shape of these undulations change greatly with changes in discharge.

To obtain the relationship between the mean velocity V , the depth y , or hydraulic radius R , Slope S and sediment size d , two different approaches for the problem of alluvial resistance can be mentioned

- 1) those which deal with the overall resistance offered to the flow using either a logarithmic or power type relationship for the mean velocity.
- 2) those in which the total resistance is separated into the grain resistance and the resistance of the undulations. Various equations under "Total Resistance Approach" are given below (Grade and Range Ragout 1985)

$$1) \quad \text{Lace} \quad : \quad V = 10.8 R^{2/3} S^{1/3}$$

$$2) \quad \text{Japanese Formula: } -\frac{V}{V_*} = 5.75 \log \left(-\frac{R}{K_s}\right) + 6.0$$

$$\log \left(\frac{K}{d} S \right) = 3.48 (1 - 0.225 \tau_*)^{-1/2}$$

$$\frac{K}{d} S = 10 \tau_*^{0.769}$$

where τ_* is dimensionless shear stress.

$$3) \text{ Liu-Hwang: } \left(\frac{V}{V_*}, S, \frac{V_* d}{\lambda}, -\frac{d}{R}, \tau_*, \frac{W_o d}{\lambda} \right) = 0$$

$$\text{Sugio : } V = k R^{0.54} S^{0.27}$$

$$k = 6.51 \text{ for ripples}$$

$$= 9.64 \text{ for dunes}$$

$$= 11.28 \text{ for transition regime.}$$

$$4) \text{ Garde - Ranga Raju:}$$

$$\frac{V}{\sqrt{\gamma_s d / \rho_f}} = k \left(\frac{R}{d} \right)^{2/3} \left(\frac{S}{\Delta \gamma_s / \gamma_f} \right)^{1/2}$$

$$k = 7.65 \text{ for ripples}$$

$$= 3.20 \text{ for dunes}$$

$$= 6.00 \text{ for transition}$$

A unique curve was obtained by plotting

$$\frac{k_1 V}{\sqrt{\gamma_s R / \rho_f}} \text{ against } k_2 (R/d)^{1/3} [S / (\Delta \gamma_s / \gamma_f)]$$

where k_1 and k_2 are, functions of sediment size.

These variations are shown in fig. 2.4 and 2.5

5) Brownlie's Method:

$$\frac{q}{\sqrt{gD^3}} = 4.57 \left(\frac{R}{D} \right)^{1.529} \frac{s^{0.389}}{\sigma^{0.161}} \quad \text{for ripple and dune regime}$$

$$= 7.51 \left(\frac{R}{d} \right)^{1.60} \frac{s^{0.46}}{\sigma^{0.128}} \quad \text{for Plane bed, standing waves and antidunes.}$$

Where q is the unit discharge and σ is the geometric standard deviation of the sediment.

In the above equations radius R has been used as the characteristic depth parameter. The use of this parameter is justified only when the roughness over the whole perimeter is the same. Such a situation can occur in a very wide channel with alluvial bed and banks. But in narrow channels and laboratory flumes which has vegetation on the banks, the resistance of the bed and banks will be different. In these case hydraulic radius of the bed R_b is commonly used.

Einstein (1942) suggested that the total area of such a channel may be divided into that corresponding to the bed (A_b)

and that corresponding to the sidewall (A_w) i.e.

$$A = A_w + A_b$$

Assuming that velocity is uniformly distributed over the whole cross section and using Manning's equation for the sides

$$V = \left(\frac{1}{n_w} \right) R_w^{2/3} S^{1/2} \quad \dots\dots (2.14)$$

For rectangular channel one can write

$$(b+2y) R = 2yR_w + bR_b$$

$$\text{or } R_b = \left(1 + \frac{2y}{b} \right) R - \frac{2y}{b} R_w$$

Thus R_b can be calculated

$$V = \frac{1}{n_b} (R_b)^{2/3} S^{1/2} \quad \dots\dots (2.15)$$

Einstein and Barbarossa (1952), were the first to propose a resistance relationship considering total resistance to be the sum of grain resistance and form resistance. Subsequently Engelund (1966), and Alam and Kennedy (1969) have also utilized this approach.

1. Einstein and Barbarossa Method: They divided the total resistance of the bed into resistance due to sand grains and resistance due to the bed formations, i.e.

$$\tau_o = \tau_o' + \tau_o'' \quad \dots\dots (2.16)$$

where τ'_0 and τ''_0 are the shear stresses corresponding to the grain and form resistance respectively. The above equation can be written as

$$\begin{aligned} \tau_f R_{bS} &= \tau_f R'_b S + \tau_f R''_b S \\ R_b &= R'_b + R''_b \end{aligned} \quad \text{.....(2.17)}$$

Where R'_b and R''_b are the hydraulic radius of the bed corresponding to grain and form resistances.

For a hydrodynamically, rough plane boundary, the Manning's roughness coefficient n' is given by strickler's equation

$$n' = \frac{d_{65}^{1/6}}{24}$$

Combining this with the Manning's equation

$$\frac{V}{V_*} = 7.66 \left(-\frac{R'_b}{d_{65}} \right)^{1/6}, \text{ where } R'_b \text{ is used as the hydraulic radius.}$$

$$\text{here } V_* = \sqrt{g R'_b S}$$

For the solution of the equations considering bed undulations they have given the solution in the form of graph as shown in Fig. 2.6, where

$$\frac{V}{V_*} = f(\psi')$$

in which
$$\psi' = \frac{\gamma_s - \gamma}{\gamma} \cdot \frac{d_{35}}{SR_b''}$$

For the value of V/V_* , R_b'' is calculated knowing the relation $V_*'' = \gamma R_{bs}''$.

Alam and Kennedy (1969) investigated the flume and river data and suggested a functional relation,

$$f'' = \phi \left(\frac{V}{\sqrt{gD_{50}}}, \frac{d_{50}}{R} \right)$$

where

$$f = f' + f''$$

$$s = s' + s''$$

$$f = \frac{8gRS}{V^2}$$

$$f' = \frac{8gRS'}{V^2}$$

$$f'' = \frac{8gRS''}{V^2}$$

By forming Fig. 2.7, f' can be obtained while f'' can be read from fig. 2.8.

Simons and Richardson (1967) suggested the following equations.

a. For a plane bed without sediment transport

$$\frac{C}{\sqrt{g}} = 5.9 \log \frac{Y}{d_{85}} + 5.44$$

- b. For a plane bed with sediment transport

$$\frac{C}{\sqrt{g}} = 7.4 \log \frac{y}{d_{85}}$$

- c. For ripples

$$\frac{C}{\sqrt{g}} = (7.66 - \frac{0.3}{V_*}) \log y + \frac{0.13}{V_*} + 11$$

- d. For dunes and antidunes

$$\frac{C}{\sqrt{g}} = 7.4 \log \frac{y}{d_{85}} \sqrt{1 - \frac{\Delta RS}{RS}}$$

The relation between ΔRS and RS is shown in fig. 2.9.

From the description of the various methods it appears that the methods based on separation of resistance may be considered to be rational.

TABLE 2.1 —Summary Description of Bed Forms and Configurations Affecting Alluvial Channel Roughness [Material Taken from ASCE (1966) Task Force on Bed Forms]

Bed form or configuration (1)	Dimensions (2)	Shape (3)	Behavior and occurrence (4)
Ripples	Wavelength less than approx 1 ft, height less than approx 0.1 ft.	Roughly triangular in profile, with gentle, slightly convex upstream slopes and downstream slopes nearly equal to the angle of repose. Generally short-crested and three-dimensional	Move downstream with velocity much less than that of the flow. Generally do not occur in sediments coarser than about 0.6 mm
Bars	Lengths comparable to the channel width. Height comparable to mean flow depth	Profile similar to ripples. Plan form variable	Four types of bars are distinguished: (1) Point; (2) alternating; (3) Transverse; and (4) Tributary. Ripples may occur on upstream slopes
Dunes	Wavelength and height greater than ripples but less than bars	Similar to ripples	Upstream slopes of dunes may be covered with ripples. Dunes migrate downstream in manner similar to ripples
Transition	Vary widely	Vary widely	A configuration consisting of a heterogeneous array of bed forms, primarily low-amplitude ripples and dunes interspersed with flat regions
Flat bed	—	—	A bed surface devoid of bed forms. May not occur for some ranges of depth and sand size
Antidunes	Wave length = $2\pi V^2/g$ (approx) ^a Height depends on depth and velocity of flow	Nearly sinusoidal in profile. Crest length comparable to wavelength	In phase with and strongly interact with gravity water-surface waves. May move upstream, downstream, or remain stationary, depending on properties of flow and sediment.

^aReported by Kennedy (1969).

TABLE 2.2

VARIATION OF DIFFERENT VARIABLES WITH REGIMES OF FLOW AND FORMS OF BED ROUGHNESS, SIMONS AND RICHARDSON
FLUME EXPERIMENTS (1971)

0.28 mm Sand							0.45 mm Sand				
	Forms of Bed Roughness	Total Load Concentra- tion (ppm)	f	n (ft ^{1/6})	F _r	Sx10 ²	Total Load Concentra- tion (ppm)	f	n (ft ^{1/6})	F _r	Sx10 ²
Lower Flow Regime	Plane Ripples	0	0.0301	0.016	0.17	0.011	0	0.0359	0.016	0.18	0.01
		1	0.0635	0.02	0.17	0.023	1	0.0521	0.020	0.14	0.01
	Dunes	to	to	to	to	to	to	to	to	to	to
		150	0.1025	0.027	0.37	0.11	100	0.1330	0.028	0.28	0.11
		150	0.0612	0.021	0.32	0.09	100	0.0489	0.019	0.28	0.06
		to	to	to	to	to	to	to	to	to	to
Transition		800	0.0791	0.026	0.44	0.16	1,200	0.1490	0.033	0.65	0.30
		1,000	0.0250	0.014	0.55	0.13	1,400	0.0415	0.016	0.61	0.37
		to	to	to	to	to	to	to	to	to	to
		2,400	0.0344	0.017	0.67	0.17	4,000	0.0798	0.022	0.92	0.49
Upper Flow Regime	Plane	1,500	0.0244	0.013	0.71	0.15					
		to	to	to	to	to					
		3,100	0.0262	0.014	0.92	0.28					
	Standing Waves						4,000	0.0200	0.011	1.0	0.36
							to	to	to	to	to
							7,000	0.0406	0.015	1.6	0.62
Upper Flow Regime	Antidunes	5,000	0.0281	0.014	1.0	0.33	6,000	0.0247	0.012	1.4	0.66
		to	to	to	to	to	to	to	to	to	to
		42,000	0.0672	0.022	1.3	1.0	15,000	0.0292	0.014	1.7	1.0

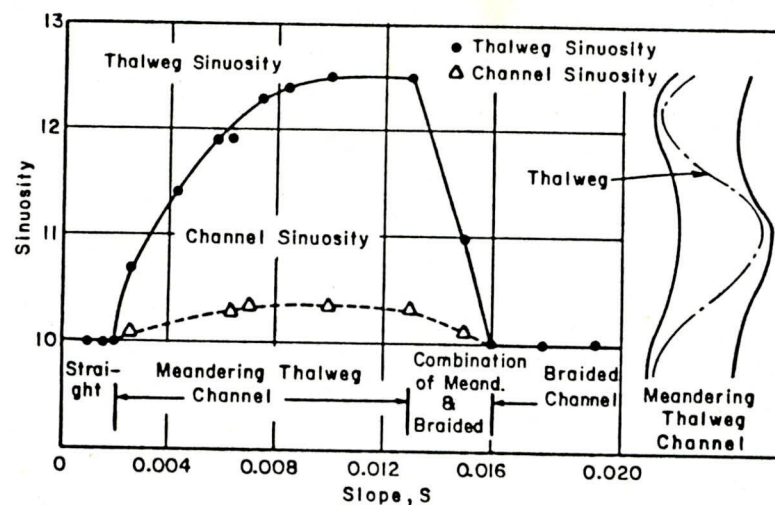
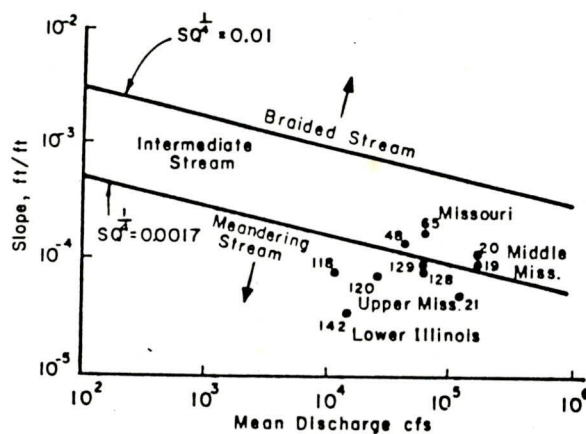


Fig. 2.1 Sinuosity versus slope for a constant discharge of 0.15 cfs (after Khan, 1971, Colorado State University).



Identification of Reaches Plotted

19 St. Louis to Chester	} Middle Mississippi	118 St. Paul to Redwing	} Upper Mississippi
20 Chester to Cape Girardeau		120 La Crosse to Lansing	
21 Ohio River		128 Hannibal to Louisiana	
48 Lower Arkansas River		129 Louisiana to Grafton	
65 Missouri River		142 Lower Illinois River	

Fig. 2.2 Slope-discharge relation for braiding or meandering in sand bed streams (after Lane, 1957).

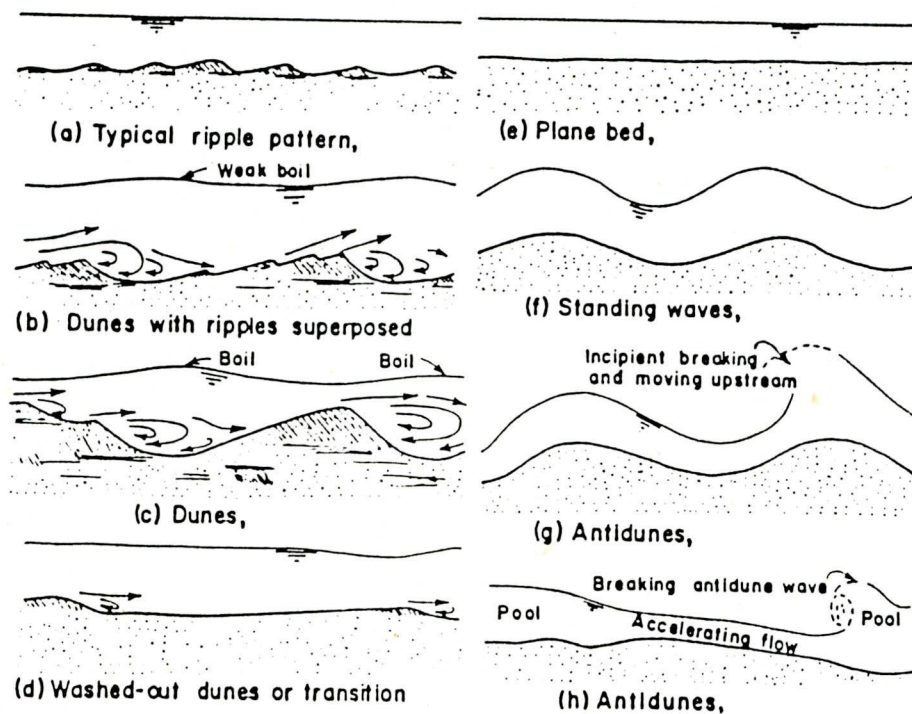


Fig. 2.3 Classification of bed-forms (after Simons and Richardson 1963).

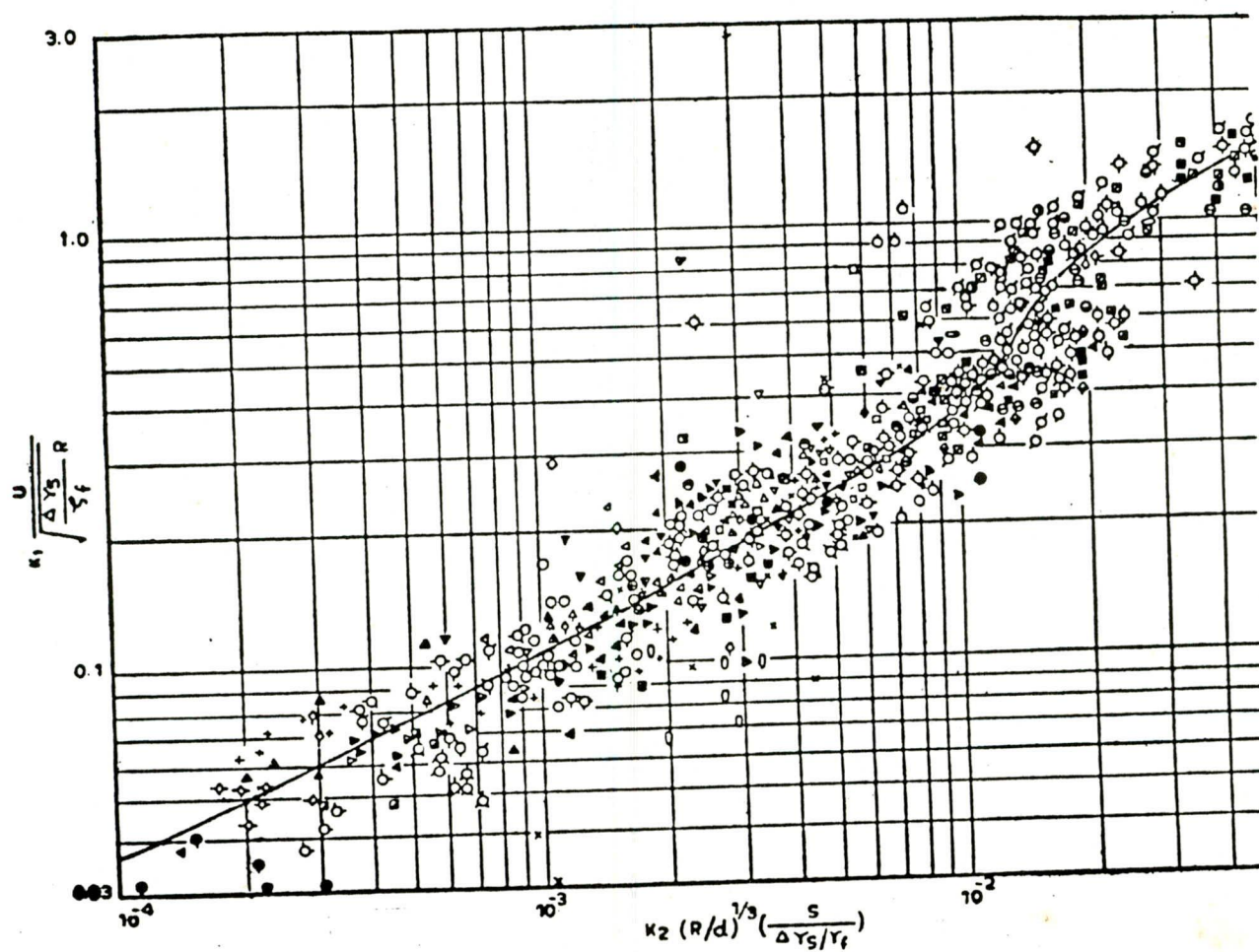


Fig 2.4 Resistance law for ripple and dune, transition and antidune regimes

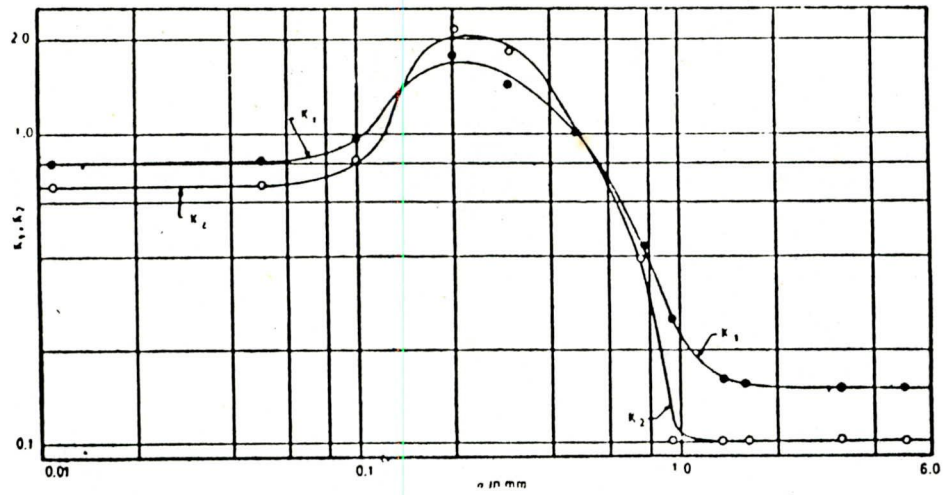


Fig. 2.5 Variation of K_1 and K_2 with sediment size

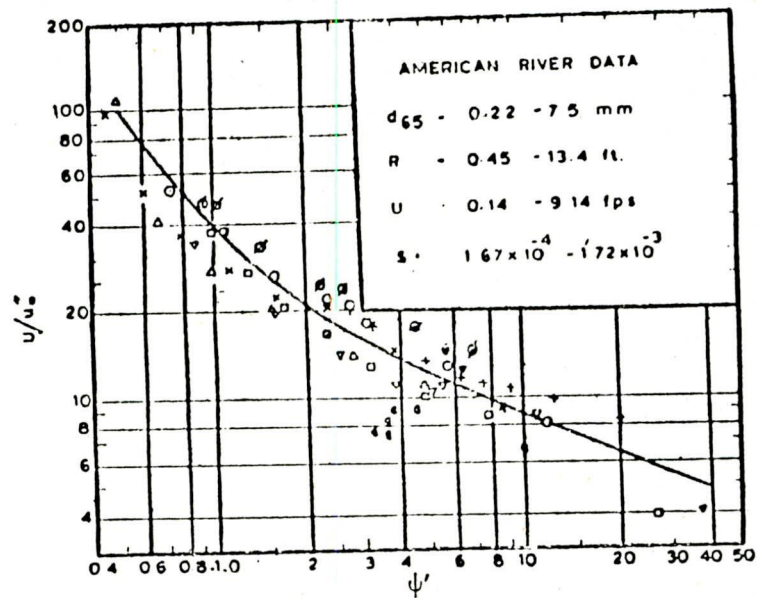


Fig. 2.6 Einstein-Barbarossa resistance relation based on river data
(1 ft = 0.305 m).

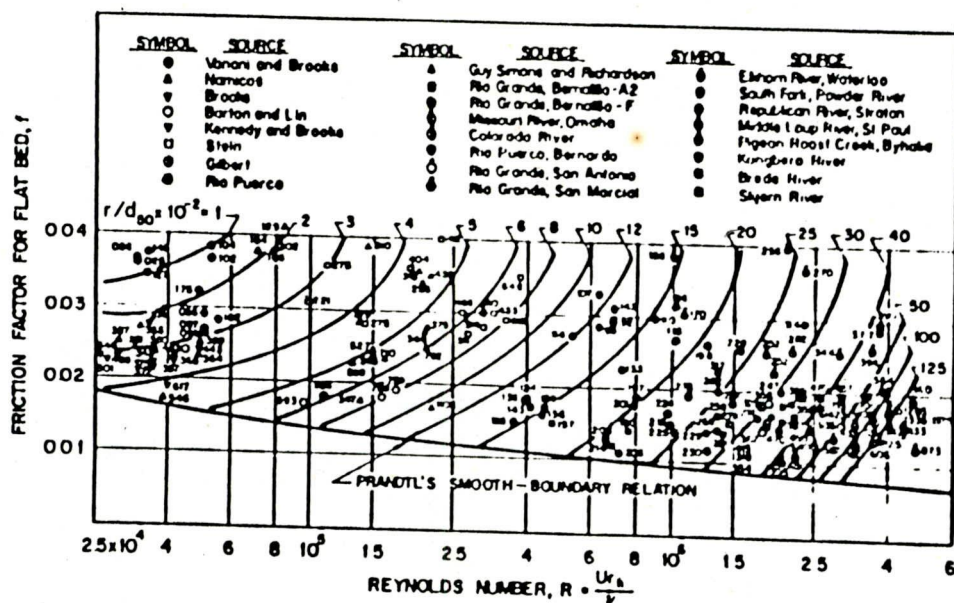


Fig. 2.7 Friction-factors for flat-bed flows in alluvial channels, the number by each point is $R/D_{50} \times 10^{-2}$ (after Lovera and Kennedy, 1969).

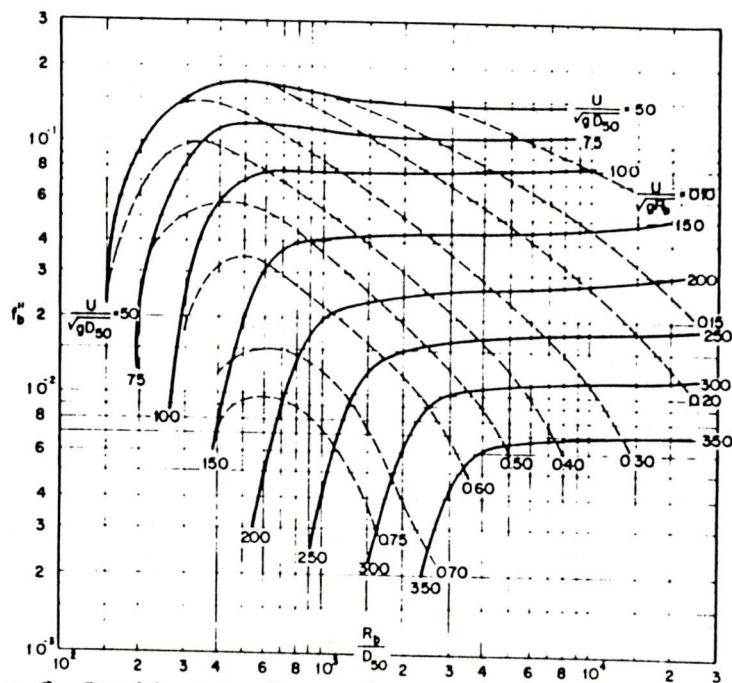


Fig. 2.8 Graphical predictor for the bed form friction factor (after Alan and Kennedy, 1969).

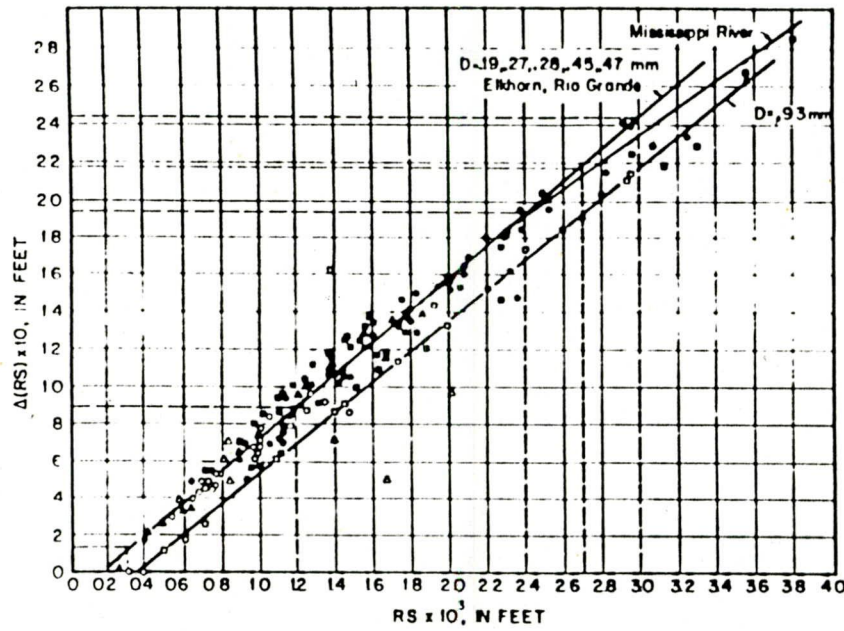


Fig. 2.9 Relation between ΔRS and RS for the dune-bed configuration. The symbols are Δ : 0.19 mm, $\circ$: 0.27 and 0.28 mm, $\triangle$: 0.45 mm, $\square$: 0.93 mm, $\odot$: Elkhorn River near Waterloo, Nebraska, $\bullet$: Rio Grande near Bernardo, New Mexico, $\blacksquare$: Mississippi River near St. Louis, Missouri (after Simons and Richardson, 1967).

CHAPTER 3

DIMENSIONAL ANALYSIS AND NON-DIMENSIONAL GROUPS

3.1 INTRODUCTION:

A principal purpose of scientific research in Engineering is the discovery of exact relationships that exists between various physical quantities. A physical quantity may be defined as anything which has an objective existence and which can be measured, and expressed in terms of numbers. When a physical system becomes too complicated then it is difficult to incorporate all the variables into mathematical equation. Hence analytical and empirical methods and techniques, to investigate the qualitative form of analysis has great importance. Though these methods do not give the complete answer to a problem but give the approximate solutions. Dimensional analysis is a guide in determining the grouping of the variables, grouping of variables can lead to a) reduction in numbers of variables (b) ease in finding inter-relationships which characterise the process and c) generalisation of the solution obtained. Such methods, which give systematic procedures for grouping variables, are called fractional analysis. These include dimensional analysis, method of similitude and normalisation of the governing differential equations of the three approaches, dimensional analysis has been developed to an appreciable extent. Dimensional analysis is a powerful tool in dealing with a complex problem, if it is

properly applied. The outcome of a dimensional analysis depends on the selection of variables. A meaningful and useful result can be expected only if each variable selected for the analysis has a physical significance pertinent to the problem involved. Dimensional analysis is a mathematical method of obtaining the equations governing certain natural phenomena by balancing the fundamental dimensions mass, length and time of the problem considered. Such a method can be applied to all types of flow resistance and in fluid mechanics. The non-dimensional constant is very important in engineering practice, as it enables the behaviour of problems of the same type to be predicted providing the linear dimensions are geometrically similar. Systematic organisation of the variables of a physical problem effectively reduce the number of unknown quantities and generalize a problem in a way that eliminates the need for specifying any particular system of units.

3.2 VARIOUS METHODS OF CONSTRUCTION OF NON-DIMENSIONAL GROUPS

Non-dimensional products may be obtained by various method. Barr (1983) has classified and critically compared the different procedures for dimensional analysis, namely:

- 1) Rayleigh's method
- 2) Buckingham's - π Theorem
- 3) Basic Stepwise method
- 4) Echelon matrix method; and
- 5) Proportionalities - Stepwise method.

Of these, the first four are involved the direct formulation of P-term non-dimensional functional equations.

The initial formulation in the fifth procedure is of an underlying (P+1) term functional equation of variables and products of common dimension. The Rayleigh and the Buckingham procedures were formulated by early of this century. Barr (1983) claimed that the newer methods are more secure in approaching indeterminate situations, when used in practice. Some of these methods are better for working towards a conventional form of non-dimensional arrangement while in others, there is a greater element of formal display of choice in arrangement.

3.3 COMPARATIVE ANALYSIS OF VARIOUS METHODS OF FORMULATION OF NON-DIMENSIONAL TERMS

3.3.1 Rayleighs method:

Lord Rayleigh (1915, after Barr 1968) proposed a method of dimensional analysis. The functional relationship is expressed in exponent form. For example, if Y is some function of independent variables, x_1, x_2, x_3 etc. the functional relationship can be written as

$$Y = \phi [x_1, x_2, x_3 \dots] \dots \dots \dots (3.1)$$

where ϕ indicates "a function of". The equation does not imply anything about the form of function.

Any function can be expressed as a series of terms each being made up of the product of variables brought to a suitable

powers as:

$$Y = K[x_1^a, x_2^b, x_3^c, \dots] \dots \dots (3.2)$$

Here K is a non-dimensional coefficient and can be determined either from physical characteristics of the problem or from experiments. The exponents a, b, c etc. are determined from the principle of dimensional homogeneity. According to the principle of dimensional homogeneity of the exponents of the dimensions on both side must be same. By equating the exponents on both sides, a set of simultaneous equation is obtained. The exponents can be determined by solving these simultaneous equations. Three simultaneous equations can be formed as there are three fundamental dimension. Some of the exponents can be obtained interms of others, if the number of exponents involved in the relationship is more than 3. The non-dimensional parameters are formed by grouping the variables with like exponent.

Example:

Let the thrust F of a screw propeller depends upon its diameter D , speed of advance V , mass density of fluid ρ , revolution of the propeller N , and viscosity of fluid μ .

According to Rayleigh's Method

$$F = \phi [D, V, \rho, N, \mu] \dots \dots (3.3)$$

or,

$$F = K [D^a V^b \rho^c N^d \mu^e] \dots \dots (3.4)$$

Writing the dimensions of the above equation

$$[MLT^{-2}] = K[(L)^a (LT^{-1})^b (ML^{-3})^c (T^{-1})^d (ML^{-1}T^{-1})^e] \dots (3.5)$$

Equating the exponents of M, L and T respectively on both sides of equation 3.5 dimensionally

$$1 = c + e \quad (3.6)$$

$$1 = a + b - 3c - e \quad (3.7)$$

$$-2 = -b - d - e \quad (3.8)$$

Solving these three equations we get

$$c = 1 - e$$

$$b = 2 - d - e$$

$$a = 1 - 2 + d + e + 3(1 - e) + e \quad (3.9)$$

$$= -1 + d + e + 3 - 3e + e$$

$$= 2 + d - e$$

Here we see that the exponents are expressed in terms of the other. As there are three equations and five unknowns substituting a, b, c in equation 3.4. We get

$$F = K [D^{2+d-e} V^{2-d-e} \rho^{1-e} N^d \mu^e] \quad (3.10)$$

$$= K D^2 V^2 \rho (DNV^{-1})^d (D^{-1} V^{-1} \rho^{-1} \mu)^e \quad (3.11)$$

$$= D^2 V^2 \rho \left(-\frac{\mu}{DV\rho}, \frac{DN}{V} \right) \quad (3.12)$$

$$\text{i.e.} \quad \left(-\frac{F}{D^2 V^2 \rho}, -\frac{DV\rho}{\mu}, \frac{DN}{V} \right) = 0 \quad (3.13)$$

where $a_1, b_1, c_1, \dots$ are constants to be determined.

The construction of an infinite series is a logically indispensable step in Rayleigh's method. Rayleigh's method becomes cumbersome when a large number of variables are involved.

3.3.2 Buckingham's π - theorem:

Buckingham's method absolves us from the indiscriminate use of infinite series. Buckingham's theorem stated that "If an equation is dimensionally homogenous, it can be reduced to a relationship among a complete set of dimensionless products. If n variables are connected by an unknown dimensionally homogeneous equation. Buckingham's theorem conclude that the equation can be expressed in the form of a relationship among $n-r$ dimensionless products, in which $n-r$ is the number of products in a complete set of dimensionless products of the variables. These dimensionless product is also known as π - terms and r is equal to the number of fundamental dimensions in the problem.

Each π - term contains r fundamental dimensions which are also called repeating variables and one-more variable of the remaining $(n-r)$ variables. Thus if x_1, x_2, x_3 are taken as repeating variables

$$\begin{aligned}\pi_1 &= x_1^{a_1} x_2^{b_1} x_3^{c_1} x_4 \\ \pi_2 &= x_1^{a_2} x_2^{b_2} x_3^{c_2} x_5\end{aligned}$$

$$\pi_{n-r} = x_1^{a_{n-r}} x_2^{b_{n-r}} x_3^{c_{n-r}} x_n$$

where $a_1, b_1, c_1, \dots$ are constants to be determined.

Following points should be considered for selection of r repeating variables

- 1) r repeating variables must contain jointly all fun-

damental dimension in the phenomena. However, if only two dimensions are involved, there will be two repeating variables and they must contain together the two dimensions involved.

2) The repeating variables must not form the non-dimensional parameters among themselves.

3) A geometrical property, a fluid property and a flow characteristics are generally most suitable as repeating variables.

The previous screw propeller problem is done by Buckingham's π -theorem as for example. The functional relationship can be written as:

$$\phi(F, D, V, \rho, N, \mu) = 0 \quad (3.14)$$

Let D , V , and ρ are repeating variables

Now according to the theorem

$$\pi_1 = D^{a_1} V^{b_1} \rho^{c_1} F \quad (3.15)$$

$$\pi_2 = D^{a_2} V^{b_2} \rho^{c_2} N \quad (3.16)$$

$$\pi_3 = D^{a_3} V^{b_3} \rho^{c_3} \mu \quad (3.17)$$

Writing the dimensions the above three equation can be written as

$$M^0 L^0 T^0 = (L)^{a_1} (LT^{-1})^{b_1} (ML^{-3})^{c_1} (MLT^{-2}) \quad (3.18)$$

$$M^0 L^0 T^0 = (L)^{a_2} (LT^{-1})^{b_2} (ML^{-3})^{c_2} (T^{-1}) \quad (3.19)$$

$$M^0 L^0 T^0 = (L)^{a_3} (LT^{-1})^{b_3} (ML^{-3})^{c_3} (ML^{-1}T^{-1}) \quad (3.20)$$

Now equating the exponents of M, L, T of the above three equations respectively we get, -

$$a_1, = -2, b_1 = -2, c_1 = -1 \quad (3.21)$$

$$a_2 = 1, b_2 = -1, c_2 = 0 \quad (3.22)$$

$$\text{and } a_3 = -1, \quad b_3 = -1, \quad c_3 = -1 \quad (3.23)$$

Now we can write

$$\pi_1 = D^{-2} V^{-2} \rho^{-1} F \quad (3.24)$$

$$\pi_2 = D^1 V^{-1} \rho^0 N \quad (3.25)$$

$$\pi_3 = D^{-1} V^{-1} \rho^{-1} \mu \quad (3.26)$$

$$\text{And finally } \phi \left(\frac{F}{D^2 V^2 \rho}, \frac{DN}{V}, \frac{\rho^{VD}}{\mu} \right) = 0 \quad (3.27)$$

3.3.3 Basic stepwise method

Bowman and Hansen outlined the stepwise approach without appreciating fully its potential advantages, as was pointed out to them by Macagno Ipsen terms it step by step and emphasised it in fallibility in avoiding the consequences of misinterpretation of rank. The step-by-step approach is effectively just an organized technique based on the notion of natural units. The easiest description of the approach is by an example. The variables that depends upon the thrust F of a screw propeller have the following dimensions:

$$F \quad \frac{ML}{T^2}$$

$$D \quad L$$

$$V \quad \frac{L}{T}$$

$$\rho \quad \frac{M}{L^3}$$

$$N \quad \frac{1}{T}$$

$$\mu \quad \frac{M}{LT}$$

$$F = f(D, V, \rho, N, \mu) \quad - \quad (3.28)$$

The procedure is now to rid the equation of each dimension in turn, F and by giving

$$\frac{F}{\rho} = f(\rho, V, D, N, \frac{\mu}{\rho}) \quad (3.29)$$

We have eliminated the dimension M from all terms excepting itself. From the equation 3.29 we see that cannot have a proper place since it is the only term involving the mass dimension. Therefore it follows that

$$\frac{F}{\rho} = f(V, D, N, \frac{\mu}{\rho}) \quad (3.30)$$

In analogous fashion, use V to eliminate the time dimension :

$$\begin{aligned} \frac{F}{\rho V^2} &= f(V, D, \frac{N}{V}, \frac{\mu}{\rho V}) \\ &= f(D, \frac{N}{V}, \frac{\mu}{\rho V}) \end{aligned} \quad (3.31)$$

Finally we use D to eliminate the length dimension

$$\begin{aligned} \frac{F}{\rho V^2 D^2} &= f(D, \frac{ND}{V}, \frac{\mu}{\rho VD}) \\ &= f(\frac{ND}{V}, \frac{\rho VD}{\mu}) \end{aligned} \quad (3.32)$$

3.3.4 Echelon matrix method:

There are three levels of complication in the obtaining of repeating variable solutions of dimensionally well set problems i.e. dealing with sets of variables which are dimensionally homogeneous, whether these are complete or incomplete or by containing more than one degree of redundancy, are over - complete from the view point of forming an equation.

The repeating variables and the rows can be ordered so as to give echelon formation in the dimensional matrix. The previously selected problem can be solved by a systematic and completely deterministic procedure: The dimensions of a chosen variables can be arranged in a dimensional matrix (Barr 1979). The initial assumption is

$$(F, V, D, \rho, \mu, N) = 0$$

Now meaningful dimension analysis largely depend on choice of repeating variables. Let D, V, and ρ as the repeating variables as the left hand side gives an echelon formation

	D	V	ρ	F	μ	N	
L	1	1	-3	1	-1	0	
T	0	-1	0	-2	-1	-1	(3.33)
M	0	0	1	1	1	0	

Now to obtain a unit matrix, for the repeating variables the dimensions of the three rows of the matrix are changed to

correspond with the base dimensions of the variables in the first three columns and finally we get the matrix as below

	D	V	ρ	F	μ	N	
(1) L	1	0	0	2	1	-1	
(1t ⁻¹)V	0	1	0	2	1	1	(3.34)
(ML ⁻³) ρ	0	0	1	1	1	0	

Now the non-dimensional functional equations can be abstracted from the 3.34 matrix, termed as solution matrix by balancing the non-repeating variables, written as numerator, with the repeating variables entered with the indicated exponents from solution matrix to form denominators as shown below:

$$\left(\frac{F}{D^2 V^2 \rho}, \frac{\mu}{D V \rho}, \frac{N D}{V} \right) = 0 \quad (3.35)$$

3.3.5 Proportionalities - stepwise procedure

Progression from Fourier's principle of Dimensional homogeneity by construction of proportionalities. Individual proportionalities can be derived from either a similitude or from a dimensional basis as follows (Barr 1971).

$$\text{Let } [a] = [A^d B^e] \quad (3.36)$$

$$[b] = [A^f B^g] \quad (3.37)$$

Where A and B are dimensions selected as appropriate for the expression of a and b and of which A has been chosen as the dimension of the desired proportionality. Then d,e,f,g are integers

positive or negative with further provision that d or f may be zero but not both. The square brackets indicates equality of dimensions.

Raising both sides of equation 3.37 to the e/g power

$$[b^{e/g}] = [A^{fe/g} B^e] \quad \dots\dots\dots (3.38)$$

Dividing each side of equation 3.38 by corresponding side of equation 3.36 gives

$$[a^{-1} b^{e/g}] = [A^{fe/g-d}] \quad \dots\dots\dots (3.39)$$

$$\text{or } A = a^{-1/[fe/g-d]} b^{(e/g)/[(fe/g-d)]} \quad (3.40)$$

The previous screw propeller problem provides a good illustration of the proportionality approach

$$\phi(F, V, D, \rho, \mu, N) = 0$$

$$\text{or } \phi\left(-\frac{F}{\rho}, D, V, N, -\frac{\mu}{\rho}, g\right) = 0$$

$$L^4 T^{-2}, L, L T^{-1}, T^{-1}, L^2 T^{-1}, L T^{-2}$$

$$\text{From (1) and (2) } -\frac{F}{\rho V^2} \leftrightarrow \frac{L^4 T^{-2}}{L^2 T^{-2}} \rightarrow L^2 \therefore -\frac{F^{1/2}}{\rho^{1/2} V}$$

$$\cong L \quad [\cong \text{ indicates dimensionally equal}]$$

$$(2) \ \& \ (3) \quad -\frac{V}{N} \leftrightarrow -\frac{L T^{-1}}{T^{-1}} \rightarrow L \quad \therefore \frac{V}{N} \cong L$$

$$(2) \ \& \ (4) \quad -\frac{\mu}{\rho V} \leftrightarrow -\frac{L^2 T^{-1}}{L T^{-1}} \rightarrow L \quad \frac{\mu}{\rho V} \cong L$$

$$(2) \ \& \ (5) \quad -\frac{g}{V^2} \longleftrightarrow \frac{LT^{-2}}{L^2T^{-2}} \longrightarrow -\frac{1}{L} \quad \therefore -\frac{V^2}{g} = L$$

$$\phi \left(D, -\frac{F^{1/2}}{\rho^{1/2}V}, -\frac{V}{N}, -\frac{\mu}{\rho V}, -\frac{V^2}{g} \right) = 0 \quad (3.41)$$

$$\text{or } \phi = \left(\frac{F}{\rho V^2 D^2}, -\frac{V}{ND}, -\frac{VD}{2}, -\frac{Dg}{V^2} \right) = 0 \quad (3.42)$$

Barr (1971) has applied the potential uses of proportionalities method through the display of full choice of arrangements considering the case of resistance to turbulent flow in rough pipe.

Proportionalities stepwise procedure falls within the mainstream development of dimensional analysis following from Fourier's Principle of Dimensional Homogeneity. The proportionalities-stepwise procedure correctly rejects as dimensionally inhomogeneous certain sets of individual variables which apparently can be treated by P-term procedures. These cases can arise where two pairs of variables, each pair of the same dimension, are considered. For the example treated, there has often been an unrecognised and physical explanation why the final conclusion is correct and why one of the pairs of variables are convert representation of alternative variables of the same dimension as the other pair as is required for homogeneity. For the P-term procedures, such error is most likely to be noted if

the echelon matrix is formed. In this regard, even for well-set problems there has been shown to be advantage in always forming an echelon matrix as a first step, however, further progress is to be achieved. Setting aside the pitfall of lack of linear independence as an infrequent occurrence, any cases where the repeating variables do not form natural echelon are thereby made more manageable by either the Rayleigh's, the Buckingham or the stepwise procedures, provided advantage is taken of the information conveyed by the echelon matrix. The proportionalities-stepwise procedure has been found to be the most helpful, because of its flexibility and its overt physical basis. Other methods of construction of non-dimensional groups have been reported by Kline (1965). They are partially overlapping methods of forming non-dimensional groups. These are

- i. The method of dimension
- ii. The method of similitude
- iii. The normalisation of the already established governing equations to a form which is expressed in terms of the appropriate non-dimensional products (inspectional where the analysis). The $(n+1)$ term equation have been deduced by a similitude argument (Barr 1968).

Moreover, Barr (1969, 1971) has introduced a procedure for formulation of non-dimensional groups known as the method of synthesis. be any form of measure of effective action, e.g. force, velocity, acceleration, time, length etc. Choice of

The method of dimension has already been discussed and the method of similitude has been quite intermittent. But the third method "by Inspection" is quite distinct from conventional methods of dimensional analysis. It involves the arbitrary grouping of dimensional variables to non-dimensional products by "Cut and try" approach. This method was successfully utilized by Rayleigh in his pioneering development of dimensional reasoning. Dimensional analysis and method of similitude gives an incomplete answer and in general, the end result of both is a dimensionless functional equations suitable for planning experimental studies or designing hydraulic models. Dimensional analysis is more directed primarily towards experimentation, and similitude method and similarity theory are more concentrated on developing model laws from which dimensionless functional equation may be derived.

3.4 METHOD OF SYNTHESIS:

The method of synthesis is best defined as a procedure for the formulation of non-dimensional functional equation in n terms from dimensionally homogeneous equation in $(n+1)$ terms and where the components of the $(n+1)$ term equation have been deduced by a similitude argument (Barr 1968).

The method can be regarded as a bridge between dimensional and similitude analysis. The term forming the dimensional equation could be any form of measure of effective action, e.g. force, velocity, acceleration, time, length etc. Choice of

appropriate measure of the effective actions depends to a great extent on the nature of the problem to be solved.

3.4.1 Potential dynamic velocity method:

For determining relationships the concept of potential dynamic velocities has recently been introduced by D.I.H. Barr. The approach appears to be a very promising one, with the allowance for the physical character of the phenomenon, the physical quantities characterizing the phenomenon have been combined by Barr into quantities having the dimension of velocity, referred to as potential dynamic velocities, which being independent, are suitable for determining any particular quantity involved in the phenomenon. A corresponding method has been developed by the author for potential dynamic accelerations and potential dynamic lengths as well. The use of potential dynamic velocities entails a number of advantages. In fact, velocity may be regarded as the kinematic quantity most characteristic of phenomena related to movement. The selection of velocities will be justified in sediment transportation or in any other hydraulic problem if the quantities to be determined are the ensuing velocities. In fluid mechanics the shear velocity, $V_* = \sqrt{gHS}$, is one of the potential dynamic velocity.

The variables dealing with the alluvial channel geometry and sediment transportation can be described by the following important physical quantities:

$$Q, H, B, d_{50}, \gamma, g, S_g, C \quad (3.42)$$

Using these physical quantities, adopted at the start, a method resembling dimensional analysis may be applied for determining the independent parameters of velocity dimension which will, naturally, be the potential dynamic velocities. By combining the above quantities the following potential dynamic velocities are obtained

$$\sqrt{gH}, \sqrt{gB}, \sqrt{gd_{50}}, \Delta/H, \Delta/B, \sqrt{gHS} \quad (3.43)$$

The above equation can be written in non-dimensional form by dividing the velocities in Eq. 3.43 by $\sqrt{gH}$ and introducing the charge C ,

$$\frac{B}{H}, \frac{D_{50}}{H}, \frac{\Delta}{H^{3/2}g^{1/2}}, \frac{\Delta}{B\sqrt{gH}}, S, C \quad 3.44$$

Equation 3.43 may also be written in non-dimensional form with the introduction of additional velocity term, V and V_* ;

$$\frac{V}{\sqrt{gHS}}, \frac{V}{\sqrt{gD_{50}S}}, \frac{V}{\sqrt{gH}}, \frac{V_*}{\sqrt{gD_{50}}}, \frac{B}{H}, \frac{H}{D_{50}}, C \quad 3.45$$

This Eq. can be written in a functional form as

$$\left(\frac{V}{\sqrt{gHS}}, \frac{V}{\sqrt{gD_{50}S}}, \frac{V}{\sqrt{gH}}, \frac{V_*}{\sqrt{gD_{50}}}, \frac{B}{H}, \frac{H}{D_{50}}, C \right) = 0 \quad (3.46)$$

Assuming the volume of flow per unit width q . The resulting flow characteristics required i.e. replacing V by q the dynamic form of flow per unit width has dimension of velocity time length. So

eq. (3.46) can be expressed as

$$\left(\frac{Q}{H\sqrt{gHS}}, \frac{V}{\sqrt{gD_{50}S}}, \frac{V}{\sqrt{gH}}, \frac{V^*}{\sqrt{gD_{50}}}, \frac{B}{H}, \frac{H}{D_{50}}, C \right) = 0 \quad (3.47)$$

Linear proportionalities

Application of the method of dynamic velocities to a number of problems showed evidence of difficulties and a change was introduced to use linear measures. These measures are called linear proportionalities.

In the linear proportionality method two or three terms having other than linear dimensions are combined to produce linear dimension. For example a problem of fluid flow governed by μ , ρ and g . The dimensions of μ , ρ and g in terms of M, L, T system are respectively

$$ML^{-1}T^{-1}, \quad ML^{-3} \text{ and } LT^{-2}. \text{ So } \frac{\mu}{\rho} = L^2T^{-1} \text{ and } \left(\frac{\mu}{\rho} \right)^2 \frac{1}{g} = L^3,$$

Therefore, $\left[\left(\frac{(\mu/\rho)^2}{g} \right) \right]^{1/3} = L$ i.e. a linear proportionality.

The variables dealing with the alluvial channel geometry are $Q, Q_s, B, H, g, S, d_{50}, Sg$ (3.48)

The resulting linear proportionalities are

$$\frac{Q^{2/5}}{g^{1/5}}, \frac{Q^{2/5}}{(Sg)^{1/5}}, \frac{Q_b^{2/5}}{(Sg)^{1/5}}, \frac{Q}{S}, \left(\frac{Q}{BH\sqrt{g}} \right)^2, \frac{gHS}{g} \quad (3.49)$$

Combining these terms with those defining the system geometry to form linear functional equation, we get

$$(H, B, d_{50}, \frac{Q^{2/5}}{g^{1/5}}, \frac{Q^{2/5}}{(Sg)^{1/5}}, \frac{Q_b^{2/5}}{(Sg)^{1/5}}, \frac{Q}{S}, \frac{gHS}{g}, \left(\frac{Q}{BH\sqrt{g}} \right)^2) = 0 \quad (3.50)$$

which gives

$$\left(\frac{B}{H}, \frac{H}{D_{50}}, \frac{Q^{2/5}}{(Sg)^{1/5} H}, \frac{Q_b}{Q}, \frac{Q}{B}, \frac{Q^{2/5}}{(Sg)^{1/5} D_{50}}, \frac{\sqrt{gHS}}{\sqrt{gD_{50}}}, \frac{Q}{BH\sqrt{gH}} \right) = 0 \quad (3.51)$$

Now in convenient form and replacing Q_b/Q by C , one non-dimensional equation may be written as:

$$\left(\frac{B}{H}, \frac{H}{D_{50}}, \frac{Q^{2/5}}{H(Sg)^{1/5}}, C, \frac{Q}{B}, \frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}, \frac{V_*}{\sqrt{gD_{50}}}, \frac{V}{\sqrt{gH}} \right) = 0 \quad (3.52)$$

All these non dimensional parameters have been used in this study to develop correlation in the water courses of alluvium. The method of synthesis has also been taken up by many investigators (Herbertson 1969, Hawez 1977, Hossain 1985, Bogardi 1974).

3.5 Previous studies of alluvial channel geometry using non-dimensional parameters:

Barr and Herbertson (1968a) applied the synthesis approach of Barr (1968-1970) to obtain the following non-dimensional terms:

$$\left[S, H/D, B/D, \frac{Q^{2/5}}{g^{1/5} D}, \frac{Q_S}{Q}, \frac{Qg^{1/5}}{g^{5/3} D}, \frac{2/3}{g^{5/3} D}, T, \frac{\rho_s}{\rho} \right] = 0 \quad (3.53)$$

For constant T, ρ, ρ_s and g El.Nur(1971) rewrote equation 3.53 as follows:

$$\phi \left(\frac{S}{Q^{2/5} g^{1/5} H} \right), \frac{B}{H}, \frac{Q_s}{Q}, \frac{g^{2/3}}{g^{1/5} D} = 0 \quad (3.54)$$

El Nur (after Nishat 1981) obtained graphical plots of the trapezoidal data for various, side slopes and argued that there is no apparent effect due to side slope variation on the geometry relations i.e. equations involving B, H and Q while increase in side slope leads to an increase in the bed slope. Alam (1977) reiterated this observation.

El Nur (after Nishat 1981) obtained geometry equation as

$$\frac{Q^{2/5}}{g^{1/5} H} = 0.30 C^{0.1} \left[\frac{g^{1/3} D}{g^{2/3}} \right]^{0.16} \left[\frac{B}{H} \right]^{0.35} \quad (3.55)$$

His slope equation (for rectangular channels) is given

$$\left[\frac{g^{1/3} Q^{5/3}}{\log\left(-\frac{1}{S}\right)} \right]^{0.065} = 1.2 C^{0.075} \left[\frac{g^{1/3} D}{g^{2/3}} \right]^{0.1} \left[\frac{B}{H} \right]^{0.1} \quad (3.56)$$

He recognized the situation of mutual adjustment of channel dimensions i.e. depth width and slope.

Alam (after Nishat 1981) directed his study towards the interdependence and mutual adjustment of channel parameters and suggested that non-dimensional plot of $g^{1/5} H / Q^{2/5}$ Vs $g^{1/5} B / Q^{2/5}$ indicates a log normal correlation between depth and width. Alam (after Nishat 1981) added some field and laboratory data to the strathclyde data and obtained the following equation

$$g^{1/5}H/Q^{2/5} = 0.772 [g^{1/5}B/Q^{2/5}]^{-0.0308} \quad - \quad (3.57)$$

His slope equations are

$$1000 H^P S = \frac{-0.57}{n} c^n \quad \text{for rectangular channel} \quad (3.58a)$$

$$1000 H^P S = \frac{-0.713}{n} c^n \quad \text{for } \frac{1}{2} : 1 \text{ channel} \quad (3.58b)$$

$$1000 H^P S = \frac{-0.245}{n} c^n \quad \text{for } 1 : 1 \text{ channel} \quad (3.58c)$$

$$1000 H^P S = \frac{0.27}{n} c^n \quad \text{for } 2:1 \text{ channel} \quad (3.58d)$$

$$P = 0.425 + 0.278T \quad (3.58e)$$

$$n = 0.9(d_{50})^{3/5} \quad (3.58f)$$

Banaga (after Nishat 1981) had previously obtained the following empirical equation using Strathclyde data

$$\left(\frac{B}{Q^{2/5}} + 1.0 \right) \left(\frac{10H}{Q^{2/5}} \right)^{\frac{1}{0.935}} = 14.5 \quad (3.59)$$

Nishat (1981) plotted the trapezoidal flume data on the basis of

non-dimensional breadth parameter $g^{1/5}B/Q^{2/5}$, against the depth parameter $g^{1/5}H/Q^{2/5}$ in a semi logarithmic papers. He obtained strong correlation between non-dimensional depth, non-dimensional width and Froude number. An overall correlation was obtained as

$$Y = A \exp(-Zx) \quad (3.60a)$$

with the non-dimensional linear measures defined as

$$Y = g^{1/5}H/Q^{2/5}$$

$$X = g^{1/5}B/Q^{2/5}$$

where A and Z are functions of Froude Number F, defined as

$$A = C_1 \exp(-K_1 F^a) \quad (3.60b)$$

$$Z = C_2 \exp(K_2 F) \quad (3.60c)$$

The values of the coefficients and indices were calculated as follows:

$$C_1 = 28.0, C_2 = 0.032, K_1 = 3.8, K_2 = 1.84 \text{ and } a = 0.1$$

Nishat (1981) used the channel data having B/H ratio greater than 5.0.

Howez (1977) obtained a good correlation, between non-dimensional parameter B/H and $Q^{2/5}/H(Sg)^{2/5}$ for a constant charge

of 800 PPM and a constant sediment size with dune covering the bed. However, his study was limited to the extent of being concerned with Strathclyde data only. The relationship developed are as follows:

$$Q_c = [(A_1 + A_2 - \frac{B}{H}) (H(Sg)^{1/5})]^{5/2} \quad (3.61)$$

Where Q_c is the calculated water discharge, A_1 , A_2 are constants for each individual channel and are defined as follows:

$$A_1 = 0.13 + 5.35T - 1.868T^2 \quad (3.62a)$$

$$A_2 = 1.0 / (0.208 + 9.8T - 3.044T^2) \quad (3.62b)$$

Where T is the side slope of the channels.

Hossain (1984) reanalyzed the above approach with the added Strathclyde data. It has been argued that the side slope in most natural channels are unknown factor and any empirical estimation of this would introduce controversy and often ambiguity without adding appreciable advantage and accuracy. Besides this determination of the constants A_1 and A_2 from equation (3.62) is cumbersome. Hossain (1985) decided to replace A_1 and A_2 with suitable numerical constant that would allow for the effects of side slope and other factors. Thus A_1 was replaced by 2.15 and A_2 by 0.205 and a final equation were obtained as follows:

$$Q_c = [(2.15 + 0.205 - \frac{B}{H}) H \times (Sg)^{1/5}]^{5/2} \quad (3.63)$$

CHAPTER 4

COMPILATION OF DATA

4.1 INTRODUCTION:

Wide Range of laboratory and field data are used in developing correlation between non-dimensional parameters which govern river geometry. Laboratory data are used to develop functional equation adopting the non-dimensional parameters. In most of the laboratory data sediment load and width are fixed by the investigator and discharge, sediment characteristics are recorded and measured depth, slope, temperature and bed form. In most of the laboratory flume, discharge is maintained at a steady level and a prolonged running often leads to a self-formed equilibrium dimension. In the laboratory data reliable observations are available for discharge, slope, depth, width and bed material size but sediment load has seldom been correctly measured or recorded.

Natural flow phenomenon are extremely complex. In the natural channel discharge and sediment load are invariably unsteady for a longer term. Thus there is always changing sequences of erosion and deposition of the alluvium which change the alluvial river pattern and position. Except this the collection of field data is often a difficult and painstaking procedure. The main problem in

river data is the determination of the flow for which corresponding values of depth, width, slope, etc. will be measured. The geometry of channels flowing in alluvium is principally dependent on the magnitude of discharge. Despite complexities, observations considered reliable are commonly used in testing the validity of the functional equation which is developed primarily by using laboratory data. In developing functional equation the numerical constants and exponents are analytically derived.

Peterson and Howell (1973) collected a large volume of alluvial channel data for both laboratory and field conditions. The effort includes corrections of errors in the earlier compendium, omission of inappropriate entries, and the addition of approximately 2500 new records. The data collection of Peterson and Howells is essentially an update of the data collection of Johnson (1943). Later Peterson and Howell (1978) added more data and published an uptodated compendium consisting a total of 6606 sets of data records.

Before any data set can be used with total satisfaction, all errors must be eliminated. Four types of errors were identified in the Peterson and Howells (1973, 1978) compendium by Brownlie (1981).

These includes:

- 1) Incorrect individual entries - these entries usually have incorrectly ordered digits or misplaced decimal points.
- 2) Conversion error - errors made in converting the data to a standard format, typically involving conversion of

transport rates to sediment concentration.

- 3) Misinterpretation of data: this error usually involved whole columns of data, and probably occurred as a result of confusing notation in the data source.
- 4) Source error: errors originating from incorrect original publication of data, discovered by checks on internal consistency.

In the development of a new data base from the Peterson and Howells, compendium, a few sets of data were omitted, because the data were not applicable or because of missing important variables. On the other hand a large quantity of field data were added. Brownlie's (1981) final data base contains 7027 records in 77 data files of which 5263 sets were laboratory data and 1,764 sets were field data.

Brownlie (1981) had used a format similar to the format used by Peterson and Howells (1978) in his data bank. Information about the data bank are as follows:

Discharge	Water discharge in liters per second.
Width	Channel width in meters, taken as the top width for field channels, unless only a portion of the cross section was measured, in which case the width of the measured area is given.
Slope	Energy slope times 1000.
D ₅₀	Medium particle size of the bed material in millimeters.

Gradation	Geometric standard deviation of bed particle size, $0.5(D_{85})/D_{50} + D_{50}/D_{16}$
Spec.Grav.	Specific gravity of bed particles.
Conc.	Concentration of the bed-material load (does not include wash load) in ppm by mass
B F	Bed Form, according to the definition given in Vanoni (1975), given by the Code
	0 Not observed
	1 Plane bed near or before initiation of motion
	2 Ripples
	3 Dunes
	4 Transition
	5 Plane bed
	6 Standing waves
	7 Antidunes
	8 Chute - Pool

4.2 SOURCES OF DATA: Data sources are given in a tabular form (Brownlie 1981)

Table 4.1 and 4.2 summarizes the compilation of the data bank for laboratory and field data respectively. Data from this data bank, used in this study for the development of correlations and their verifications are shown in Table 4.3

TABLE 4.1
SUMMARY OF DATA BANK

LIST OF INVESTIGATORS FOR LABORATORY DATA:

Sl.No.	Data Code	No.of Records	Investigator(s)
1.	OBOE	10	Abdel - Aal, F.M. (1969)
2.	BAL	28	Barton, J.R., Lin. P.N. (1955)
3.	BEN	18	Government of West Bengal (1965)
4.	BOY	48	Bogardi, J., Yen. C.H (1936)
5.	BRO	21	Brooks, N.H., (1957)
6.	CAS	92	Casey, H.J. (1935)
7.	CHY	32	Chyn, S.D (1935)
8.	COS	28	Costello, W.R. (1974)
9.	DAV	79	Davies, T.R. (1971)
10.	EAC	16	Einstein, H.A., Chien, N. (1955) _
11.	EPA	68	E. Pakistan Water and Power (1967)
12.	EPB	56	Govt. of E. Pakistan (1966, 1968, 1969)
13.	FOL	12	Foley, M. (1975)
14.	FRA	19	Franco J.J. (1968)
15.	GIB	9	Gibbs, C.H. Niell, C.R. (1972)
16.	GIL	889	Gilbert, G.K. (1914)
17.	GKA	125	Gilbert, G.K. (1914), Energy Slope

Table 4.1 Contd.

Sl.No.	Data Code	No. of Records	Investigators
18.	GKB	62	Gilbert,G.k.(1914),Uniform flows
19.	GUY	339	Guy,H.P., et al. (1966)
20.	HIL	46	Hill,H.M., et al. (1969)
21.	HPY	80	HO, P. (1939)
22.	JOR	26	Jorissen,A.N.,(1938)
23.	KAH	9	Kalinske,A.Hsia,C.(1945)
24.	KAL	23	Kalinske, G. (1957)
25.	KEN	41	Kennedy, J.F. (1961)
26.	KNB	9	Kennedy,J.F.,Brooks,N.H.(1965)
27.	LAU	24	Laursen,E.M. (1958)
28.	MAV	293	Mavis,F.T. et al. (1937)
29.	MCD	74	MacDougal, C.H. (1933)
30.	MPR	135	Meyer-Peter,E.Muller,R.(1948)
31.	MUT	28	Mutter,D.G (1971)
32.	NEI	51	Neill, C.R. (1967)
33.	NOM	30	Nomicos G. (1957)
34.	NOR	62	Nordin, C.F. (1976)
35.	OBR	83	O,Brien, M.P. (1936)
36.	OJR	14	Onishi, Y. et al. (1972)
37.	PAI	96	Paintal, A.S. (1971)

Table 4.1 Contd.

Sl.No.	Data Code	No. of Records	Investigators
38.	PRA	60	Pralt, C.J. (1970)
39.	SAT	243	Sato, S., et al. (1958)
40.	SIN	305	Singh, B. (1960)
41.	SON	23	Soni, J.P. (1980)
42.	STE	56	Stein, R.A. (1965)
43.	STR	24	Straub, L.G. (1954, 1958)
44.	TAY	39	Taylor, B.D. (1971)
45.	VAB	15	Vanoni, V.A., Brooks, N.H. (1957)
46.	VAH	16	Vanoni, V.A., Hwang, L.S. (1965)
47.	WIL	31	Willis, J.C. (1979)
48.	WLM	177	Williams, G.P. (1970)
49.	WLS	96	Willis, J.C. et al. (1972)
50.	WSA	330	US Waterways Exp. Sta. (1935A)
51.	WSB	102	US Waterways Exp. Sta. (1936A)
52.	WSL	298	US Waterways Exp. Sta. (1936C)
53.	WSS	313	US Waterways Exp. Sta. (1936B)
54.	WTT	23	US Waterways Exp. Sta. (1935B)
55.	ZNA	36	Znamenskaya, N.S. (1963)

TABLE 4.2

FIELD DATA

Sl.No.	Data Code	No. of Records	Investigator(s)
1	ACP	151	ACOP data of Mahmood et al (1979)
2	AMC	11	American Canal data of Simons(1957)
3.	ATC	72	Atchafalaya River Data of Toffaleti (1968)
4.	CHI	32	Indian Canal Data Published by Chitale (1966)
5.	CHO/CHP	33	India Canal Data of Chaudry et al. (1970)
6.	COL	131	Colorado R. Data of the U.S. Bureau of Reclamation (1958)
7.	HII	38	Hii River data of Shinohara and Tsubaki (1959)
8.	LEO	72	River Data of Leopold (1969)
9.	MID	38	Middle loup River Data of Hubbell and Matejka (1959)
10.	MIS	165	Mississippi River Data of Toffaleti (1968)

Table 4.2 Contd.

Sl.No.	Data Code	No. of Records	Investigators
11.	MOR	25	Missouri River Data of Shen et al. (1978)
12.	MOU	100	Mountain Greek Data of Einstein (1944)
13.	NED	113	Rio Magdalena and Canal Del Dique Data of NEDECO (1973)
14.	NIO	40	Niobrara River Data of Colby and Hembree (1955)
15.	NSR	55	N. Saskatchewan R. and Elbow R. Data of Samide (1971)
16.	OAK	17	Oak Creek Data of Milhous (1969)
17.	POR	219	Portugal River Data of Dac Cunha (1973)
18.	RED	30	Red River Data of Toffaleti (1968)
19.	RGC	33	Rio Grande Conveyance Channel Data of Culbertson et al. (1976)
20.	RGR	293	Rio Grande Data of Nordin and Beverage (1965)

Table 4.2 Contd.

Sl.No.	Data Code	No. of Records	Investigators
21.	RIO	38	Rio Grand near Bernalillo data given by Toffaleti (1968)
22.	SNR	21	Snake and Cleanwater River Data of Selitz (1976)
23.	TRI	4	Trinity River Data of Knott(1974)

TABLE 4.3

Data used for the Development of Correlation and Verification
of the Developed Correlation

(The first number within the parenthesis indicates the
laboratory data and the second number indicates the field data).

Correlation Parameters	Overall Concentration Range	Overall Flow Froude Number Range	Overall Particle Froude Number Range
$\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$	(100-10000)ppm (670,892)	0.2 - 0.8 (670,505)	0.4 - 1.3 (492,435)
$\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$	-	0.2 - 0.8 (670,505)	-

CHAPTER 5

METHODOLOGY

5.1 DEVELOPMENT OF NON-DIMENSIONAL PARAMETERS:

As a first step in this study simple and dimensionally homogeneous expressions was developed for the assessment of alluvial river geometry. Method of synthesis was used to form the non-dimensional parameters by taking into consideration the important variables that govern alluvial river geometry.

The variables dealing with the alluvial channel geometry are

$$Q, Q_s, B, H, g, S, D_{50}, S_g$$

The resulting linear proportionalities from the above variables, derivation of which has been discussed in section 3.4, are

$$\frac{Q^{2/5}}{g^{1/5}}, \frac{Q^{2/5}}{(S_g)^{1/5}}, \frac{Q_b^{2/5}}{(S_g)^{1/5}}, \frac{Q}{S}, \left(\frac{Q}{BH\sqrt{g}}\right)^2, \frac{gHS}{g} \quad 5.1$$

Combining these terms with those defining the system geometry to form linear functional equation, we get

$$\phi \left(H, B, D_{50}, \frac{Q^{2/5}}{g^{1/5}}, \frac{Q^{2/5}}{(S_g)^{1/5}}, \frac{Q_b^{2/5}}{(S_g)^{1/5}}, \frac{Q}{S}, \frac{gHS}{g}, \left(\frac{Q}{BH\sqrt{g}}\right)^2 \right) = 0 \quad 5.2$$

which gives

$$\left(\frac{B}{H}, \frac{H}{D_{50}}, \frac{Q^{2/5}}{(S_g)^{1/5} H}, \frac{Q_b}{Q}, \frac{Q}{BS}, \frac{Q^{2/5}}{(S_g)^{1/5} D_{50}}, \frac{\sqrt{gHS}}{\sqrt{gD_{50}}}, \frac{Q}{BH\sqrt{gH}} \right) = 0 \quad 5.3$$

Now in convenient form and replacing Q_b/Q by C , one non-dimensional equation may be written as:

$$\left(\frac{B}{H}, \frac{H}{D_{50}}, \frac{Q^{2/5}}{H(Sg)^{1/5}}, C, \frac{Q}{B\sqrt{S}}, \frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}, \frac{V_*}{\sqrt{gD_{50}}}, \frac{V}{\sqrt{gH}} \right) = 0 \quad 5.4$$

All these non-dimensional parameters is used in this study to develop correlation in the water courses in alluvium. These non-dimensional parameters was initially correlated using laboratory data. Then the developed correlation was tested against field data and finally continuity between laboratory and field data would be checked.

The form of correlation developed is $y=ax^b$, where a and b are the coefficient and exponent respectively. Numerical coefficients and exponents for these equations was evaluated using the regression techniques against laboratory data. For the verification of the developed correlation large volume of field data was used. The data listing used in this study include majority of the worldwide available data within appropriate limiting conditions. Testing of the continuity of the correlation from laboratory circumstances through to field circumstances is also undertaken.

5.2 DATA USED IN THIS STUDY:

Data obtained from various sources throughout the world have been compiled by Peterson and Howells (1973,1978). Peterson and Howells data compendium were later modified by Brownlie (1981). The data base contains 7027 records in total of which 5263 sets are laboratory data and 1764 sets are field data. Data used for

the development of correlation and also for verification to channels having width-depth ratio greater than 5.0 i.e. for wide channel, flow Froude number range from 0.2 to 0.8, specific gravity of the bed particles 2.65, concentration range of (100-10,000) ppm, and median particle size of the bed material less than 2mm.

5.3 CORRELATION OF THE PARAMETERS:

At the initial stage of this study correlation between non-dimensional $\frac{B}{H}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for different concentration range flow Froude number range and $\frac{V}{V_*}$ range are tried. Again correlation between $\frac{Q_t}{Q}$ and S for different $\frac{B}{H}$ ratio and $\frac{H(Sg)^{1/3}}{2/3}$ for different concentration and flow Froude number range, $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different $\frac{V}{V_*}$, $\frac{H}{D_{50}}$ and $\frac{Q}{B^2}$ for different concentration range are tried but no acceptable results were obtained.

Good correlations obtained between non-dimensional $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different concentration range, flow Froude number range and particle Froude number range and between non-dimensional $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for different flow Froude number range. For the development of correlation the concentration range, flow Froude number range and particle Froude number range are divided into numbers of bands.

The non-dimensional parameter $\frac{B}{H}$ is a measure of channel shape, and the shape of the alluvial channel is closely related to discharge and sediment concentration, depth of flow, slope of

the channel, acceleration due to gravity and shape of the channel. So correlation between non-dimensional $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different concentration range are developed.

Resistance to flow is important in predicting alluvial river geometry. The configuration of the bed changes with changes in flow conditions. The changing bed condition makes it extremely difficult to describe the resistance due to these bed forms by a constant resistance coefficient. But flow Froude number is helpful in predicting bed forms. So the correlation between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different flow Froude number are used.

The material that goes into suspension changes the flow and fluid characteristics and has significant influence on the velocity distribution and hence on the mean velocity. Mean velocity is one of the important factors influencing resistance i.e. alluvial water courses. So particle Froude number $\frac{V_*}{\sqrt{gd_{50}}}$ is one of the important resistance form. Now correlation between non-dimensional terms $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different $\frac{V_*}{\sqrt{gd_{50}}}$ is indicative of alluvial river geometry prediction.

The correlation are developed between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for different flow Froude number range. Flow in alluvial channels are much more complex situation. In mobile boundary flow the resistance is provided by grain roughness so the relative roughness $\frac{H}{D_{50}}$ is another important parameter. Bed forms itself is a changing quantity but it varies with flow Froude number. Roughness and flow Froude number are important for forming alluvial river shape

and bed form. So the correlation developed between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}^{1/5}(S_g)^{1/5}}$ for different flow Froude number may be suggested as an alternative approach to correlate alluvial river resistance with shape.

CHAPTER 6

DEVELOPMENT OF CORRELATION OF NON DIMENSIONAL PARAMETER WITH LABORATORY DATA

6.1 INTRODUCTION:

Simple and dimensionally homogeneous expressions developed for the assessment of alluvial river geometry. Numerical coefficient and constant of the non-dimensional equations were developed, using the laboratory data. The non-dimensional parameters were formed as mentioned earlier with the variable that control the alluvial, river geometry using the method of synthesis.

The equation thus obtained were then assessed against a large volume of field data collected from various sources all over the world. The correlations thus developed showed good agreement with field data. The closer the representation of the laboratory condition to field situation the better is the prediction obtained.

6.2 DEVELOPMENT OF LOG-LOG CORRELATION BETWEEN SHAPE FACTOR
 (B/H) AND NON-DIMENSIONAL DISCHARGE $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ FOR
 DIFFERENT CONCENTRATION RANGE, FROUDE NUMBER AND PARTICLE
 FROUDE NUMBER RANGE:-

Correlations were developed between the non-dimensional parameters using laboratory data initially. This data contained 5263 sets laboratory data. The laboratory data had a discharge range of 0.878 l/sec to 2213.952 l/sec, d_{50} median particle size of the bed material ranged from 0.013 mm to 22.200 mm, slope ranged from 0.0000287 to 0.036700, width ranged from 0.076 m to 2.438m and depth ranged from 0.0113m to 0.8600m. The laboratory data was plotted on the basis of non-dimensional shape factor $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ for different concentration range, flow Froude number range and particle Froude Number range. The non-dimensional parameters were plotted on a log-log plotting and good correlations had been obtained between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ for different concentration range, flow Froude number range and particle Froude number range.

Correlation between width depth ratio $\frac{B}{H}$ which is a measure of channel shape with the discharge parameter $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ for a concentration range 100 ppm to 10000 ppm are plotted in a log-log plotting dividing into six band. Fig. 6.1 to 6.6 show the plots for concentration bands of 100 ppm-250ppm, 250 ppm-500ppm, 500ppm-750 ppm, 750 ppm-1000 ppm, 1000 ppm-2000 ppm, 2000 ppm-10000 ppm respectively. These plotting are helpful for visual observations of degree of achievements of correlation.

Regression equations of the power type were developed to explain functional relation. Independent correlations between $-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for various concentration ranges are obtained which themselves varied in a systematic manner. This is shown in table 6.1. The form of correlation developed using the laboratory data could be expressed by the equation

$$y = ax^b \quad (6.1)$$

where

$$y = B/H$$

and

$$Q^{2/5}$$

$$x = \text{-----}$$

$$H[Sg]^{1/5}$$

and a, b are coefficient and exponent respectively. The coefficients and exponents are obtained by statistical method using large volume of laboratory data divided according to concentration range. For concentration range from 100 ppm to 250 ppm, the power type regression equation may be expressed by

$Y = 0.2781 X^{1.85264}$ for which the coefficient of correlation is 0.931084, standard error of $Y_{estimate}$ is 0.071539, and standard error of coefficient is 0.050087. For other concentration ranges the power type regression equations and other statistical properties are provided in table 6.1. From this table it can be observed that coefficient of correlation varies from 0.67 to 0.931 and as sediment concentration increases, coefficient of

correlation decreases. Coefficient of correlation is maximum when concentration range 100 ppm to 250 ppm and for this range standard error of $Y_{estimate}$ and standard error of coefficient is minimum. For the laboratory data when divided into six bands than the exponent varies from 1.6 to 1.96 and the coefficient varies from 0.257 to 0.442. When all laboratory data for concentration range 100 ppm to 10000 ppm are considered for correlation of non-dimensional parameters $-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ then a correlation coefficient of 0.8323653 is obtained with standard error of $Y_{estimate}$ 0.098528, standard error of coefficients 0.044973 and the exponent and coefficients are 1.745699 and 0.3470483 respectively.

Correlation have been developed between shape factor $-\frac{B}{H}$ and non-dimensional discharge parameter $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ using laboratory data for different Froude Number range. The non-dimensional parameters $-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ are plotted on log-log plotting for flow Froude number ranges of 0.2 to 0.8 divided into six bands, via. 0.2 to 0.3; 0.3 to 0.4; 0.4 to 0.5; 0.5 to 0.6; 0.6 to 0.7; and 0.7 to 0.8. For the clear understanding of correlation between non-dimensional $-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different flow Froude number are plotted separately according to the chosen bands. These plotting are shown in figs. 6.7 to 6.12. Fig. 6.7 shows the correlation between non-dimensional shape factor $-\frac{B}{H}$ and non-dimensional discharge $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for flow Froude number from 0.2 to 0.3. Similarly Fig. 6.8 to 6.12 are used for showing correlation between $-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for flow Froude number, ranges

from 0.3 to 0.4, 0.4 to 0.5; 0.5 to 0.6; 0.6 to 0.7 and 0.7 to 0.8 respectively. Independent correlations for various Froude number range are developed using laboratory data. Statistical properties for the correlation of these two parameters for various flow Froude number ranges are shown in Table 6.2. The power type regression equation for flow Froude number 0.2 to 0.3 can be written as, $Y = 0.4511282 X^{1.685354}$, with a coefficient of correlation; 0.6705863, standard error of Y Estimate 0.094333 and standard error of coefficient 0.498284. Table 6.2 shows the power type regression equation and other statistical properties of the correlation for different flow Froude number range. From table it appears that coefficient of correlation varies from 0.67 to 0.892. Exponent and coefficient of the regression equations varies from 1.685 to 2.13 and 0.18083 to 0.4511 respectively. Standard error of Y_{Estimate} and coefficient varies from 0.079164 to 0.103106 and 0.09496 to 0.498284. From the table 6.2 it is also observed that correlation coefficient is maximum 0.892 for flow Froude number range 0.6 to 0.7 and for this range of flow Froude number exponent and coefficients of the regression equation are respectively 2.005039 and 0.1931256.

For flow Froude number from 0.2 to 0.3 correlation coefficient is minimum, 0.6706, and for this range of flow Froude number exponents and coefficients are respectively 1.685354 and 0.45113. Using all laboratory data i.e. 670 sets of data correlation between non-dimensional parameters $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ for all flow Froude number range from 0.2 to 0.8 are developed.

In this case correlation coefficient is found to be 0.8323653 and exponent and coefficients of the regression equation are 1.745 and 0.35 respectively. Standard error of $Y_{estimate}$ and coefficients have low value such as 0.0985 and 0.045 respectively.

The non-dimensional parameters $-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ are correlated using laboratory data in the same manner for different particle Froude number range. The particle Froude number varies from 0.4 to 1.3. This range is subdivided into nine selected bands. The terms $-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ are plotted in a log-log plotting for various bands of particle Froude number as shown in fig. 6.13 to fig. 6.21. The selected Froude number bands are: 0.4 to 0.5; 0.5 to 0.6, 0.6 to 0.7; 0.7 to 0.8; 0.8 to 0.9; 0.9 to 1.0; 1.0 to 1.1; 1.1 to 1.2 and 1.2 to 1.3. The numerical value of the statistical properties of the correlation between non-dimensional B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different particle Froude number range are shown in tabular form. The power type non-dimensional regression equation for particle Froude number range for instance for a Froude number range of 0.4 to 0.5 is $Y = 0.1438533X^{2.158318}$ with a correlation coefficient of 0.95999, standard error of $Y_{estimate}$ 0.046472 and standard error of coefficient 0.065635. Statistical properties for the correlation of non-dimensional B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different particle Froude number are summarized in the Table 6.3. From the table it may be observed that the coefficient of correlation varies for particle Froude number greater than 0.4 but less than 0.9. The exponent of the regression equation for different particle Froude number range varies from 1.1057 to

2.158. Using all laboratory data having particle Froude number ranges from 0.4 to 1.3, a numerical correlation between non-dimensional terms B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ are developed. In this case the regression equation may be expressed by, $Y = 0.3920396 X^{1.6996}$, with a correlation coefficient 0.803061, standard error $Y_{Estimate}$, 0.09853 and standard error of coefficient 0.044973.

In calculating the particle Froude number V_* shear velocity is adopted instead of flow velocity V , and median particle size of the bed material D_{50} is adopted as the characteristic length.

6.3 DEVELOPMENT OF LOG-LOG CORRELATION BETWEEN RELATIVE ROUGHNESS H/D_{50} AND NON-DIMENSIONAL PARAMETER $Q^{2/5}/[D_{50} [Sg]^{1/5}]$ FOR DIFFERENT FLOW FROUDE NUMBER RANGE.

Correlations were developed between the non-dimensional parameter using laboratory data initially. Power type non-dimensional correlation were developed between H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for different flow Froude number ranges using the regression technique. For the correlation between non-dimensional terms, H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for flow Froude number ranges, 0.2 to 0.3, 0.3 to 0.4, 0.4 to 0.5, 0.5 to 0.6, 0.6 to 0.7 and 0.7 to 0.8 are shown in figs. 6.22 to figs. 6.27 in log-log plotting. For the development of numerical correlation between H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for these flow Froude number ranges, statistical properties such as regression equation, coefficient of correlation, standard error of $Y_{Estimate}$ and standard error of coefficients are determined,

for flow Froude number range from 0.2 to 0.3 power type regression equation is of the form $Y = 0.3581624 X^{0.929638}$ with correlation coefficient 0.9807058, standard error of Y_{Estimate} is 0.047301 and standard error of coefficient, 0.049525. For all flow Froude number range from 0.4 to 1.3, the statistical properties are determined and systematically represented in table 6.4. From the table it appears that coefficient of correlation is very high and for all the selected bands.

This value for all selected band is 0.98 and higher. Standard error of Y_{Estimate} and standard error of coefficients are very low. Using all laboratory data for flow Froude number range from 0.2 to 0.8 numerical correlations between H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ are also developed. the regression equation for flow Froude number range from 0.2 to 0.8 were found to be $Y = 0.1247125 X^{1.027099}$, with a coefficient of correlation, 0.9846694, standard error of Y_{Estimate} 0.083840 and standard error of coefficients are 0.007039.

TABLE 6.1

Summary of the statistical properties for the correlation of non-dimensional parameters, B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$, for various concentration range using laboratory data. (Number within the parenthesis indicates the no. of data used in the correlation)

Concentration Range	Regression Equation	Coefficient of correlation	Std Error of Y Estimate	Std Error of Coefficient
(100-250) ppm (212)	$Y = 0.2781 X^{1.8526}$	0.9311	0.07154	0.0501
(250-500) ppm (127)	$Y = 0.3896 X^{1.696}$	0.86938	0.07822	0.0862
(500-750) ppm (73)	$Y = 0.2571 X^{1.9614}$	0.86075	0.08229	0.1376
(750-1000) ppm (63)	$Y = 0.380 X^{1.7464}$	0.80223	0.0852	0.1664
(1000-2000) ppm (123)	$Y = 0.4426 X^{1.59997}$	0.7222	0.11271	0.1393
(2000-10000) ppm (79)	$Y = 0.3754 X^{1.6441}$	0.6687	0.15178	0.2083

$$Y = B/H, \quad X = \frac{Q^{2/5}}{H(Sg)^{1/5}}$$

TABLE 6.2

Summary of statistical properties for the correlation of non-dimensional parameters, B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$, for different flow Froude number range using laboratory data (Number within the parenthesis indicates the no. of data used in the correlation)

Froude Number Range	Regression Equation	Coefficient of Correlation	Std Error of $Y_{Estimate}$	Std Error of Coefficient
0.2-0.3 (16)	$Y = 0.45113 X^{1.6853}$	0.67059	0.09433	0.49828
0.3-0.4 (103)	$Y = 0.21485 X^{2.11042}$	0.84642	0.08023	0.13211
0.4-0.5 (141)	$Y = 0.18084 X^{2.1349}$	0.87640	0.07916	0.09950
0.5-0.6 (190)	$Y = 0.22442 X^{1.9353}$	0.82971	0.090631	0.09496
0.6-0.7 (115)	$Y = 0.193126 X^{2.00504}$	0.89222	0.09155	0.09549
0.7-0.8 (105)	$Y = 0.22384 X^{1.9574}$	0.86083	0.10311	0.11343

$$Y = B/H, \quad X = \frac{Q^{2/5}}{H(Sg)^{1/5}}$$

TABLE 6.3

Summary of statistical properties for the correlation of non-dimensional parameters, B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$, for different particle Froude number range using laboratory data (Number within the parenthesis indicates the no. of data used in the correlation)

$\frac{V_*}{\sqrt{gd_{50}}}$	Range	Regression Equation	Coefficient of Correlation	Std. Error of Y Estimate	Std. Error of Coefficient
0.4-0.5 (94)		$Y = 0.14385 X^{2.1583}$	0.95999	0.04647	0.06564
0.0-0.6 (59)		$Y = 0.23175 X^{1.9593}$	0.88495	0.06429	0.13636
0.6-0.7 (43)		$Y = 0.19663 X^{2.1089}$	0.89759	0.06373	0.16176
0.7-0.8 (40)		$Y = 0.23888 X^{1.9964}$	0.87346	0.05979	0.18052
0.8-0.9 (59)		$Y = 0.23435 X^{2.0362}$	0.85358	0.1011	0.16420
0.9-1 (54)		$Y = 0.42552 X^{1.7056}$	0.71693	0.13117	0.22996
1-1.1 (41)		$Y = 0.5112696 X^{1.5772}$	0.78803	0.08916	0.19730
1.1-1.2 (56)		$Y = 0.6431762 X^{1.4178}$	0.70472	0.12398	0.194244
1.2-1.3 (46)		$Y = 1.3990924 X^{1.1057}$	0.61363	0.10514	0.2145

 $Y = B/H,$
 $X = \frac{Q^{2/5}}{H(Sg)^{1/5}}$

TABLE 6.4

Summary of statistical properties for the correlation of the non-dimensional parameters, H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$, using laboratory data for different range of flow Froude number.

(Number within the parenthesis indicates the no. of data used in the correlation)

Froude Number Range	Regression Equation	Coefficient of Correlation	Std Error of Y_{Estimate}	Std Error of Coefficient
0.2-0.3 (16)	$Y = 0.35816 X^{0.9296}$	0.98071	0.04730	0.04953
0.3-0.4 (103)	$Y = 0.20885 X^{0.9765}$	0.98057	0.05999	0.01944
0.4-0.5 (144)	$Y = 0.2224 X^{0.9606}$	0.98195	0.065897	0.015,
0.5-0.6 (191)	$Y = 0.14348 X^{1.0027}$	0.98670	0.06944	0.012014
0.6-0.7 (116)	$Y = 0.1154569 X^{1.02415}$	0.98652	0.08915	0.01591
0.7-0.8 (105)	$Y = 0.16023 X^{0.9809}$	0.98620	0.08897	0.01622

$$Y = H/D_{50}, \quad X = \frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$$

$$\frac{m^2 T^{-1}}{m \frac{m T^{-2}}{m^2 T^{-1}}}$$

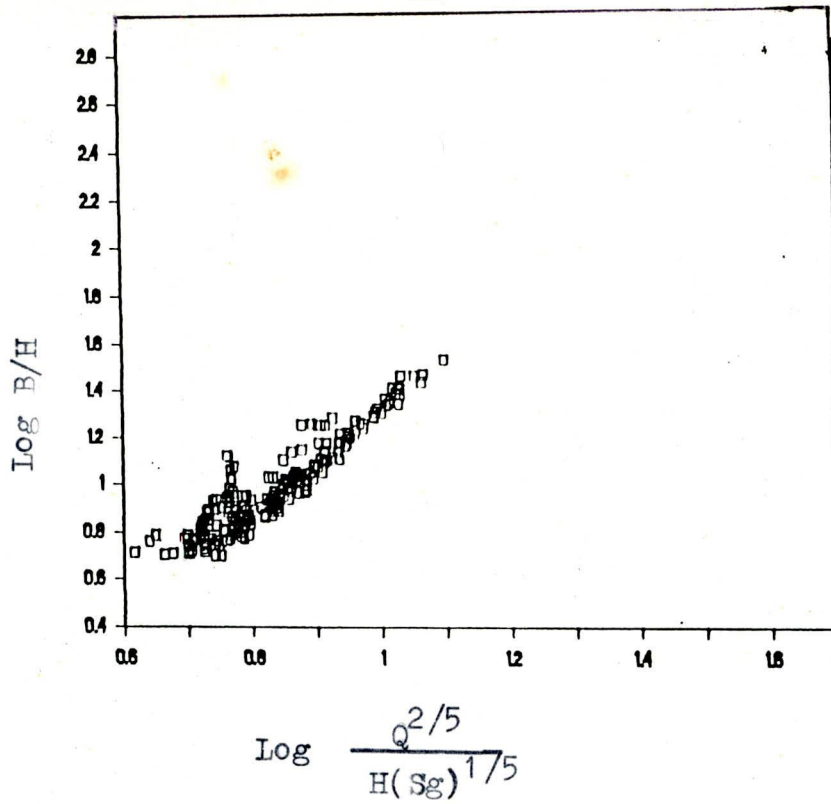


Fig.6.1 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from (100-250)ppm

(Laboratory data)

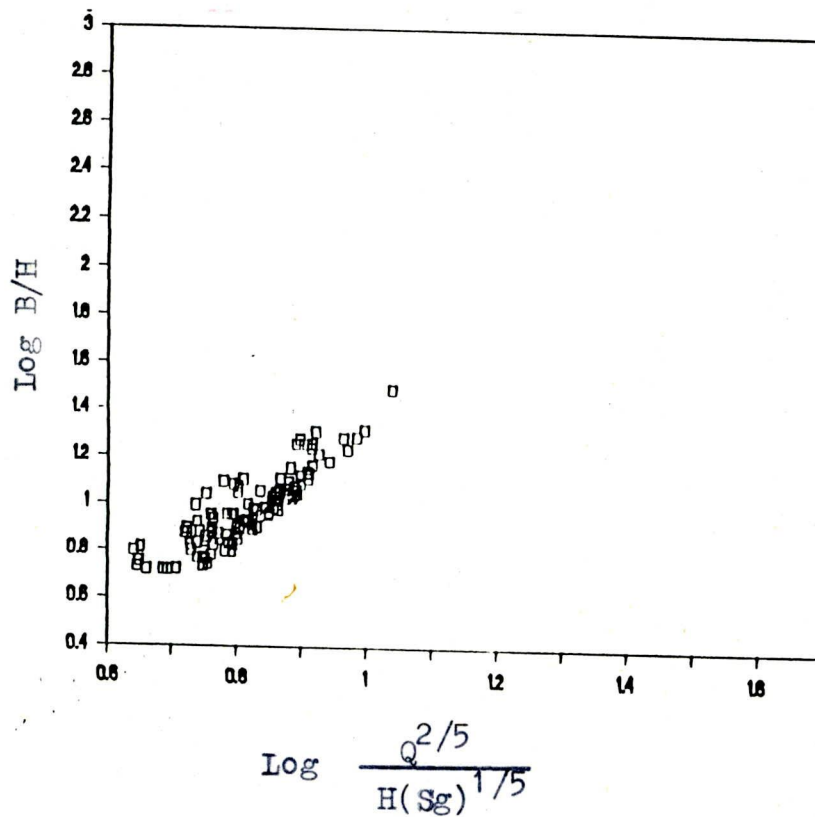


Fig.6.2 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from (250-500)ppm

(Laboratory data)

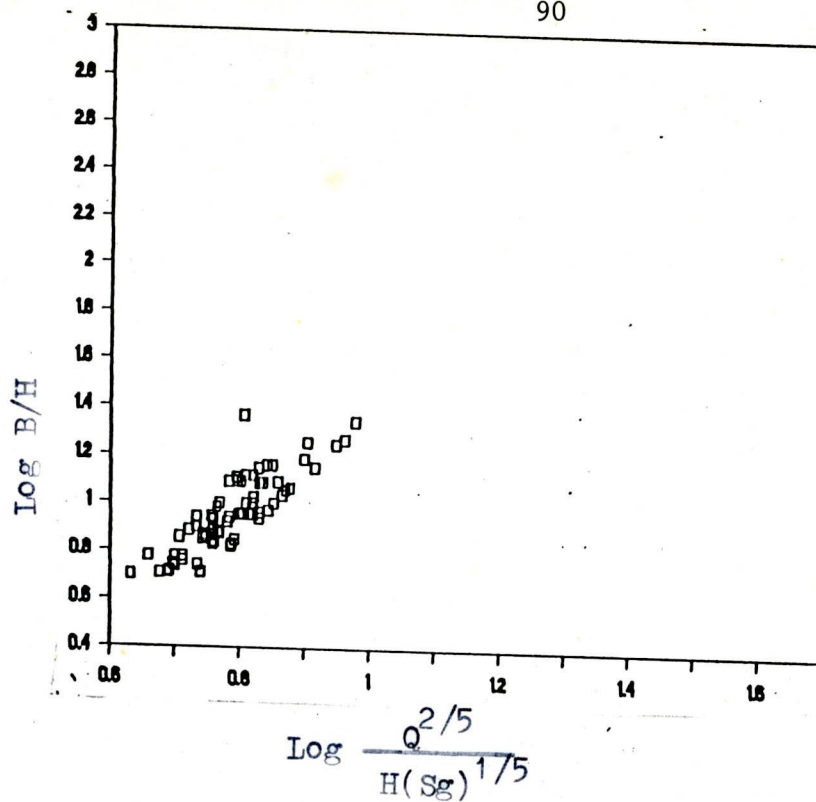


Fig. 6.3 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from $H(Sg)^{1/5}$
(500-750) ppm
(Laboratory data)

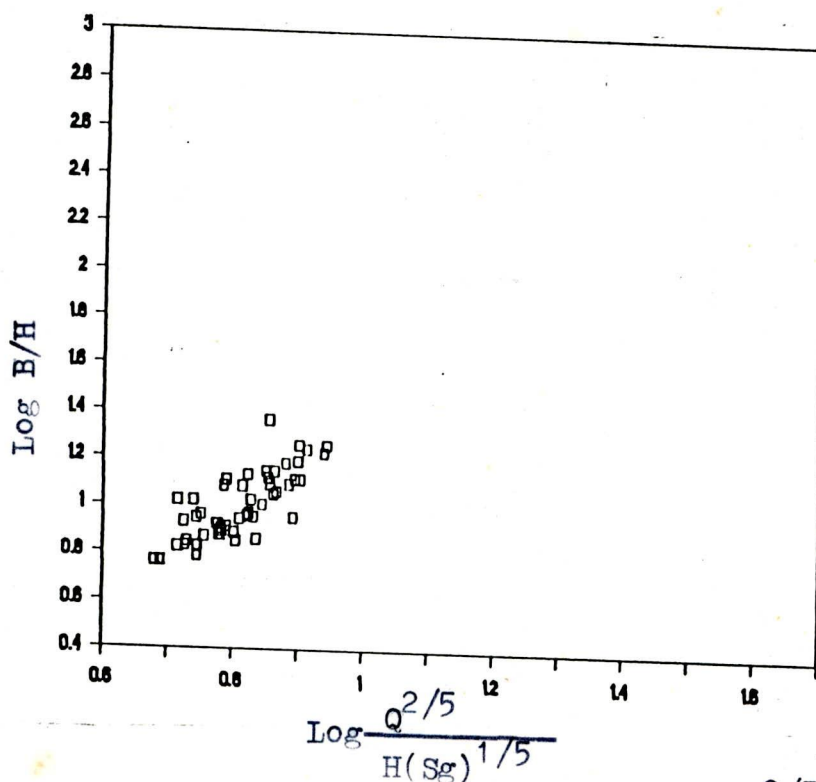


Fig. 6.4 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from $H(Sg)^{1/5}$
(750-1000) ppm
(Laboratory data)

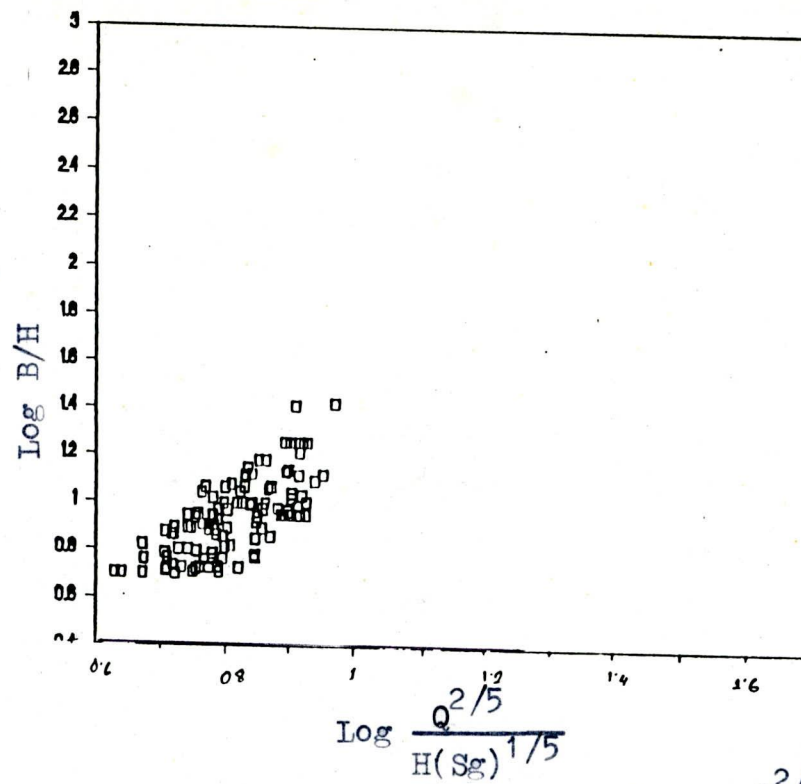


Fig.6.5 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from $H(Sg)^{1/5}$
(1,000-2,000)ppm
(Laboratory data)

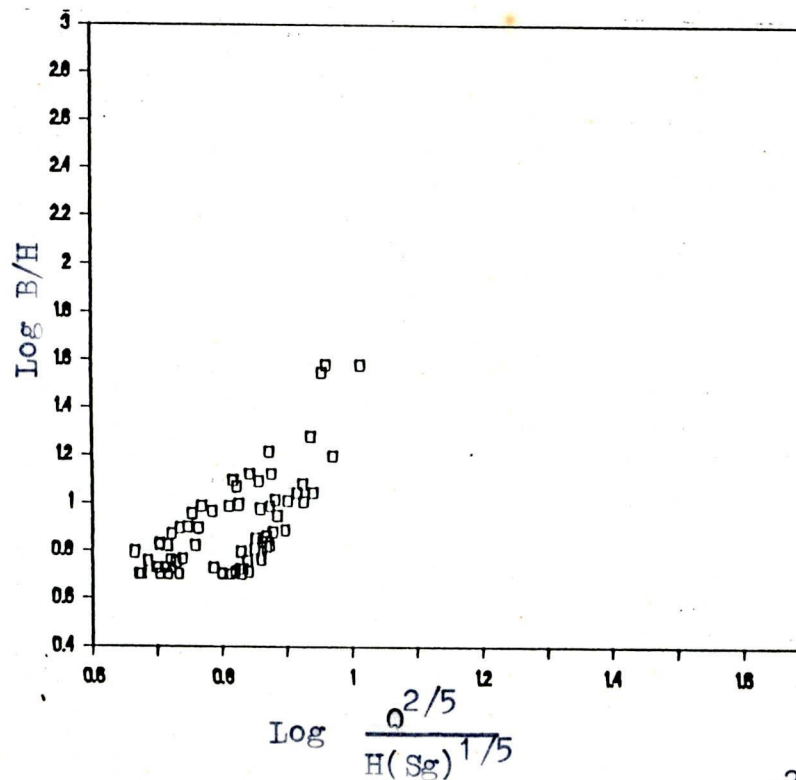


Fig. 6.6 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from $H(Sg)^{1/5}$
(2,000-10,000)ppm
(Laboratory data)

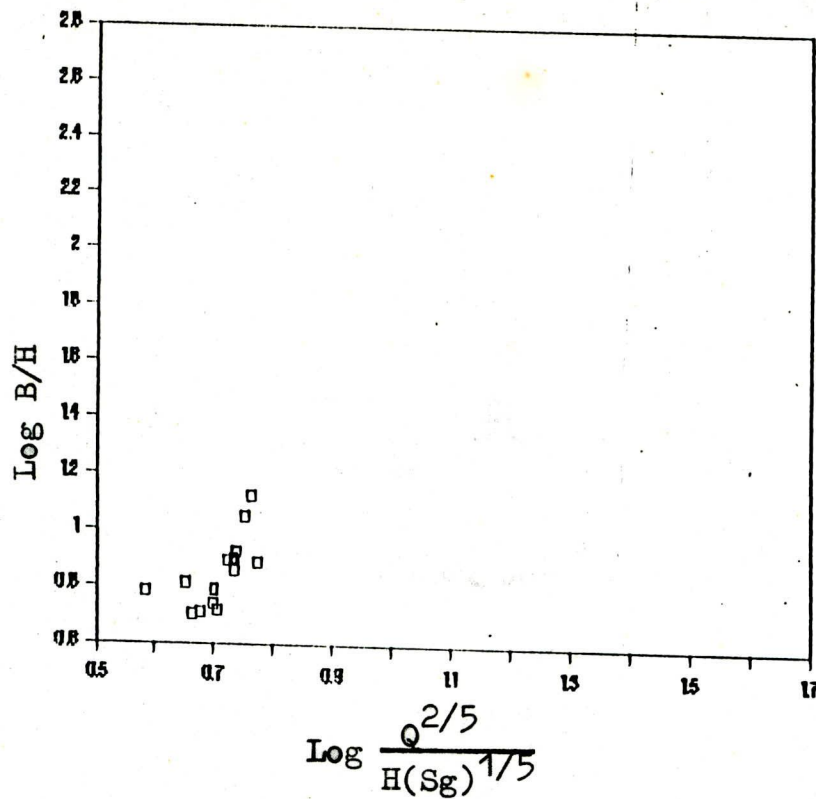


Fig. 6.7 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr.No. 0.2-0.3
(Laboratory data)

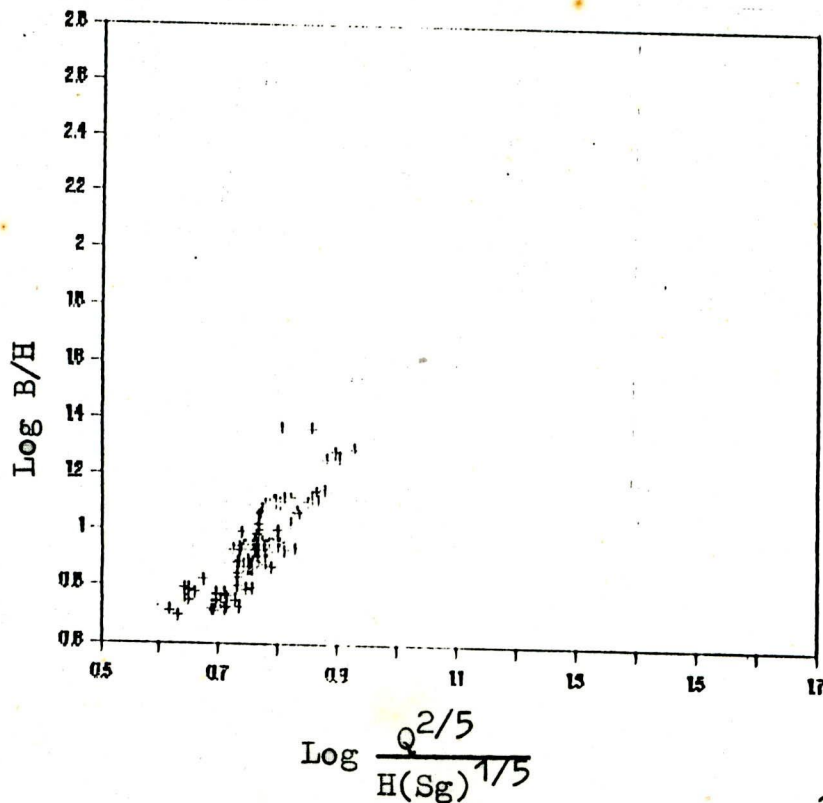


Fig. 6.8 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
flow Fr.No. 0.3-0.4
(Laboratory data)

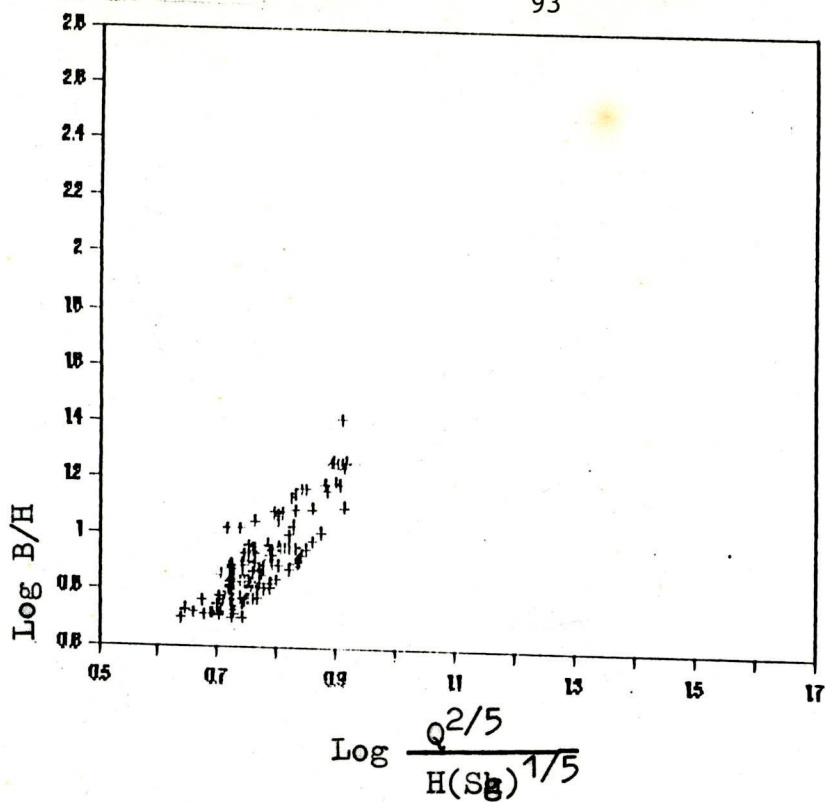


Fig. 6.9 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
flow Fr. No. 0.4-0.5
(Laboratory data)

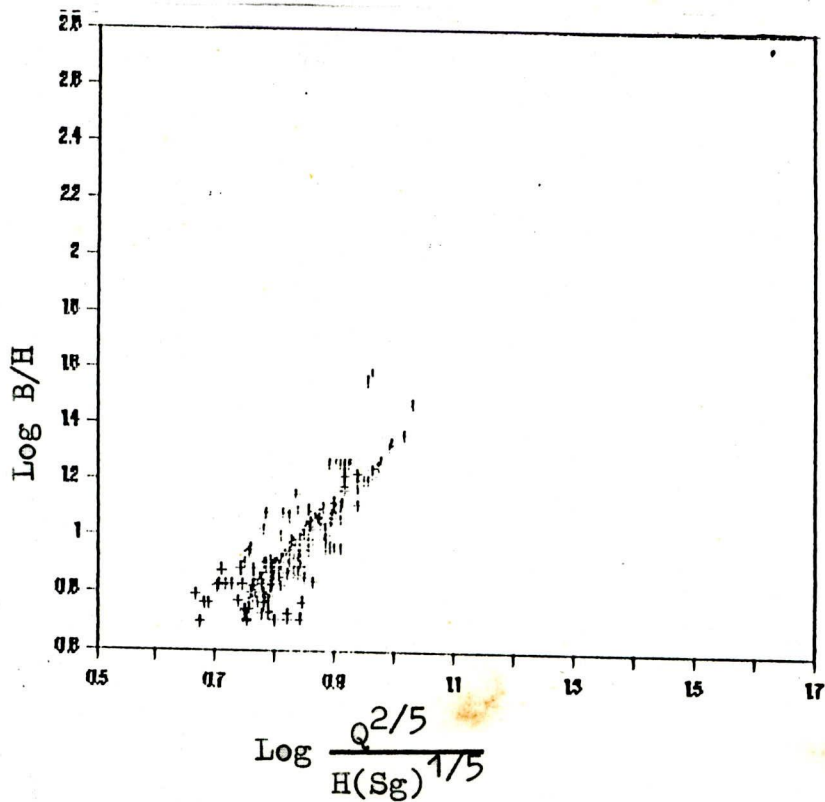


Fig. 6.10 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr. No. 0.5-0.6
(Laboratory data)

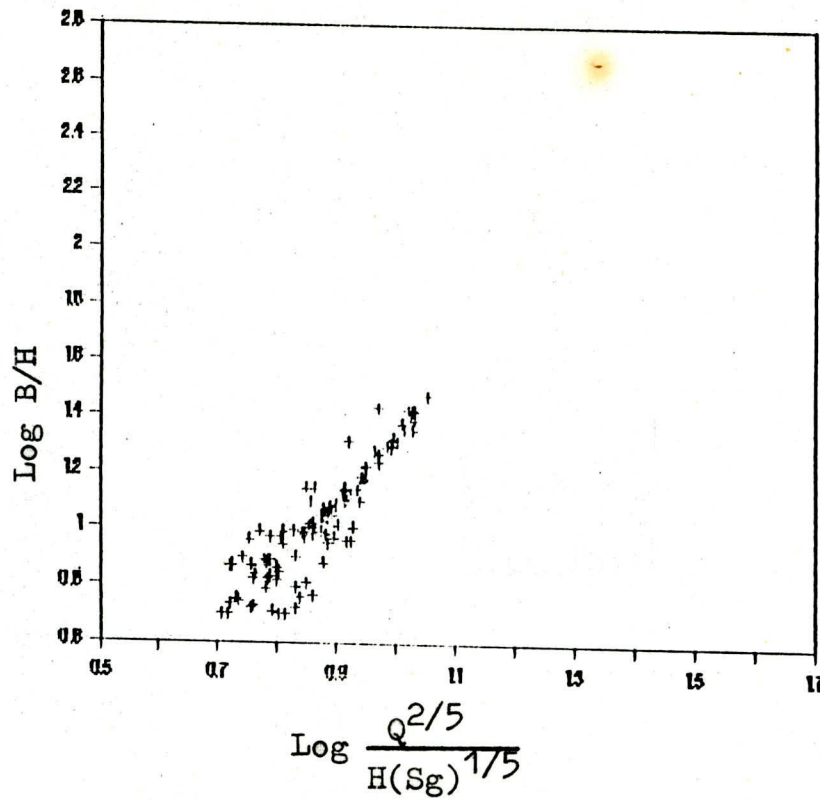


Fig. 6.11 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr.No. 0.6-0.7
(Laboratory data)

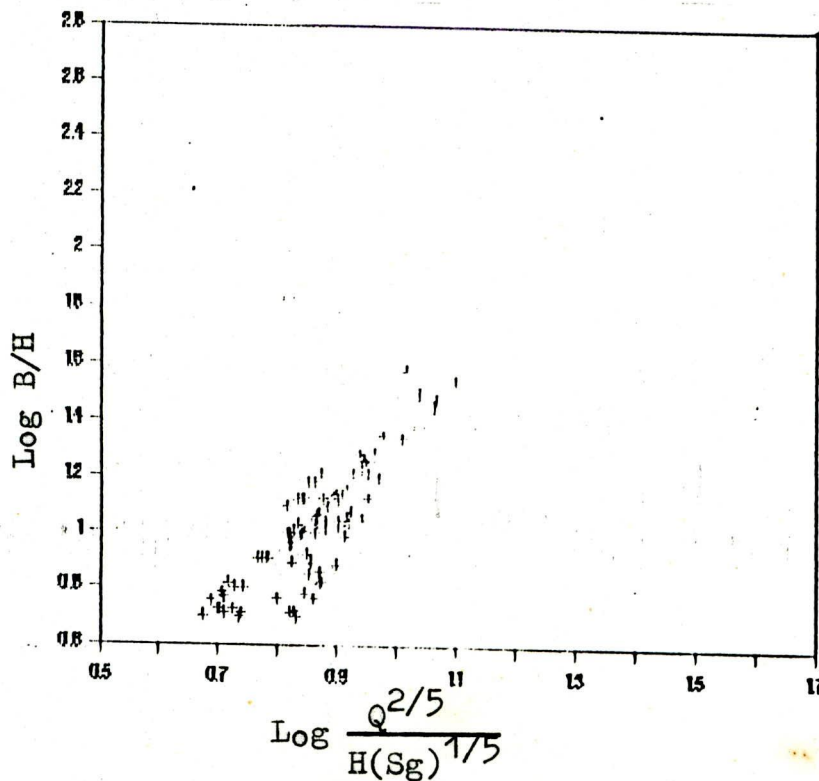


Fig. 6.12 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr.No. 0.7-0.8
(Laboratory data)

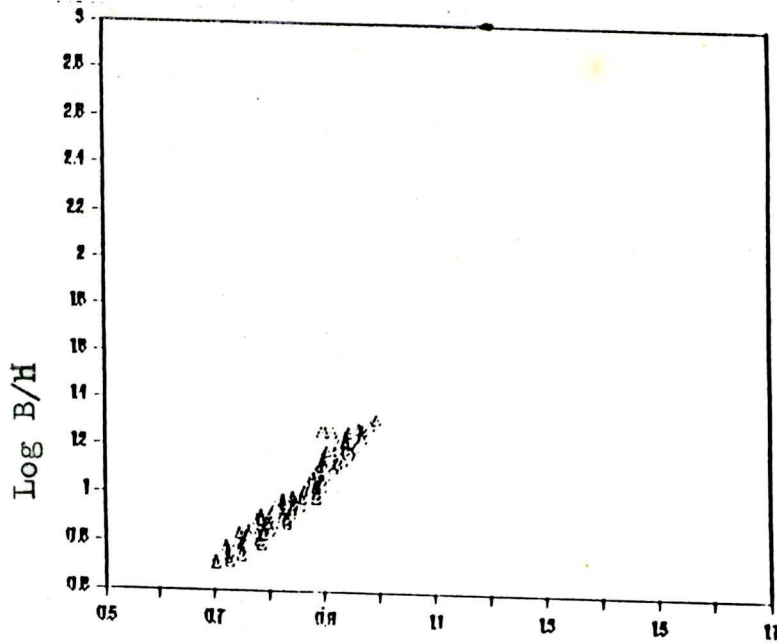


Fig.6.13 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for particle Fr.No.0.4-0.5
(Laboratory data)

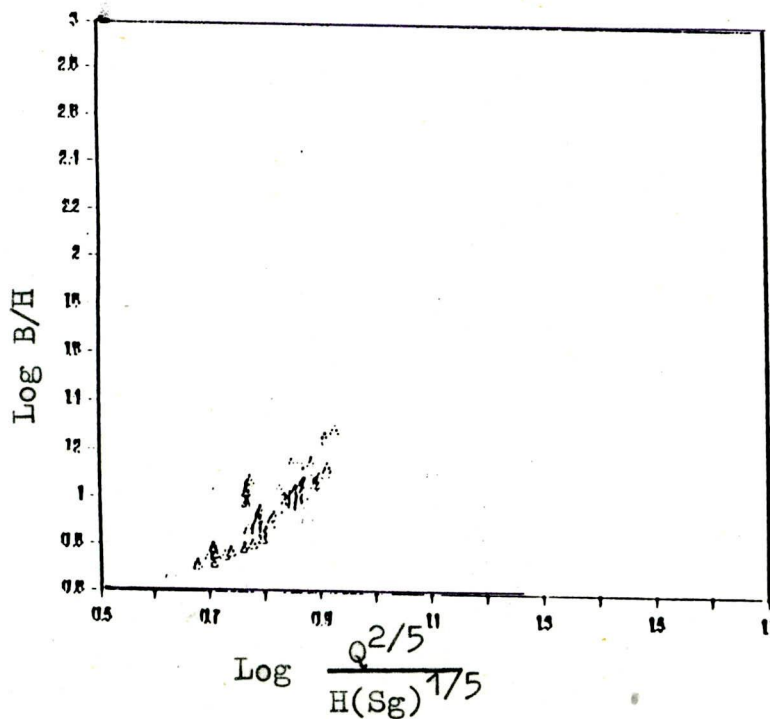


Fig.6.14 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for particle Fr.No.0.5-0.6
(Laboratory data)

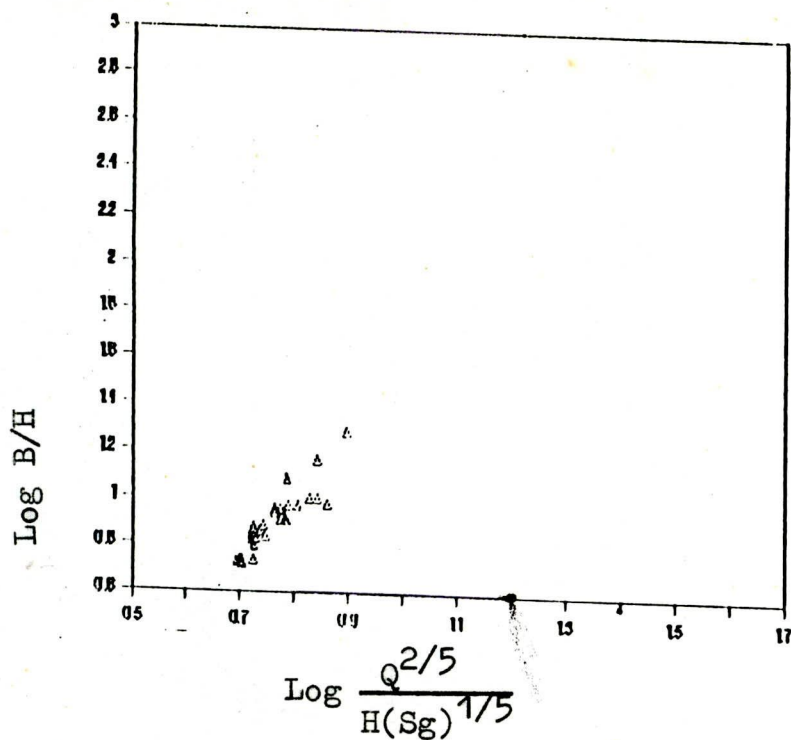


Fig.6.15 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for particle Fr.No.0.6-0.7
(Laboratory data)

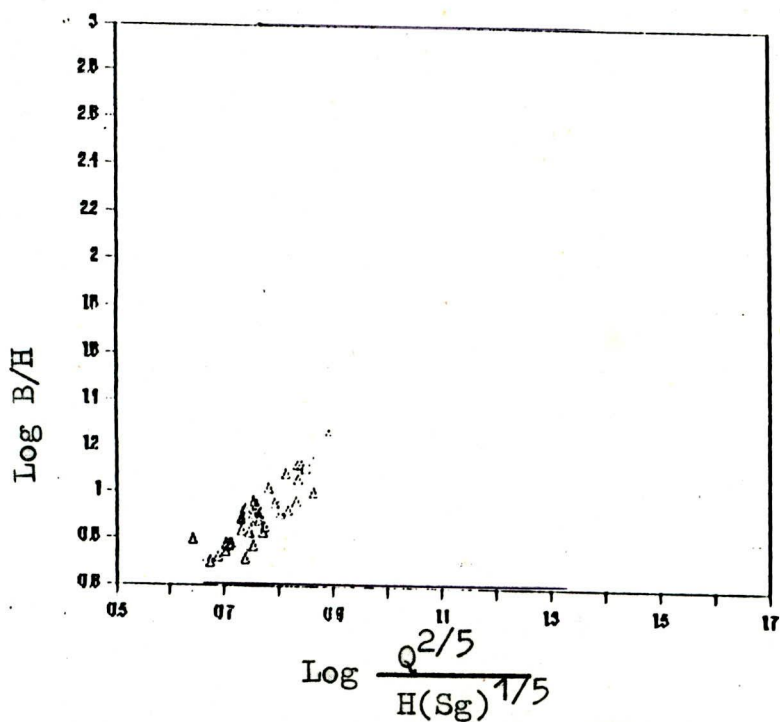


Fig.6.16 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for particle Fr.No.0.7-0.8
(Laboratory data)

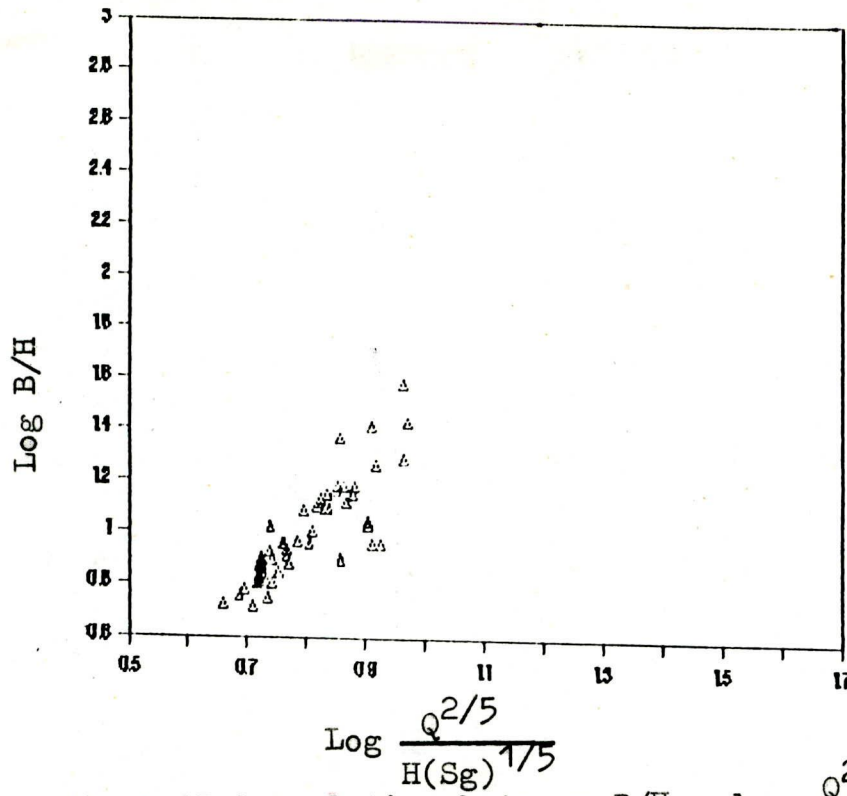


Fig.6.17 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for particle Fr.No.0.8-0.9 (Laboratory data)

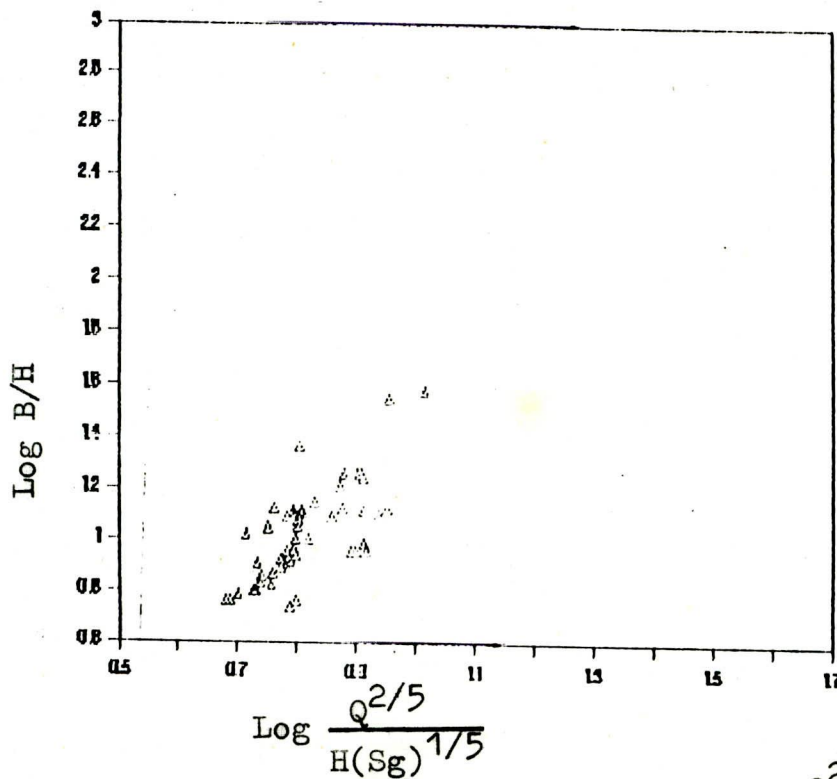


Fig.6.18 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for particle Fr.No.0.9-1.0 (Laboratory data)

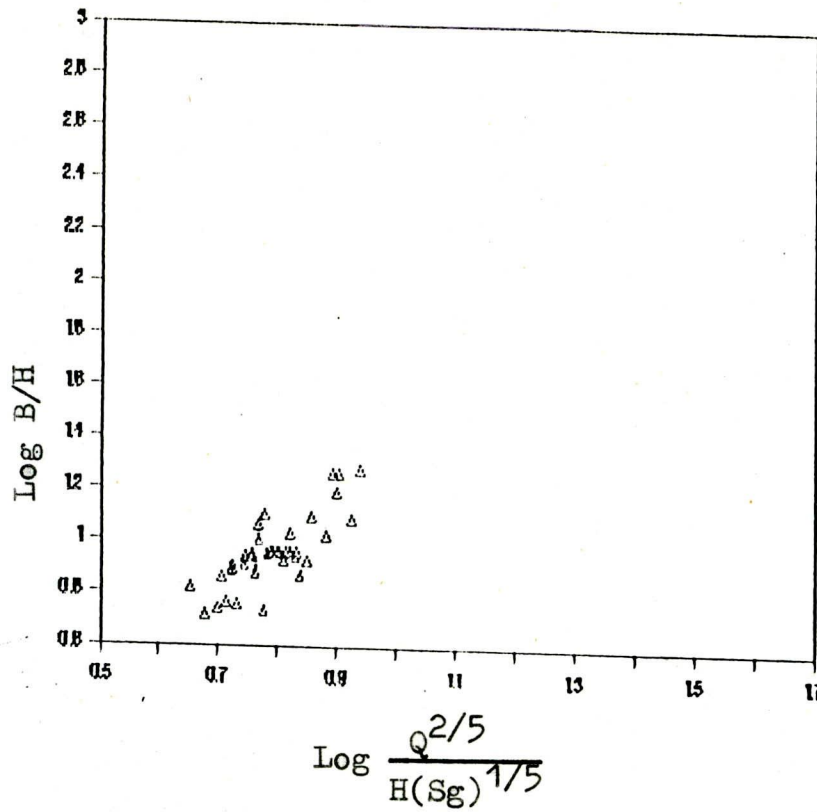


Fig.6.19 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for particle Fr.No.1.0-1.1 (Laboratory data)

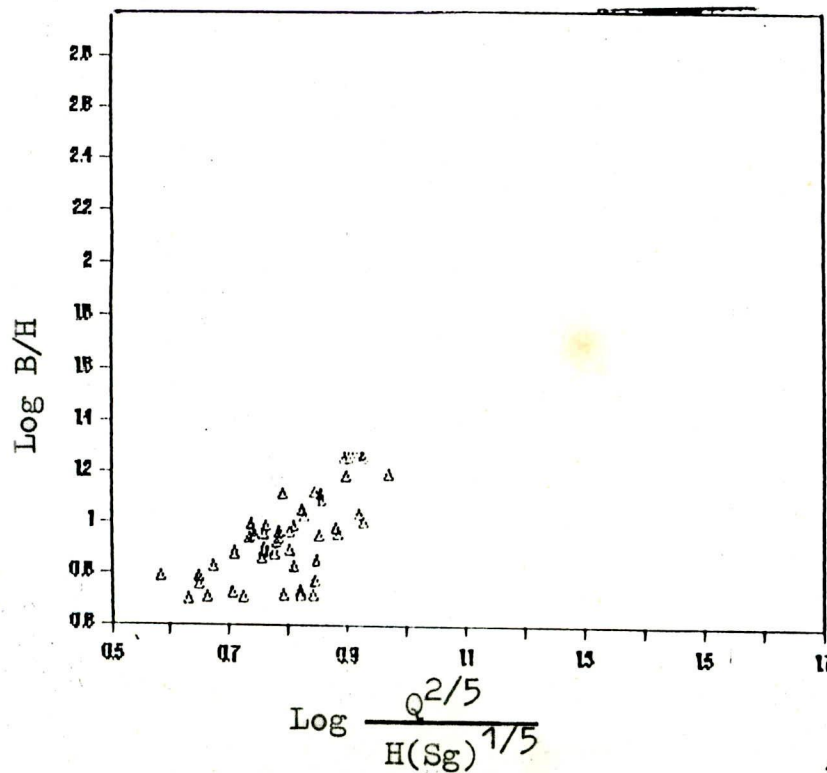


Fig.6.20 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for particle Fr.No.1.1-1.2 (Laboratory data)

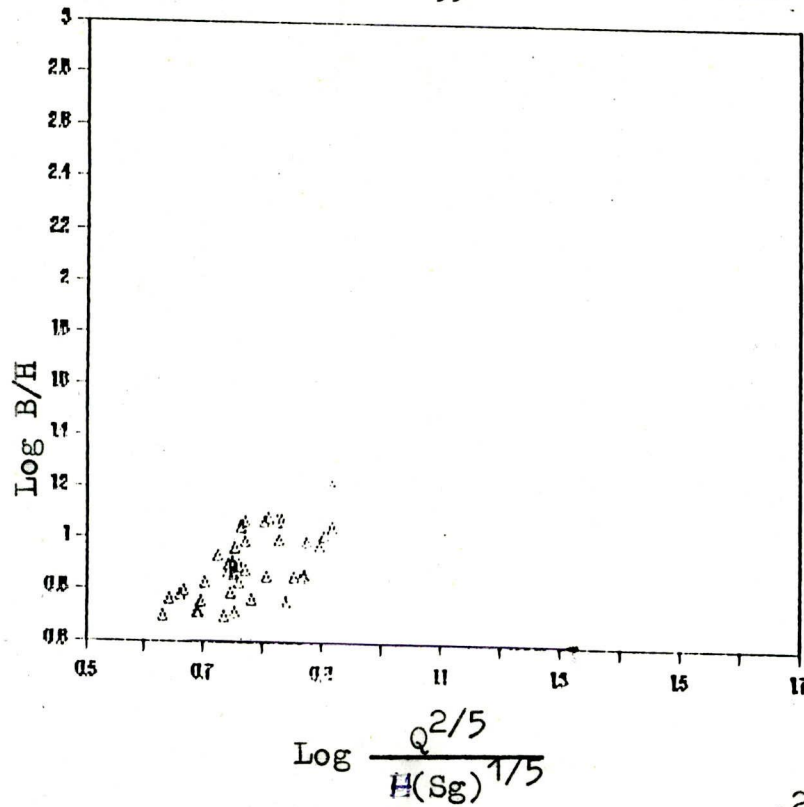


Fig. 6.21 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for particle Fr.No.1.2-1.3
(Laboratory data)

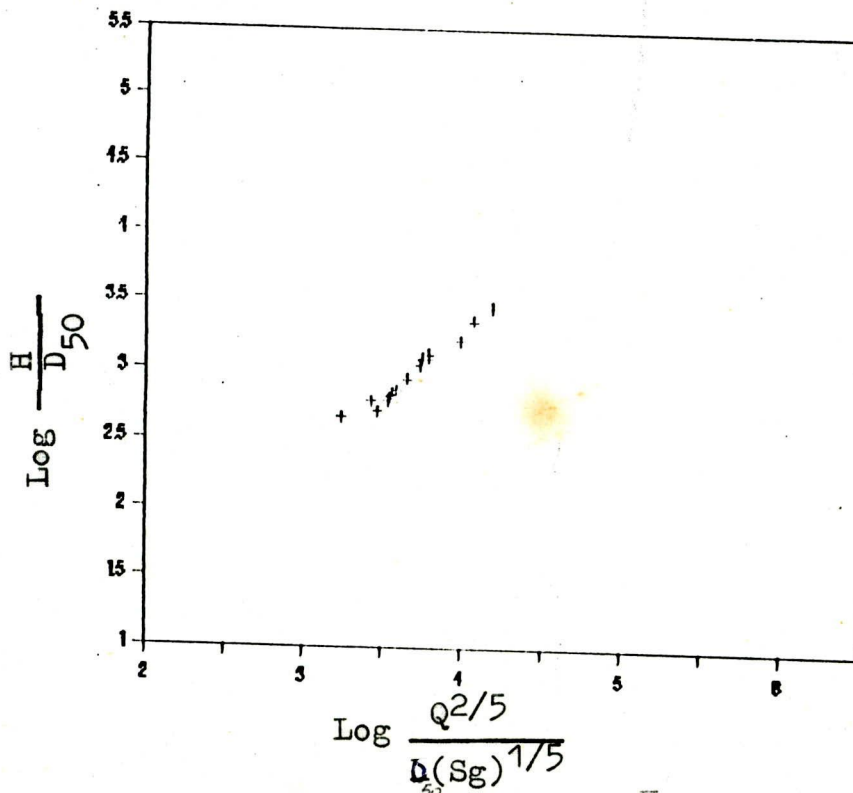


Fig.6.22 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$
for flow Fr.No.0.2-0.3
(Laboratory data)

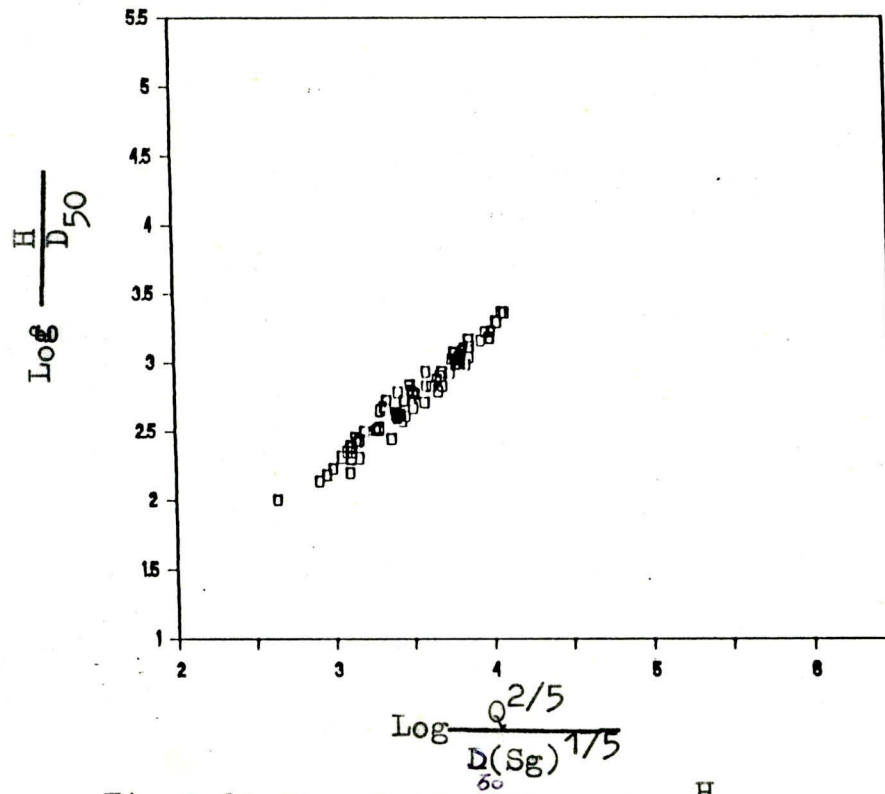


Fig.6.23 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D(Sg)^{1/5}}$
(Laboratory data)

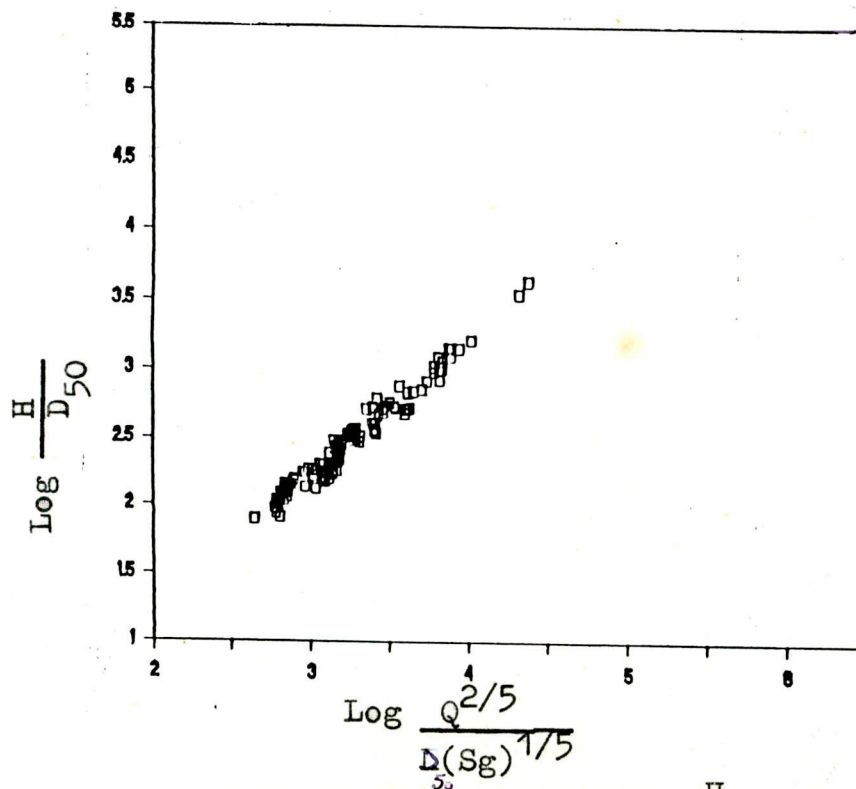


Fig. 6.24 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D(Sg)^{1/5}}$
(Laboratory data)

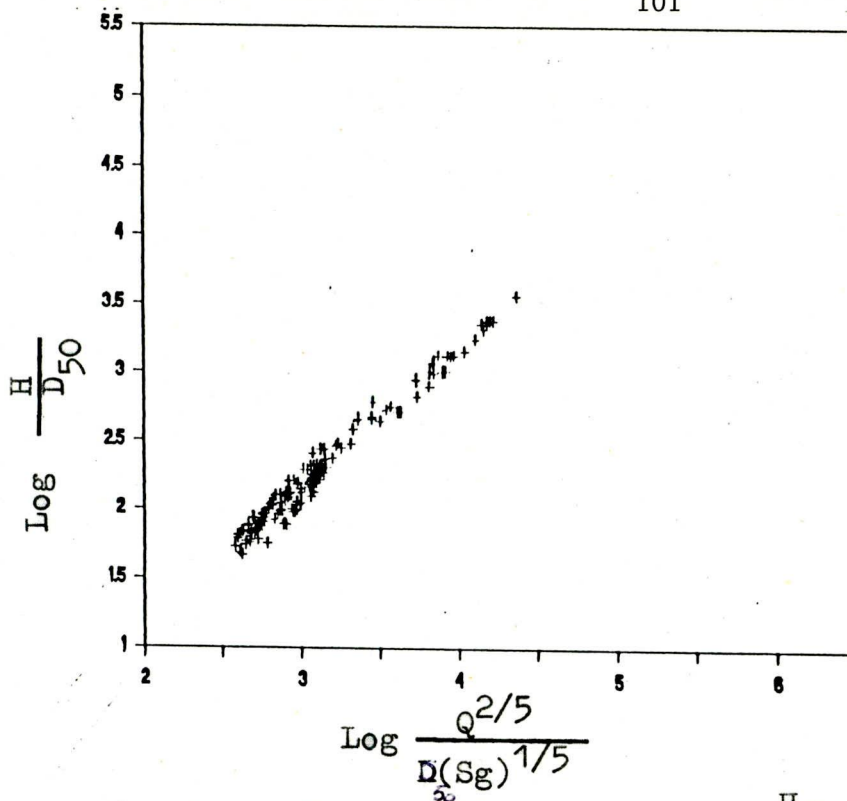


Fig. 6.25 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D(Sg)^{1/5}}$
for flow Fr.No.0.5-0.6
(Laboratory data)

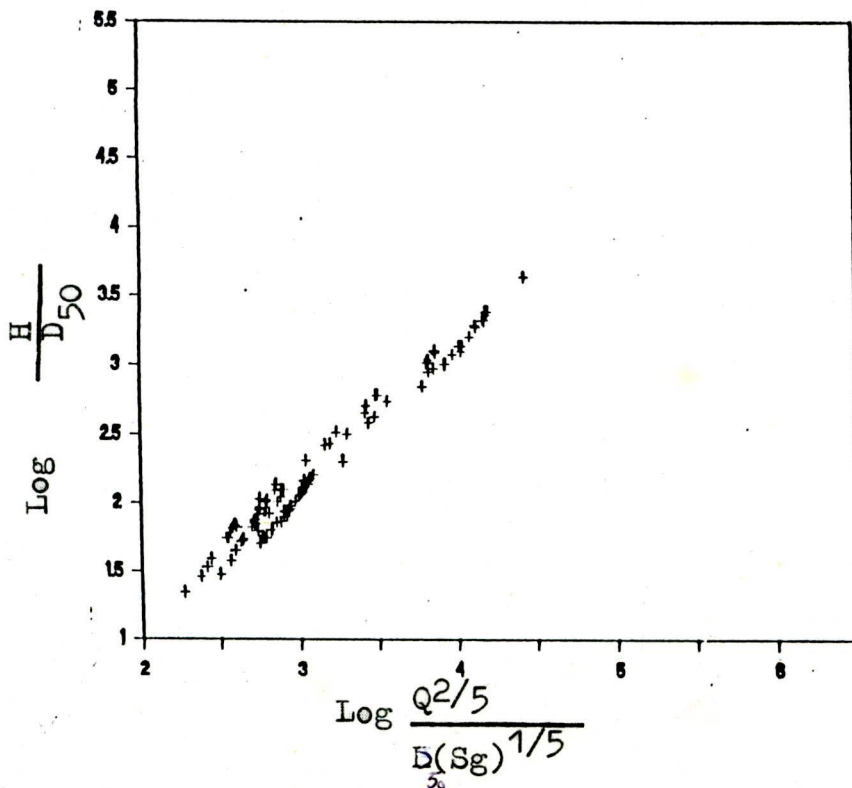


Fig.6.26 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D(Sg)^{1/5}}$
for flow Fr.No.0.6-0.7
(Laboratory data)

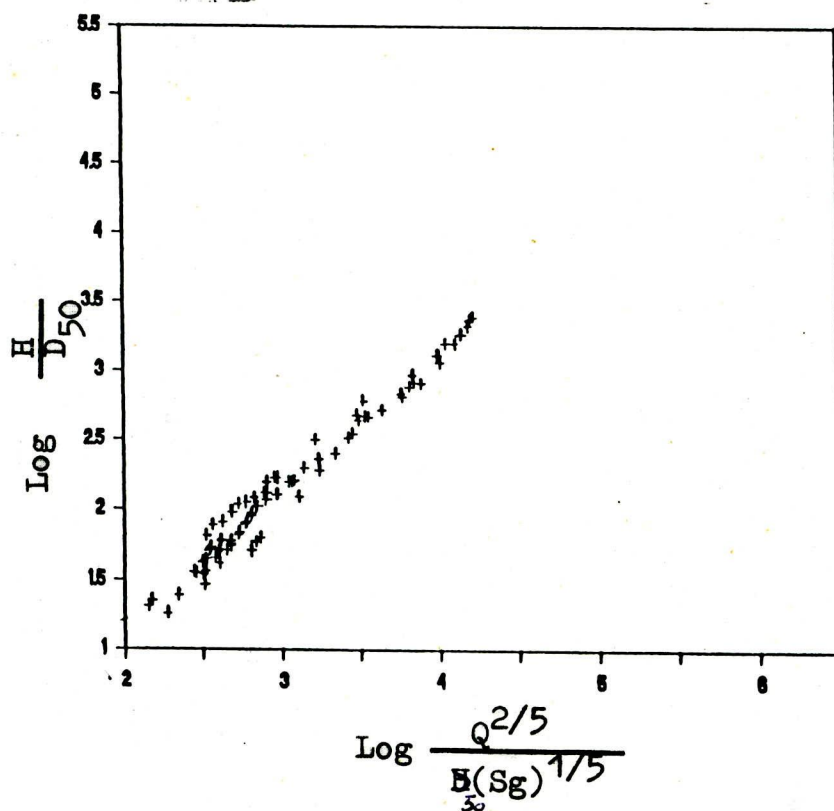


Fig.6.27 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr.No.0.7-0.8
(Laboratory data)

CHAPTER 7

COMPARATIVE TESTING AND ASSESSMENT OF COMPLIANCE OF THE DEVELOPED CORRELATION AGAINST FIELD DATA

7.1 INTRODUCTION:

Laboratory data was initially used in developing the log-log correlation between non-dimensional parameter $-\frac{B}{H}$ and $-\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different concentration, flow Froude number and particle Froude number ranges. The correlation between $-\frac{H}{D_{50}}$ and $-\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ was also developed using the same data for different flow Froude number range. The numerical values of the various parameters developed by the regression technique showed reasonable consistency as depicted in table 6.1, 6.2, 6.3 and 6.4. Now suitability of developed equations against field data would strengthen the viability of the developed equations.

7.2 VERIFICATION OF THE DEVELOPED CORRELATION BETWEEN NON-DIMENSIONAL PARAMETERS

The data compendium contain 1764 sets of field data. For this data the discharge varies from 64.431 l/sec. to 28825680.00 l/sec., width varies from 0.346 m to 1109.472m, depth varies from 0.0189m to 17.2822m, slope varies from 0.0000021 to 0.0126 and median size of bed material varies from 0.020 mm to 76.113mm. Testing of the non-dimensional parameter derived in chapter 3. using field data has been carried out. The findings are sum-

marized in tabular form. During the analysis the data were selected for a concentration range of (100 - 10,000) ppm, median particle size of the bed material less than 2mm, flow Froude number less than 0.8 mm, width depth ratio greater than 5.0, specific gravity of the particle 2.65.

7.2.1 Verification of the non-dimensional terms, $-\frac{B}{H}$ and $-\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for various concentration range with field data only:

Regression equation of non-dimensional parameters $-\frac{B}{H}$ and $-\frac{Q^{2/5}}{H(Sg)^{1/5}}$ were developed solely on the basis of laboratory data were then tested against field data. The equations considered for same concentration range as used in the case of laboratory situation. Statistical properties for the numerical correlation of non-dimensional parameter $-\frac{B}{H}$ and $-\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for various concentration range were determined using field data. Then field and laboratory data were combinedly considered for the correlation of $-\frac{B}{H}$ and $-\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for the selected concentration range to verify the correlation and continuity between laboratory and field situations when only field data were considered, the regression equation between $-\frac{B}{H}$ and $-\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for the chosen concentration range from (100 - 250)ppm was, $Y = 0.416 X^{1.8091}$. For this case coefficient of correlation was 0.8807593. The standard error of $Y_{estimate}$, and standard error of coefficient were found to be 0.106326 and 0.056065 respectively. All of these statisti-

cal properties for other concentration ranges i.e. from (250 - 500)ppm, (500 - 750)ppm, (750 - 1000)ppm, (1000 - 2000)ppm and (2000 - 10,000)ppm were determined using field data and are shown in table 7.1. From the table 7.1 it may be observed that coefficient of correlations are 0.88 and above standard error of $Y_{estimate}$ is below 0.153 and standard error of coefficients are below 0.111 for all concentration range. The exponent of the power type regression equation varies from 1.809 to 2.564. Maximum value of coefficient of correlation 0.973 is obtained for concentration range from (750 - 1000)ppm and in this case the regression equation is $Y = 0.07923 X^{2.564}$. To correlate all the field data (i.e. 890 sets of data for concentration range from 100 ppm to 10,000 ppm regression analysis was carried out and the equation was found to be $Y = 0.143797 X^{2.261112}$. The overall coefficient of correlation is 0.9270296 and a standard error of $Y_{estimate}$ 0.134234 and standard error of coefficient, 0.030658 was obtained.

7.2.2 Verification of the continuity of non-dimensional terms

$\frac{B}{H}$ and $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ for various concentration range using both laboratory and field data combinedly:

Statistical properties for the verification of the initially developed numerical correlation using laboratory data between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ for different concentration range are then considered taking both laboratory and field data combinedly. Regression equation between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ for concentration

range from (100 - 250)ppm using laboratory and field data combinedly was found to be $Y = 0.174 X^{2.133}$. The coefficient of correlation 0.9616, standard error of $Y_{estimate}$ is 0.102183 and standard error of coefficient is 0.026885 were achieved in this case. Statistical properties for other concentration range, i.e. from (250 - 500)ppm, (500 - 750)ppm, (750 - 1000)ppm, (1000 - 2000)ppm, and (2000 - 10000)ppm were also determined using laboratory and field data combinedly. These are summarized in table 7.2. From this table it may be observed that coefficient of correlation vary from 0.96 and above, which indicates the developed correlation between non-dimensional terms, B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different concentration range is feasible and justifiable. From the table 7.2, it can be observed that the exponent and coefficient of the regression equation varies from 2.133 to 2.473 and 0.09065 to 0.17402 respectively. Standard error of $Y_{estimate}$ and standard error of coefficient varies from 0.1022 to 0.14071 and 0.027 to 0.0508 respectively. To visualize the continuity between laboratory and field situation and also for visual observation of the correlation between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different concentration range laboratory and field data are combinedly plotted in the log-log plotting. Fig. 7.1 to 7.6 shows $\log \frac{B}{H}$ Vs. $\log \frac{Q^{2/5}}{H(Sg)^{1/5}}$ for concentration range from (100 - 250)ppm, (250 - 500)ppm, (500 - 750)ppm, (750 - 1000)ppm, (1000 - 2000)ppm, (2000 - 10000)ppm respectively.

From these figures, it can be observed that field data are the continuation of the laboratory data and there are no discon-

tinuity between laboratory and field circumstances. The closer in the matching between the laboratory conditions to field the better is the correlation achieved.

7.2.3 Verification of the non-dimensional terms, $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for various flow Froude number range with field data only:

Numerical correlation were developed between non-dimensional terms $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different flow Froude number range using laboratory data in chapter 6. Now these developed correlation are verified by using field data. The statistical properties are determined between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different flow Froude number range using field data. Regression equation between non-dimensional terms $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for flow Froude number from 0.2-0.3 was found to be $Y = 0.0811951 X^{2.56544}$ with correlation coefficient 0.883511, standard error of $Y_{estimate}$ 0.156838 and standard error of coefficient 0.124681. Statistical properties using field data for flow Froude number ranges from 0.3 - 0.4, 0.4 - 0.5, 0.5 - 0.6, 0.6 - 0.7, 0.7 - 0.8 were determined and are described in table 7.3. From table 7.3 it may be seen that correlation coefficient are above 0.88. Standard error of $Y_{estimate}$ and standard error of coefficient are below 0.157 and 0.1134 respectively. Correlation coefficient as high as 0.9903 for flow Froude number range 0.7-0.8 is also noticeable and for this range of Froude number regression equation has the form $Y = 0.494 X^{1.7993}$. The standard error of $Y_{estimate}$ is 0.029542 and

standard error of coefficient is 0.076171. Using all field data together for flow Froude number range from 0.2 to 0.8 a general regression equation between $-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ is developed and this equation is found to be $Y = 0.225741 X^{2.138748}$. In this case, the correlation coefficient of 0.9304, standard error of $Y_{estimate}$, 0.13063 and standard error of coefficient 0.037573 is obtained.

7.2.4 Verification of the continuity of non-dimensional terms

$-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for various flow Froude number using both laboratory and field data combinedly:

For numerical correlation between laboratory and field data, statistical properties between $-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different flow Froude number ranges are determined using laboratory and field data combinedly. When laboratory and field data are combinedly considered the regression equation between $-\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for flow Froude number range 0.2 - 0.3 is $Y = 0.13314 X^{2.38}$, correlation coefficient 0.9392, standard error of $Y_{estimate}$ of 0.152796 was obtained with standard error of coefficient, 0.074902. All of these statistical properties for other flow Froude number ranges using both laboratory and field data are determined and are summarized in table 7.4. From the tables it may be noticed that coefficient of correlation is higher for combined laboratory and field data then individual use of laboratory data or field data. This confirms the existence of correlation between laboratory and field data with continuity. From the table

it can also be observed that exponent and coefficient of the regression equation varies from 1.799 to 2.565 and 0.07512 to 0.4939 respectively. Standard error of $Y_{estimate}$ and standard error of coefficients are below 0.157 and 0.125 respectively. To visualize the continuity between laboratory and field situation and also for visual observation of the correlation between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different flow Froude number range laboratory and field data are combinedly plotted in the log-log plotting in the same paper. Fig. 7.7 to Fig. 7.12 show the log-log plotting of $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for flow Froude number range from 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-0.8 respectively. From the figs. it can be observed that the correlation developed using laboratory data closely match and extend upto field conditions. Thus numerical correlation as well as plottings indicates that the developed correlation has conceptual basis for its viability.

7.2.5 Verification of non-dimensional terms $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for various particle Froude number range with field data only:

The statistical properties verified by using field for B/H and $Q^{2/5}/[H(Sg)^{1/5}]$ for the same range of particle Froude number as used in the case of laboratory data are determined. The regression equation between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for particle Froude number from 0.4 to 0.5 using field data were found to be $Y = 0.14714 X^{2.266253}$ with a coefficient of correlation 0.983573, standard error of $Y_{estimate}$ 0.00967, and standard error

of coefficients 0.077232. Now all of these statistical properties for these two non-dimensional parameter using field data for particle Froude number ranges from 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-0.9, 0.9-1.0, 1.0-1.1, 1.1-1.2, and 1.2-1.3 are given in a tabular form (Table 7.5). From this table it may be observed that coefficient of correlation is higher than 0.89 and standard error of $Y_{estimate}$ and standard error of coefficients are lower than 0.163 and 0.2634 respectively, which indicates an acceptable relation exist between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for selected particle Froude number ranges. The regression equation using 435 sets of field data within particle Froude number 0.4 to 1.3 between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ was found to be $Y = 0.1200134 X^{2.352}$ with a coefficient of correlation, 0.9393 standard error of $Y_{estimate}$, 0.1326 standard error of coefficient is 0.0413.

7.2.6 Verification of continuity of non-dimensional parameter

$\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different particle Froude number range using both laboratory and field data combinedly:

When laboratory and field data were considered together the regression equation between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for particle Froude number range from 0.4 to 0.5 was found to be $Y = 0.0682103 X^{2.55341}$ with a coefficient of correlation 0.9838, standard error of $Y_{estimate}$ and coefficients were 0.051247 and 0.041957 respectively. These statistical properties for other particle Froude number ranges, i.e. 0.4-0.5, 0.5-0.6, 0.6-0.7,

0.7-0.8, 0.8-0.9, 0.9-1.0, 1.0-1.1, 1.1-1.2, and 1.2-1.3 were determined and are shown in table 7.6. From this table it may be observed that coefficient of correlations are above 0.950 for all particle Froude number range. The exponent and coefficient of the regression equation varies from 2.01984 to 2.553407 and 0.0682103 to 0.2422757 respectively. Standard error of $Y_{estimate}$ and standard error of coefficient varies from 0.051247 to 0.148487 and 0.041957 to 0.075945 respectively. From this table it may also be observed that the highest correlation coefficient is 0.98899 for particle Froude number from 0.7-0.8 and for this range regression equation may be expressed by $Y = 0.149695 X^{2.266595}$ and standard error of $Y_{estimate}$ and standard error of coefficient are 0.074865 and 0.042065 respectively. From tables 7.2, 7.4 and 7.6 it can be seen that coefficient of correlation had higher values when considered combinedly i.e. laboratory and field data taken together than the individual correlation developed using either field data or laboratory data separately. To visualize the continuity between laboratory and field situation and also for visual observation of the continuity of correlation between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ for different particle Froude number range, laboratory and field data are combinedly plotted in the log-log plotting. Fig. 7.13 to Fig. 7.21 show these plottings for particle Froude number range from 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-0.9, 0.9-1.0, 1.0-1.1, 1.1-1.2 and 1.2-1.3 respectively. From the figures, it may be observed that field situations are the continuation of the laboratory situations. Numerical correlation and

also from the visual observation of the correlation i.e. from plottings indicates that laboratory situation is capable to represent the field situation correctly.

7.2.7 Verification of non-dimensional parameter H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for various flow Froude number range using field data:

Regression equation of non-dimensional terms, H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ developed using only laboratory data were tested against field data. The equations were verified by the field data for same flow Froude number range as used for the case of laboratory data. Statistical properties for the numerical correlation of non-dimensional parameter $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for different flow Froude number range are determined using field data. When only field data were considered, the regression equation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for the chosen flow Froude number range from 0.2-0.3 was obtained as $Y = 0.070086 X^{1.0054}$. For this case coefficient of correlation was 0.9705256. The standard error of $Y_{estimate}$ and standard error of coefficient were 0.116138 and 0.023080 respectively. Statistical properties for other flow Froude number range such as from 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-0.8, are determined and are shown in table 7-7. From this table it may be observed that coefficient of correlations are above 0.84 and standard error of $Y_{estimate}$ and standard error of coefficient are below 0.137 and 0.087623 respectively for all ranges of flow Froude number. The exponent and coefficient of the

power type regression equation varies from 0.84 - 0.9968169 and from 0.070086 to 0.57875 respectively. The highest coefficient of correlation, 0.9968169 was found for flow Froude number range, 0.7-0.8, for which the regression equation may be expressed by $Y=0.41464 X^{0.76425}$. The standard error of $Y_{estimate}$ and standard error of coefficient were found to be 0.0293 and 0.0180 respectively. Correlation were tried for all data (505 sets of data) taken together for flow Froude number range from 0.2-0.8, and the regression equation obtained was $Y=0.224688 X^{0.878403}$. The overall correlation coefficient was then achieved as 0.9272315, standard error of $Y_{estimate}$ 0.1403 and standard error of coefficients is 0.01154.

7.2.8 Verification of the continuity of non-dimensional terms

H/D_{50} and $\frac{Q^{2/5}}{D_{50}^{1/5}(Sg)^{1/5}}$ for various flow Froude number with both laboratory and field data combinedly.

Statistical properties of the correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}^{1/5}(Sg)^{1/5}}$ for different flow Froude number range were developed using both laboratory and field data combinedly. The regression equation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}^{1/5}(Sg)^{1/5}}$ for flow Froude number range from 0.2-0.3 for this case could be expressed as $Y=0.336X^{0.8634}$ with correlation coefficient, 0.9410913, standard error of $Y_{estimate}$ 0.161663, and standard error of coefficient 0.026901. Statistical properties for other flow Froude number ranges such as 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7 and 0.7-0.8 were

determined and are shown in table 7-8. From this table it appears that coefficient of correlations are 0.927 and above which indicates that degree of compliance between H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for different flow froude number ranges are acceptable. From this table, it is observed that the exponent and coefficient of the regression equation varies from 0.656823 to 0.889528 and 0.2782915 to 2.2698335 respectively. Standard error of $Y_{estimate}$ and standard error of coefficient varies from 0.12362 to 1.61663 and 0.011263 to 0.026901 respectively.

To visualize the continuity between laboratory and field situation and also for visual observation of the correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for different flow Froude number range, laboratory and field data are combinedly plotted in the log-log plotting. Fig. 7.22 to 7.27 show these log log plottings for different range from 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7 and 0.7-0.8 respectively. From the plotting it can be observed that field situation slightly deviate from laboratory situation. Probable deviation of laboratory data may be due to resistance.

In the laboratory cases, the width is fixed discharge and bed material size are pre-determined. Often charge and in some instances slope is also controlled. Thus too many constraints are imposed. Moreover laboratory condition do not properly simulate the field flow complexities. Nevertheless, the deviation was small and the correlation continuity may be acceptable.

TABLE 7.1

Summary of the statistical properties for the correlation of non-dimensional parameters, $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ and B/H , for different concentration range using field data. (Number within the parenthesis indicates the no. of data used in the correlation)

Concentration Range	Regression Equation	Coefficient of correlation	Std Error of Y Estimate	Std Error of Coefficient
(100-250) ppm (303)	$Y = 0.416 X^{1.8091}$	0.88076	0.10633	0.0561
(250-500) ppm (163)	$Y = 0.1005 X^{2.4005}$	0.91422	0.1355	0.0838
(500-750) ppm (96)	$Y = 0.0757 X^{2.5408}$	0.92111	0.1525	0.1107
(750-1000) ppm (46)	$Y = 0.0792 X^{2.5638}$	0.97284	0.11362	0.0919
(1000-2000) ppm (152)	$Y = 0.1306953 X^{2.3502}$	0.94851	0.11479	0.0640
(2000-10000) ppm (138)	$Y = 0.1745862 X^{2.15961}$	0.95417	0.12499	0.0580

$$Y = B/H, \quad X = \frac{Q^{2/5}}{H(Sg)^{1/5}}$$

TABLE 7.2

Summary of the statistical properties for the correlation of non-dimensional parameters, $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$, for different concentration range using both laboratory and field data combinedly. (Number within the parenthesis indicates the no. of data used in the correlation)

Concentration Range	Regression Equation	Coefficient of correlation	Std Error of Y Estimate	Std Error of Coefficient
(100 - 250) ppm (515)	$Y = 0.17402 X^{2.1328}$	0.9616	0.10218	0.0269
(250 - 500) ppm (290)	$Y = 0.12714 X^{2.3015}$	0.9584	0.11871	0.04037
(500 - 750) ppm (169)	$Y = 0.12015 X^{2.3716}$	0.9697	0.12916	0.04625
(750 - 1000) ppm (109)	$Y = 0.1001 X^{2.4691}$	0.9781	0.10422	0.05081
(1000-2000) ppm (262)	$Y = 0.09065 X^{2.4731}$	0.9747	0.12408	0.03513
(2000-10000) ppm (217)	$Y = 0.1236 X^{2.271}$	0.9697	0.14071	0.03904

$$Y = B/H, \quad X = \frac{Q^{2/5}}{H(Sg)^{1/5}}$$

TABLE 7.3

Summary of statistical properties for the correlation of non-dimensional parameters, B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$, for different flow

Froude number range using field data (Number within the parenthesis indicates the no. of data used in the correlation)

Froude Number Range	Regression Equation	Coefficient of Correlation	Std Error of Y_{Estimate}	Std Error of Coefficient
0.2-0.3 (121)	$Y = 0.0812 X^{2.565}$	0.88351	0.15684	0.12468
0.3-0.4 (175)	$Y = 0.1879 X^{2.255}$	0.95698	0.11432	0.05198
0.4-0.5 (128)	$Y = 0.15699 X^{2.251}$	0.98927	0.04939	0.02961
0.5-0.6 (45)	$Y = 0.18203 X^{2.1243}$	0.97313	0.06328	0.07665
0.6-0.7 (23)	$Y = 0.075117 X^{2.3425}$	0.97627	0.06068	0.11338
0.7-0.8 (13)	$Y = 0.4939 X^{1.799}$	0.99029	0.02954	0.076171

$$Y = B/H, \quad X = \frac{Q^{2/5}}{H(Sg)^{1/5}}$$

TABLE 7.4

Summary of the statistical properties for the correlation of non-dimensional parameters, B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$, for different flow Froude number range using both laboratory and field data combinedly. (Number within the parenthesis indicates the no. of data used in the correlation)

Froude Number Range	Regression Equation	Coefficient of Correlation	Std Error of Y Estimate	Std Error of Coefficient
0.2-0.3 (137)	$Y = 0.13314 X^{2.3800}$	0.93918	0.1528	0.0749
0.3-0.4 (278)	$Y = 0.1479 X^{2.3379}$	0.983403	0.10399	0.02596
0.4-0.5 (269)	$Y = 0.1351 X^{2.3034}$	0.990594	0.06736	0.01947
0.5-0.6 (235)	$Y = 0.1289 X^{2.2889}$	0.979116	0.08835	0.03032
0.6-0.7 (138)	$Y = 0.15879 X^{2.10399}$	0.981256	0.08786	0.03543
0.7-0.8 (118)	$Y = 0.13807 X^{2.20105}$	0.95733	0.10267	0.06169

$$Y = B/H, \quad X = \frac{Q^{2/5}}{H(Sg)^{1/5}}$$

TABLE 7.5

Summary of statistical properties for the correlation of non-dimensional parameters, B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$, for different particle Froude

number range using field data. (Number within the parenthesis indicates the no. of data used in the correlation)

V_* $\sqrt{gd_{50}}$	Range	Regression Equation	Coefficient of Correlation	Std Error of Y_{Estimate}	Std Error of Coefficient
0.4-0.5 (31)		$Y = 0.14714 X^{2.266}$	0.9836	0.00967	0.07723
0.5-0.6 (14)		$Y = 0.12903 X^{2.327}$	0.9593	0.08276	0.19766
0.6-0.7 (10)		$Y = 0.17591 X^{2.1559}$	0.9451	0.16320	0.26340
0.7-0.8 (27)		$Y = 0.1633 X^{2.2386}$	0.9810	0.09332	0.08846
0.8-0.9 (27)		$Y = 0.27407 X^{1.9725}$	0.9140	0.1383	0.17513
0.9-1 (47)		$Y = 0.14717 X^{2.2749}$	0.95187	0.14071	0.10919
1 -1.1 (74)		$Y = 0.07051 X^{2.5651}$	0.9281	0.12518	0.12133
1.1-1.2 (84)		$Y = 0.1089 X^{2.4145}$	0.8965	0.14778	0.13179
1.2-1.3 (121)		$Y = 0.134 X^{2.2858}$	0.92550	0.13885	0.08575

$$Y = B/H, \quad X = \frac{Q^{2/5}}{H(Sg)^{1/5}}$$

TABLE 7.6

Summary of statistical properties for the correlation of non-dimensional parameters, B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$, for different particle Froude number range using both laboratory and field data combinedly. (Number within the parenthesis indicates the no. of data used in the correlation)

V_* $\sqrt{gd_{50}}$	Range	Regression Equation	Coefficient of Correlation	Std Error of Y Estimate	Std Error of Coefficient
0.4-0.5 (125)		$Y = 0.06821 X^{2.5534}$	0.9838	0.05125	0.04195
0.5-0.6 (73)		$Y = 0.10928 X^{2.3662}$	0.9674	0.07231	0.07346
0.6-0.7 (53)		$Y = 0.19036 X^{2.1265}$	0.96898	0.08633	0.07594
0.7-0.8 (67)		$Y = 0.149695 X^{2.2666}$	0.98899	0.07487	0.04206
0.8-0.9 (86)		$Y = 0.24228 X^{2.0198}$	0.9490	0.11247	0.07320
0.9-1 (101)		$Y = 0.15658 X^{2.2460}$	0.9675	0.13802	0.05900
1-1.1 (115)		$Y = 0.112502 X^{2.3997}$	0.9778	0.1192	0.04840
1.1-1.2 (140)		$Y = 0.10996 X^{2.4012}$	0.96412	0.14849	0.05628
1.2-1.3 (167)		$Y = 0.14479 X^{2.2526}$	0.96065	0.13723	0.05070

$$Y = B/H, \quad X = \frac{Q^{2/5}}{H(Sg)^{1/5}}$$

TABLE 7.7

Summary of statistical properties for the correlation of the non-dimensional parameters, H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$, for different flow Froude number range using field data (Number within the parenthesis indicates the no. of data used in the correlation)

Froude Number Range	Regression Equation	Coefficient of Correlation	Std Error of Estimate	Std Error of Coefficient
0.2-0.3 (119)	$Y = 0.07009 X^{1.0054}$	0.97053	0.11614	0.0230
0.3-0.4 (175)	$Y = 0.57875 X^{0.7824}$	0.93083	0.13644	0.0233
0.4-0.5 (128)	$Y = 0.2534 X^{0.8653}$	0.97707	0.12092	0.0168
0.5-0.6 (45)	$Y = 0.16603 X^{0.8938}$	0.84117	0.123797	0.0876
0.6-0.7 (23)	$Y = 0.107273 X^{0.9153}$	0.92969	0.11373	0.0791
0.7-0.8 (13)	$Y = 0.41464 X^{0.7642}$	0.99682	0.02935	0.0184

$$Y = H/D_{50}, \quad X = \frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$$

TABLE 7.8

Summary of statistical properties for the correlation of the non-dimensional parameters H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$, for different flow Froude number range using both laboratory and field data combinedly. (Number within the parenthesis indicates the no. of data used in the correlation)

Froude Number Range	Regression Equation	Coefficient of Correlation	Std Error of $Y_{Estimate}$	Std Error of Coefficient
0.2-0.3 (135)	$Y = 0.33568 X^{0.8634}$	0.94109	0.16166	0.0269
0.3-0.4 (273)	$Y = 2.2698 X^{0.6568}$	0.9175	0.15384	0.0173
0.4-0.5 (272)	$Y = 0.8307 X^{0.7608}$	0.9555	0.14799	0.0142
0.5-0.6 (236)	$Y = 0.58374 X^{0.7977}$	0.9776	0.12362	0.01126
0.6-0.7 (139)	$Y = 0.4649 X^{0.81845}$	0.97113	0.15752	0.01717
0.7-0.8 (118)	$Y = 0.2783 X^{0.8895}$	0.96323	0.14115	0.02304

$$Y = H/D_{50}, \quad X = \frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$$

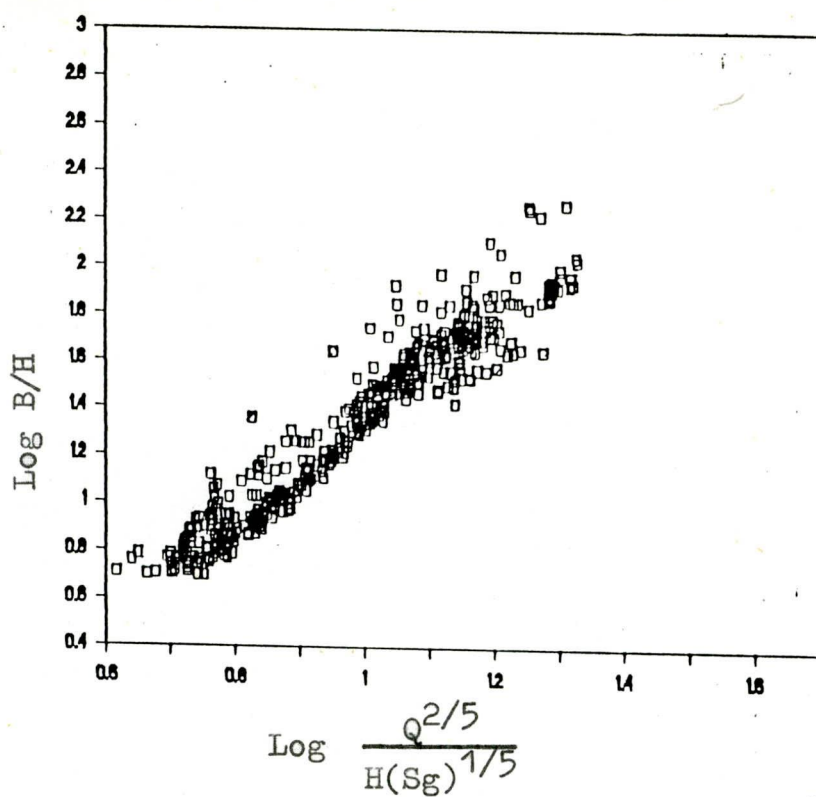


Fig.7.1 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from $H(Sg)^{1/5}$
(100-250)ppm
(Laboratory and field data combinedly)

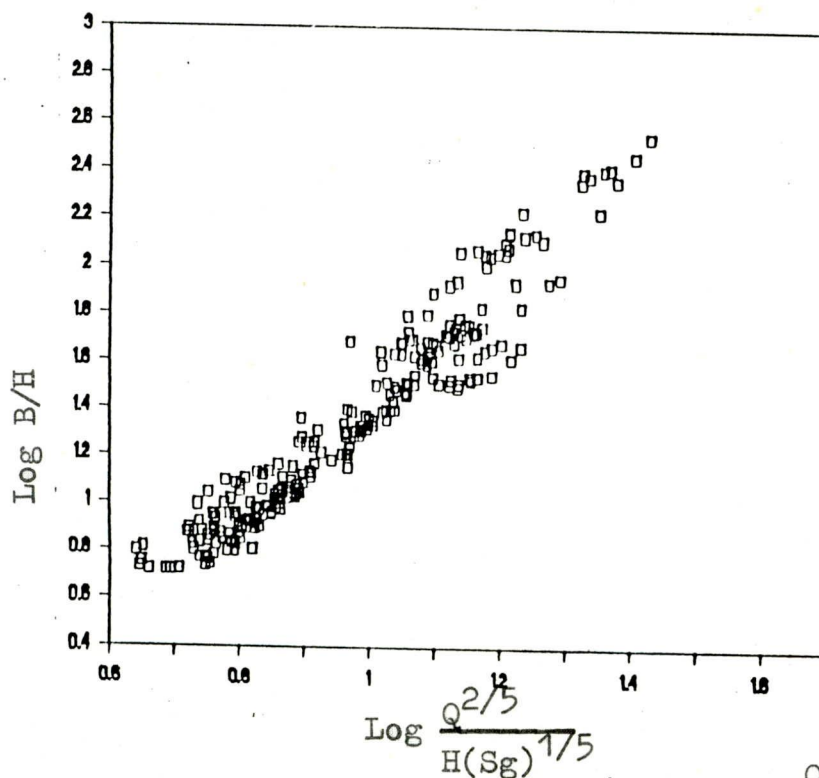


Fig.7.2 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from $H(Sg)^{1/5}$
(250-500)ppm
(Laboratory and field data combinedly)

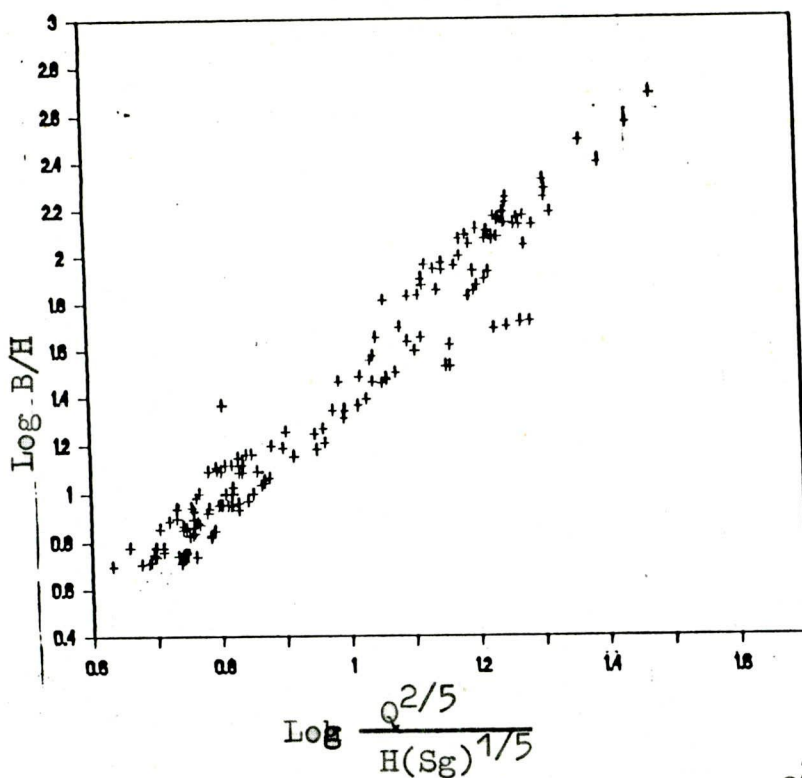


Fig.7.3 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from $H(Sg)^{1/5}$
(500-750)ppm
(Laboratory and field data combinedly)

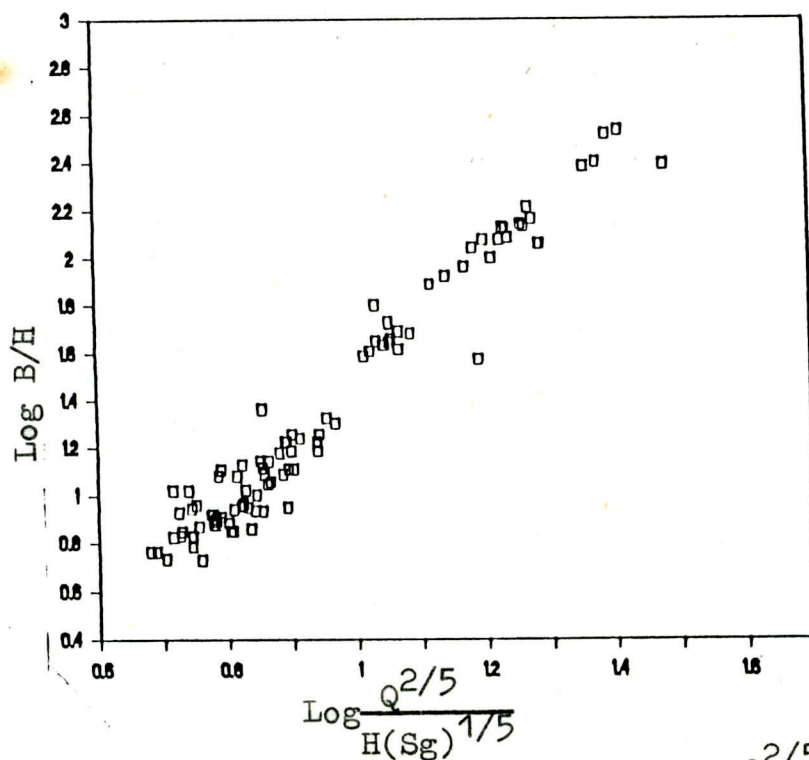


Fig.7.4 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from $H(Sg)^{1/5}$
(750-1000)ppm
(Laboratory and field data combinedly)

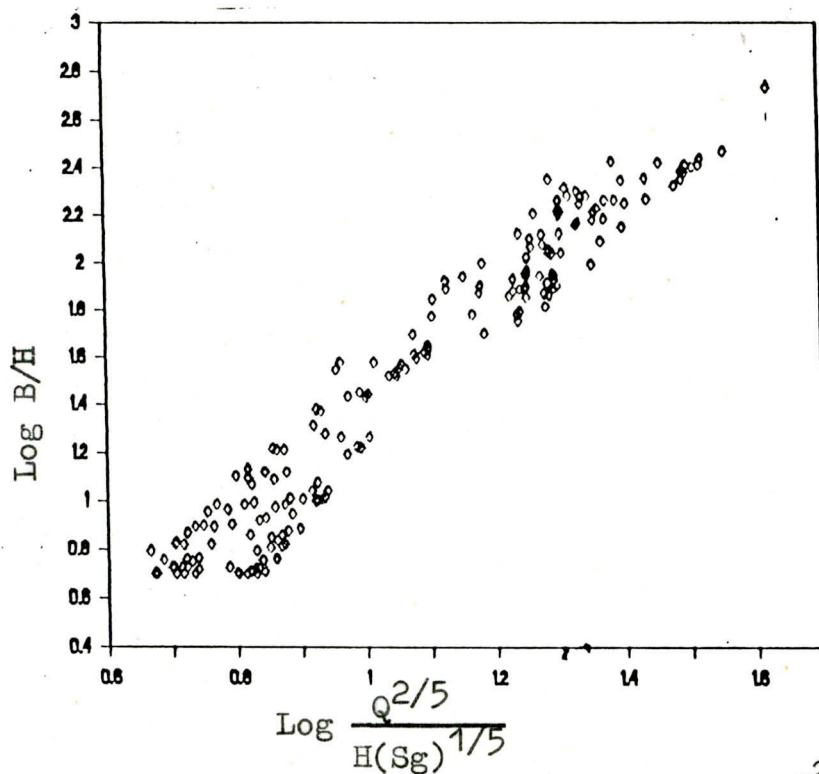


Fig.7.5 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from $H(Sg)$
(1,000-2,000)
(Laboratory and field data combinedly)

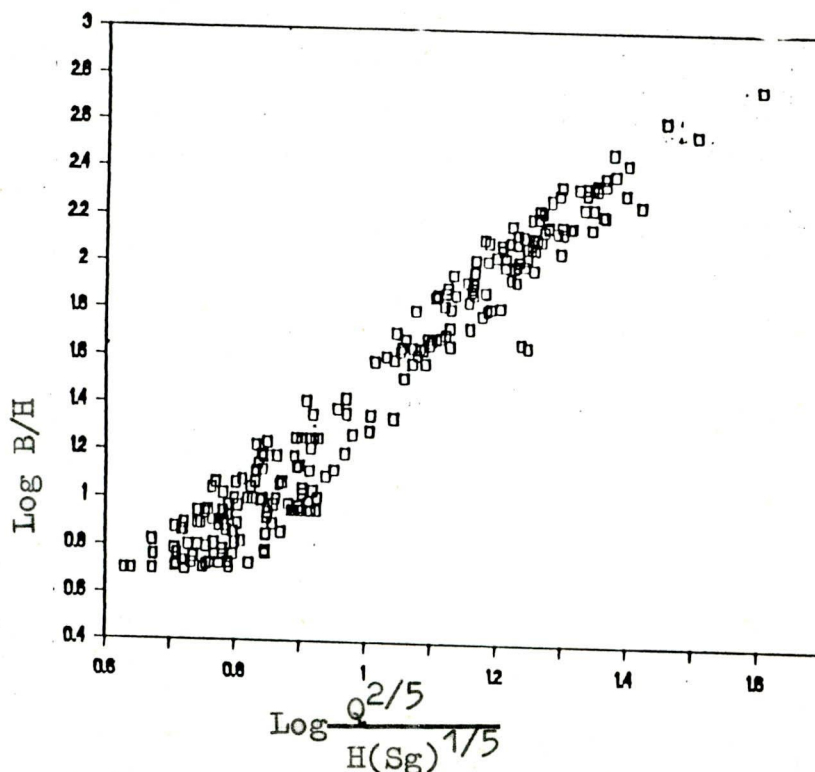


Fig.7.6 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for concentration range from $H(Sg)$
(2,000-10,000)ppm
(Laboratory and field data combinedly)

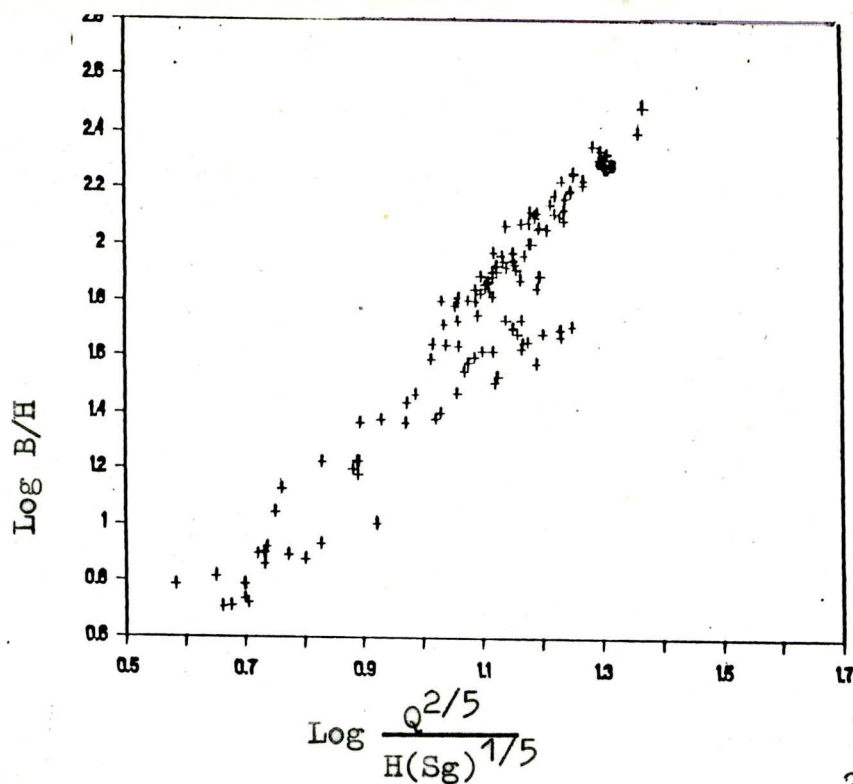


Fig.7.7 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr.No.0.2-0.3
(Laboratory and field data combinedly)

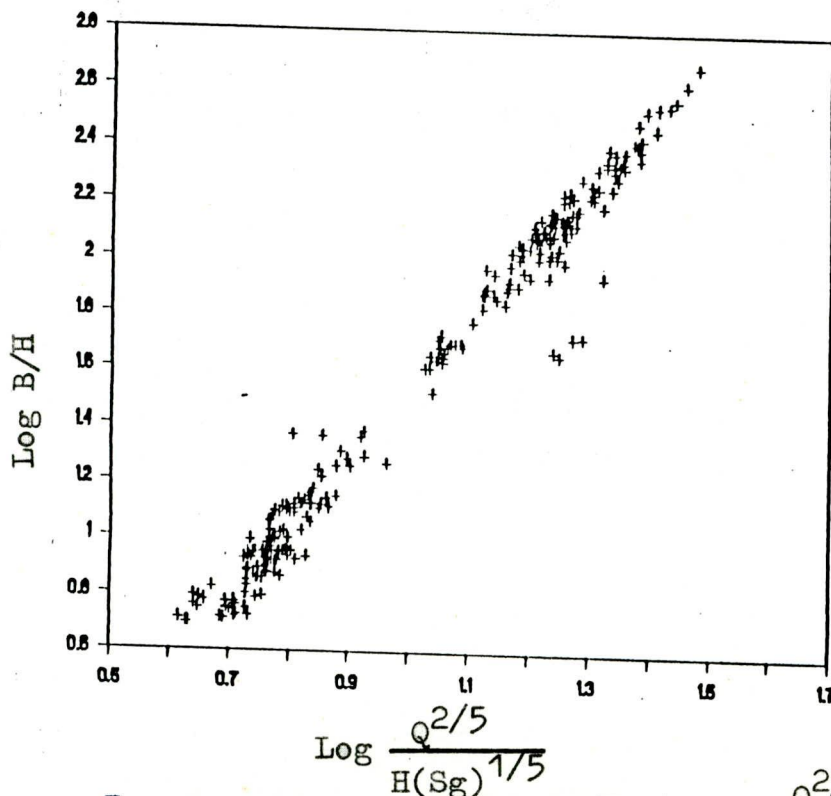


Fig.7.8 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr.No.0.3-0.4
(Laboratory and field data combinedly)

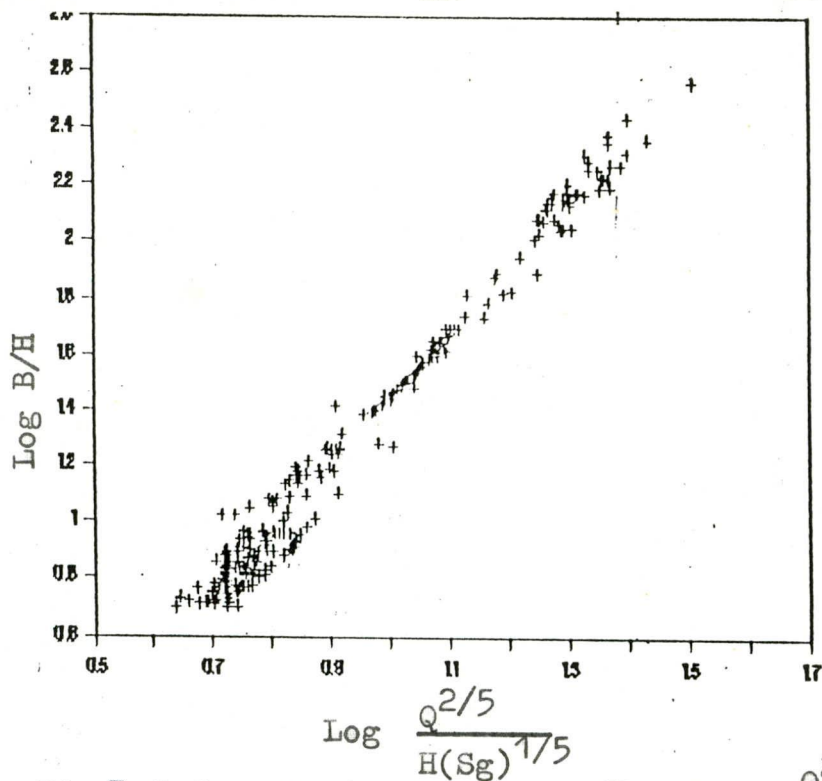


Fig.7.9 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr.No.0.4-0.5
(Laboratory and field data combinedly)

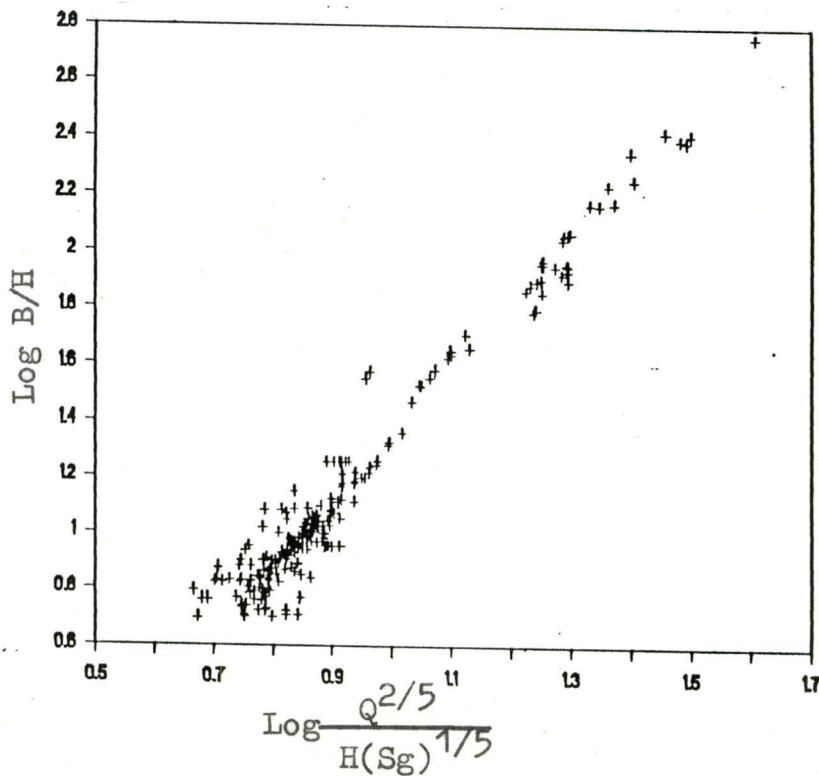


Fig.7.10 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr.No.0.5-0.6
(Laboratory and field data combinedly)

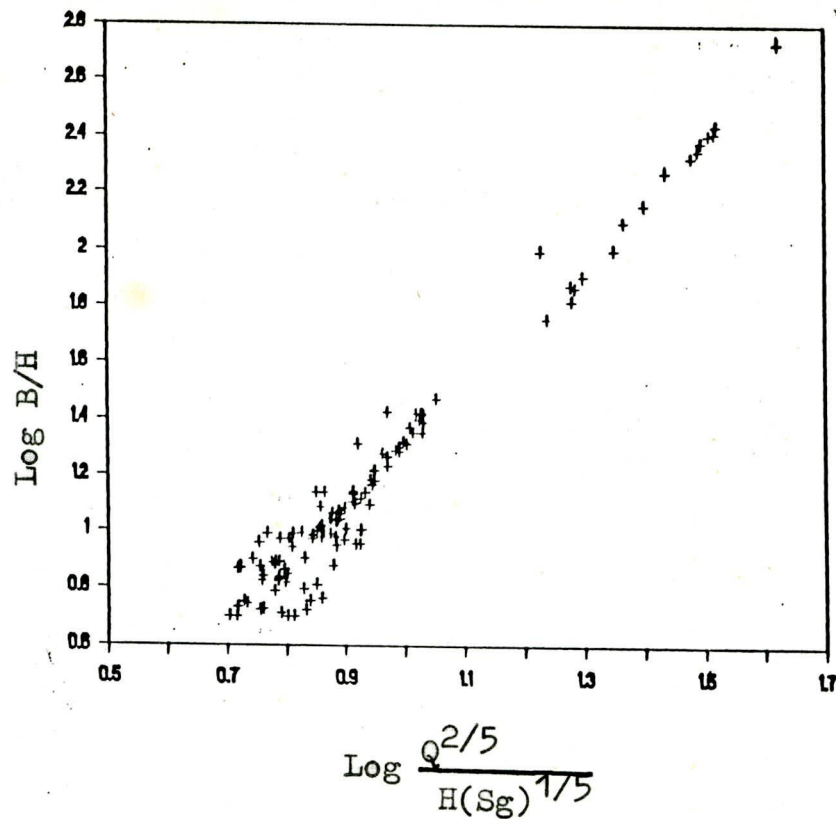


Fig. 7.11 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr.No. 0.6-0.7
(Laboratory and field data combinedly)

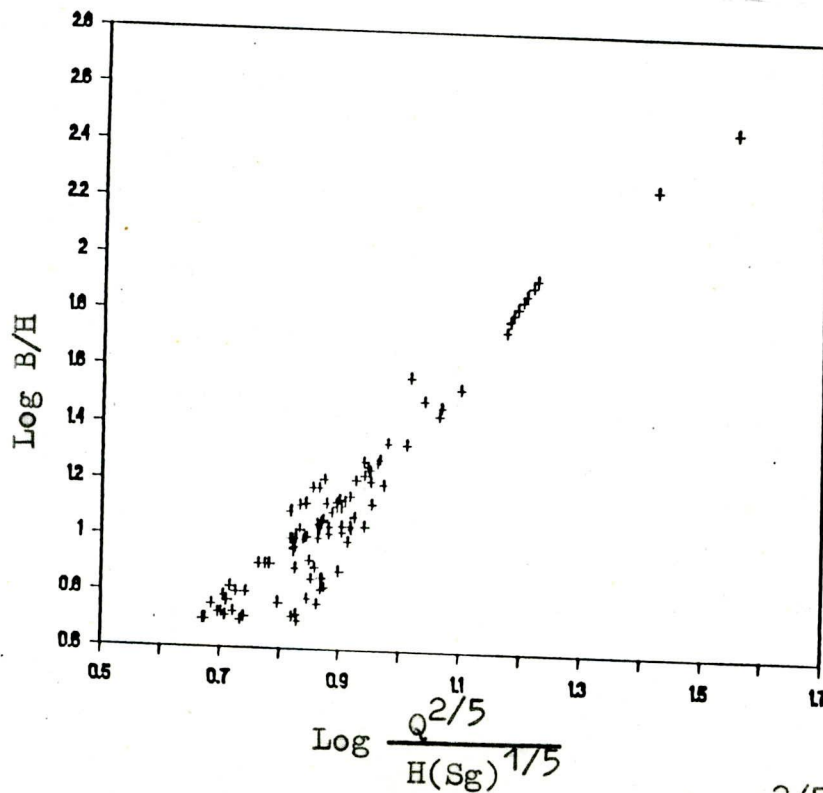


Fig. 7.12 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for flow Fr.No. 0.7-0.8
(Laboratory and field data combinedly)

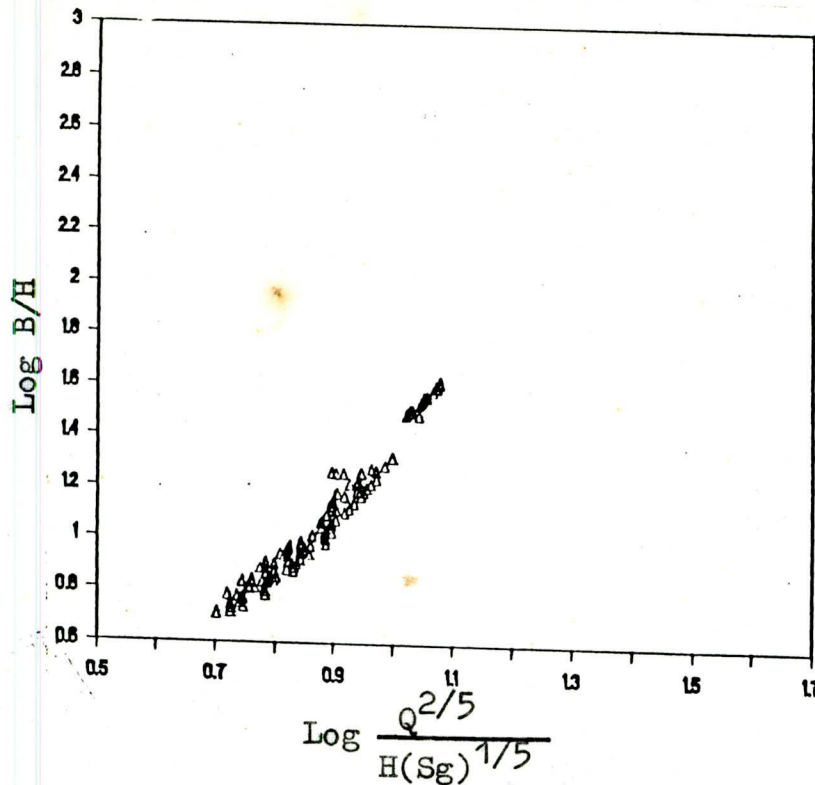


Fig.7.13 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for particle Fr.No.0.4-0.5
(Laboratory and field data combinedly)

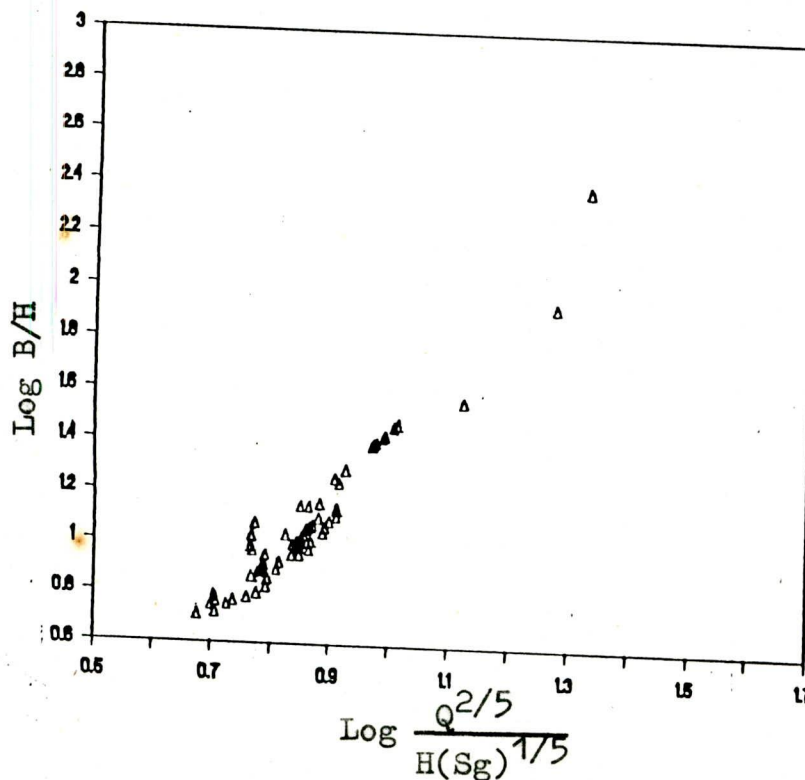


Fig.7.14 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for particle Fr.No.0.5-0.6
(Laboratory and field data combinedly)

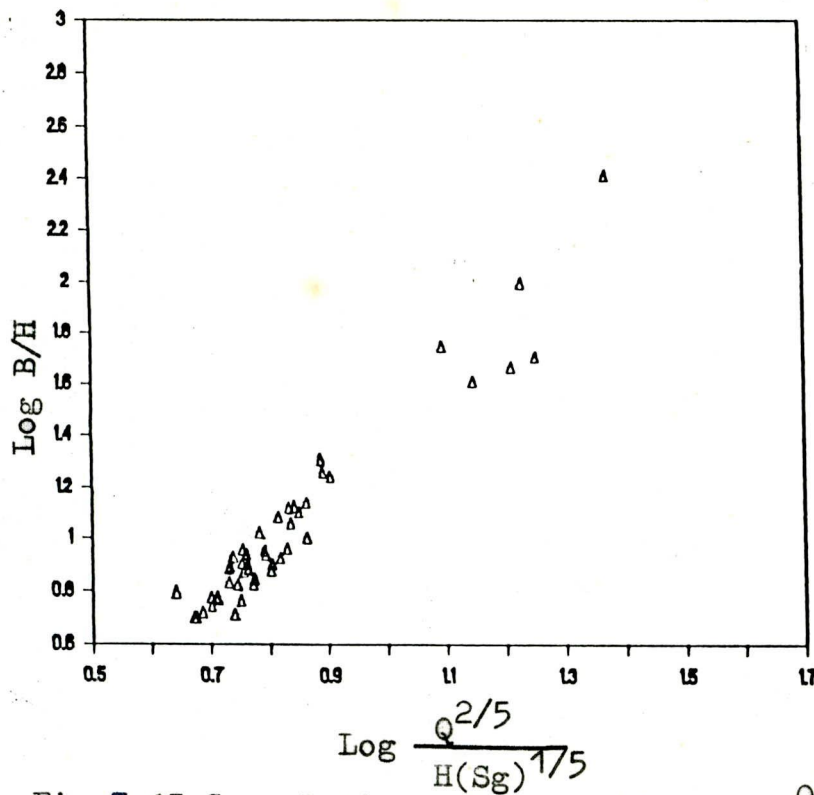


Fig.7.15 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for particle Fr.No.0.6-0.7
(Laboratory and field data combined)

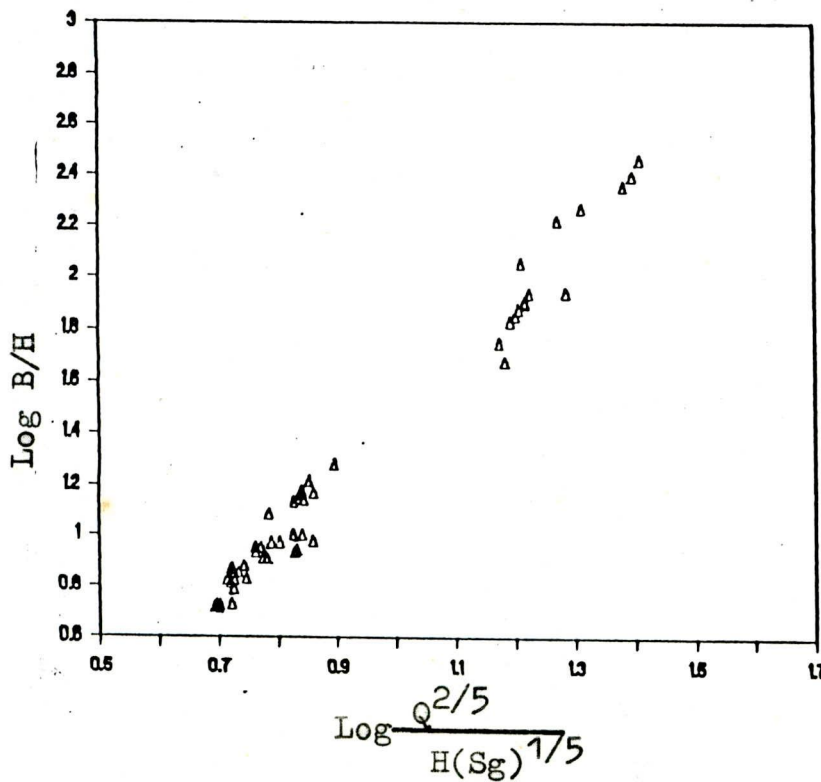


Fig.7.16 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for particle Fr.No.0.7-0.8
(Laboratory and field data combined)

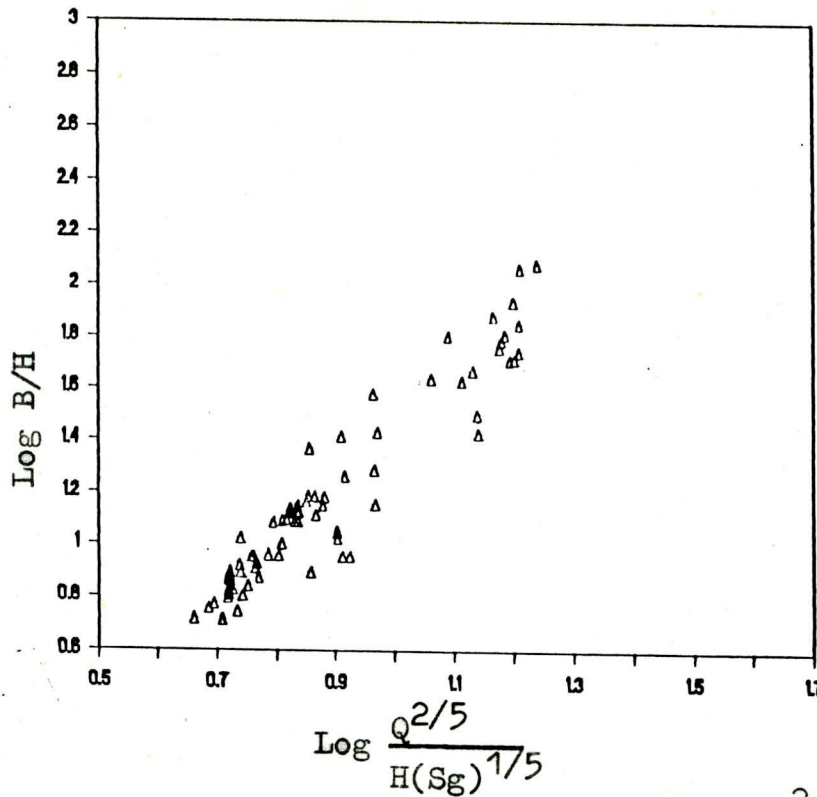


Fig. 7.17 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for particle Fr.No. 0.8-0.9
(Laboratory and field data combinedly)

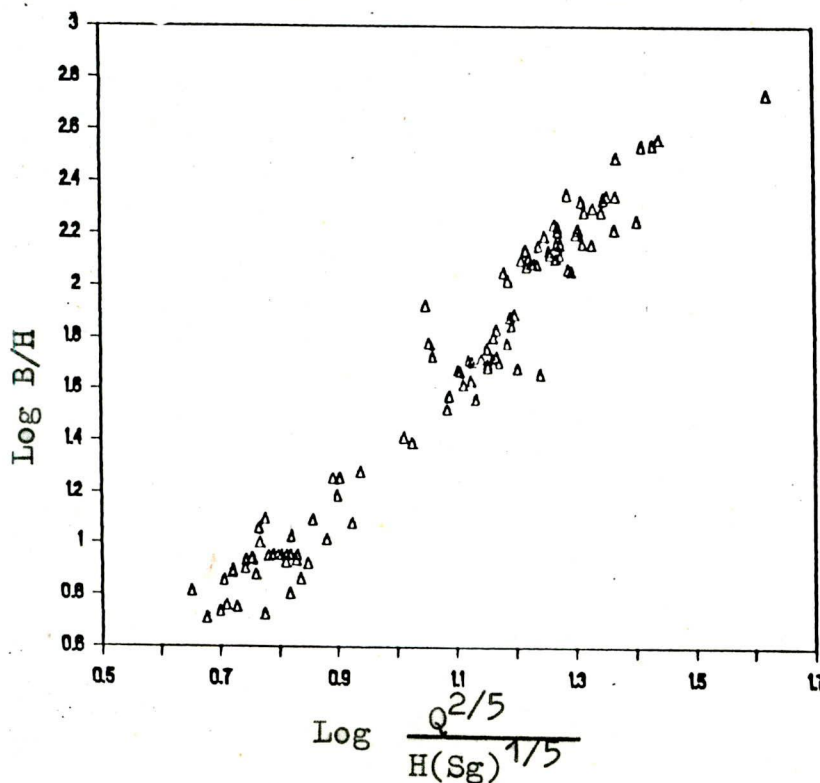


Fig. 7.18 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for particle Fr.No. 0.9-1.0
(Laboratory and field data combinedly)

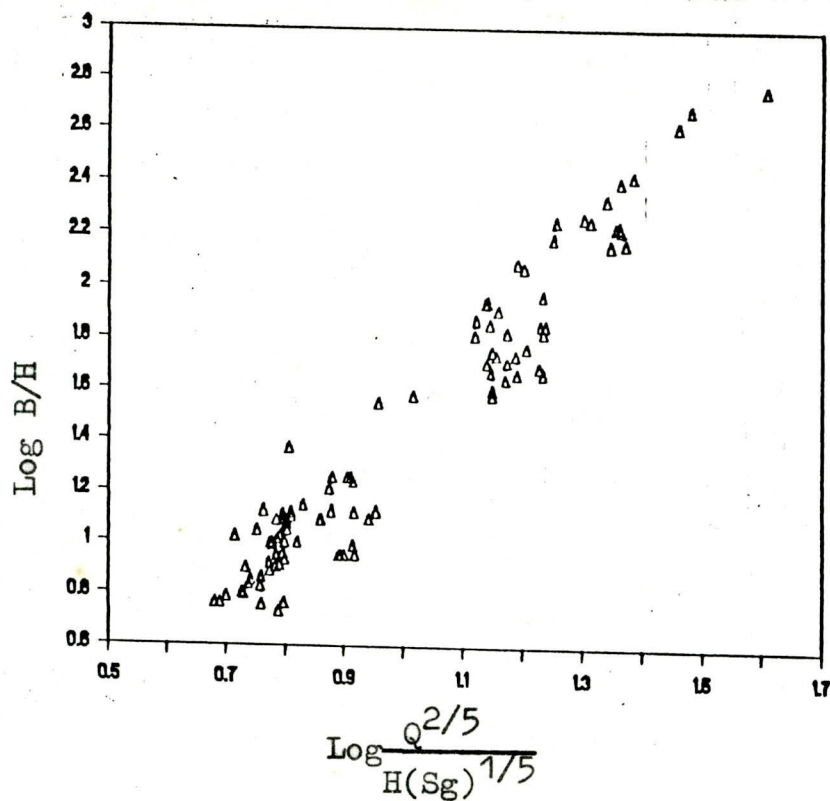


Fig. 7.19 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for particle Fr.No. 1.0-1.1 (Laboratory and field data combinedly)

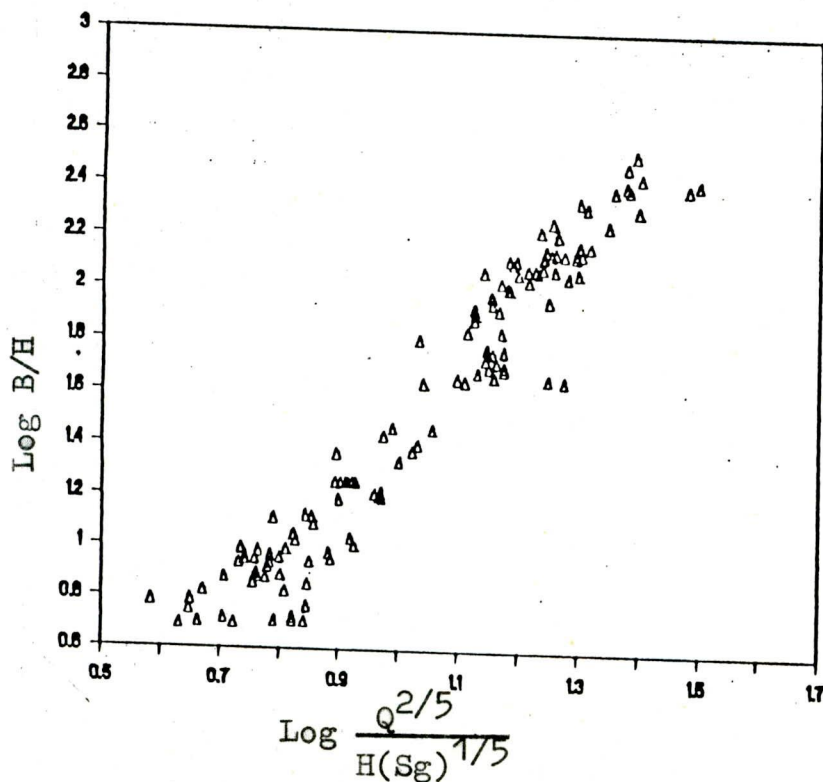


Fig. 7.20 Correlation between B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for particle Fr.No. 1.1-1.2 (Laboratory and field data combinedly)

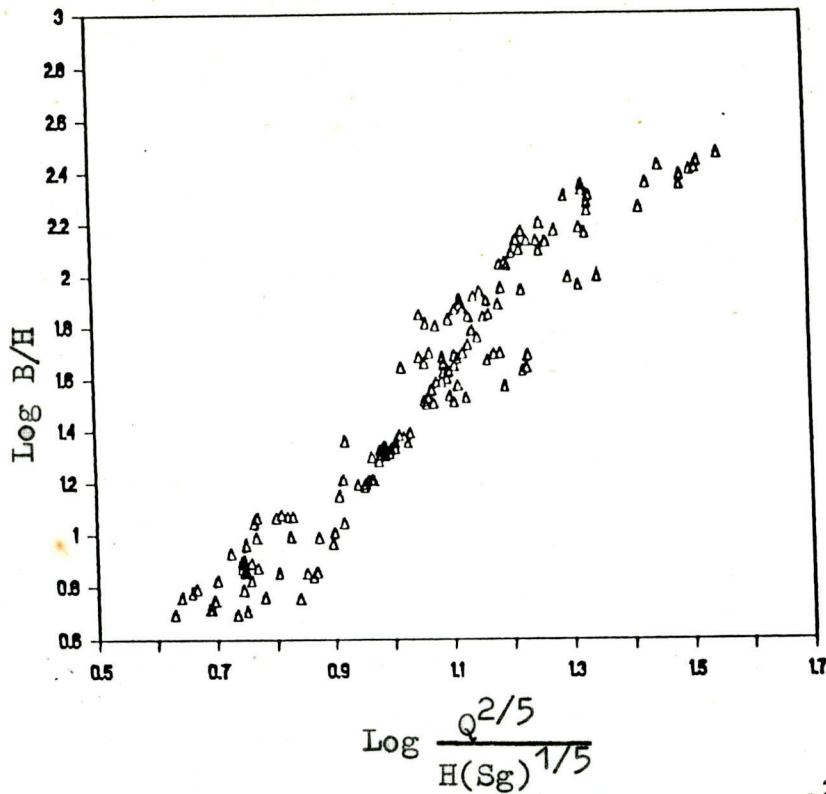


Fig. 7.21 Correlation between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$
for particle Fr.No. 1.2-1.3
(Laboratory and field data combinedly)

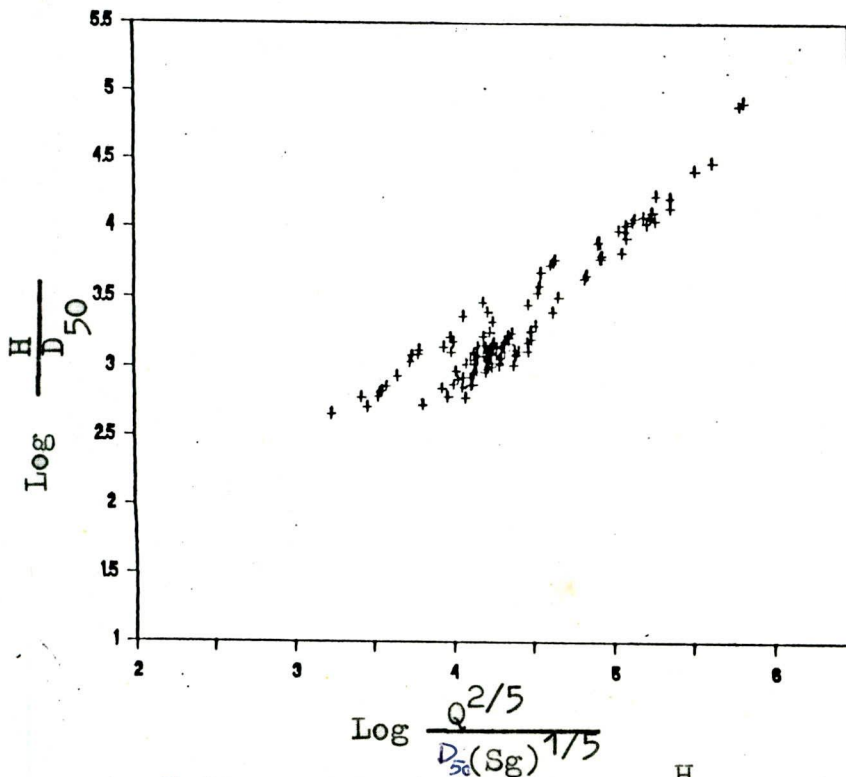


Fig. 7.22 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$
for flow Fr.No. 2.0-0.3
(Laboratory and field data combinedly)

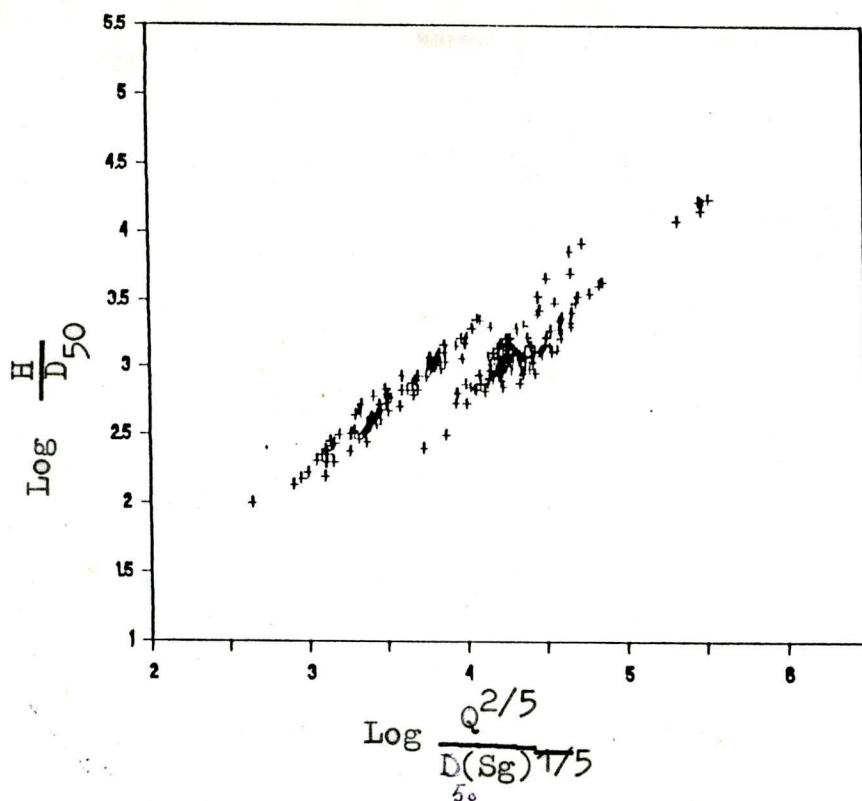


Fig.7.23 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D(Sg)^{1/5}}$
for flow Fr.No.0.3-0.4
(Laboratory and field data combinedly)

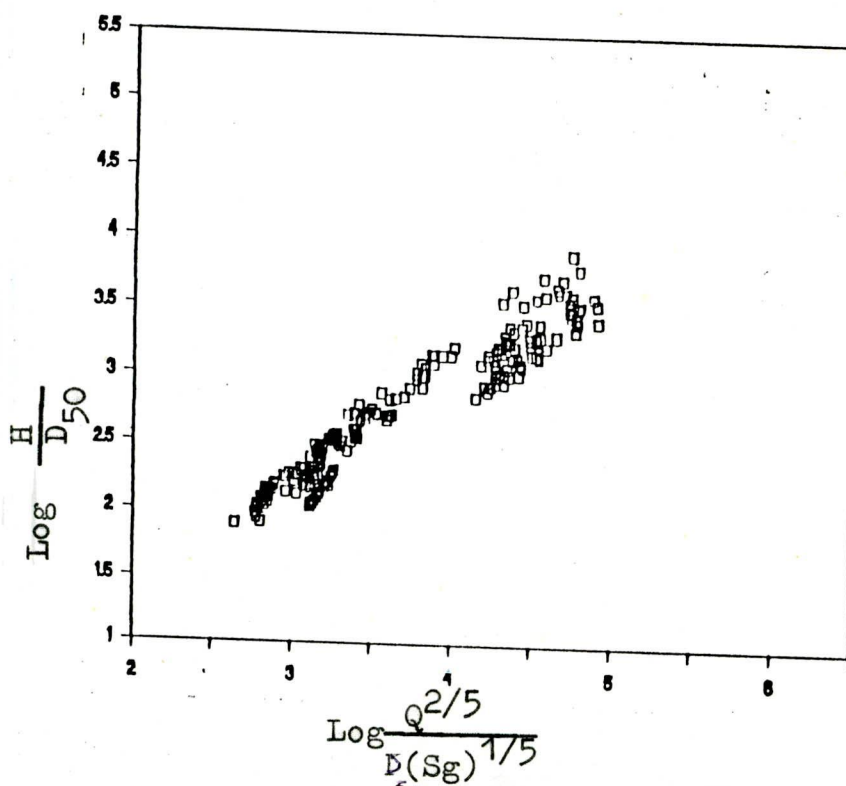


Fig.7.24 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D(Sg)^{1/5}}$
for flow Fr.No.0.4-0.5
(Laboratory and field data combinedly)

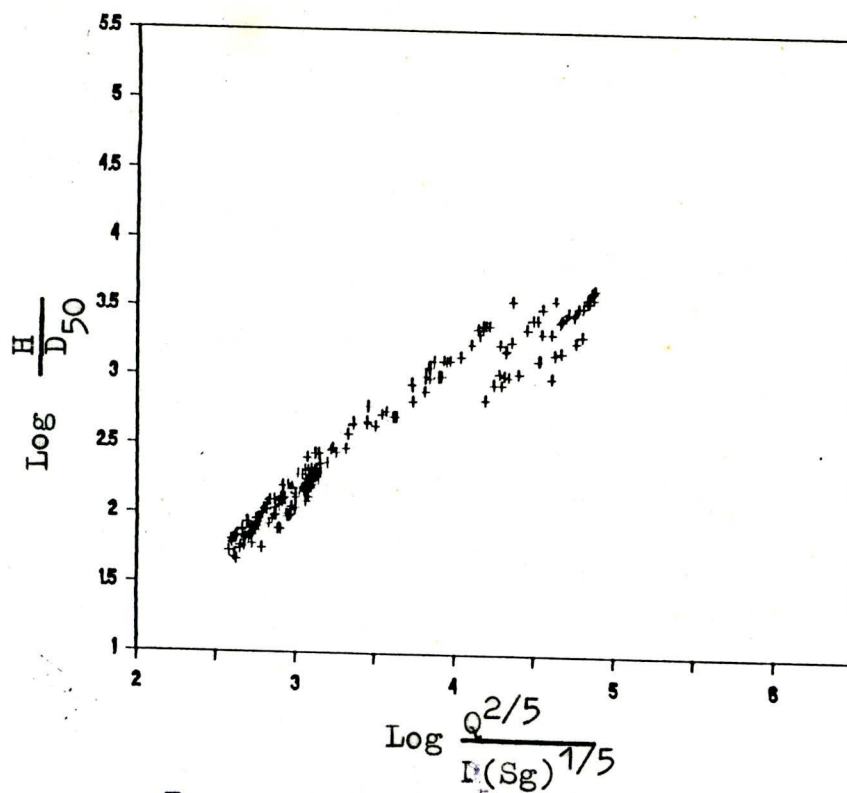


Fig. 7.25 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D(Sg)^{1/5}}$ for flow Fr.No. 0.5-0.6 (Laboratory and field data combinedly)

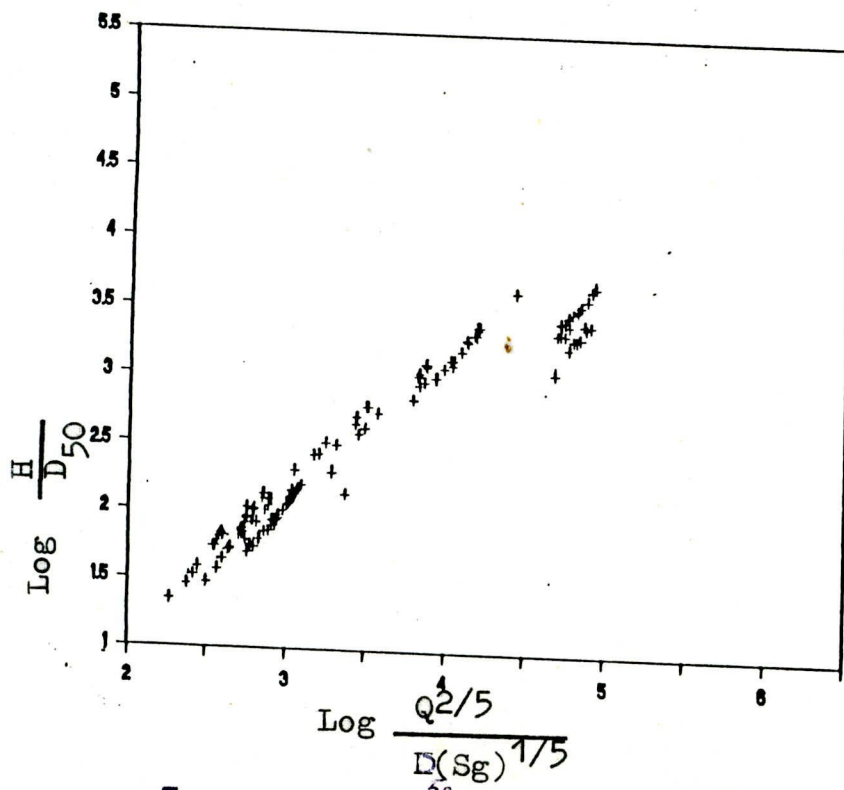


Fig. 7.26 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D(Sg)^{1/5}}$ for flow Fr.No. 0.6-0.7 (Laboratory and field data combinedly)

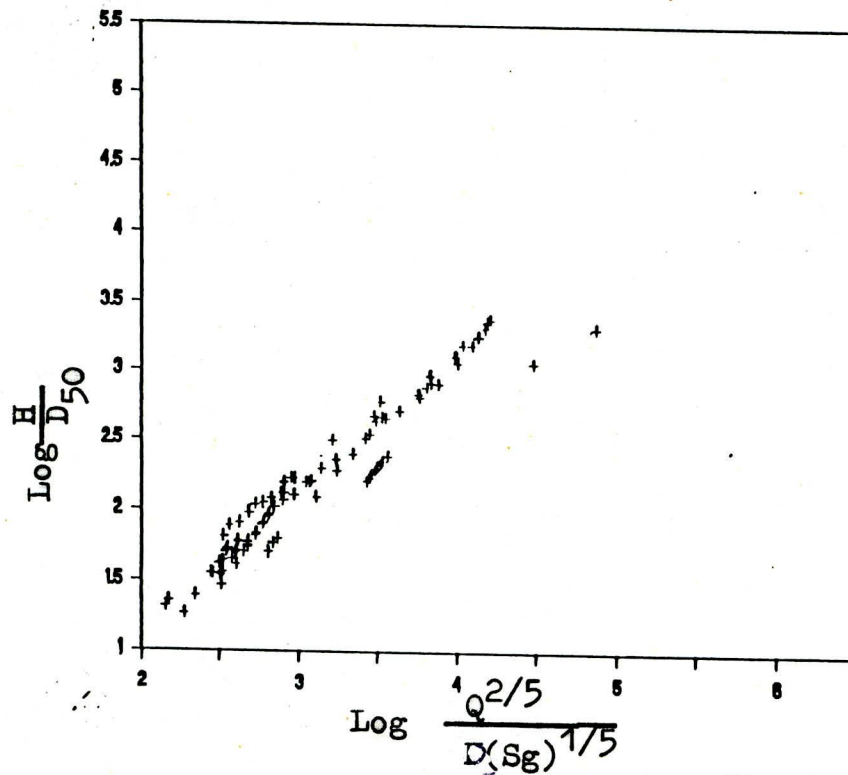


Fig.7.27 Correlation between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$
for flow Fr.No.0.7-0.8
(Laboratory and field data combinedly)

CHAPTER 8

CONCLUSION AND RECOMMENDATION FOR FURTHER INVESTIGATION

8.1. SUMMARY:

As too many variables influence the alluvial river geometry, so it is difficult to incorporate all the variables into one set equation. For practical purpose, dominant variables are selected which govern alluvial river geometry and these variables are used to formulate non-dimensional parameters and numerical correlations are developed using the laboratory and field data. This type of study for alluvial river is becoming potentially dependent on extensive use of different non-dimensional parameters originating from theoretical analysis. Then the combination which gives acceptable results are normally adopted. Laboratory data obtained under idealized condition by controlling only few selected variables may be first analysed for evidence of existence of relationships and development of correlations between various non-dimensional parameters. The developed correlation may then be verified against the available field data. If continuity exists between the laboratory and field conditions then a generalized function may be developed. If a definite shift in trend is observed then only adjustment in coefficient or exponent of the equations may suffice. However, if two different trends are observed then it may be concluded that the laboratory condition does not necessarily represent the prototype condition.

In this study, non-dimensional parameters were formed using the principle outlined in the method of synthesis. The functional equation were obtained for alluvial channel geometry between non-dimensional parameter $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ with different sediment concentration range maintaining continuity. The non-dimensional parameter $\frac{B}{H}$ is a measure of channel shape, and the shape of the alluvial channel is closely related to discharge, slope, depth of flow and sediment concentration.

Resistance to flow is important in predicting alluvial river geometry. The configuration of the bed changes with changes in flow conditions. The changing bed condition makes it extremely difficult to describe the resistance due to these bed forms by a constant resistance coefficient. But flow Froude number is helpful in predicting bed forms. So the correlation between $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different flow Froude number used. Again the material that goes into suspension changes the flow and fluid characteristics and has significant influence on the velocity distribution and hence on the mean velocity. Mean velocity is one of the important factors influencing resistance i.e. alluvial water courses. So particle Froude number $\frac{V^*}{\sqrt{gD_{50}}}$ is one of the important resistance form. Now correlation between non-dimensional terms $\frac{B}{H}$ and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for different $\frac{V^*}{\sqrt{gD_{50}}}$ is indicative of alluvial river geometry prediction.

Correlation were developed between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for different flow Froude number range. Flow in alluvial channels are much more complex situation. In mobile boundary flow the resis-

tance is provided by grain roughness, so the relative roughness $-\frac{H}{D_{50}}$ is another important parameter. Bed forms itself is a changing quantity but it varies with flow froude number. Roughness and flow Froude number are important for forming alluvial river shape and bed form. So the correlation developed between $\frac{H}{D_{50}}$ and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for different flow froude number may be suggested as an alternative approach to correlate alluvial river resistance with shape. Details of the findings from this investigation are presented in the individual chapters. The equations 8.1 - 8.6 and the equations listed in tables 6.1 to 6.4 and 7.1 to 7.8 can be applied to predict changes in geometry of alluvial rivers based on imposed conditions.

8.2 CONCLUSIONS

The main conclusions drawn from this study may be summarized as follows:

(1) Strong relationships exist between shape and depth parameter B/H and $\frac{Q^{2/5}}{H(Sg)^{1/5}}$ for varying range of sediment load. Regression equation and statistical properties for the non-dimensional relationship for six bands of sediment concentration range between 100 to 10000 ppm using laboratory data, field data and laboratory and field data combinedly have been obtained (shown in table 6.1, 7.1 and 7.2). Regression equation obtained for the concentration range 100-10000 ppm using laboratory and field data are as follows:

For laboratory data

$$\frac{B}{H} = 0.347 \left[\frac{Q^{2/5}}{H(S_g)^{1/5}} \right]^{1.746} \quad r = 0.83 \quad (8.1)$$

for field data

$$\frac{B}{H} = 0.144 \left[\frac{Q^{2/5}}{H(S_g)^{1/5}} \right]^{2.26} \quad r = 0.93 \quad (8.2)$$

(2) Strong relationships also exists between channel shape and depth parameter B/H and $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ for varying range of flow Froude numbers. Regression equation and statistical properties for each band of flow Froude number (between 0.2 to 0.8) using laboratory data, field data and laboratory and field data combindely are shown in table 6.2, 7.3 and 7.4 respectively. Regression equation for whole range of flow Froude number i.e. between 0.2 - 0.8 are as follows:

for laboratory data

$$\frac{B}{H} = 0.347 \left[\frac{Q^{2/5}}{H(S_g)^{1/5}} \right]^{1.746} \quad r = 0.83 \quad (8.3)$$

for field data

$$\frac{B}{H} = 0.226 \left[\frac{Q^{2/5}}{H(S_g)^{1/5}} \right]^{2.139} \quad r = 0.93 \quad (8.4)$$

(3) Another set of strong correlation between shape and depth parameters B/H and $\frac{Q^{2/5}}{H(S_g)^{1/5}}$ were also established for particle Froude number range 0.4 - 1.3 dividing into nine bands. Regression equation and statistical properties for nine bands of

particle Froude number range using laboratory data, field data and laboratory and field data combinedly have been obtained shown in table 6.3, 7.5 and 7.6). Regression equation for whole range of particle Froude number i.e. between 0.4 - 1.3 are as follows:

for laboratory data

$$\frac{B}{H} = 0.347 \left[\frac{Q^{2/5}}{H(Sg)^{1/5}} \right]^{1.7} \quad r = 0.803 \quad (8.5)$$

for field data

$$\frac{B}{H} = 0.1200 \left[\frac{Q^{2/5}}{H(Sg)^{1/5}} \right]^{2.352} \quad r = 0.94 \quad (8.6)$$

(4) Strong relationships exists between non-dimensional H/D_{50} and $\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}}$ for varying range of flow Froude number. Regression equation and statistical properties for six bands of flow Froude number (between 0.2 to 0.8) using laboratory data, field data and laboratory and field data combinedly are shown in table 6.4, 7.7 and 7.8 respectively. Regression equation for whole range of flow Froude number i.e. between 0.2 to 0.8 are as follows:

for laboratory data

$$\frac{H}{D_{50}} = 0.125 \left[\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}} \right]^{1.027} \quad r = 0.985 \quad (8.7)$$

for field data

$$\frac{H}{D_{50}} = 0.225 \left[\frac{Q^{2/5}}{D_{50}(Sg)^{1/5}} \right]^{0.89} \quad r = 0.93 \quad (8.8)$$

8.3 RECOMMENDATIONS FOR FURTHER STUDY

Many avenues of possible additional study have been opened in this work. The correlation obtained so far have been found to be quite effective in representing the shape factor of the alluvial river for different ranges of concentration flow froude number and particle froude number. The relative roughness was also correlated with discharge parameters for different range of flow froude number. The suggested correlation in the form of power type regression equation for predicting the alluvial river geometry has been found to be reasonably satisfactory in its present form. But there is still need for more to be done towards its improvement. The equations are developed for wide channel. So equations may be developed for correlations of narrow channel. The developed equations are not valid for antidune bed condition. Also these equations are not applicable for gravel bed condition. So a similar set of equation for correlation of various parameters may be developed for application in gravel bed and antidune bed forms.

The equations are developed considering the data having specific gravity of bed particles 2.65. Hence, a similar type of equations may be developed for bed materials with specific gravity, other than 2.65.

Moreover, considerations could be given to other variables as dominant variable such as composition of bed and bank particles, gradation and shape of the sediment particle, wash load, size and shape of channel section. Based on these, a different set of functional equations could be developed. But again it would have been difficult to isolate the roles of the individual variables as they act simultaneously.

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