STUDY OF VORTEX TYPE SEDIMENT EXTRACTOR FOR JALDHAKA HYDROELECTRIC PROJECT

A DISSERTATION

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "Study of Vortex type Sediment Extractor for Jaldhaka Hydroelectric Project", in partial fulfillment of the requirement for the award of the degree of Master of Technology in Water Resources Development (Civil), submitted in the Department of Water Resources Development and Management (WRD&M), Indian Institute of Technology, Roorkee, Roorkee is an authentic record of my own work carried out during the period of July 2004 to June 2005 under the supervision of Dr. Nayan Sharma, Professor, Department of Water Resources Development and Management, and Prof Devadutta Das, Professor, Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee, India.

I have not submitted the matter embodied in this dissertation for the award of any other degree.

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ABSTRACT

Sediment transport by natural stream flow constitutes one of the major problems in the design/operation of river valley projects (hydroelectric /irrigation scheme). The sediment load reaching the power plant passes through the turbine and damages the turbine runner blades/buckets where as in case of irrigation channel, the sediment load tends to deposit in it thus causing silting of the canal that results in a reduction of discharge carrying capacity of the channel itself. Thus for successful functioning of a hydroelectric project, the removal of unwanted sediment is the most important factor which requires great attention and that systematic control of sediments is to be done at the proper time and proper place with suitable device.

The measures for control of sediment entry into a canal system can be applied either at the canal head works/intake structure or in the canal downstream; in exceptional cases at both these locations the measures are provided. The method/devices adopted for this purpose at canal head works/intake structures are known as excluding devices where as the devices used in the canal itself are known as sediment ejectors or sediment extractors. Various ejectors such as tunnel type, vortex tube sand traps, settling basins, vortex chamber type extractor are being generally used in practice.

Vortex chamber type sediment extractor has been found to have large efficiencies (of the order of 90 percent or above) for removal of sediment at small water abstraction ratio (about 3 to 10 percent) to be used for flushing of settled sediment. To remove sediment a vortex chamber type sediment extractor utilizes the secondary flow generated by the circulatory flow induced in a circular basin. The secondary flow moves the fluid layers near the basin floor toward the orifice of the flushing pipe installed at the center of the basin. Sediment particle heavier than the fluid are thus moved along spiral paths from the basin periphery toward the orifice. The design of vortex chamber type extractor includes the determination of the basin dimensions and sediment removal efficiency when the flow related parameters are known. Since there is no general relationship available from analytical background for

designing a vortex chamber type extractor, empirical equations as proposed by different investigators can be adopted as a guide lines for designing a vortex chamber type extractor.

To study the effects of variation of different components on sediment removal efficiency of a vortex chamber type extractor, a hydraulic model study was carried out in the River Engineering Laboratory of WRD&M, IIT, Roorkee. For study purposes, necessary data have been adopted from Jaldhaka hydroelectric project, WBSEB. Experimental investigation has been done on a geometrically similar model of 1/10 scale. In the model, the sediment size was simulated by "Froude's Law" and "Criterion of fall velocity". This dissertation report deals with the findings of the model investigation of proposed vortex chamber type of extractor.

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LIST OF SYMBOLS

A = Cross sectional area of the channel

A^* = A function

a_0 = Factor of proportionality

B = Bed width of the inlet channel

C_1 = Free vortex constant

$\bar{c}$ = Average sediment concentration

c = Concentration of sediment at a distance y above bed

c_a = Concentration of sediment at a distance a above bed

c_d = Discharge coefficient of flushing pipe orifice

D_T = Diameter of the vortex chamber

d = Median size of sediment particle

d_0 = Diameter of flushing outlet

d_a = Arithmetic mean diameter of sediment

F = Force

F_d = Froude's number

f = Darcy-Weisbuch friction factor

g = Acceleration due to gravity

H_T = Basin height

h = Depth of flow in the inlet channel

h_T = Total head

h_0 = Depth of flow over flushing orifice

h_f = Head loss between inlet and outlet channel

h_1 = Height of diaphragm from bed of inlet channel

h_2 = Basin depth at its periphery from inlet channel bed

h_p = Depth of flow at the periphery of vortex chamber

K_1 = Particle mobility number

K_2 = Coefficient of settling

k = A constant used in determination of removal efficiency

k_0 = Von-karman constant

L = Length parameter

N_T= Circulation number

n = Manning's roughness coefficient

n_s = Manning's roughness coefficient due to grain resistance

P = Pressure intensity

Q_d = Design discharge

Q_c = Discharge in Inlet channel

Q_0 = Discharge through flushing outlet

Q_w = Weighted discharge

q = Discharge per unit width of channel

q_B = Rate of bed load transport in weight per unit width

q_s = Rate of suspended load transport in weight per unit width

q_T = Rate of total load transport in weight per unit width

R = Hydraulic Radius

R_b = Hydraulic radius with respect to bed

R_e = Reynolds' number

R_T = Radius of vortex chamber

r_c = Distance of intersection point for free and forced vortex

r_0 = Radius of air core vortex/ radius of flushing pipe outlet

r_1 = Dimensionless radius (r/r_0)

S = Water surface slope/bed slope

S_T = Radial slope of vortex chamber

T = Time

u_* = Shear velocity

v = Mean velocity of flow in the inlet channel

v_s = Average forward velocity of sediment particle

v_r, v_θ, v_z = Components of velocity along radial, tangential and vertical directions

v_x, v_y, v_z = Component of velocity along flow, transverse and perpendicular directions

v_{tp} = Tangential velocity at basin periphery

v_{t0} = Maximum tangential velocity at basin periphery

v_i = Average velocity at inlet of the vortex chamber

W_v = Total influent sediment in the flow just upstream of the basin

W_F = Sediment excluded through the flushing pipe

W_i = Sediment deposited in the inlet channel

W_t = Total sediment fed through the feeder

W_0 = Sediment passed in outlet(power) channel/ deposited in tank

Z_0 = Theoretical exponent in suspended sediment distribution

Z_h = Difference between the bed of vortex chamber and outlet channel

γ_f = Unit weight of fluid

γ_s = Unit weight of sedimentary particle

$\Delta\gamma_s$ = Difference in specific weight between sediment and fluid

η = A coefficient

η_0 = Sediment removal efficiency

μ = Dynamic viscosity

ν = Kinematic viscosity

ξ = Sheltering coefficient

ρ_f = Mass density of fluid

ρ_s = Mass density of sedimentary particle

τ_0 = Average shear stress on channel boundary

τ_c = Critical shear stress

τ' = Grain shear stress

τ_* = Dimensionless shear stress parameter.

φ_s = A coefficient

ω = Angular velocity of forced vortex

ω_0 = Fall velocity of sedimentary particle

Γ = Circulation parameter

ε_s = Sediment Diffusion Coefficient

ε_m = Momentum transfer coefficient

ABBREVIATIONS

APWA= American Public Works Association

ASCE= American Society of Civil Engineers

IAHR= International Association of Hydraulic Research

ICID= International Commission of Irrigation and Drainage

JHD= Journal of Hydraulic Division

JHE= Journal of Hydraulic Engineering

JHR= Journal of Hydraulic Research

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INTRODUCTION

1.1 General :

Soil erosion in the catchments of a river and scouring of its bed and banks have been identified as the chief sources of sediment. The water borne sediment creates a variety of complicated problems on various works whether it is a dam or multipurpose project or a diversion weir or an irrigation, navigation or power channel or storage tank. Excessive sediment load can cause damage in a variety of ways and presents many serious problems(9) such as (a) meandering of streams, (b) reduction of channel capacity, (c) silting up of canals, (d) damage to power units on power channel, (e) obstruction to navigation, (f) sediment bars at stream junctions, (g) silting up of reservoirs (h) shoaling of harbors at the river mouths and (i) destroying the value of streams for pisciculture and recreational utility, etc.

A success of a river valley project depends to a large extent on the degree of control achieved on the sediment entry in the off-taking channel. The entry of sediment load in a power channel particularly sharp edge silt/ sand load may lead to damage to the turbine runner blades/vanes. The abrasion of guide vane bearing, its bronze brushes, cup seals and rubber chord causes high leakages. The shaft seals get damaged frequently due to high silt content in water and turbine pits get flooded. The high silt content in water causes choking of cooling tubes of power house thereby causing rise in temperature of machine bearing, stator and generator transformer beyond permissible limit which results in tripping or forced shut down of the machine. The turbines of Florida Alta plant(28) in Chile (head 95 m) were found to have entirely worn out after 2000 hours of operation because of presence of sand in water. On the other hand, at Chila power house in U.P., the turbine worn out in 2 years after it was commissioned in 1981 and the power plant was shut down for a period of 3 months for repair thereby causing enormous loss of power and revenue. The deposition of sediment in irrigation canals causes reduction in their discharge carrying capacity and needs removal of the sediment from it at frequent intervals entailing great expenditure. Sediment deposited in irrigation distributaries reduces the rate and hence volume of water delivered to irrigated areas. The deposition of coarser sediment in irrigation areas reduces soil fertility, while colloidal reduces permeability, both of which result in the reduction of productivity of irrigated lands. Thus cleanout and maintenance cost of irrigation ditches and reduced productivity of irrigated soil represents an enormous amount of extra expenditure. The large scale land slide in the upper Himalayas during 1970 caused the entrainment of high sediment load in Ganga canal and deposited approximately 0.17 million m^3 of sand in a 13 km reach (average depth of deposition 2.1m) between head works at Haridwar and the power house at Pathri. The clearance of material necessitated an expenditure of about 10 million rupees including the closer of canal for 2 months in crop season(16). For the trouble free and efficient functioning of an irrigation and power project, the removal of the unwanted sediment is the most important factor which requires great attention and that systematic control of sediments is to be done at the proper time and proper place with suitable device. Efforts to exclude sediments from water drawn from the stream or other sources, for use in hydropower, irrigation and domestic purposes, starts at the intake structure. However, in spite of elaborate measures planned and taken upstream of head regulator, some sediment load still enters the off-taking channel. Therefore measures to eject such sediment become necessary as per requirement of the type of the project.

The measure for control of sediment entry into a canal can be applied either at the canal intake/ canal head regulator or in the canal downstream; in exceptional cases at both these locations the measures are provided. The method/devices installed at the intake before water finds entry to the canal system are termed as preventive. On the other hand, the exclusion devices installed in the water conductor system after the intake structure are termed as curative. Siting an off-take using favorable curvature effect, provision of under-sluices and divide wall at the diversion structure, adding excluder tunnels and withdrawing river water supplies over a high sill at the head regulator etc are all preventive devices. Sediment ejectors, settling basins, vortex tube sand traps, tunnel type extractors, slits, desilting basins, vortex chamber type extractor are the examples of curative methods.

1.2 Criteria for sediment exclusion for hydro power stations

As silt particles of different sizes, shapes and hardness pass over the under water parts of hydro-turbine, damage is caused to various parts in varying degree in the following manner(11):

(i) Solid hard particles of rock i.e. quartz, mica etc. which are carried along with the water impinge at an angle on the surface of various turbine components against which these are pressed perpendicularly. As they move over the surface, they scratch furrows causing removal of microchips of metal. This is known as sliding abrasion/scouring caused by tangential flow over the surface of material.

(ii) When sediment particles impinge on the surface at a wide angle, they cause material fatigue failure due to repeated impacts. Brittle and hard coatings are prone to such impact abrasion (also known as erosion) while tough elastic material is more resistant to such wear.

(iii) Where cavitations problem also exists besides abrasion such areas experience accelerated material damage.

Hydropower plants require elimination of sediment charges of coarse, sharp and pointed silica fraction from water to increase the life of lining of water carrying conductor namely, penstocks, valves and turbines. In the case of turbines working under different heads, the permissible size of sediments as recommended by Mosonyi(21) are as follows:

Medium head plant (15 m to 50 m)	---------	0.20 mm to 0.50 mm
High head plant (above 50 m)	---------	0.10 mm to 0.20 mm

By experience gained on the working of existing plants and evaluating the damage caused by erosion, it has been found that the maximum particle size, which can be permitted safely will vary between 0.10 mm and 0.70 mm depending upon the type of turbine(22) as given in following table :

Sl.No.	Type of turbine	Permissible particle size in (mm)
1	Pelton turbine	0.10 to 0.20
2	Francis turbine	0.30 to 0.50
3	Kaplan turbine	0.50 to 0.70

Of course a recent study(7) regarding determination of optimal sediment size to be removed from a run of the river project performed in case of Hydro-electric projects situated in Sutlej river shows that it is economical to exclude particle size of + 0.35 mm as against practice +0.20 mm.

Other factors which determine the choice of the limit of the particle size are:

a) Composition of silt: If silt is composed of hard material like quartz, the particle size should be limited to a lower particle size may be allowed.

b) Clearance between moving an stationary ring: the clearance between the runner and the stationary ring is an important consideration in the case of Francis and Kaplan runners.

Bharat Heavy Electrical Limited (B.H.E.L)(2) has given some guide lines with regards to the size and hardness of the particles, their concentration in the stream flow and head acting on the turbine. Their recommendations for design of hydro-turbine are as follows:

a) Desilting or removal of harmful particles to the extent of 85% to 95%.

b) Particles greater than 0.25 mm size and having a hardness beyond 5 on Moh's scale are considered harmful.

c) If concentration of harmful particles is more than 200 ppm and size ranges from 0.25 mm and above, then desilting is necessary.

1.3 The Problem-Jaldhaka Hydroelectric Project:

The Jaldhaka hydroelectric project of West Bengal State Electricity Board (WBSEB) situated in Darjeeling district of West Bengal utilizes the combined flows from three rivers namely, Ni-Chu, Di-Chu and the Bindu-Chu to generate 27 MW of power at the Stage-I power plant. The Ni-Chu and Di-Chu flow from the Indian territory where as Bindu-Chu flows from the east (left bank) from the Bhutanese territory. For excluding the harmful grade of sediment from the water conductor, a pressurized desilting basin was provided much after the commissioning of the project. However due to choking of flushing arrangements of the existing desilting basin, subsequently the runner blades of the turbines are getting damaged sooner than expected, thereby affecting operation. At present, the existing desilting system is not performing as desired, and hence there was a necessity for developing an appropriate sediment exclusion device which could reduce the sediment load on the existing desilting plant.

As a measure to reduce the problem of silting and choking of desilting device, the project authorities have diverted the waters of Bindu-Chu river during monsoon season exclusively for generation of power. An intake across the Bindu-Chu river has been constructed for diverting the desired flow to the water conductor system through a power channel constructed over the barrage. During the monsoon season the sediment concentration of Bindu-Chu river is relatively less than that in Jaldhaka river - this proposal is conducive for providing necessary desilting device at a relatively less cost and efficient manner. For extraction of silt size ranging between 0.20 mm to 0.50 mm from the flow with due consideration for economical, efficient and water conserving alternative, vortex chamber type sediment extractor is proposed to be adopted for Jaldhaka hydroelectric project.

1.4 Objective of the present study

(i) To design a suitable desilting device using the concept of vortex chamber type sediment extractor to be adopted in Jaldhaka hydroelectric project.

(ii) To analyze the efficiency of vortex chamber type extractor by suitably varying the height of diaphragm and deflector.

(iii) To determine the diameter of flushing pipe outlet at which the sediment removal efficiency of the proposed vortex chamber is maximum.

1.5 Limitations

(i) Only the geometric configuration of vortex chamber extractor with the provision of diaphragm, deflector and by-pass side channel as given in Paul et al (1989) was studied.

(ii) Circular cylinder type vortex chamber having diameter of 1.18m was used for present study.

(iii) The inlet channel having dimensions 4.30 m length, 0.236 m bed width and 0.345 m depth was used. The outlet channel dimensions were length equal to 2.90 m, width 0.236 m and depth equal to 0.345 m. Both the inlet and outlet channels were trapezoidal in shape having side slope of 1:1 (H:V).

(iv) Cohesion less uniform sediments sizes ranging from 0.192 mm to 0.197 mm was used in the study.

(v) Suspended sediment in the order of 2000 ppm was used in the experimentation work.

1.6 Organization of the study

The study is presented in six chapters. The contents of each chapter in brief are given bellow:

Chapter-I

This chapter gives an introduction to the problems and necessity of sediment exclusion from water to used in river valley project, criteria for sediment exclusion from water for hydropower development, problems associated with Jaldhaka hydroelectric project, objectives and scope of the study, limitations and organization of the dissertation report.

Chapter-II

In this chapter, literature review on sediment characteristics, different sediment control measures, mechanism of flow in vortex chamber type extractor, recent study on different types of vortex chamber extractor, design concepts of vortex chamber extractor have been presented.

Chapter-III

This chapter deals with the methodology of desired study which covers the detailed hydraulic model theory, model formulation for vortex chamber type extractor, simulation of sediment and details of experimental set-up for the present investigation

Chapter-IV

In this chapter description is given of the detailed experimental procedure adopted for the present investigation.

Chapter-V

The detail analysis of data and results obtained there form are presented in this chapter.

Chapter-VI

This is the last chapter of this dissertation report which contains the final conclusions related to the study conducted.

REVIEW OF LITERATURE

2.1 General

In nature, the denudation of the surface of the earth goes on continuously. Sediment is generally generated by disintegration of earth's crust mainly by the action of temperature, running water, wind, ice, vegetation and human intervention. The disintegrated materials are transported in stages. The sediment transportation by streams may take place by traction, siltation, suspension and solution.

For a trouble free performance of any water resources project, sediment control is an essential requirement. To arrive at the effective stage of sediment control, it can be done in the catchment area itself or at the place where the trouble is created. Depending upon the location of sediment control measures, it can be categorized as (i) preventive and (ii) curative. The preventive devices prevent entry of sediment into power channel by trapping or diverting it before the intake structure whereas the creative measures are located after the intake structure to eject the unwanted sediment from the flow in water conductive system.

Vortex chamber type extractor is a curative type of device for performing the task of silt extraction from a power channel. This device has been evolved by IPRI, Amritsar and combines the long settling basin in a compact circular basin and utilizes the force of an air core vortex to extract sediment carried by the flow of the power channel.

2.2 Sediment characteristics

2.2.1 Origin, formation of sediment and its classification

Sediment is defined geologically as any fragmental material transported or deposited by water or air. The source of sediment is rock. The weathering of rocks(16) due to mechanical, chemical and organic process and human activities are responsible for production of sediment.

On account of weathering action, chemical mechanical or organic rocks in the mountain disintegrate into granular material. The disintegration is brought about by sun, wind, frost, rains, running water, animals and depends upon various factors such as vegetal cover, the steepness of valley slopes and nature of rocks. In regions where natural changes in temperature are abrupt, the rock masses break up by sudden expansion and contraction. The presence of minerals further helps in the silting of the rocks.

The nature of lower watershed, the characteristics of the valley and the constitution of the soil through which the stream flows, are important factors in the sediment charge of a stream. Protective influence of the forest is very considerable. The clearing away of wood and brush-wood, unrestricted grazing, cultivation, uncontrolled bank erosion and landslides are some of the causes of sediment production in the large quantity.

Of the 'total-load ' or 'bed-building load' transported by a channel, a part of the sediments is transported without getting into contact with the channel bottom and is termed as 'wash load' (composed of fine grained material finer than bed material originating exclusively from its catchment area or banks of channel). Another part is transported in suspension but in continuous exchange with the bed material; is termed as 'suspended load'. The remaining fraction comprising the coarsest particles is transported by sliding or rolling in permanent or quasi-permanent contact with the channel bed, and is termed as 'bed-load'. All the three modes of transportation of sediment are closely inter-related and it is rather difficult to establish a boarder line to completely demarcate these because the same sediments can be transported as wash load, suspended load or bed load depending upon the flow conditions. In practice this difficulty has been over come by considering the total load to comprise (1) bed-load and (2) the suspended load.

2.2.2 Hydraulics of sediment transport

When a sediment particle is placed on an alluvial channel, it is subjected to two types of forces:-

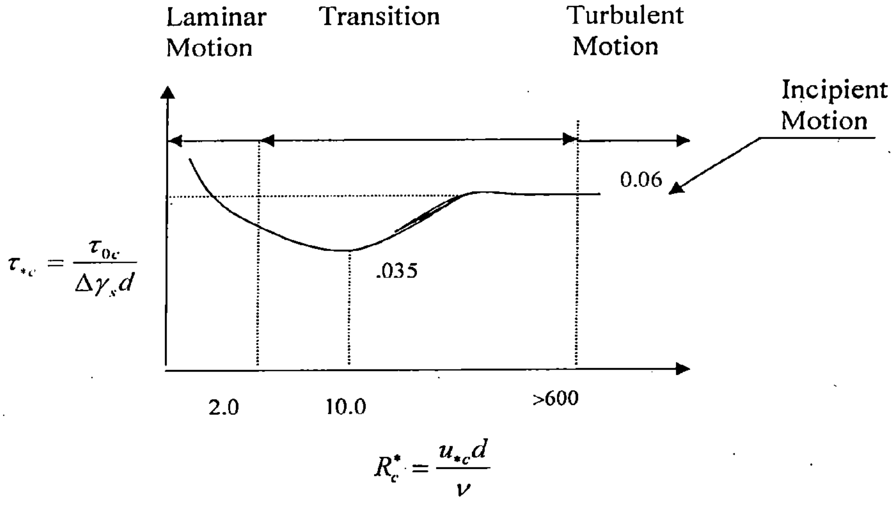
- Dynamic forces excreted by the flow
- Resisting forces which primarily depend on size and relative density of sediment.

Obviously the particle will move if the dynamic forces are more than the resisting forces. On the other hand, if the dynamic forces are smaller than the resisting force, the particle will remain on the bed. The condition in which the dynamic force is just equal to the resisting force is known as the **incipient motion condition** or **critical condition** for the sediment particle. Under this condition, the particle will be just on the verge of motion i.e., a slight increase in dynamic force will set the particle into motion. The different approaches used to establish the condition for incipient motion of sediment particles are-(i) competency approach (ii) lifting force approach (iii) critical tractive force approach. Out of the different approaches, over the years, the critical tractive force approach has been found favor with hydraulic engineers and used quite often today.

Critical tractive force approach: In this, the most commonly used empirical methods are those of Shields and Yaline and Kärahan. These methods give the value of critical shear stress τ_c to move a given particle of size 'd' and unit weight γ_s. Obviously, if the shear stress on the bed exerted by the flow τ_0 is more than τ_c then the particle will move. These could be expressed as

$\tau_0 > \tau_c$ motion
$\tau_0 = \tau_c$ incipient motion
$\tau_0 < \tau_c$ no motion

On the basis of data collected for 'd' in the range of 0.4 mm to 3.4 mm and ρ_s / ρ_f varying from 1.06 to 4.25, Shields[(16)] proposed the following relationship in the form of a diagram known as Shields diagram.



From the shield diagram, it is seen that for $R_c^* > 600$, the value of τ_{*c} is constant or equal to 0.06. This range usually occurs for relatively coarse material and for this range viscous effects are negligible. Recently Yalin and Karahan(16) have used a larger volume of data at critical conditions and found that limiting value of τ_{*c} is 0.045 instead of 0.06 and this value is attained for R_c^* equal to or greater than 70.

2.2.3 Measurement of sediment load

A) Estimation of suspended sediment

The suspended load of a stream can be estimated by the following two methods: (I) Sampler method (II) Analytical method

Sampler method: In this method of sediment sampling, the following types of sediment samplers are commonly being used.

- Vertical pipe type
- Instantaneous vertical type
- Instantaneous horizontal type
- Bottle type
- Integrating type
- Pumping type

The point integrating sampler and the depth integrating sampler are quite popular types of samplers. They are ideal for taking representative samples with the least disturbance to the flow at the entry.

Analytical method: Various investigators have given analytical methods for the determination of suspended load of a flowing stream. The methods generally used are:

(i) **Turbulent diffusion theory:** O' Brien(23) in 1933 made the most significant contribution in the field of transport of sediments in the turbulent streams in suspension and derived an equation by equating the rate of upward transfer with the settling rate. Dobbins, Iwagaki and Mc Noun also have been given a general differential equation for diffusion of foreign particles in a fluid for the steady uniform flow as

$$\omega_0 c + \varepsilon_s \frac{dc}{dy} = 0$$

Where, ω_0 = fall velocity of sediment

c = sediment concentration

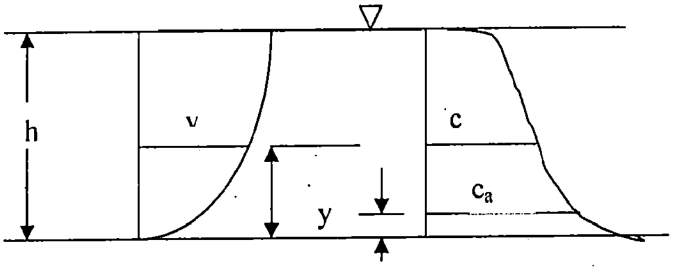
ε_s = sediment diffusion coefficient

Integrating the above equation between limits a and y and assuming $\varepsilon_s = \varepsilon_m$ the final form of correlation given by Rouse using Prandt – Von Karman velocity deflect law is

$$\frac{c}{c_a} = \left(\frac{h-y}{y} \times \frac{a}{h-a} \right)^{Z_0}$$

and $Z_0 = \dfrac{\omega_0}{u_* k_0}$

where c_a is the concentration of sediments with settling velocity ω_0 at level $y=a$, h is the depth of flow, k_0 is the von-karman's constant and $u_* = \sqrt{\dfrac{\tau_0}{\rho}}$.



To obtain the total suspended load per unit width of the channel q_s, integrating of product of velocity and concentration over the entire depth.

$$q_s = \int_{2d}^{D} cudy$$

(ii) Lane and Kalinske method:

Lane and kalinske$^{(18)}$ showed that even though ε_s or ε_m varies with y, a constant value of $\varepsilon_s = \varepsilon_m = h\sqrt{(ghS)}/15$ can be used in the vertical wide river. Thus integrating

$w_0 c + \varepsilon_s \dfrac{dc}{dy} = 0$ gives the following relationship

$$\frac{c}{c_a} = \exp\left\{-\frac{\omega_0}{u_*}\left(\frac{y}{h} - \frac{a}{h}\right)15\right\}$$

Integrating the above equation for total suspended load q_s and Further simplifying yields

$$q_s = qc_a P \exp\left\{15\left(\frac{\omega_0}{u_*}\right)A\right\}$$

in which *Y = y/D, A= a/D and* $P = \int\left(\dfrac{\omega_0}{u_*}, \dfrac{u_*}{k_0 v}\right)$.

(iii) Samaga et al method:

Samaga and Samaga et al[(16)] proposed a method of calculation of suspended load by considering the individual fraction in a mixture for uniform sediment and showed the relationship of φ_s and τ_* by the following relationship:

$$\varphi_s = 28.0\tau_*^{6}$$

where $\varphi_s = \left(\dfrac{q_s}{\gamma_s d}\right)\sqrt{\left(\dfrac{\gamma_f}{\Delta\gamma_s}\right)\dfrac{1}{gd}}$

and $\tau_* = \dfrac{\tau_0}{\Delta\gamma_s d}$

for uniform sediment the relation is as follows

$$\varphi_s = 28.0\left[\frac{\xi_s \tau_0}{\Delta\gamma_s d_i}\right]^6$$

$$\varphi_s = \frac{i_s q_s}{\gamma_s d_i i_b}\sqrt{\frac{\gamma_f}{\Delta\gamma_s}\frac{1}{gd_i}}$$

(B) Estimation of bed load:

Like wise suspended sediment load the bed load can also be measured by

(i) Sampler method (ii) Analytical method

Sampler method: In this method, the samples of stream water are taken with the help of various types of samplers, such as box type samplers and slot type samplers. The bed load is obtained after drying the sample and determining the mass of dry solids. However, the samplers do not give a reliable value of the bed load. It is the usual practice to determine the bed load from the suspended load. Generally the bed load is taken as 3 percent to 25 percent of the total suspended load, depending upon the nature of the bed material. An average value of 10 percent is quite common.

Analytical method: The commonly used analytical methods are:

(i) Mayer-Peter-Müller equation: It is the most commonly used empirical equation to find the bed load of sediment transport, the equation can be represented by the following:

$$\left(\frac{n_s}{n}\right)^{3/2}\tau_* = 0.047 + 0.25\Phi^{2/3}$$

where $\tau_* = \dfrac{\gamma_f R_b S}{(\gamma_s - \gamma_f)d_a}\left(\dfrac{n_s}{n}\right)^{3/2}$

and $\Phi = \dfrac{q_B}{\gamma_s}\sqrt{\dfrac{\rho_f}{\rho_s - \rho_f}}\left[\dfrac{1}{gd_a^{3}}\right]^{1/2}$

(ii) Shields' equation: Shields has proposed(16) the following dimensionless homogenous equation for bed load transport.

$$\frac{q_B\left(\left(\frac{\rho_s}{\rho_f}\right)-1\right)}{q\gamma_f s} = 10\left[\frac{\tau_0 - \tau_{0c}}{(\gamma_s - \gamma_f)d}\right]$$

Here, q is the discharge per unit width of the channel.

(iii) Garde-Albertson approach: According to Garde-Albertson(16), for uniform material, the velocity of bed load equation can be expressed

$$\frac{q_B}{u_*\gamma_s d} = f\left\{\frac{\tau_0}{(\gamma_s - \gamma_f)d} - \frac{\tau_{oc}}{(\gamma_s - \gamma_f)d}\right\} = f(\tau_* - \tau_{*c})$$

if τ_* much greater than τ_{*c} one can write

$$q_B^{*} = f(\tau_*)$$

where $q_B^{*} = \dfrac{q_B}{u_*\gamma_s d}$

(C) Estimation of total load

Since the total load comprises of bed load and suspended load, the estimation of total sediment load is the sum of bed load and suspended load measured either by sampler method or by analytical method. In the analytical estimation, besides the methods described earlier, the following methods also can be used.

(i) **Laursen method**: The functional relationship for total sediment transport capacity of a channel as derived by Laursen (16) is

$$\frac{\overline{C}}{\left(\frac{d}{h}\right)^{7/6}\left[\left(\frac{\tau_0'}{\tau_{0c}}\right)-1\right]}=f\left(\frac{u_*}{\omega_0}\right)$$

where $\overline{C}$ = total load concentration by weight

τ_0' = grain shear stress

τ_{0c} = critical shear stress

u_* = shear velocity

ω_0 = particle settling velocity

(ii) **Garde and Dattatri method**: According to this method the total sediment transport rate(16) per unit width of a channel q_T can be obtained as

$$\frac{q_T}{\gamma_s u_* d}=16.0\tau_*^{4.0}$$

where τ_* = dimensionless critical shear stress parameter

u_* = shear velocity

γ_s = unit weight of sedimentary particle

The above equation is valid for sediment size ranges between 0.011 mm to 0.93 mm.

(iii) **Engelund and Hansen's method**: Engelund and Hansen have proposed a total load equation relating the sediment transport to the shear stress and the friction factor of the bed. For the flume data in a range of 0.19mm to 0.93mm and bed configuration for dunes, transition, standing wave and antidunes, the relation becomes as

$$f\Phi_T = 0.4\tau_*^{5/2}$$

where f = friction factor = $\frac{8gRS}{v^2}$

τ_* = dimensionless critical shear stress parameter

$$\Phi_T = \frac{q_T}{\gamma_s}\left[\frac{1}{\left(\frac{\rho_s}{\rho_f}-1\right)gd^3}\right]^{1/2}$$ =dimensionless parameter

2.3 Sediment control measures

The aim of all sediment control and exclusion measures and devices is to prevent or remove sediment concentrated in the bottom layers so that the channels are left with sediment near to their sediment carrying capacity. To arrive at the effective stage of sediment control it can be done in three stages i.e.

- Sediment control in the catchment
- Sediment control at upstream of intake structure
- Sediment control at downstream of intake structure

A) **Sediment control in the catchment**: Controlling the rate of sediment formation in the catchment areas of the streams can help a lot in reducing the trouble lower down. The control measures adopted in the catchment can be the following:

I. Biological measure
  - Plantation
  - Pasture development

II. Engineering measure
  - Good forming practices.
  - Control and elimination of gullies
  - Control of erosion on mountain roads
  - Stabilization of hill torrents
  - Restricted grazing.

B) **Sediment control at upstream of intake structure:** This can be achieved by providing:

I. Sediment preventive measures: Entry of sediment into a channel can be discouraged by adopting certain preventive measures like
   - (a) River approach condition
   - (b) River training
   - (c) River regulation.

II. Sediment control devices: These devices are generally used to divert the bed load portion of sediment away from the intake structure/head regulator.
   - (a) Guide vanes
   - (b) Cantilever and skimmer platform
   - (c) Provision of sluice ways or under sluices
   - (d) Inclusion of divide wall in diversion head work
   - (e) Providing sediment excluder.

(C) **Sediment control at downstream of intake structure**

In-spite of elaborate measures planned and taken upstream of the intake structure, some sediment load may still enter the off-taking channel. Hence it is necessary to extract the same and it is particularly were essential if the off-taking channel happen to fill the hydro power plant so as to avoid wear and tear of turbine blades. This goal is achieved by constructing sediment extracting structure in the channel; these are called ejectors / extractors. In this study only sediment ejectors/extractors are studied. There are different types of ejecting devices which can be used to control sediment in the flowing channel such as (a) Tunnel extractor (b) Desilting basin (c) vortex tube sand traps and (d) Vortex chamber type sediment extractor

Tunnel extractor: A tunnel extractor or ejector basically consists of a horizontal slab a little above the canal bed which separates the sediment laden bottom layers from the top layers. Under the diaphragm, are tunnels which carry these bottom layers into escape channel. In each tunnel there are sub-tunnels which are formed by constructing curved vanes. The downstream end of the tunnel is located in the bank from which the escape channel takes off; the tunnels usually converge at the downstream end. Figure 2.1 shows a typical type of tunnel extractor. The amount of water diverted into the canal head works must be increased by 15 percent to 25 percent to operate an ejector of this type(25). Tunnel ejectors are better suited when canal carries coarser sediment.

Desilting basins: Desilting basin is one of the most effective devices for removing relatively finer sediment particles from flowing water. In situations where head to operate sediment ejector is not available or the canal slope is not adequate to ensure sediment transport capacity, desilting basins are provided to obtain relatively sediment free water by excluding the suspended sediment or grains below 0.25 mm(14). Generally settling basins are constructed simply by widening and deepening the canal section to produce an enlarged cross section that produce lower velocity. Figure 2.2 shows a typical desilting basin for a hydropower project. Such reduction in the velocity also reduces the bed shear stress and the turbulence. Reduction in the velocity, shear stress and the turbulence, if adequate stops the bed material from moving and also causes part of the suspended material to deposit. The deposited sediment is removed by sluicing, flushing or by other mechanical means with an additional discharge of 10 to 20 percent of the design discharge(1). However, large dimensions (width, length and depth) for settling basins are required for obtaining high efficiency of removal of deposited sediments which make them costly.

Vortex tube sand trap: A vortex tube sand trap can be described as a tube with an opening along the top and placed in the bed of a canal at angle of about 45 to direction of flow. As flow passes over the opening, a spiral motion is set up within the tube. Material traveling along the bed is drawn or dropped into the tube and carries to an outlet where it is to be discharged in to a return channel. The device was observed to be very effective in removing large material even to the size of cobble stones. Vortex-tube sediment extractors are relatively inexpensive when compared to other sediment control devices. The majority of the bed-material sediments can often be removed from a canal at the expense of between 10% and 20 percent of the canal discharge(6). Figure 2.3 shows a typical vortex tube type ejector.

Vortex chamber type sediment extractor: A vortex chamber type extractor makes use of vortex flow in a chamber or basin as a separation device. A higher velocity of flow is introduced tangentially into a cylindrical basin having an orifice at the center of its bottom. This gives rise to combined vortex forming near the orifice and free vortex forming in the outer region toward the periphery; as a result sediment concentration gradient builds up across the vortex and a diffusive flux proportional but opposite to the centrifugal flux is induced. The secondary flow resulting from this causes the fluid layers near the basin floor to move toward the outlet of orifice. The sediment particles present in the flow move along helicoidal path toward the orifice (Fig 2.4). There by obtaining a long settling length compared to the basin dimensions. Thus relatively higher velocities can be allowed in the chamber. The sediment reaching the chamber can be flushed out through the orifice continuously. Relatively sediment free water is allowed to leave the basin through an outlet channel/pipe as shown in Fig 2.5. As compared to the conventional type of settling basins the vortex chamber sediment extractor has the advantage of smaller dimensions and low flushing discharge for obtaining a certain efficiency of sediment removal. It can also be used for water treatment process, removal of fish waste and removal of wastewater in pulp and paper industry.

2.4 Mechanism of flow in the vortex chamber

The flow mechanism in a vortex chamber sediment extractor is similar to the Rankine vortex in which a forced vortex core is surrounded by an irrotaional or free vortex zone (Fig 2.8). Experimental studies have been conducted by several investigators for investigating the flow structure and similarity in vortex chamber.

Anwar(3) (1965) was probably the first who carried out theoretical analysis of flow in a free vortex using Euler's equations of motion in cylindrical co-ordinate system. Assuming steady and axi-symmertic flow, the flow continuity equation along with the Euler's equations of motion were written as;

$$\frac{\partial v_r}{\partial r}+\frac{v_r}{r}+\frac{\partial v_z}{\partial z}=0 \tag{2.1}$$

$$v_r\frac{\partial v_r}{\partial r}+v_z\frac{\partial v_r}{\partial z}-\frac{v_0^2}{r}=-\frac{1}{\rho}\frac{\partial P}{\partial r} \tag{2.2}$$

$$v_r\frac{\partial v_r}{\partial r}+v_z\frac{\partial v_r}{\partial z}+\frac{v_r v_0}{r}=0 \tag{2.3}$$

$$v_r\frac{\partial v_z}{\partial r}+v_z\frac{\partial v_z}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial z} \tag{2.4}$$

Here v_r, v_0 and v_z are the velocity components along radial, tangential and axial directions respectively, P is the pressure, r is the radial distance and ρ is the mass density of the fluid.

Experimental data were obtained in an open transparent cylindrical chamber 0.91 m in diameter and 1.52 m in height. Circulation was generated by means of a set of diametrically opposite placed nozzles. Water was led into the tank tangentially by means of nozzles at the tank circumference. A central outlet pipe 100 mm in diameter and 2.73 m long, flush with the bottom was used. Top of the tank was closed to produce vortices with strong circulation. Anwar(3) (1969) reports that when the top and bottom surfaces of the tank were smooth, the distribution of the tangential velocity corresponded to that for laminar flow and the injection of dye revealed a number of vertical layers. Outside the vortex core, the measured tangential velocities follow the profile for irrotational vortex. The observed and computed tangential velocity distribution by Anwar (1969) is shown in Fig. 2.6. It is clear from these figures that a Rankine type vortex is formed which is a combination of forced vortex near the center/core and free vortex towards the periphery.

Cecen(10) (1977) measured the tangential velocities in the vortex chamber by using a miniature current meter at various distances from the bottom in four sections of the vortex chamber having the inflow and outflow configuration as shown in Fig. 2.7. The observed distributions of tangential velocity are also plotted in Fig. 2.7. The intersection of the free and forced vortices was found by Cecen (1977) to occur at a distance r_c, which was related as $r_c=\sqrt{c_1/\omega}$. Here c_1 is constant of free vortex and ω is the angular velocity. The value of r_c was given by some other investigators such as Rott

(1958) gave a relation for r_c as $r_c = \sqrt{2\nu / a_o}$ where the constant $a_o = 1.93$ $(g/h_0)^{0.50}$, h_0 is the head over the intake. Anwar (1967) proposed $r_c \approx r_o$ or $d_0./2$, Odgaard (1986) suggests $r_c = \sqrt{\nu / a_o}$. Here ν is the kinematic viscosity and a is a factor of proportionality given as $\approx v_z / 2h_p$. In the above expression d_0 is the diameter of the outlet orifice and r_o is the radius of vortex air-core. Some non-uniformity among the velocity distributions at various sections presumably due to effect of entrance conditions is evident in Fig. 2.7.

According to Cecen (1977), the chamber of a circular cylindrical vortex type extractor can be divided into four regions (see Fig. 2.7) for describing the flow variation in it. Along the periphery of the chamber, flow enters and leaves the chamber through the inlet and overflow outlet channels respectively. Flow conditions in this region are highly complex and depend to a large extent on the geometry of the entrance and the overflow outlet. However, the flow near the periphery can be approximated by a forced vortex. Adjacent to this region a forced vortex is formed in which the tangential velocity increases with the radius. Near the center, where outlet orifice exists, the velocity distribution follows the characteristics of a forced vortex in which the tangential velocity increases with the radius i.e. towards the center. Air-core may also be present at the center depending upon the size of the orifice.

Also within the vortex flow, fluid layers near the chamber floor are decelerated due to friction. The non-uniformity of centrifugal forces along a vertical section thus causes the sediment particles near the floor to be moved towards the center of curvature. Through any solid particle that enters the chamber follows a helicoidal path towards the center. Hence such a system provides to a sediment grain a much larger settling length which is many times larger than the dimensions of the vortex chamber. Thus the velocity higher than those exists in classical settling basin can be permitted in the chamber.

Rea(26) (1984) conducted experiments on a circulation chamber sediment extractor to observe and measure the secondary currents within the chamber. A perspex model was used in which secondary flow pattern was observed using a photographic technique. Small neutrally buoyant particles were introduced into the flow. As the water circulated within the chamber the particles were illuminated as they passed through a narrow, radial beam of light. Long exposure photographs of the particles were taken at right angles to the beam. Vertical and radial velocities were therefore shown on the photographs by bright streaks. The secondary flow velocities were measured by placing a rotating fan in front of the camera. The following inferences were made:

(i) Near to the bed there was a region of high radial velocity towards the center of the chamber. In this region the maximum radial velocity was found to be inversely proportional to the distance from the center. The vertical distribution of radial velocity within the region is similar to that given by the exact solution of boundary layer flow for fluid rotating with uniform angular velocity over a stationary planer boundary.

(ii) Away from the bed the secondary flow were very complex and also unsteady. However, the patterns were cyclic with a time period corresponding to the period of revolution of water i.e. at 0.70 times the chamber radius. it is possible that these secondary current cells were similar to those, which have been observed in unstable flow between concentric rotating cylinders. The secondary flow pattern was simplified and stabilized by installing a horizontal deflector plate within the vortex chapter. Photographs taken of the secondary flow patterns at a different position showed that the cells changed in space as well as in time.

Julien(17) (1985 b) studied the motion of a small spherical particle in a Rankine type vortex flow. A Rankine combined vortex is a simple two-dimensional model describing vortices in homogeneous fluids. It combines a rotational vortex core or forced vortex surrounded by an irrotational vortex or free vortex of constant circulation $\Gamma = 2\pi\omega r_o^2$. The variation of tangential velocity in Rankine combined vortex is shown in Fig. 2.8. Julien (1985 b) also observed that in the combined Rankine vortex having an initial homogeneous mixture of fine sediments, the particles heavier than the surrounding fluid were moved outside of the vortex core by centrifugal action. As a sediment concentration gradient was built up across the vortex, a diffusive flux opposite to the centrifugal flux was induced and equilibrium was reached when the two fluxes were equal.

Mashauri(19)(1986) conducted both theoretical and experimental investigations regarding velocity distribution across the vortex chamber of a sediment extractor. Three geometrically similar models were used for this purpose. The observed velocity distributions are shown in Fig. 2.9. This figure indicates that there is relatively high tangential velocity at some distance from the centre of the rotation and at the side wall. Midway across the half section of the basin, the velocity is at its lowest. This velocity situation is comparable to the findings of Cecen (1977). For theoretical investigations, Mashauri (1986) made the following assumptions.

(i) Flow in the vortex chamber is axi-symmetric i.e. it is independent of angular position, thus the flow was described with only two independent variables i.e. the vertical height z and radial spacing r.

(ii) The inflow tangential velocity was considered to be constant around the periphery of the chamber and taken to be equal to the mean velocity at the entrance. Thus, while the inlet to the physical model was at one point, tangential to the circumference of the chamber, in the mathematical model it was assumed to be through a porous wall equal in height to the diameter of the inlet pipe and of length equal to the perimeter of the chamber. The theoretical model developed by Mashuri (1986) computes the tangential, radial and axial velocities, which are shown in Fig. 2.10.

Vatistas(30) (1989) performed theoretical and experimental investigation for free surface formation of fluids caused by the influence of a prevailing combined vortex. The experiments were performed in 28.6 cm cylindrical container filled with water in which a strong study and axi-symmetric vortex was generated by means of a magnetic stirrer. An approximately constant diameter vortex core in z direction was formed and made visible using a water- soluble dye. Liquid ripples on the free surface as a result of inertial waves were observed. Vortices with long thin cores and rotating in the direction of spinning stirrer with regular period were also observed to develop about the geometric centre of the container. To visualize the secondary flow the light slicing technique was used. The light source was produced by produced by a 16 mw He-NE laser and chalk powder was used for seeding. Vatistas (1989) derived the following similarity relationship between tangential velocity and radius (see Fig. 2.11)

$$\frac{2\pi r_o v_0}{\Gamma} = \frac{1}{r_1}\left[1 - \exp\left(-\eta r_1^2\right)\right] \tag{2.5}$$

Here r_1 is the dimensionless radius defined as r/r_0 and η is a constant.

Zhu(5) et.al. (1989) studied the flow characteristics inside a sand funnel using Laser Dropler Anemometer (LDA). The sand funnel is a device, which has geometric configuration very much similar to that of a vortex chamber sediment extractor. It looks like a cone and is used for extracting sediment by vortex action. The test was conducted on a pilot model of sand funnel with diameter of 100 cm having 10 cm diameter orifice at its centre. A deflector with 50 mm width was used to divert sediment-laden water towards the bottom orifice. In order to take observation by LDA, a square box was installed in the circumference of sand funnel so that water flowed into a spilling box before entering the inlet canal. Measurements were done for tangential, radial and axial velocities at different vertical and radial distances. The following conclusions were drawn:

(i) Circulatory flow in sand funnel generates a free vortex in the inner region and a forced vortex in the outer region. There is maximum tangential velocity at the interaction of two vortices.

(ii) Radial components of velocity field were larger close to bottom and gradually decreased towards the water surface. On the other hand, radial velocities in the near center of sand funnel were larger than outer regions.

(iii) Axial or vertical velocities are smaller than tangential and radial velocities in the flow fields. The direction of axial velocities at intersection of free and forced vortices was unsteady.

(iv) The vertical upward velocities may decrease the trapping efficiency of the chamber.

(v) The sediment extractor demand that water-head in its inlet be only more than 0.20m.

Paul et al(25) (1991) measured the tangential velocities in a vortex chamber sediment extractor at different floor depths and radial distances using a miniature propeller current meter. Observed distribution of mean tangential velocity in the vortex chamber was found to be dissimilar to the velocity distribution obtained previously by Anwar(1969). The possible reason for this may be that in Anwar's experiment, inlet flow was uniformly distributed over the entire chamber periphery because water was led tangentially into the chamber with eight inlet nozzles along the circumference.

Review presented above on variation of velocity components in vortex chamber reveals that flow field in the vortex chambers resembles very much with the Rankine vortex system except that it is also affected by inlet and outlet conditions as well. Tangential and radial velocities are found to remain uniform over most part of the flow depth in vortex chamber, whereas vertical velocity is significant only near the orifice at the centre of the chamber.

2.5 Recent study on the types of vortex chamber extractors

As mentioned earlier, vortex chamber type of sediment extractor has smaller size as compared to the conventional settling basins. Available literature reveals that sediment present in flow both as suspended load and bed load can be extracted by vortex chamber type extractor with high rate of removal efficiency and for small amount of flushing or abstraction discharge. However, sufficient information is not available regarding phenomenon of sediment settling in a vortex chamber; as result definite criteria are not available for its design. In the following paragraphs the review is presented on various types of extractors that employ circulation of flow for sediment removal.

Geiger (1942) used the grit chamber extractor as shown in Fig 2.12 for separation of solids from sewage. This type of vortex chamber sediment extractor is also called as swirl concentrator (sullivan et al. 1974). Geiger equated the vortex-settling phenomenon to the settlement of sediment of the inside of a curve if fluid is moving in a curvilinear path. Geiger assumed the grit separator to behave like a combined Rankine vortex flow. The sediment particles move to the centre of the chamber mainly due to cross current in the flow which is downward near the outer wall and moves along the basin bottom and up at the center annulus. Friction between the water and the basin bottom decelerates the sediment particles near or at the floor thus carrying them to the centre. Geiger's aim was to remove grit particles greater than 0.20 mm from the flow. The system worked well except that, the free vortex flow could not be controlled and some particles were rotating continuously or floating instead of settling done. To correct this behavior on this it was proposed to remove the free vortex flow by inserting a flow deflector at the chamber entrance port.

Sullivan(29) (1972) and Sullivan et al. (1974, 1978 and 1982) utilized the swirl concentrator principle in removing particles of various grain sizes and specific gravity. The swirl concentration principle involves development of a flow chamber utilizing circular long path kinetic energy to induce separation of solids from liquid and settling of the particles. General view of a grit separator or swirl concentrator is shown in Fig. 2.13. Settling is achieved by ensuring optimum hydraulic conditions and the removal of solids without the use of mechanical accessories. The hydraulic model studies carried out by Sullivan (1974) led to the following inferences.

(i) A flat floor is inadequate over wide ranges of discharge. At lower flows deposits are likely to be a serious problem.

(ii) A hopper (with cone angle = 60^0) was found to be satisfactory over a wide range of sizes.

(iii) The ratio of height to chamber diameter is in the range $0.167 < H_T / D_T < 0.32$. Here H_T is the overall height of the vortex chamber and D_T is the diameter of the chamber.

Velioglu(5) (1972) suggested the use of vortex settling basin as an intermediate unit in water and wastewater treatment processes. Velioglu observed that the sediment removal efficiency decreased as the free vortex size increases in the basin. In other words so long as the free vortex flow is dominant (over the forced vortex) settling efficiency will be relatively low. This agrees with the findings of Sullivan (1972) who studied flow behavior in a swirl concentrator having geometric configurations as shown in Fig. 2.13. Sullivan (1972) proposed replacement of free vortex with forced vortex, which is more effective in solid- liquid separation.

Curi et al(13) (1975) investigated the use of vortex as a separation device as one of the possible solutions to the problem of high velocity solid-liquid separation. According to them if in a cylindrical tank having an orifice at its center, a relatively high velocity flow is introduced, the resulting flow will be a combination of free and forced vortices. The model used by Curi et al for experimentation comprised of a cylindrical tank with 90 cm diameter and with inlet and outlet channels laid tangential to the tank periphery and an orifice of variable diameter equal 1.27 cm to 5.08 cm located at the center (see Fig. 2.14). Green and red lentil, white polystyrene, volcanic tuff, and wood staving were used as test materials. The analysis of the data indicated that for optimum efficiency, water abstraction ratio was equal to 5 percent and if this ratio is increased beyond 5 percent, trapping efficiency became independent of orifice size d_0 or the flushing discharge Q_0.

Salakhov(27) (1975) used a circulation chamber for sediment removal. It consisted of a circular tank with a vertical wall to which water is supplied through a closed pipe tangential to its circumference (see Fig. 2.15). The clarified water escaped through a circular open trough, around the periphery of the chamber in its upper part. A flushing pipe is connected to a port in the center of the chamber floor to remove the settled sediment to the downstream. The main aim was to clarify water for hydropower plants in mountain rivers characterized by steep slopes and high sediment load. The amount of water required to flush the settled sediment particles, i.e. flushing discharge was found to be a function of the air funnel/core formed at the center of the flushing pipe orifice. The air-funnel, in turn depended on the velocity of flow in the basin which was influenced by discharge entering the basin and the inlet velocity sediments, heavier than water, traveled along a spiral trajectory on the chamber towards the center, from where they are discharged through the flushing pipe. The transport of the sediment from chamber's periphery towards the center of the chamber is caused by bottom (secondary) flows which are formed due to rotary motion of stream in the chamber and are intensified by the flushing opening. Experiments were conducted using sediment ranging from 0.5 mm to 1.0 mm in size. The inlet discharge Q_c, basin diameter D_T and fall velocity of the sediment ω_0 used were found to be related together as,

$$D_T = 1.414\left(\frac{Q_c}{\omega_0}\right)^{0.50} \tag{2.6}$$

Following conclusions were also arrived from this study.

(i) The stream flow in the circulation chamber is asymmetrical.

(ii) In all cases where the flushing discharge escapes to the atmosphere, the air-core is formed over the orifice piercing the entire flow depth and causing water to be released through the orifice having a comparatively small cross-section.

(iii) When the exit end of the flushing pipe is submerged, the air-core in the chamber becomes less deep and lifted resembling Rankine combined vortex. A circular boundary line is observed on the free surface of the stream. Floats entering the area inside this line are carried over the funnel cavity and into the orifice while those outside this are diverted towards the edge of the chamber.

(iv) The greater the velocity of water entering the basin, the greater is the size of funnel.

(v) Flushing discharge is relatively very small compared to the total chamber discharge 5 percent < Q_0 / Q_c < 8 percent.

(vi) When a one sided inlet to the basin is employed, the axis of the air-core doesn't coincide with the axis of the orifice / chamber. It tends to shifts towards the sector of the third quarter of the circle in the direction of flow movement. The magnitude of the shift being dependent on the stream circulation intensity in the chamber.

(vii) Entire flow in the chamber was considered as potential flow.

(viii) The peripheral velocity was found to increase with decreasing radius, which is a characteristic of a free vortex flow. The peripheral velocity along the orifice radius r_0 was almost constant (maximum value $v_{t0} = \sqrt{2gh_T}$.

(ix) Sediment fractions with size 0.50 mm $\leq d \leq 1.0$ mm tend to settle in the circulation chamber with diameter D_T given by the relationship.

$$D_T^2 = 2\ Q_c / \omega_0 \tag{2.7}$$

Cecen$^{(10)}$ (1977) further studied a vortex chamber type-settling basin, which is almost the same as Salakhov's (1975) circulation chamber. Cecen conducted experiments with three different geometric models viz. (i) peripheral – spilling weir as outlet and flat bottom (ii) tangential outlet and flat bottom, and (iii) tangential outlet and bottom with a slope of 10 percent. All three models had tangential inlets. Cecen's observations agreed with Salakhov, that the secondary flows near the bottom of the basins are responsible for the movement of sediment towards the center. The cause of secondary flows is thought to be due to two reasons. The first reason is the deceleration of fluid layers near the bottom by friction between the fluid and basin bottom. The second reason is the secondary flow caused by the cross-currents Thus, the non-uniformity of centrifugal forces along a vertical causes particles near the bottom to move inward towards the orifice. Figure 2.13 shows a schematic view of the phenomenon of secondary flows in a vortex chamber. This figure illustrates the "tea-cup" effect of settling in vortex chamber. The solid particles follow a helicoidal path from the entrance to the orifice. This makes the settling length larger than the actual dimension of the basin. This in turn implies that higher velocities can be permitted in comparison with classical basins. The discharge through the underflow was almost proportional to the diameter of the orifice. However, this discharge never exceeded 3 to 10 percent of the inflow discharge. The flow enters the basin tangentially at bottom of the chamber and leaves the chamber at some higher location but again tangentially. The settled matter is flushed out at the center through the underflow.

Conclusions drawn from this study are:

(i) The solid sediment particles follow a helicoidal path from the entrance towards orifice. This makes the settling length larger than the actual dimension of the basin.

(ii) The discharge through the under flow is almost proportional to the diameter of the orifice. However, this discharge never increased more than 3 to 10 percent of inflow discharge.

(iii) The zone immediately near the side-wall had a very complex flow pattern which expands on the design of both the inlet and outlet ports.

(iv) A forced vortex is formed adjacent to the zone near the wall where the tangential velocity increases with the radius, while a free vortex in which tangential velocities increases with decreasing radius is produced near the central air-core.

(v) This type of settling basin showed superior performance especially in the removal of coarser materials, which made it ideal for hydropower plants. It also removed finer settable materials to a certain extent.

Chrysostomou(12) (1983) studied the flow pattern and detention period in the vortex – settling basin. He defined detention period as the time for which a definitive quantity of water remains in the settling basin. Longer the detention time, longer the sediment particles remain in the basin to settle to bottom and eventually flushed thereby yielding higher removal efficiency. The detention time was measured by introducing a tube at the boundary between inlet channel and the deflector. Dye was introduced using a hypodermic needle and a syringe. To facilitate the visualization of secondary flow, neutrally buoyant particles with 0.04 mm size, silver in color and having a dispersion angle of 90^0 in water, were used as they neither float nor sink but follow the flow or current patterns in vortex settling basin. Tests were conducted using different chamber deflector with various chamber depths. The conclusions drawn from the study are as below:

(i) It was observed that for certain deflector conditions and water depths in the basin at its periphery, the vortex oscillated around the center of the basin in an elliptical orbit offset at times by as much as 0.05 m, i.e. 18 percent of the basin radius and at 17^0 with the basin axis.

(ii) Greater the water depth in the basin, smaller is the detention time and thus $h_p / D_T > 0.26$.

(iii) The optimum peripheral basin depth below the inlet channel bed h_2 has to be such that $h_2/h_1 = 0.60$ or $h_1/D_T = 0.058$ and $h_1/D_T =$ 0.100.10.

(iv) Decrease in B increases detention time for a given value of V_c with peripheral chamber depth, $h_2 / h_1 = 0.60$ or $h_2 / D_T = 0.058$ and $D_T / B = 7.86$.

Design aspects of vortex settling basin were studied at Irrigation and Power Research Institute of Malakpur, Punjab (IPRI, 1988). Two models having similar geometric configurations were constructed for experimentation.

Diameter of the basin was varied in between 3B and 5B where B is bed width of the inlet canal. The size of under flow orifice varied from B / 24 to B/6. Sand (relative density = 2.65) of various sizes were used as test material. Data were collected for sediment removal efficiency as well as tangential and radial velocities at various depths and various radial locations. It was observed that for all sizes of vortex settling basin tested, the removal efficiency increased with decrease in D_T / d_0 at constant water abstraction ratio. For higher values of diameter ratio the efficiency of the basin falls down to 20 percent. For higher water abstraction ratio efficiency remains fairly constant at about 90 percent value.

Ogihara et al(24) (1984) reported investigations in a circulating tank for separating sediments from water flows using the rotating flow (see Fig. 2.16). When flow rotates horizontally in a cylindrical tank, secondary flow is generated which comprises of a vertical upward flow in the center of the tank and downward flow nearby the inside part of the tank wall. As such, water on the surface flows from center outwards and that at the bottom vice-versa. These secondary flows transport deposited sediment to the center of the tank Ogihara et al (1984) carried out both theoretical as well as experimental analysis to study four aspects; namely the main rotating flow, circulation of secondary flow, sediment transportation and sedimentation in the tank. A relationship between velocity of inlet flow and velocity of rotating flow was developed using energy of the inlet flow. In the experimentation, data were collected on above process by using three models of the tanks. The diameter of first tank was 43 cm while other two tanks had same diameter equal to 200 cm. Following conclusions have been drawn from this study:

(i) The analysis clearly established relations for the velocity of flow inside the basin for different h_p / R_T values such as 0.5, 1.0 and 2.0. The upward velocity in the center of the tank becomes larger in case h_p / R_T is larger.

(ii) Separation of sediments from the inlet flow is determined by the relationship between the fall velocity of sediments and vertical upward velocity at the center of the tank.

(iii) The sediment with larger fall velocity than its upward velocity, go down to the bottom of the tank.

(iv) When the discharge is larger, the upward velocity is controlled by the flow at outlet portion of surface intakes structure instead of secondary rotating flow.

Mushauri[19] (1986) investigated the flow characteristics inside the vortex chamber type sediment extractor and developed the criterion for finding the settling efficiency of the basin in terms of basin discharge, basin slope, basin height and the ratio of basin diameter to underflow diameter. Two mathematical models, namely the "analytical model" and the "numerical model" were developed for vortex type extractor. Extensive experimental testing was conducted by using two laboratory models, and a prototype vortex type extractor. General geometric configuration of the vortex type extractor used by Mashauri is shown in Fig. 2.17. The vortex type extractor used by Mashauri (1986) generally consisted of tangential pipe inlet and pipe outlets. Both inlet and outlet pipe were in same alignment but at different bed levels. In the first model the bottom of the vortex chamber was kept horizontal while in other two cases a slope of 1:10 was provided to encourage the flushing. A horizontal guide plate is provided at the inlet part to prevent short circuiting of the incoming flow to the outlet above, and also to confine the turbulence resulting from collision of the incoming and incumbent flows to the lower fluid layers. The results from mathematical models were compared with the results from the experimental testing. The main conclusions made were as follows:

(i) The vortex chamber is smaller in size as compared to conventional settling basins handling the same discharge and is hence relatively inexpensive. It can, therefore, be incorporated in existing conventional treatment processes.

(ii) Tangential inlet and outlet arrangements combined with use of flow deflector make it possible to impart swirling flow motion in the vortex chamber. The secondary circulation caused by this is responsible for improving removal efficiency.

(iii) The analysis indicates that for optimum efficiency, water abstraction ratio Q_0/Q_c equals to 5 percents and as discharge ratio increases beyond 5 percent, trapping efficiency becomes independent of orifice size d_0 or the flushing discharge Q_0.

A collaborative study was conducted by Paul et al(25) (1988), IPRI, Punjab (India) and Hydraulic Research Limited Wallingford, England with the objective of formulating mathematical model and bringing out a manual to facilitate the design of vortex settling basins. Three basins with diameter 0.55m, 5 m and 17 m were constructed with Perspex sheet. General layout of the vortex extractor used is shown in Fig. 2.18. In all three models of settling basins, the inlet and outlet channels were kept tangential to basin periphery and in the same alignment. The bottom slope S_T was kept as 1:10.7. The ratio of chamber diameter to orifice diameter was varied from 1:11.47 to 1:55.56. Uniform sand with relative density of 2.65 and median sizes of 0.175 mm, 0.22 mm and 5.55 mm was used as test material. The circular basin on its outer periphery had a perspex jacket filled with water to facilitate visualization of flow and trajectories of sediment particles with the aid of a powerful light source. A, 11.0 cm wide deflector wall was also used in alternative geometric to encourage the settling of sediment particles. Following conclusions were drawn from these studies:

(i) In the vortex – settling chamber there is a characteristics region of flow located at distance of R_T – B from the geometric center and extending over a width equal to the bed width of the inlet channel B. The properties of this region are;

  (a) Ratio of tangential velocity to average inlet channel velocity v_θ / v_i remains constant.

  (b) Ratio of radial velocity to average inlet velocity v_r / v_i remains constant.

  (c) Experimental data suggest that the optimum size of vortex chamber has a diameter D_T equal to five times bed width of the inlet channel.

  (d) The provision of a deflector in a vortex basin increases its trapping efficiency. If no deflector is provided some sediment, which is in process of settling in the basin may be picked up and get escaped with the spill flow in to the downstream channel.

  (e) When Q_c increases beyond the design limit Q_d, trapping efficiency of vortex basin reduces. For maximum trapping efficiency, the water abstraction ratio (Q_0/Q_c) should be equal to 0.05. A sloping bed of vortex chamber helps in keeping the bed clear of sediment deposit.

Esen(15) (1989) constructed a model of vortex chamber type sediment separator for separating sediments from liquids. An initial model with 90 cm diameter based on the findings of Akmandor (1973) was constructed. The orientation of inlet and outlet channels, shapes of inlet plate and approach wall were fixed by making use of Akmandor criterion. Based on results obtained from preliminary studies, a large vortex separator with nominal diameter as 1.35 m was constructed as shown in Fig. 2.19. The sizes of the orifice used were 1.9 cm, 3.7 cm and 7.5 cm. Noryl, luran and sands with different mean sizes were used as test materials. Sudden batch load injection method was adopted. The following conclusions were drawn from this study:

(i) The orifice diameter d_0 and underflow discharge Q_0 do not significantly affect the removal efficiency. However, bell mouth orifices minimized air entertainment and produced stable and smooth flow patterns, with stream vortex core.

(ii) The water abstraction ratio Q_0 / Q_c was between 0.022 and 0.242 with a median value of about 0.05 (Esen, 1989).

(iii) The detention time of flow in vortex chamber was found to be less than 30 s.

(iv) The total head loss between the inlet and outlet channel h_f was less than 0.027 m.

Zhu et al (1989) analyzed the data of Salakhov's circulation chamber and used a similar type of sediment exclusion device for discharging bed load. For construction of vortex chamber in prototype cement concrete was used while plexi-glass and polyvinyl chloride plastic materials were used in the model in order to satisfy the similarity of roughness. Natural sand with median size of 0.25 mm and relative density 2.65 was used as model sand. Experiments were conducted for varying inflow sediment concentration. Three test conditions were adopted. In first case test was carried out in such a way that the over flow takes place through entire periphery of the vortex basin. In second case only the half perimeter of the basin was used as over flow spillway while in third case test were carried out for strong spiral flow induced by adjusting curved vanes. Following inferences were made:

(i) When vane was not used in the experimental set-up the forced vortex was formed at the periphery and free vortex near the center leaving an intermediate zone of less velocity. The sediment passing through this zone settled at the bed and could not be trapped thus rendering lower efficiency. When vane was in action the velocity of flow increased throughout the chamber and zone of less velocity also got modified. Due to strong spiral vortex all sediment were caught by the vortex flow and flushed out thus increasing the efficiency of the system.

(ii) Due to the use of vane the air funnel forming at the center was also enlarged. This enlarged air funnel tended to form a spiral flow having higher ability of transporting sediment.

In an elaborate study, Athar(5) (2000) investigated the

(i) Variation of velocity components in tangential and radial directions in the vortex chamber having different geometric configurations,

(ii) Variation of sediment concentration in the vortex chamber

(iii) Developed the predictor for determination of the efficiency for removal of sediment by vortex extractor having different geometric configurations

The study was conducted in the Hydraulic Laboratory at Civil Engineering Department, University of Roorkee, Roorkee. Two models of different geometric configurations of the extractor each having the diameter of the vortex chamber equal to 1.0 m as shown in Fig 2.20(A) and 2.20(B) were used in the experimentation work. In the first model, the axis of the inlet and outlet channels were co-planar and these joined the vortex chamber tangentially while in the second model, the outlet channel was provided at a distance equal to the chamber diameter. An electromagnetic liquid velocity meter was used for velocity measurement. It measures simultaneously the two mutually perpendicular velocity components at the location of its sensor. Variation of suspended sediment concentration within the vortex chamber was measured by simultaneously varying the water abstraction ratio, sediment size and other parameters. In addition all the laboratory and field data available in the literature on above aspects were compiled and used in the study. Close study of observed velocity distribution indicated these to follow the pattern of combined Rankine vortex in some segments of the vortex chamber. However, the vortex system is greatly affected due to inflows and outflows of the chamber. Values of the radial and tangential velocities were found to be in good agreement with their corresponding observed values. Variation of suspended sediment concentration within the vortex chamber was computed using the numerical method of solution. A comparison was made between observation and such computed values which revealed a satisfactory agreement between these two. The relation for sediment removal efficiency of the vortex chamber type extractor by Curi et al (1979), Mashauri and Paul et al (1991) have been checked for their accuracy using a wide range of data from laboratory and field. It is noted that these relations are not able to produce a realistic estimate of the sediment removal efficiency for different range of data. Therefore re-analysis of available laboratory and field data was carried out and the following equation was derived for η_0

$$\eta_0 = K\left(\frac{Q_0}{Q_c}\right)^{0.25}\left(\frac{Z_h}{h_p}\right)^{0.35}\left(\frac{\omega_0 d}{\nu}\right)^{0.15}\left(\frac{Q_w^2}{gR_T^3 h_p^2}\right)^{0.11} \tag{2.8}$$

where K is a constant depending on geometric configuration, Q_0 and Q_c are discharges corresponding to inlet channel, outflow pipe, Q_w is the weighted discharge, Z_h is difference between the bed levels of vortex chamber and outlet channel, h_p is depth of flow at periphery of vortex chamber, w_0 is fall velocity of the particle, d is the median size of sediment particle and R_T is the radius of vortex chamber.

The above equation was found to produce results with a maximum of ± 40 percent error and relations for developed as above are expected to be used by the designer in their day to day work.

Conclusion drawn from the study can be summarized as follows:

(i) Vortex chamber type of sediment extractor is suitable alternative to conventional extractor due to smaller dimension, higher sediment removal efficiencies and smaller water abstraction ratio.

(ii) Flow pattern with the vortex chamber extractor resembles to some extent with the Rankine vortex system. Segments of vortex chamber having flow pattern similar to that of Rankine vortex extend only up to the half of the diameter lengths of the vortex chamber.

(iii) Within the vortex chamber, the velocities in radial and tangential directions are found not to vary significantly along vertical directions.

(iv) The relationship for sediment removal efficiencies of the vortex extractor follows logically from the relationship for distribution of velocity components and sediment continuity equation.

2.6 Design of vortex chamber type sediment extractor(25)

Vortex chamber type sediment extractor has been found to have large efficiencies (of the order of 90 percent or above) for removal of sediment at small water abstraction ratio (about 3 to 10 percent) to be used for flushing of settled sediment. To remove sediment a vortex chamber type sediment extractor utilizes the secondary flow generated by the circulatory flow induced in a circular basin. The development of secondary flow is due to :

- The decelaration of bottom layers of the fluid by friction between the basin floor and the fluid and
- Cross-flow current

The secondary flow moves the fluid layers near the basin floor toward the orifice of the flushing pipe of diameter d_o, installed at the center of the basin. Sediment particle heavier than the fluid are thus moved along spiral paths from the basin periphery toward the orifice. The design of vortex chamber type extractor includes the determination of the basin dimensions and sediment removal efficiency when the flow related parameters are known. At present there is no general relationship available from analytical background for designing a vortex chamber extractor. Rather a set of empirical equations as proposed by different investigators are available as a guide lines for designing a vortex chamber type extractor. The different parameters to be considered in the design of vortex chamber extractor include:

(i) Basin diameter 'D_T'

(ii) Basin height 'H_T'

(iii) Basin depth at periphery 'h_2'

(iv) Basin floor slope S_T

(v) Flushing discharge, Q_0

(vi) Flushing pipe diameter/ size of orifice 'd_0'

The symbols used to define the different parameters can be obtained from figure 2.18.

(i) Basin Diameter

Various correlations for basin diameter are given in table below:

No	Investigator	Basin Diameter (D_T)
1	APAW Practice (Sulivan 1972)	6 B
2	Salakov (1975)	$(2Q_{cc}/\omega_0)^{0.5}$ for d = 0.5mm to 1.0 mm
3	Cecen and Bayazit(1975)	5.274 A
4	Paul (1983)	5 B
5	Chrysostomou (1983)	7.86 B
6	Mashauri (1986)	5.316 A*

where : A^* = A function= $(K_1K_2u_*/v_{tp})^{1/4}(Q_{cc}/\omega_0)^{1/2}$

K_1 = Particle mobility number $(=\omega_0/u_*)$

K_2 = Coefficient of settling $(=\omega_0 D_T/v_{tp}h_p)$

u_* = Shear Velocity =$(0.035 \text{ to } 0.050)v_{tp}$

v_{tp} =Tangential velocity at basin periphery

v = Mean velocity of flow in the inlet canal or pipe

ω_0 = Settling velocity of sediment particles.

The relation by Paul et al (1983), D_T=5B has been deduced analytically. Experiments conducted by Chrysostomou's (1983) shows that with D_T=7.86B lengthens the residence time by 10% compared with the one for D_T =5B. Hence it is reasonable to adopt D_T =5B.

(ii) Basin Height 'H_T'

The two depth of flow in the basin are:-

h_p =depth at the basin periphery

h_0 =depth of flow over the orifice.

Mashauri (1986) deduced the following relationship based on definition of K_1 and K_2

$$\frac{h_p}{D_T} = \frac{\omega_0}{K_2} v_{tp}$$

Putting $\omega_0 = u_* K_1$ and $u_* = 0.050 v_{tp}$ in above equation, yields

$$\frac{h_p}{D_T} = 0.262 + 0.0042 / K_2$$

or $$\frac{h_p}{D_T} > 0.262$$

Again based on residence time studies, Chrysostomou (1983) shows the following relationship

$$\frac{h_p}{D_T} > 0.26$$

It is judicious to adopt $\frac{h_p}{D_T} > 0.26$ and the height of side wall H_T should be fixed as $0.26D_T$+ a free board not less than 0.30m.

(iii) Basin Depth at periphery

A ratio of $h_2/h_1 = 0.6$ is an optimum basin depth because any further reduction in h_2/h_1 simply decreases the resident time. It is therefore, suggested that peripheral basin depth, $h_2 = 0.6\ h_1 = 0.2\ h$ would yield better results, where h is full supply depth in canal, h_1 is the diaphragm height above canal bed and h_2 is the basin depth at periphery.

(iv) Basin Floor Slope

Salakov (1975) suggested a slope $S_T >= 50$ whereas Cecen (1977) proposed S_T=10. So a slope not steeper than $S_T = 10$ is suggested for better trap efficiency and with least flushing discharge.

(v) Flushing Discharge

Salakov(1975) and Cecen(1977), suggested a limiting flushing discharge(Q_0) of 3% to 10% of upstream(inlet) canal discharge(Q_c). Of course, higher percentages are obtained in basin with sloping floor. But as per Alquire (1982) et. al trap efficiency is not much effected by an increase in flushing discharge(Q_0) more than 10%.

(vi) Size of Orifice

After fixing Q_0 and h_0 with a known value of C_d, d_0 can be computed from

$$Q_o = C_d.\pi.d_0^2\sqrt{\frac{g.h_0}{8}}$$

$$C_d = \frac{0.22R_e^{\,0.075}N_T^{\,0.054}F_d^{\,0.965}}{\left[\frac{h_0}{d_0}\right]^{0.375}}$$

where R_e = Reynold number $(Q_0 / v.d_0)$

N_T = Circulation Number $(= \frac{\pi\, d_0^2 v_{t0}}{Q_0})$

F_d= Froude's number $(= \frac{4Q_0}{\pi\, d_0^2 \sqrt{gd_0}})$

v = Kinematic viscosity

It has been suggested that $2.5 < D_T/d_0 < 40$ results in good trapping efficiency.

2.7 Sediment removal efficiency of vortex chamber type extractor

Sediment removal efficiency η_0 of vortex chamber type sediment extractor is defined as;

$$\eta_o = \frac{\text{(Weight of the sediment flushed out through underflow orifice)} + \text{(Weight of the sediment settled in vortex chamber)}}{\text{Total weight of the sediment in the vortex chamber}} \qquad (2.9)$$

METHODOLOGY

3.1 General

A number of approaches for determining the size of basin are available. These are based on experimental data and on certain assumptions. The experience has been that each gives a size quite different from the other for same sediment removal efficiency. No design criteria of general application for the design of vortex chamber type sediment extractor is available. In the absence of any definite design criteria, the design is generally based on broad guidelines, assumptions and experiences as provided by different investigators. The verification of these assumptions and adequacy of the layout as well as other design aspects is, therefore assessed by conducting studies in hydraulic models.

The methodology of the 'Study of vortex chamber type extractor for Jaldhaka hydroelectric project' is to construct a physical hydraulic model based on preliminary design criteria and then to investigate its performance by varying the dimensions of different components in order to optimize its sediment removal efficiency. The dimensions of different components of a vortex chamber type extractor was calculated based on design discharge of the power house as 28.32 cumec (1000 cusec) plus a preliminary assumed flushing discharge of 5 percent of the design discharge which has been shown in appendix-I. This chapter will cover the detail concepts of hydraulic model theory, physical model formulation for vortex chamber type extractor, simulation of sediment, experimental setup to conduct model study, accessories of experimental setup etc have been discussed elaborately.

3.2 Hydraulic model theory(8)

"Experimenting with models seems to afford a ready means of investigating and determining before hand the effects of any proposed hydraulic structure; a means, after what I have seen, I should feel it madness to neglect before entering upon any costly undertaking", so says Osbrone Reynolds.

A model study is simply making a model of a real world object. The more similar to the real object, the better the model. Usually, models are made to give he scientist something easier to study than the real object the model was based upon. Factors such as size, location or accessibility may make it difficult to study some real objects in nature. A good model is the next best thing. If the model is scaled to match the real thing in proportions and made accurate to work like the real thing, then it may remove the need to study the real object.

Model studies are made for two purposes viz., in order to avoid costly mistakes and to obtain information that will help in the design of the prototype. Owing to a number of complex factors in the design of hydraulic structures, adequate answers to various problems can't yet be obtained by analytic methods. Small-scale hydraulic models therefore, become a very effective and handy tool for the engineer in the solution of his problems. Model cost, an insignificant fraction of the expenditure of a project besides suggesting improvement in design. They also eliminate the designer's doubts and indecision and enable visualize the whole problem. In the following paragraphs the different aspects of hydraulic model theory such as principles of similitude, analytical criteria for similitude, types of hydraulic models, choice of material in the model, verification of model and limitations of model studies etc have been discussed.

3.2.1 Principles of similitude

The design of hydraulic models is based upon the principles of similitude. There are mainly three types of similarities:

(a) Geometric Similarity
(b) Kinematics similarity
(c) Dynamic similarity

Geometric similarity exists when the ratios of all homologues dimensions are equal. In other words, it involves similarity of form or shape. Kinematics similarity postulates similarity of form and motion. This exists if the patterns or paths of motion of corresponding particles are geometrically similar and if the ratios of velocities of homologues practices involved in the motion are equal. Dynamic similarity is similarity of masses and forces besides geometric and kinematics similarity. This exists when the ratios of the homologous forces, which, in any way, affect the motion of homologous particles, are equal.

In the problem to be studied by models, one has to consider initially which of the forces predominate and influence the hydraulic phenomena. If gravity is the only force producing the motion, Froude's law will be applicable; if frictional forces govern the motion, Reynolds law will be applicable. Generally Froude's Law and Reynolds' Law are decisive in fixing the type and scales of models. Froude's Law postulates direct variation of velocity with respect of square root of the depth where as Reynold's Law requires inverse variation of velocity of depth. Consequently complete similitude is scarcely attainable in hydraulic model testing.

The requirements of similitude are generally stated in terms of dimensionless number. The significance of a dimensionless number is that when it is equal for model and prototype at corresponding points then dynamic –similarity is ensured. It is usually built up of three variables viz., length, velocity and force. The significant of these variables may be interrelated that length postulates geometrical similarity, velocity the kinematic similarity and force dynamic similarity. Hence the equivalence of dimensional number in two systems built-up of these variables could ensure complete similitude.

3.2.2 Analytical criteria for similitude

Newton's Law of motion, viz., Force =mass x acceleration is the fundamental relation governing all the hydraulic phenomena like irrotational motion of flow over weirs and through sluices, viscous flow in pipes, turbulent flow in pipes and open channels, sediment transportations and control, tidal flow, wave-motion and wave action etc. This law can be expressed in the form of a dimensionless number called the Newton's number. The other dimensionless number such as Froude number, Reynolds number, Weber number and Cauchy number are related to the forces of gravity, fluid friction, capillarity and elasticity respectively.

According to Newton's Second Law (Law of motion)

Force = Mass X Acceleration

$= (\rho L^3) \times (L/T^2)$ (where ρ = density and L = Linear dimensions)

$= \rho L^2 v^2$ (Since L/T = v)

Introducing the suffice 'p' for prototype, 'm' for model and 'r' for the ratio of model to prototype $F_r = \rho_r \, L_r^2 \, v_r^2$ (3.1)

or $$\frac{F_r}{\rho_r \, L_r^2 \, v_r^2} = 1 \quad (3.2)$$

The expression $\frac{F}{\rho L^2 v^2}$ is a dimensionless number designated as Newton's number, which is independent of the nature of operating forces. Thus dynamic similarity can exist in two fluid motions it the ratio of the inertial forces F_r equals the ratio of the vector sum of the active forces model to prototype.

In the case when gravitational force is the predominating force,

$$F_r = \rho_r g_r (L_r)^3 \quad (3.3)$$

From equation (3.1) and (3.3)

$$\rho_r (L_r)^2 (v_r)^2 = \rho_r g_r (L_r)^3$$

or $$\frac{(v_r)^2}{g_r L_r} = 1$$

or $$\frac{v_r}{\sqrt{g_r L_r}} = 1 \quad (3.4)$$

The term $\frac{v}{\sqrt{gL}}$ is a dimensionless number, defined as Froude's Number.

Since $g_r = 1$, from Equation (3.4)

$$v_r = \sqrt{L_r} \quad (3.5)$$

Again $$v_r = \frac{L_r}{T_r}$$

or $$T_r = \sqrt{L_r} \quad (3.6)$$

Again, $Q_r = A_r v_r$

$$= L_r^2 \sqrt{L_r}$$

$$Q_r = (L_r)^{5/2} \qquad (3.7)$$

In the case when the predominant forces are those due to friction between fluid particles,

$$F_r = \mu_r L_r v_r \qquad (3.8)$$

From Equation (3.1) and (3.8)

$$\rho_r (L_r)^2 (v_r)^2 = \mu_r L_r v_r$$

or $$\frac{L_r v_r}{(\mu_r / \rho_r)} = 1$$

or $$\frac{v_r L_r}{\upsilon_r} = 1 \quad \text{(since } \mu/\rho = \upsilon\text{, kinematic viscosity)} \qquad (3.9)$$

The expression $\frac{vL}{v}$ is known as Reynolds number.

Therefore $$v_r = \frac{\upsilon_r}{L_r} \qquad (3.10)$$

$$T_r = \frac{L_r}{v_r} = \frac{L_r}{\upsilon_r / L_r} = \frac{L_r^2}{\upsilon_r} \qquad (3.11)$$

and $$Q_r = (L_r)^2 \frac{\upsilon_r}{L_r} = L_r \upsilon_r \qquad (3.12)$$

When more than one type of forces are dominant, techniques generally employed are:

a) Employing a fluid in the model different from that in the prototype

b) Adjustment of model rugosity by trial and error

c) Tilting

d) Vertical distortion

e) Extrapolation, and

f) Local distortion

3.2.3 Types of hydraulic models

Hydraulic models are mainly of two types.

a) Geometrically similar modes: In this type, all dimensions are reduced to the same scale while experimenting with models, one would naturally like to get quantitative results as far as possible in respect of flow conditions, velocity and acceleration of flow, forces involved etc. This can be achieved if a close dynamic similarity is obtained while operating the models, which is possible only when geometrically similar models are used. Generally from geometrically similar models results obtained can be transferred quantitatively, with simple laws of similarity, to the prototype.

b) Vertically exaggerated or distorted models: It is frequently necessary to design hydraulic models with vertical scales greater than the horizontal. It is useful specially, in studies of sand exclusion from canals taking off from barrages or weirs, river training measures for arresting bank erosion and safeguarding bridges across alluvial rivers etc. The requirement for distortion arises because of the following several reasons:

(i) In nature when the size of the stream is small, depth increase relatively in proportion to widths, which is nature's way of maintaining turbulence. To conform with this, river models, are made with vertical scales larger than horizontal scales.

(ii) For the study of flow condition in model suitably, the flow should be turbulent. This is possible, usually if vertically exaggerated models are adopted.

(iii) To obtain adequate bed movement in the model, it is usually necessary to distort the scale.

(iv) By choosing small depth scales, accuracy in vertically measurements will have to be scarified.

Vertically exaggerated model can be typed as:

(1) Rigid model: Models with rigid boundaries are generally employed for studies of flood levels. In this type of model, bed roughness is adjusted, generally by means of small blocks or studs fixed to the sides and the bed

(2) Semi-rigid model: In these models, the sides and some times parts of the bed are made rigid. A bank slope exaggeration can thereby be adopted, for in excess of what would otherwise be possible.

(3) Movable bed model: In these models, both bed and sides are erodible. The advantage of erodible model is obvious, since they

can indicate changes in bed configuration brought about by various measures tested.

3.2.4 Choice of material in model

Sufficient bed movement is the criterion deciding the choice of material, so that bed configuration is properly simulated. Bed material should move in the model at the stage corresponding to which active bed movement exists in the prototype. Grade reduced to model dimensions would be excessively fine and float on the water surface due to the surface tension. Moreover, fineness of grade brings in cohesiveness and higher velocities would be required to move such materials.

Where velocities in models are not enough to move sand on bed, lighter materials are used as described below:

(a) Coal dust : Coal dust from collieries is of an average specific gravity of 1.4 to 1.5 and severs as an excellent bed material. The main draw back is that it does not give a uniform size of material.

(b) Saw dust : It floats. Hence it can simulate suspended load, however as it becomes wet, it sinks to form a lump due to fungus. To avoid this, treatment with saturated lime-water, washing and then treating with 1% copper sulphate solution.

(c) Pumic stone: Specific gravity is 1.4 to 1.7. Grain size 1 to 3 mm.

(d) Plexiglass or plastic sand: Sp. gr. is 1.8 but it is very costly.

(e) Powdered bakelite: Sp. gr. is 1.37 and free from defects like absorption of moisture, lump formation etc. and cheap.

(f) Lignite: Sp. gr. 1.2 to 1.6. Drawback is it is water repellent and hence should be treated with wetting agent.

(g) Lac: Sp. gr. 1.47 and can be varied by varying proportion of breates.

(h) Walnut shell: Sp. gr. 1.4 and can be crushed.

(i) Shallow: Sp. gr. 1.07.

3.2.5 Verification of models

The design of scales is no guarantee for the satisfactory performance of the model. Before a model can be used as handy tool for answering problems it needs be proved to reproduce known phenomena in the prototype. Addition and alterations, imposition of flow conditions at entry or exit, etc. become necessary in order that the model reproduces prototype condition. As it is not possible to attain complete dynamic similarity, it becomes necessary to adjust various hydraulic forces so as to bring about in the model corresponding prototype conditions. However, these adjustments have often to be based on judgment and experience. Though a strict hydraulic similitude cannot be obtained it can be closely approximated to by mans of an empirical process known as "verification", which is a progressive modifications of the hydraulic forces and model operating technique until the model reproduces hydraulic changes known to have accrued in the prototype.

3.2.6 Limitations for model studies

It does not necessarily follow that model study provide ready answers to all questions. For, one cannot devise a suitable model test or interpret the model test results, unless one understands the basic theory of the phenomenon under study. Time and money are wasted by a test of a model that does not adequately represent the prototype. Some times it is impracticable to build a model that will furnish all the desired information. And lastly, it is wasteful to result to model study if the results can be predicted by theory.

In nature, the forces that play, cannot be gauged accurately, neither the duration of forces for which the resultant action is responsible is known. It is therefore, to be found out from actual experiments, the optimum hour that a particular model should be run so as to able to faithfully represent the prototype conditions. It is only possible for a skilled observer with long practical experience in this line to diagnose from the behavior of a model, how for the results can be relied on and to what extent they can be applied in practice.

It is difficult to simulate all the conditions and properties of nature in the hydraulic models and consequently difficulties do arise in the transients of results obtained from studies in the models. The hydraulic models have, therefore, been considered as means towards an end in predicting certain factors at least qualitatively to be met within the prototype.

3.3 Model formulation for vortex chamber type extractor

Model studies for open channel type flow like vortex chamber extractor are generally conducted in geometrically similar rigid bed models. The scales of such models are determined on similarity of geometry and Froude's law. Due to presence of an open water surface which is free to change in position and shape, the technique of open channel model is complicated. In this the dominating force is that of gravity or weight and thus Froude's law of similitude is applicable. Effects of friction if they exist may and frequently are not represented clearly. Efforts should be made in the design and operation of the model to minimize effects of viscous shear. Large models and smooth boundaries are helpful in this regard.

A geometrically similar model was built to a scale of 1/10 to conduct the hydraulic studies of the proposed vortex chamber extractor. To achieve dynamic similarity on the model, Froude's law is to be satisfied. Thus the scale relationships for different parameter can be obtained from equation (3.5) to equation (3.7) as follows:

1	Length scale	1: 10
2	Time scale	$1:\sqrt{(10)}=1:3.16$
3	Velocity scale	$1:\sqrt{(10)}=1:3.16$
4	Discharge Scale	$1:(10)^{5/2}=1:316$

The design discharge for power house (28.32 m^3/sec) was determined as 89.6 liter per sec for the model. To represent the proper bed roughness in the model, transparent acrylic sheet was used in the model. The detail layout of the experimental model is described in art 3.5.

3.4 Simulation of sediment

In this geometrically similar scale model, the sediment size was simulated by "Froude's Law" and "Criterion of fall velocity". The technique followed for sediment simulation is that the ratio of the average velocity of sedimentary particles to the fall velocity is kept same in the model and the prototype". $\left(\frac{v_s}{\omega}\right)_p = \left(\frac{v_s}{\omega}\right)_m$

$$\Rightarrow \frac{(v_s)_p}{(v_s)_m} = \frac{\omega_p}{\omega_m} \qquad (3.13)$$

Where, v_s = Average forward velocity of sediment particle

ω = Fall velocity of sediment particle

and subscripts p, m = stands for prototype and model respectively

From Froude's Law "Froude number has to be same in model and prototype"

$$\left(\frac{v_s^2}{Lg}\right)_p = \left(\frac{v_s^2}{Lg}\right)_m$$

$$\Rightarrow \left(\frac{v_s^2}{L}\right)_p = \left(\frac{v_s^2}{L}\right)_m \qquad \text{(since } g_p = g_m\text{)}$$

$$\Rightarrow \frac{(v_s)_p}{(v_s)_m} = \sqrt{\frac{L_p}{L_m}} = \sqrt{L_r} \qquad (3.14)$$

From equation (3.13) and (3.14)

$$\frac{\omega_p}{\omega_m} = \sqrt{L_r}$$

$$\Rightarrow \omega_p = \omega_m \sqrt{L_r} \qquad (3.15)$$

Using equation (3.15) with $L_r = 10$, the fall velocity of particle for prototype can be obtained from the fall velocity of model sediment. The fall velocity of model sediment was obtained by using Rubey's curve. The simulation procedure for size of sediment in prototype with that of model is illustrated as follows:

Let particle size on the model be =0.15 mm

Fall velocity of particle in stagnant water (using Figure 3.7)= 1.5 cm/sec

Fall velocity of the simulated particle in prototype = $1.5 \times \sqrt{10}$ =4.74cm/sec

Size of the particle on prototype corresponding to 4.74 cm/sec =0.375 mm (using Figure 3.7)

3.5 Experimental set-up

The sediment extractor used for experimentation mainly consisted of the following:

(a) Circular cylinder vortex chamber
(b) Inlet channel or flume
(c) Outlet channel or flume
(d) Flushing conduit or pipe
(e) Diaphragm and deflector
(f) Sediment feeder.

Circular cylindrical vortex chamber of internal diameter equal to 1.18 m was provided in the experimental setup. The vortex chamber was made of 6 mm thick transparent acrylic sheet. The bottom of the chamber was given a slope of 1:10 towards the center to facilitate the sediment movement towards the outlet orifice at the center. The overall height of the chamber was 0.46m. A sharp edge orifice having varying internal diameter was provided at the center of the chamber and further connected to an flushing pipe with diameter equal to the diameter of orifice for flushing out the sediment collected at the center of the vortex chamber.

The inlet channel was 4.30 m long, 0.345 m deep and having a longitudinal slope of 1:1565. The section of the inlet channel was kept trapezoidal having bed width 0.236 m and side slope 1:1. The inlet channel bed and sides were made-up of perpex sheet.

The outlet channel provided in the extractor was trapezoidal shape having bed width 0.236 m depth, 0.345 m and side slope 1:1. The length of outlet channel was 2.90 m. Both the inlet channel and outlet channel were kept in an alignment following a straight line tangential to the vortex chamber.

To allow for passing heavy sediment laden water of lower layer into the vortex chamber, a diaphragm at varying height from the bed of inlet channel was provided. This discharge was entered into vortex chamber tangentially by 0.546m opening so as to induce a strong vortex. The remaining discharge of upper layer of flow was by-passed through a side channel of width equals to 0.47m which was joined with the outflow channel tangentially. Inside the vortex chamber, a deflector at the level of diaphragm was provided to dampen the swirls and increase the residence time. A 0.560m long overflow spillway was provided at 0.422 m above the bed of vortex chamber to pass the relatively clear water back into the outlet channel. Tail regulating gate was also provided in the outlet channel to maintain the desired depth of flow in the channel.

Outflow from the outlet channel was collected in a rectangular tank having sides and bottom made of painted steel. The discharge passing through flushing pipe outlet was passed over a pre-calibrated v-notch through a tank where a part of sediment was deposited.

The sediment removal efficiency of vortex chamber was computed using the following formula:

$$\eta_0 = \frac{W_F}{W_V} \qquad (3.16)$$

where,

W_V = Total influent sediment in the flow just upstream of the vortex basin = (sediment fed through sediment feeder – sediment deposited in the inlet channel) = $W_t - W_i$

W_F = Sediment excluded through flushing pipe of vortex basin = (Total sediment entered in vortex chamber – sediment deposited in downstream tank/passed in outlet channel) = $W_v - W_0$

Layout plan of experimental setup was shown in Fig. 3.1, where as photographic views of the extractor are given in Fig. 3.2 to Fig. 3.5.

3.6 Accessories of the experimental set-up

3.6.1 Acoustic Doppler Velocity meter (ADV)

ADV was used to measure the 3-D velocities at inlet / outlet channel and in the vortex chamber. The Acoustic Doppler Velocity meter is a versatile, high precision instrument that measures all three flow velocity components. The measurements are insensitive to water quality, which allows for a wide range of applications. ADV is used in laboratories, wave basins, river estuaries and oceanographic research.

The instrument consists of three modules, the measuring probe, the conditioning module and the processing module. The measuring probe is attached to the water-proof conditioning module, which contains low noise electronic circuit. The housing and cable attachment are rugged and can be deployed up to 30 m in the standard configuration.

For taking reading 3-D down looking probe have been used for collecting data in three directions v_x, v_y and v_z where velocity v_x refers to the velocity along the x-axis. The direction of y-axis and z-axis are based on the definition of a right-handed co-ordinate system where z is pointing upwards. For collecting data, high frequency cable from the single conditioning module is connected to the processor. Explorer V (version 1.5 and version 2.7) have been used for running program and for collecting data, version 3.2 has been used. The detail of ADV instrument is shown in Fig. 3.6.

3.6.2 Sediment used:

Sand having relative density of 2.65 was used as sediment in present experimental work. The median size of sand used was 0.197 mm. The sand was washed and dried before being used for feeding the sediment into flow of inlet channel. The sediment feeding device consisted of a hollow rectangular type box made of M.S sheet with conical bottom having variable opening (Fig.3.5). The variable opening can be controlled by a mechanical lever to regulate the quantity of sediment to be mixed with water. The sediment feeder could be kept across the width of inlet channel at top with the help of a horizontal railing. The sediment passing with flow in outlet (power) channel was collected in the trap placed at downstream M.S tank.

3.6.3 V- notch:

It was used to measure the discharge through inlet channel and discharge passing through flushing outlet. The formula used for discharge in v-notch is

$$Q = \frac{8}{15} c_d \sqrt{2g}.\tan(\theta/2) H^{5/2} \qquad (3.17)$$

where H is the depth of water above vertex of v-notch at the upstream of v-notch.

EXPERIMENTAL PROGRAMME

4.1 General

The main aim of this proposed model experiments is to optimize the height of deflector / diaphragm as well as fixation of diameter of flushing pipe of the proposed vortex chamber type sediment extractor which may appear as highly efficient in removing harmful sediment from the flow of Jaldhaka hydroelectric project. Carefully controlled experiments were planned to study the velocity distribution and the sediment removal efficiency of the vortex chamber type extractor having varying diaphragm height and different flushing pipe diameter. Uniform sand of relative density 2.65 was used as sediment. These experiments were conducted in the River Engineering Laboratory of Water Resources Development and Management, IIT, Roorkee.

4.2 Objectives of the experimental study

(i) Determination of the height of diaphragm for the proposed vortex chamber type sediment extractor for maximum sediment removal efficiency.

(ii) Determination of the diameter of flushing pipe outlet for maximum efficiency in removing the desired sediment size through the vortex extraction.

4.3 Laboratory flume and accessories for experimental study

The laboratory experimental setup mainly consists up:

(i) Circular vortex chamber with inlet, outlet and by pass side channel

(ii) Measuring devices and equipment.

The detail of experimental setup is already described in article 3.5 and 3.6.

4.4 Experimental procedure

4.4.1 Determination of the sediment removal efficiency

Sediment removal efficiency of the vortex chamber type extractor was measured by systematically varying the height of the diaphragm and diameter of the flushing pipe. Tail gate provided at the end of outlet channel was operated to maintain sub-critical flow for the entire system. Having established the desired flow condition, the total sediment to be transported by the flow in duration of 15 minutes was computed. This amount of sediment was fed into the flow in approach channel at a distance of 3.30 m upstream of the vortex chamber at a uniform rate of 2 gm / sec / liter over 15 minutes duration using the sediment feeder. The water drained out of the flume and the sediment trapped by the sediment trap at the end of outlet channel as well as sediment deposited in the upstream channel bed were collected. Appreciable deposition of sediment was not found to occur within the vortex chamber, which means that all the sediment settled inside the chamber moved towards the outlet orifice at its center and then it was flushed out through the flushing pipe. The sediment thus collected was dried and weighed and sediment removal efficiency was determined using equation 3.16.

4.4.2 Hydraulic model investigation

For determining the optimum sediment removal efficiency of the proposed vortex chamber type extractor following experimentation works have been carried out.

(i) **Diameter of flushing pipe equal to 0.05 m and height of diaphragm at h/3:** In the initial setup the diameter of flushing pipe was kept as 0.05 m whereas the height of deflector from channel bed was fixed at h/3. The model was run with the design discharge of 89.6 liter per second for a period so as to attain a steady state flow condition maintaining down stream depth of 0.285 m. The inflow and flushing discharges were measured and the flow pattern observed. It was found that the water entered the vortex chamber smoothly. However the flushing discharge was very less i.e. nearly 2 percent of inflow discharge and no air core vortex formed in the vortex chamber. It was concluded that the model did not prove and it is required to increase the diameter of flushing pipe.

(ii) **Diameter of flushing pipe equal to 0.075 m and height of diaphragm at h/3:** The diameter of flushing pipe was increased to 0.075 m keeping the diaphragm and deflector heights unchanged. The model was then run with the design discharge and the flow pattern observed. It was found that the flushing discharge increased to 3.90 percent of inflow discharge and an air core vortex formed at the centre of orifice. The model was therefore found proved for conducting experiments to determine the sediment flushing efficiency.

The model was run with design discharge of 89.6 liter per sec and maintaining the tail water depth at 0.285 m. After attaining a steady state flow condition, sediment having specific gravity 2.65 and median diameter of 0.197 mm was fed at a rate of 2000 ppm (2gm/sec/litr) for 15 minutes. The flow conditions are shown in figure 4.1 and figure 4.2. After draining the water the sediments were collected from bed of the inlet channel and that deposited in downstream tank. The collected sediments were dried, weighed and the recorded in table 4.1.

(iii) **Diameter of flushing pipe equal to 0.075 m and height of diaphragm at h/2:** In order to allow more sediment - laden water into the vortex chamber so as to increase the sediment exclusion efficiency of the system, the diaphragm as well as deflector height was raised to h/2 and all other elements were kept unaltered. The model was run with the design discharge and tail water depth. It was seen that a strong air entraining vortex formed in the vortex chamber. The flushing discharge increased to 6.80%. The proposal was next tested for sediment exclusion efficiency with sediment feeding for 15 minutes at a uniform rate of 2000 ppm. The sediments collected were dried, weighed and recorded in table 4.2.

(iv) **Diameter of flushing pipe equal to 0.075 m and height of diaphragm at 0.6 h:** Encouraged with the increase of efficiency by raising the height of diaphragm, the next alternative was tried in the model in which the diaphragm and the deflector were provided at 0.6 h. The diameter of flushing pipe was kept 0.075 m and all other elements were kept unaltered. The model was run with the design discharge and depth. Observation of flow pattern revealed that a strong air core vortex formed at the centre of vortex chamber. Figure 4.3 and figure 4.4 illustrates the flow condition in vortex chamber. The discharge through flushing pipe was calculated to be 7.65 percent of inflow discharge. The sediment of specific gravity 2.65 and median diameter of 0.197 mm was fed for 15 minutes at the rate of 2000 ppm. After draining water from the flume the sediment collected were dried, weighed and recorded in table 4.3. Sediment gradation analysis were done for sediment fed in the model through sediment feeder, collected from the bed of inlet channel and that deposited in downstream tank(passed in power/outlet channel) and were presented in table 4.5 to table 4.7.

(v) **Diameter of flushing pipe equal to 0.085 m and height of diaphragm at 0.6 h:** The next investigation was made with keeping the diaphragm and deflector height equal to 0.6h but increasing the diameter of flushing pipe to 0.085 m. The model was run with the design discharge and depth. Observation of flow pattern revealed that a strong air core vortex formed at the centre of vortex chamber. The discharge through flushing pipe was calculated to be 7.65 percent of inflow discharge i.e., there is no increment of discharge through the flushing outlet. The sediment of specific gravity 2.65 and median diameter of 0.197 mm was fed for 15 minutes at the rate of 2000 ppm. After draining water from the flume the sediment collected were dried, weighed and recorded in table 4.4.

Table 4.1 Sediment observation in different components of experimental flume

Height of diaphragm, $h_1=h/3$

Diameter of flushing pipe, $d_0=0.075$ m

No of run	Duration of run, T (min)	Inflow Discharge, Qc (m^3/sec)	Total sediment fed, W_T (kg)	Sediment deposited in inlet channel, W_i (kg)	Sediment deposited in downstream tank, W_o (kg)	Remarks
1	2	3	4	5	6	7
1	15	0.09408	168.00	38.20	77.00	
2	15	0.09408	168.00	38.00	77.20	
3	15	0.09408	168.00	37.80	77.40	

Table 4.2 Sediment observation in different components of experimental flume

Height of diaphragm, $h_1=h/2$

Diameter of flushing pipe, $d_0=0.075$ m

No of run	Duration of run, T (min)	Inflow Discharge, Q_c (m^3/sec)	Total sediment fed, W_T (kg)	Sediment deposited in inlet channel, W_i (kg)	Sediment deposited in downstream tank, W_o (kg)	Remarks
1	2	3	4	5	6	7
4	15	0.09408	168.00	40.00	49.00	
5	15	0.09408	168.00	40.25	48.75	
6	15	0.09408	168.00	39.75	49.25	

Table 4.3 Sediment observation in different components of experimental flume

Height of diaphragm, $h_1=0.6h$

Diameter of flushing pipe, $d_0=0.075$ m

No of run	Duration of run, T (min)	Inflow Discharge, Q_c (m^3/sec)	Total sediment fed, W_T (kg)	Sediment deposited in inlet channel, W_i (kg)	Sediment deposited in downstream tank, W_o (kg)	Remarks
1	2	3	4	5	6	7
7	15	0.09408	168.00	39.65	31.85	
8	15	0.09408	168.00	40.35	31.15	
9	15	0.09408	168.00	40.00	31.50	

Table 4.4 Sediment observation in different components of experimental flume

Height of diaphragm, $h_1=0.6h$

Diameter of flushing pipe, $d_0=0.085$ m

No of run	Duration of run, T (min)	Inflow Discharge, Q_c (m^3/sec)	Total sediment fed, W_T (kg)	Sediment deposited in inlet channel, W_i (kg)	Sediment deposited in downstream tank, W_o (kg)	Remarks
1	2	3	4	5	6	7
10	15	0.09408	168.00	40.50	35.35	
11	15	0.09408	168.00	39.90	35.65	
12	15	0.09408	168.00	40.20	35.50	

Table 4.5 : Gradation analysis of sediment fed through sediment feeder

Sieve No (mm)	Wt Retained (gms)	Percent (%) Retained	Cum Percent (%) Retained	Percent (%) Finer	Remarks
1.000	0.201	0.040	0.040	99.960	
0.850	0.096	0.019	0.060	99.940	
0.600	0.548	0.110	0.169	99.831	
0.425	16.02	3.210	3.380	96.620	
0.300	46.755	9.370	12.749	87.251	
0.150	293.225	58.762	71.511	28.489	
0.075	85.775	17.189	88.700	11.300	
Pan	56.388	11.300	100.000	0.000	
Total	499.008				

Table 4.6: Gradation analysis of sediment deposited in inlet(upstream) channel

Sieve No (mm)	Wt Retained (gms)	Percent (%) Retained	Cum Percent (%) Retained	Percent (%) Finer	Remarks
1.000	0.201	0.040	0.040	99.960	
0.850	0.124	0.025	0.065	99.935	
0.600	1.048	0.210	0.275	99.725	
0.425	25.313	5.073	5.348	94.652	
0.300	79.545	15.941	21.289	78.711	
0.150	327.119	65.555	86.843	13.157	
0.075	43.962	8.810	95.653	4.347	
Pan	21.69	4.347	100.000	0.000	
Total	499.002				

Table 4.7: Gradation analysis of sediment deposited in downstream tank /passed in outlet/power channel

Sieve No (mm)	Wt Retained (gms)	Percent (%) Retained	Cum Percent (%) Retained	Percent (%) Finer	Remarks
1.000	0.141	0.028	0.028	99.972	
0.850	0.064	0.013	0.041	99.959	
0.600	0.163	0.033	0.074	99.926	
0.425	3.982	0.798	0.872	99.128	
0.300	21.083	4.225	5.096	94.904	
0.150	274.722	55.051	60.147	39.853	
0.075	133.007	26.653	86.800	13.200	
Pan	65.87	13.200	100.000	0.000	
Total	499.032				

ANALYSIS OF DATA, RESULTS AND DISCUSSION

5.1 General

The detail analysis of data and results obtained thereform are presented in this chapter.

5.2 Sediment removal efficiency of vortex chamber type extractor

The sediment removal efficiency of a vortex chamber type extractor was determined from equation 3.16. The efficiency was computed using data from table 4.1 to table 4.4 for different height of diaphragm and for different diameter of flushing pipe (Appendix-II). The computed efficiencies were presented in table 5.1.

Table 5.1 Sediment removal efficiency of vortex chamber extractor

Sl no	Height of diaphragm h_1	Diameter of flushing pipe, d_0 (m)	Inflow discharge, Q_c (m^3/sec)	Discharge through flushing outlet, Q_0 (m^3/sec)	Abstraction ratio (Q_0/Q_c)	Efficiency η_0	Remarks
1	2	3	4	5	6	7	8
1	h/3	0.075	0.09408	0.00312	3.33	40	
2	h/2	0.075	0.09408	0.00640	6.80	62	
3	0.6h	0.075	0.09408	0.00716	7.65	75	
4	0.6h	0.085	0.09408	0.00716	7.65	72	

Graphical plots are made for

(i) Efficiency as a function of height of diaphragm (Fig 5.1)

(ii) Efficiency as a function of water abstraction ratio (Fig 5.2}

(iii) Water abstraction ratio as a function of height of diaphragm (Fig5.3)

From the above plots it can be seen that

(i) Sediment removal efficiency is directly proportional to the diaphragm height when the diameter of flushing pipe remains same.

(ii) Sediment removal efficiency increases as diameter of flushing pipe increases up to 0.075 m. Any further increase in diameter beyond 0.075 m will not effect any increase in the efficiency.

Size wise sediment removal efficiency by vortex chamber extractor was determined for diaphragm height at 0.6h and diameter of flushing pipe outlet equal to 0.075 m. From the sediment gradation analysis presented in table 4.4 to table 4.6 gradation curves for sediments were plotted as shown in fig 5.4. Using fig 5.4 and the known weight of sediment collected from bed of inlet channel and that deposited in downstream tank (also termed as sediment passed in power/outlet channel), sediment removal efficiency for different sizes has been worked out as shown in table 5.2. A close study of this table shows that efficiencies for all the sizes of sediment are above 71 percent. Using the method of simulation of sediment as discussed earlier the sediment removal efficiency of the prototype can be determined as shown in table 5.3.

5.3 Concluding remarks:

Experimental data on sediment removal efficiency with varying diaphragm/deflector height and flushing pipe outlet diameter are analyzed herein. Though the available literature indicated that diaphragm/ deflector should be located at h/3 position, this experimental study proved that sediment removal efficiency increases as the height of diaphragm increases beyond h/3. This is due to the reason that at higher elevation of diaphragm, more sediment will be diverted in to the vortex chamber thereby increasing the sediment removal efficiency. From the study it is appearing that sediment removal efficiency is not increasing much if the diameter of flushing pipe outlet is increased beyond 0.075m, i.e., the removal efficiency for proposed vortex chamber extractor is maximum at d_0=0.075m (D_T/d_0=16%). Again from the study it can be concluded that sediment removal efficiency for coarser graded sediment will be higher than the finer sediment.

Table 5.2: Size wise sediment removal efficiency of vortex chamber type extractor

Size of sediment (mm)	Sediment fed through sediment feeder		Sediment deposited in inlet (upstream) channel		Sediment entered in vortex chamber		Sediment deposited in downstream tank (passed in outlet/power channel)		Sediment flushed through flushing outlet		Sediment removal efficiency
	% Finer	Wt (kg)	% Finer	Wt (kg)	% Finer	Wt (kg)	% Finer	Wt (kg)	% Finer	Wt (kg)	(%)
1	2	3	4	5	6	7=(3-5)	8	9	10	11=(7-9)	12=(11/7)x100
0.075	11.300	18.984	4.347	1.739		17.245	13.200	4.158		13.088	76
0.150	28.489	47.862	13.157	5.263		42.599	39.853	12.554		30.046	71
0.300	87.251	146.581	78.711	31.485		115.097	94.904	29.895		85.202	74
0.425	96.620	162.322	94.652	37.861		124.461	99.128	31.225		93.236	75
0.600	99.831	167.716	99.725	39.890		127.826	99.926	31.477		96.349	75
0.850	99.940	167.900	99.935	39.974		127.926	99.959	31.487		96.439	75
1.000	99.960	167.932	99.960	39.984		127.948	99.972	31.491		96.457	75

Table 5.3: Size wise sediment removal efficiency of vortex chamber type extractor

Size of sediment projected in proto. (mm)	Sediment fed through sediment feeder		Sediment deposited in inlet (upstream) channel		Sediment entered in vortex chamber		Sediment deposited in downstream tank (passed in outlet/power channel)		Sediment flushed through flushing outlet		Sediment removal efficiency
	% Finer	Wt (kg)	% Finer	Wt (kg)	% Finer	Wt (kg)	% Finer	Wt (kg)	% Finer	Wt (kg)	(%)
1	2	3	4	5	6	7=(3-5)	8	9	10	11=(7-9)	12=(11/7)x100
0.140	11.300	18.984	4.347	1.739		17.245	13.200	4.158		13.088	76
0.200	16.400	27.552	5.500	2.200		25.352	22.5	7.090		18.262	72
0.375	28.489	47.862	13.157	5.263		42.599	39.853	12.554		30.046	71
0.500	40.000	67.200	25.000	10.000		57.200	52.000	16.380		40.820	71
1.400	87.251	146.581	78.711	31.485		115.097	94.904	29.895		85.202	74
2.750	96.620	162.322	94.652	37.861		124.461	99.128	31.225		93.236	75
4.500	99.831	167.716	99.725	39.890		127.826	99.926	31.477		96.349	75
7.000	99.940	167.900	99.935	39.974		127.926	99.959	31.487		96.439	75
9.000	99.960	167.932	99.960	39.984		127.948	99.972	31.491		96.457	75

CONCLUSIONS

6.1 Summary

The main objective of the present investigation was to evolve the best configuration of a vortex chamber type sediment extractor for Jaldhaka hydroelectric project with optimum sediment removal efficiency. For removal of all the sediment ranging from 0.20 mm to 0.50 mm and above from the flow of power channel, a vortex chamber type sediment extractor was considered in this investigation. The preliminary dimensions of the vortex chamber was worked out considering the design discharge of power house as 28.32 m^3/sec (1000 cusec) and following the guidelines provided in Paul et al(25). A geometrically similar model built to a scale of 1/10 was utilized to conduct the hydraulic studies in the River Engineering Laboratory, WRD&M, IIT, Roorkee. In the model investigation, only the height of diaphragm/ deflector as well as diameter of flushing pipe/orifice was varied when all other dimensions were kept unaltered. The results thus obtained from the model investigation were analyzed and presented in chapter V.

6.2 Conclusions

From the study, the following conclusions can be drawn:

⇒ Vortex chamber type sediment extractor is an efficient alternative to conventional extractor due to its smaller dimensions, higher sediment removal efficiency, and smaller water abstraction ratio.

⇒ The circular basin should have diameter equal to five times the bed width of the inlet channel and radial slope of its floor should be no steeper than 10. For extraction of sediment smaller than 0.50mm, provisions of diaphragm, deflector is required to ensure better sediment removal efficiency whereas for sediment size larger than 0.50mm, these are not essential.

⇒ A vortex chamber extractor having internal diameter equal to 11.80 m, chamber height 4.61 m, diameter of flushing pipe outlet equal to

0.75 m can be adopted as a desilting device for the proposed hydroelectric project.

⇒ A horizontal diaphragm having a length equal to 6.00m extending in the inlet channel and positioning at an elevation of 0.6h from the bed of the inlet channel can be adopted for removal of the harmful grade of sediment from the power channel.

⇒ With this configuration, the overall sediment removal efficiency of the vortex chamber can be expected as 75 percent which seems to be favorable for the hydroelectric project considered in this study.

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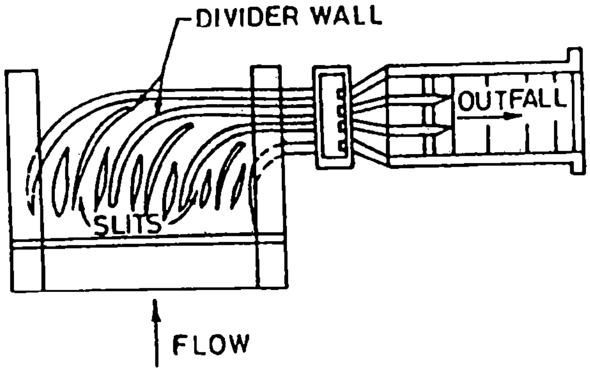


Fig 2.1: Tunnel Type Sediment Extractor used on Salampur Feeder in Punjab (Sujudi, 1988)

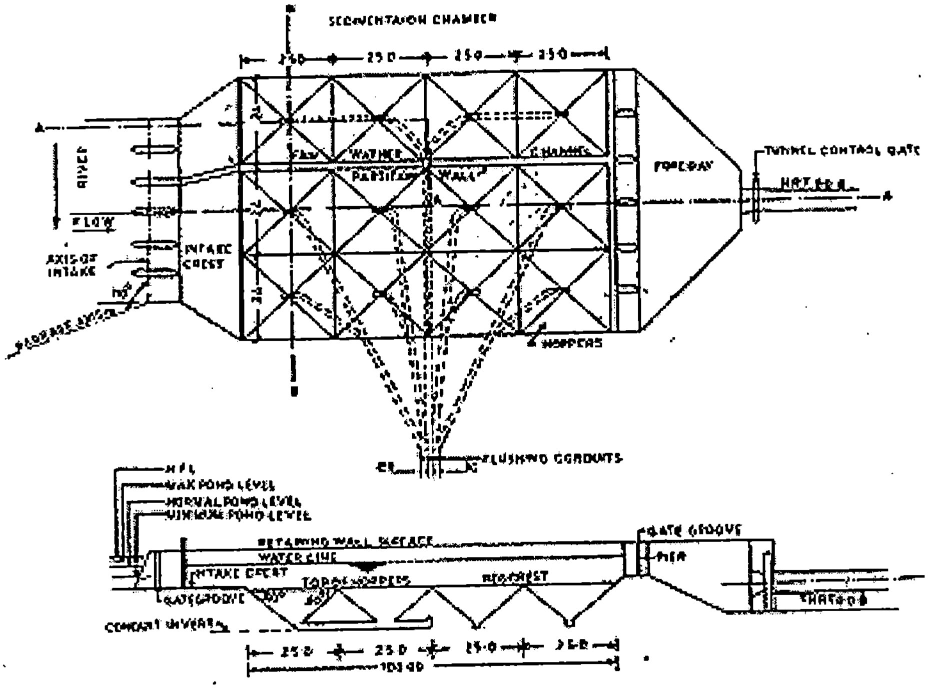


Fig.2.2: Plan and Section of a Typical Disilting basin

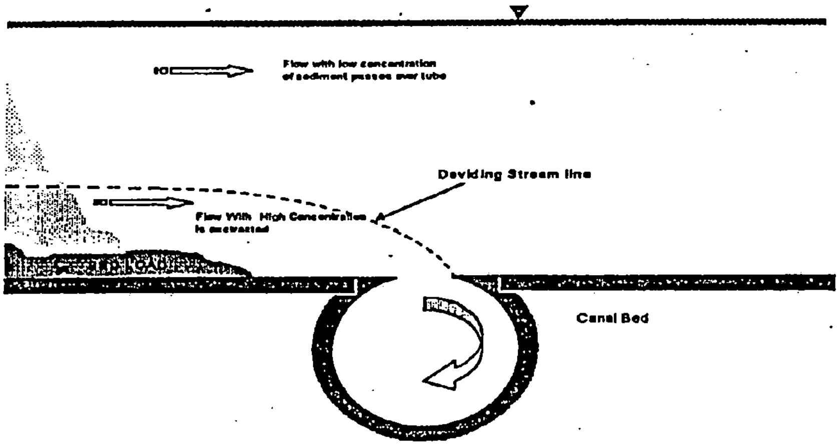


Fig.2.3 : Typical Vortex Tube Sand Trap

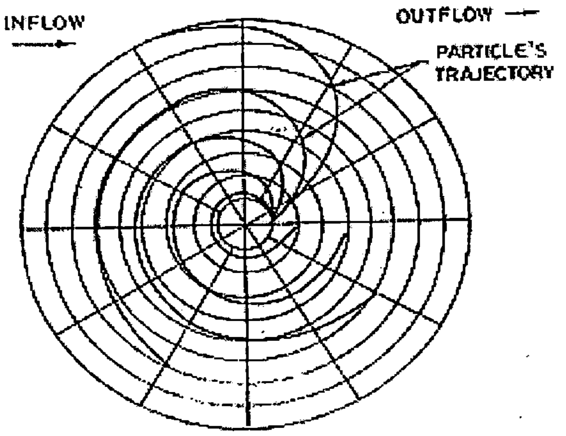
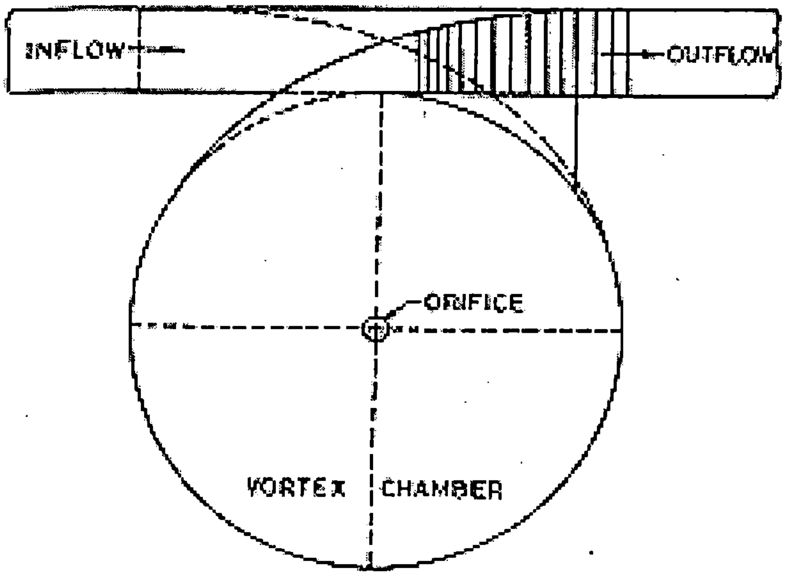
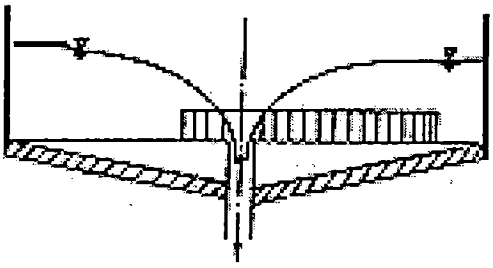


Fig.2.4: Particle Trajectory in Vortex Chamber Type Extractor (Mashauri, 1986)



PLAN



SECTIONAL ELEVATION

Fig.2.5 Typical Vortex Chamber Type Sediment Extractor (Cecen, 1977)

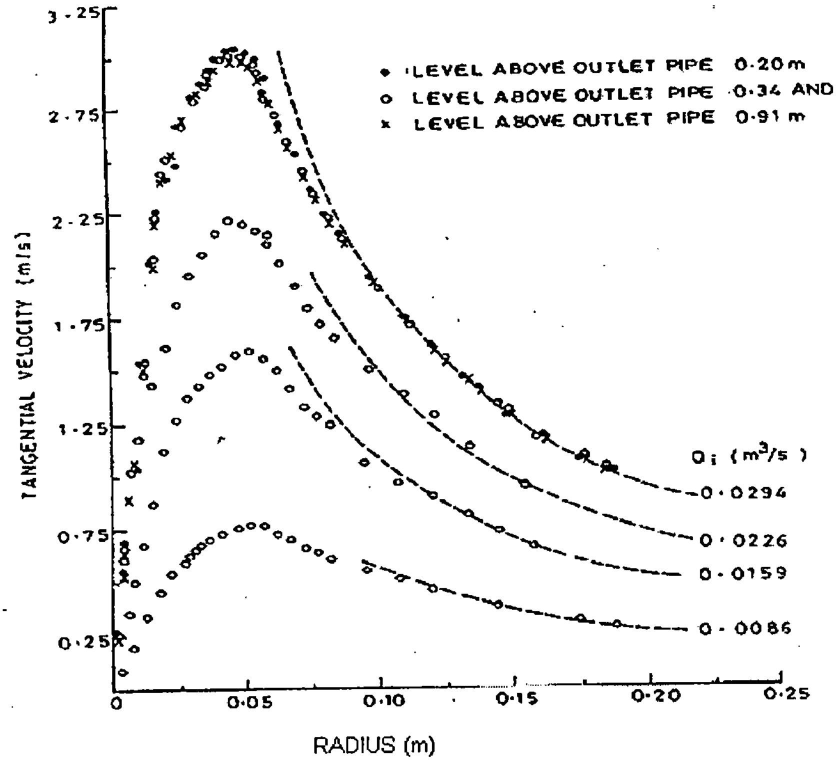


Fig.2.6: Particle Trajectory in Vortex Chamber Type Extractor (Mashauri, 1986)

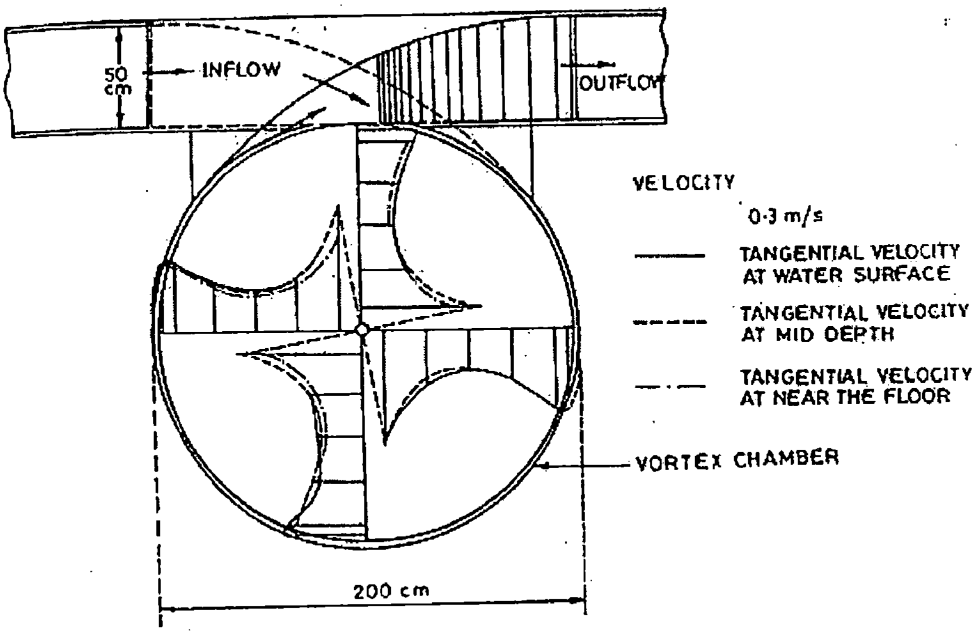


Fig 2.7: Tangential Velocity Distribution (Cecen,1977)

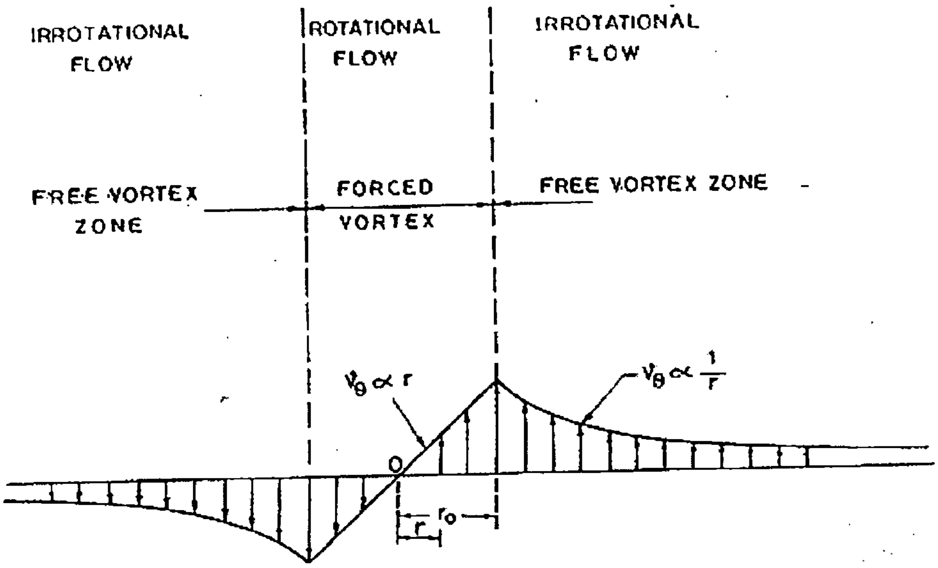


Fig 2.8: Distribution of Tangential Velocity (Julien, 1985)

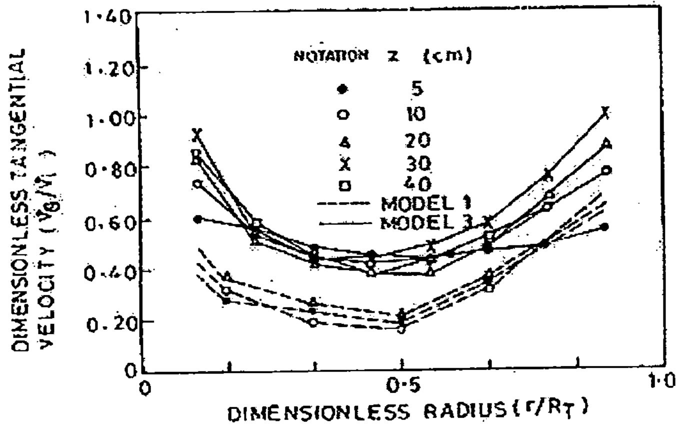


Fig 2.9 Variation of Tangential Velocity within Vortex Chamber Extractor (Mashauri, 1986)

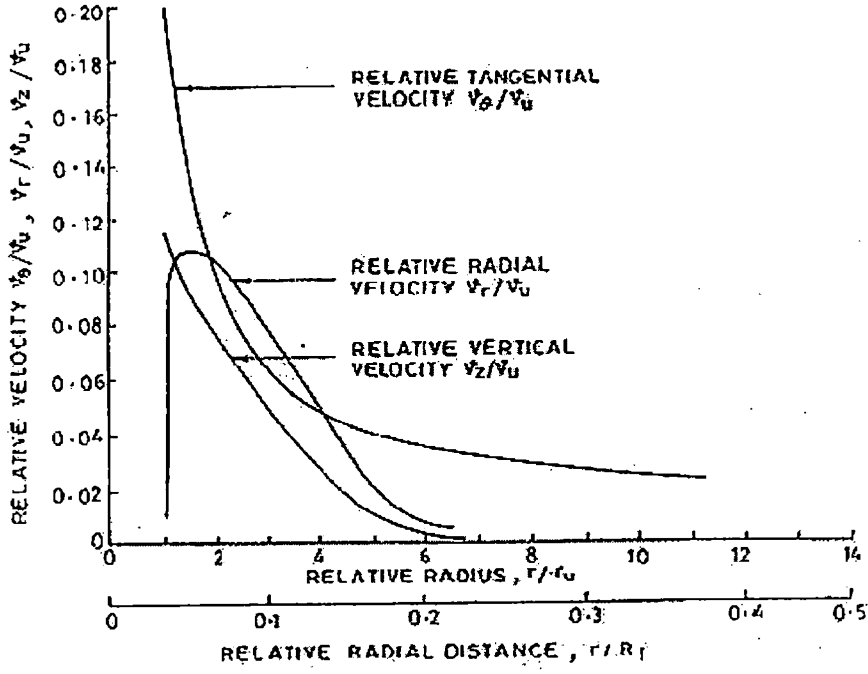


Fig 2.10: Computed Variation in Velocity Components as a Function of Radial position in the Vortex Chamber (Mashauri, 1986)

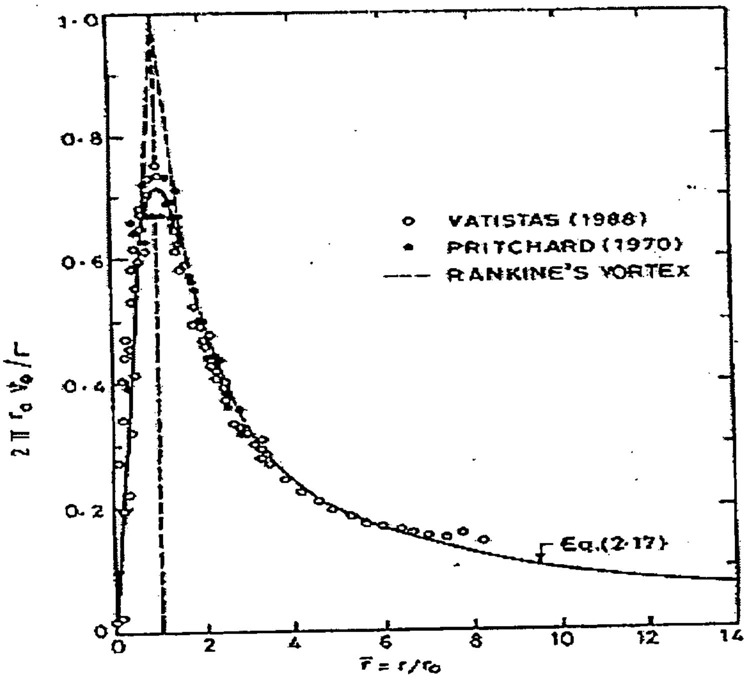
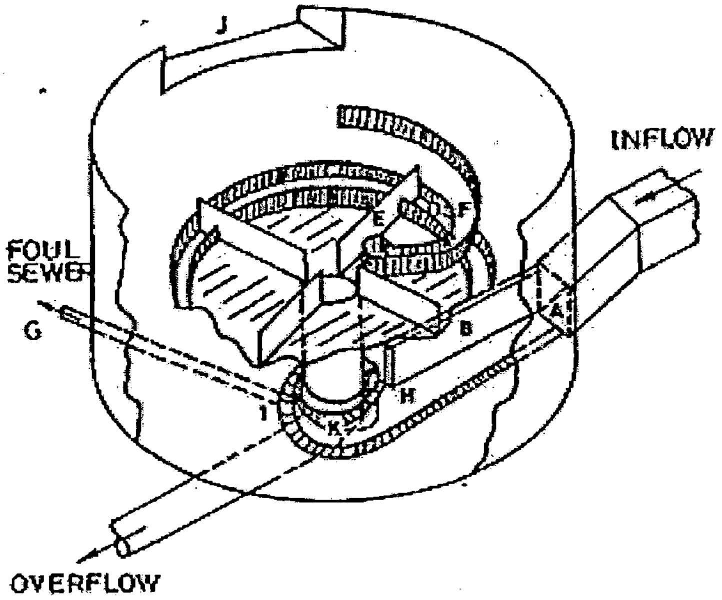
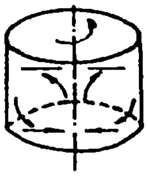


Fig 2.11: Variation of Tangential Velocity with Radius (Vatistas, 1989)

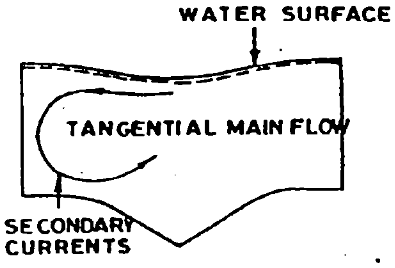


A	INLET RAMP
B	FLOW DEFLECTOR
C	SCUM RING
D	OVERFLOW WEIR AND WEIR PLATE
E	SPOILERS
F	FLOATABLES TRAP
G	FOUL SEWER OUTLET
H	FLOOR GUTTERS
I	DOWNSHAFT
J	SECONDARY OVERFLOW WEIR
K	SECONDARY GUTTER

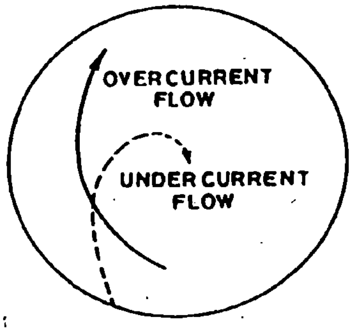
Fig 2.12 General View of Grit Separator (Sullivan,1974)



(a) GENERAL FLOW CHARACTERISTICS



(b) LONGITUDINAL SECTION OF FLOW



(c) PLAN VIEW OF FLOW

Fig 2.13: Schematic of Under Current Flow in Swirl Concentrator (Sullivan,1972)

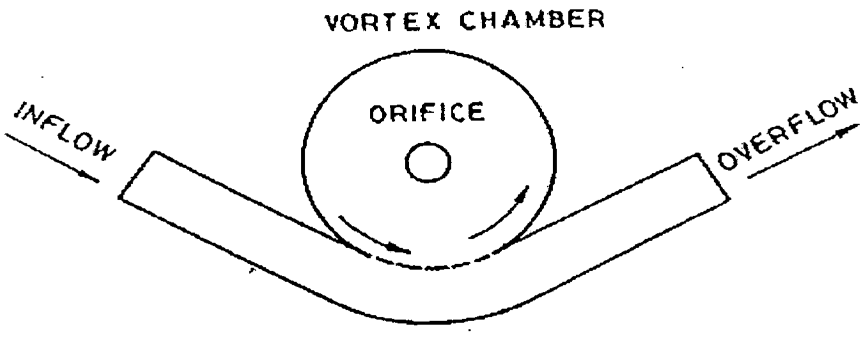


Fig 2.14: Vortex Type Separator (Curi et al., 1975)

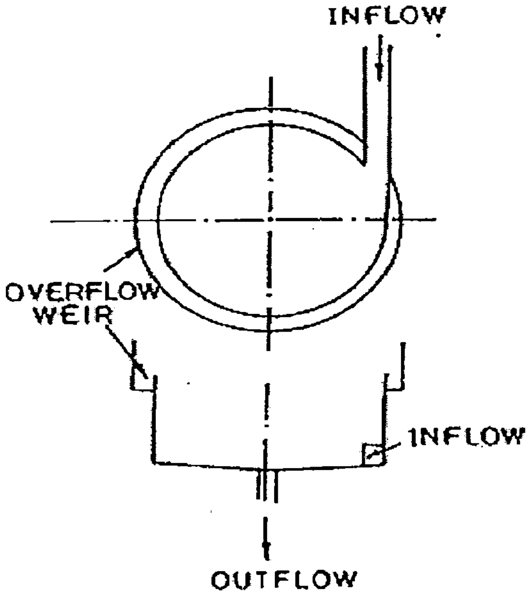


Fig 2.15: Circulation Chamber Studied by (Salakhov (1975)

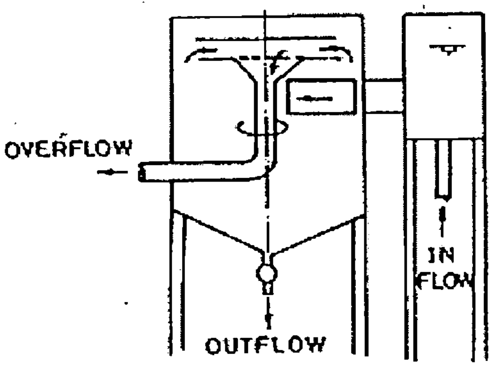


Fig 2.16: Model Tank (Ogihara and Sakaguchi, 1984)

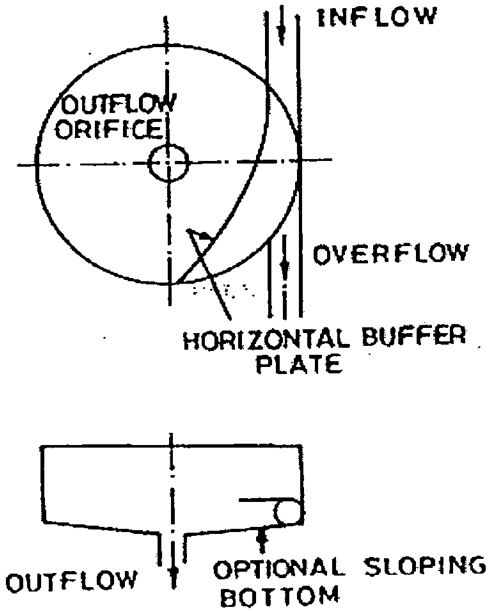


Fig 2.17: Geometric configuration of Vortex Chamber model used by Mashauri (1986)

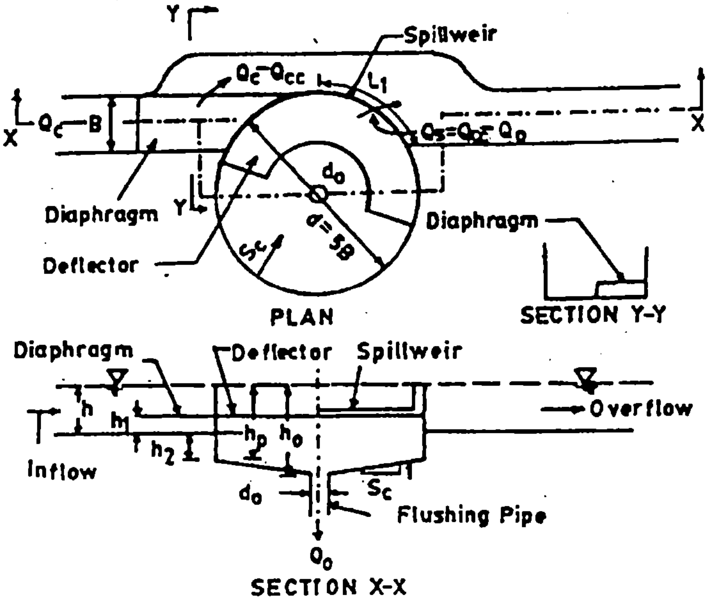


Fig 2.18: Vortex Settlin Basin Model-I (Paul et al. 1988 a)

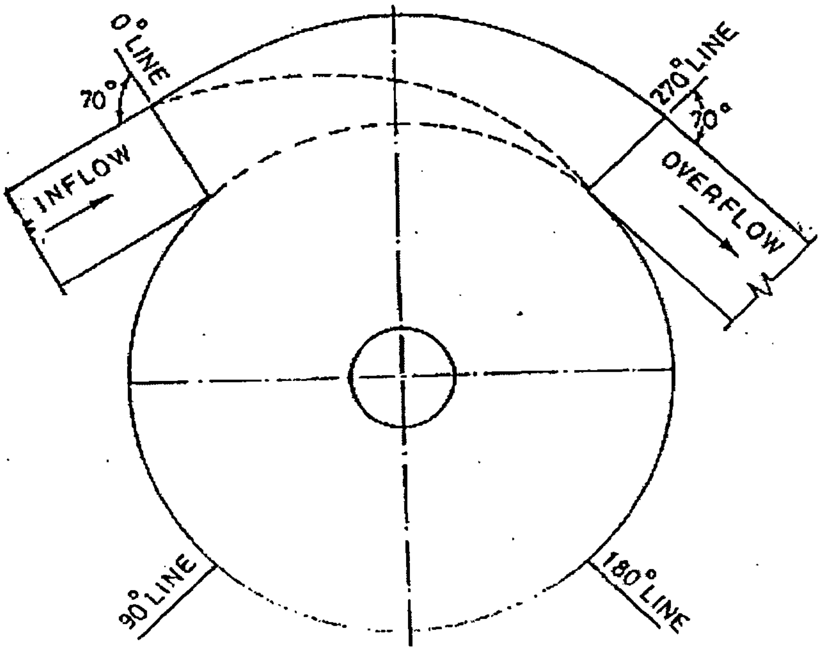


Fig 2.19: Vortex Chamber Sediment Separator (Esen, 1989)

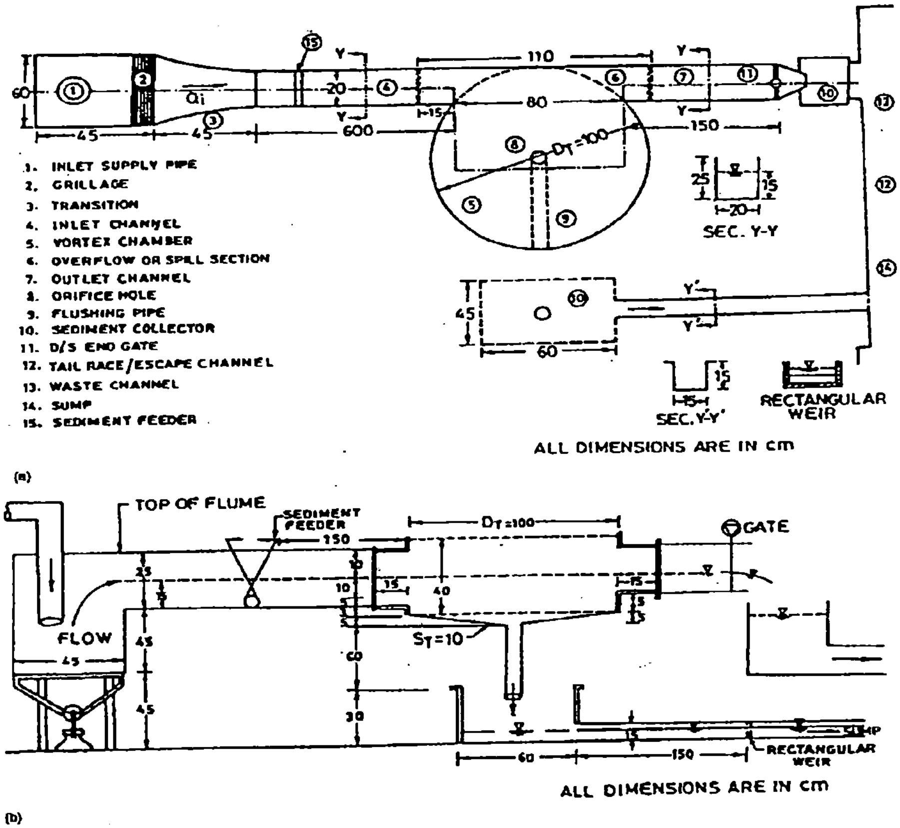


Fig 2.20(A): Plan and Sectional view of Vortex Chamber Extractor Geometrical Model-I (Athar, 2000)

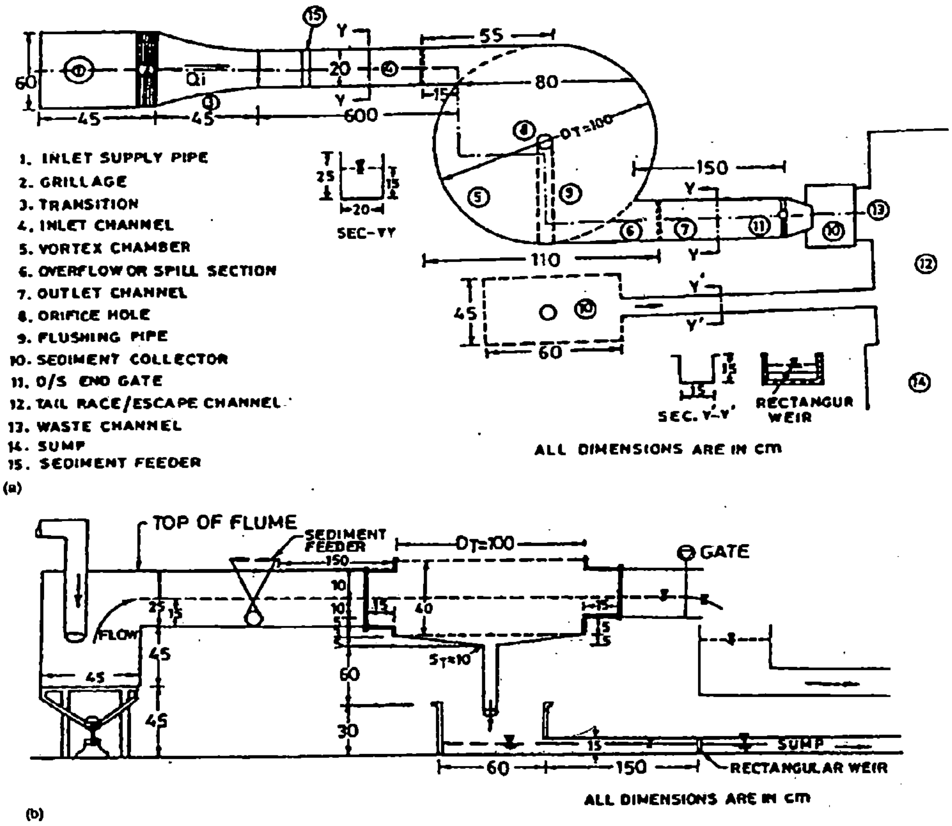


Fig 2.20(B): Plan and Sectional view of Vortex Chamber Extractor Geometrical Model-II (Athar, 2000)

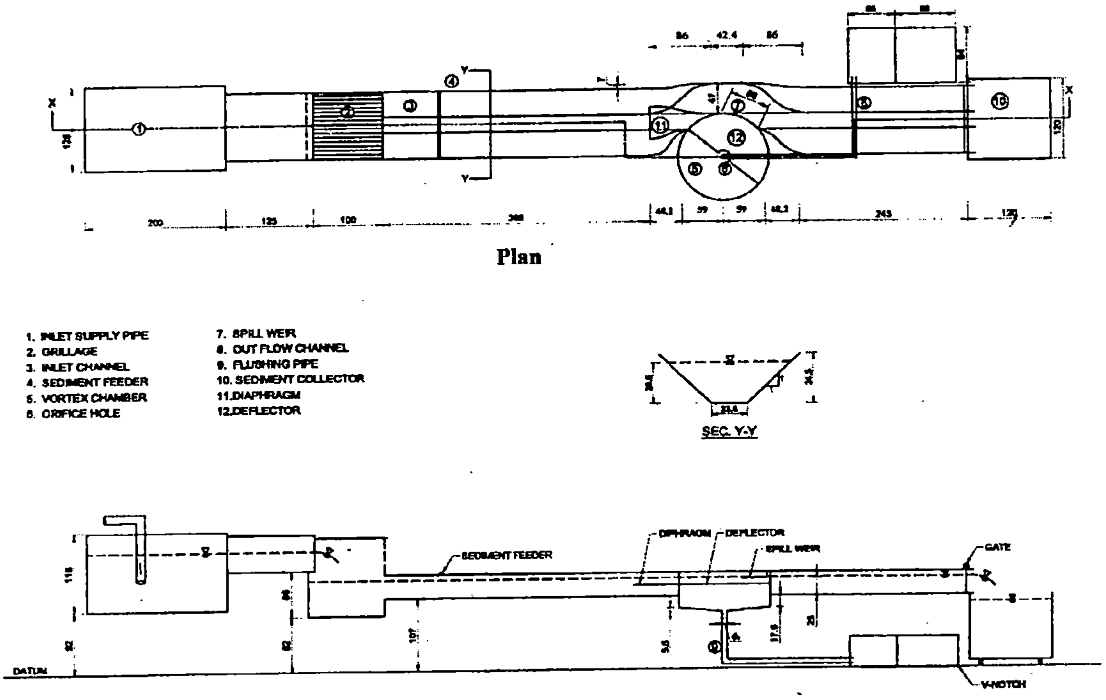


Fig 3.1: Layout Plan of Experimental Set-up of Vortex Chamber Type Extractor

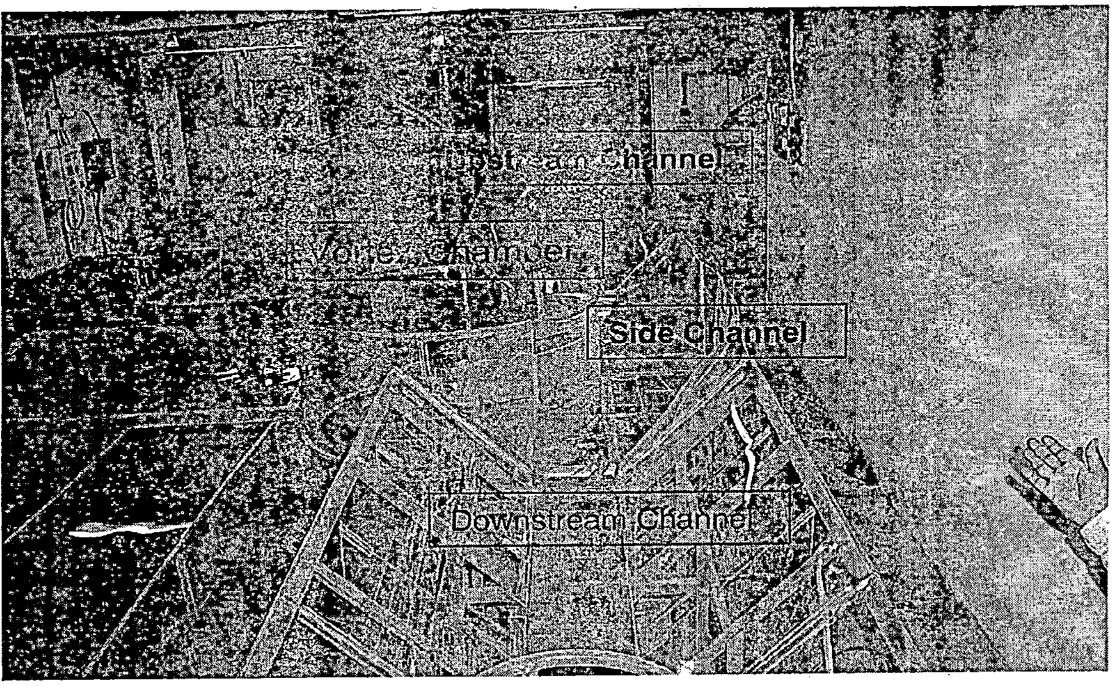


Fig 3.2 : Photographic view of the vortex chamber extractor (Layout plan)

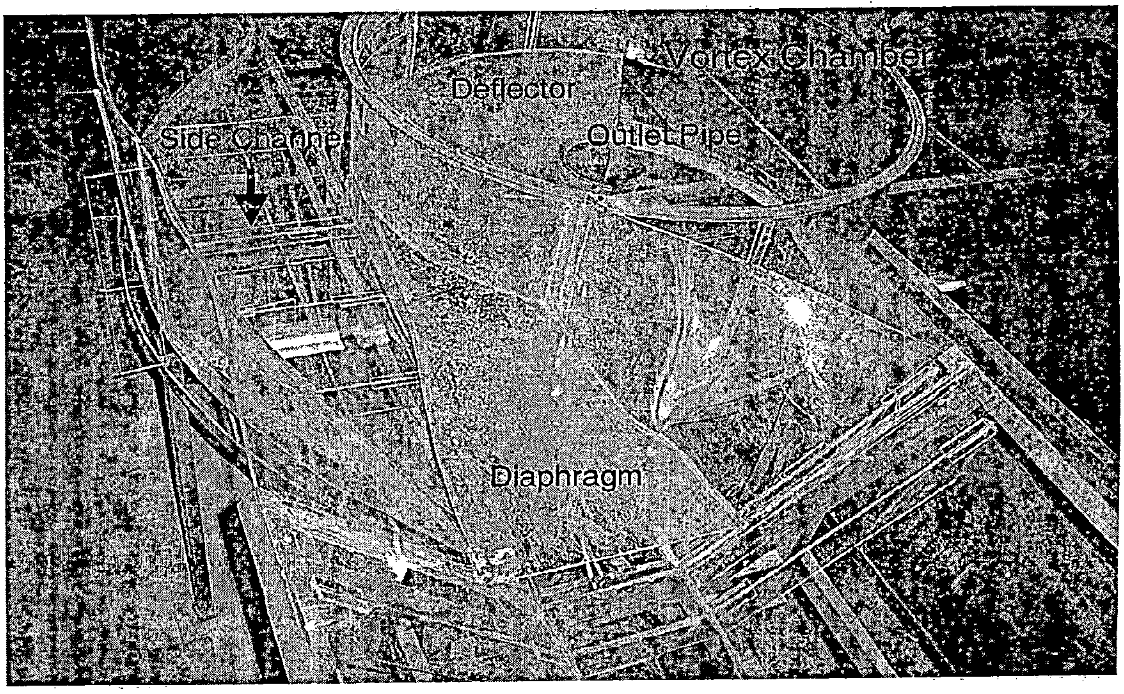


Fig 3.3 : Photographic view of the vortex chamber extractor
(Details of vortex chamber)

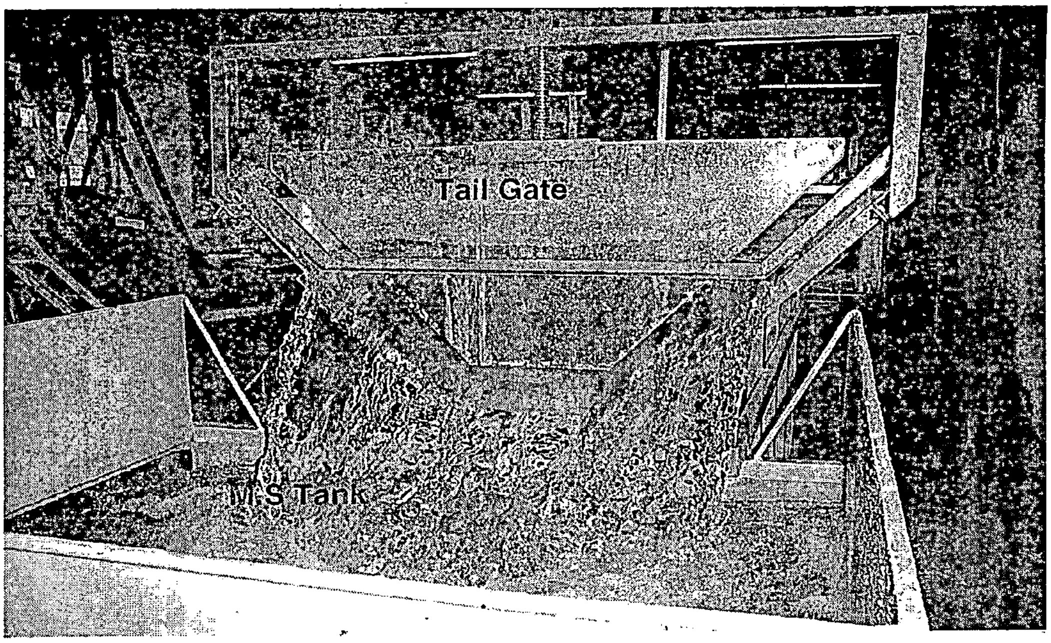


Fig 3.4 : Photographic view of the vortex chamber extractor (Downstream tank)

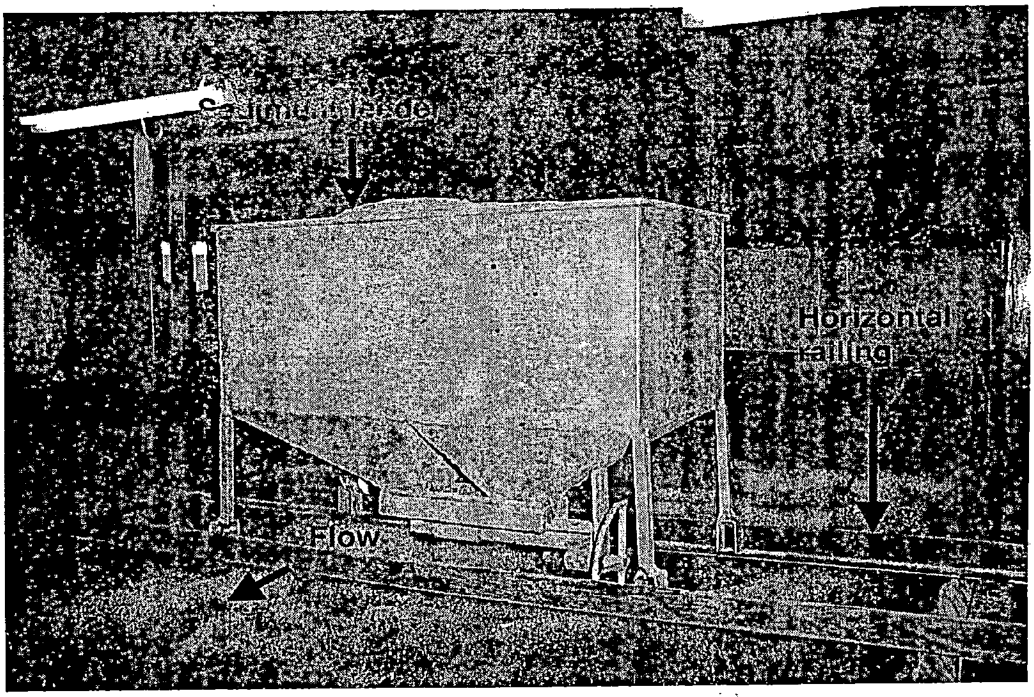


Fig 3.5 : Photographic view of the vortex chamber extractor (Sediment Feeder)

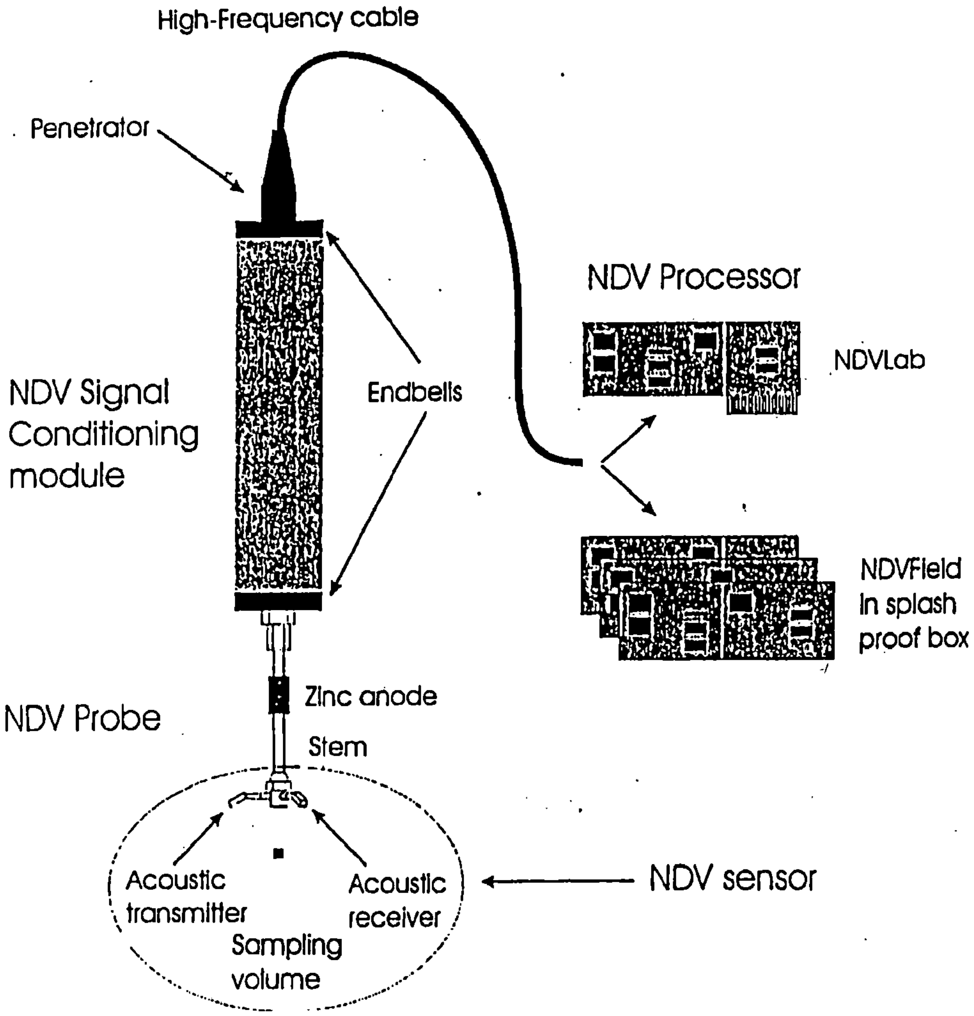


Fig 3.6: 3-D Down Looking Probe Acoustic Doppler Velocimeter

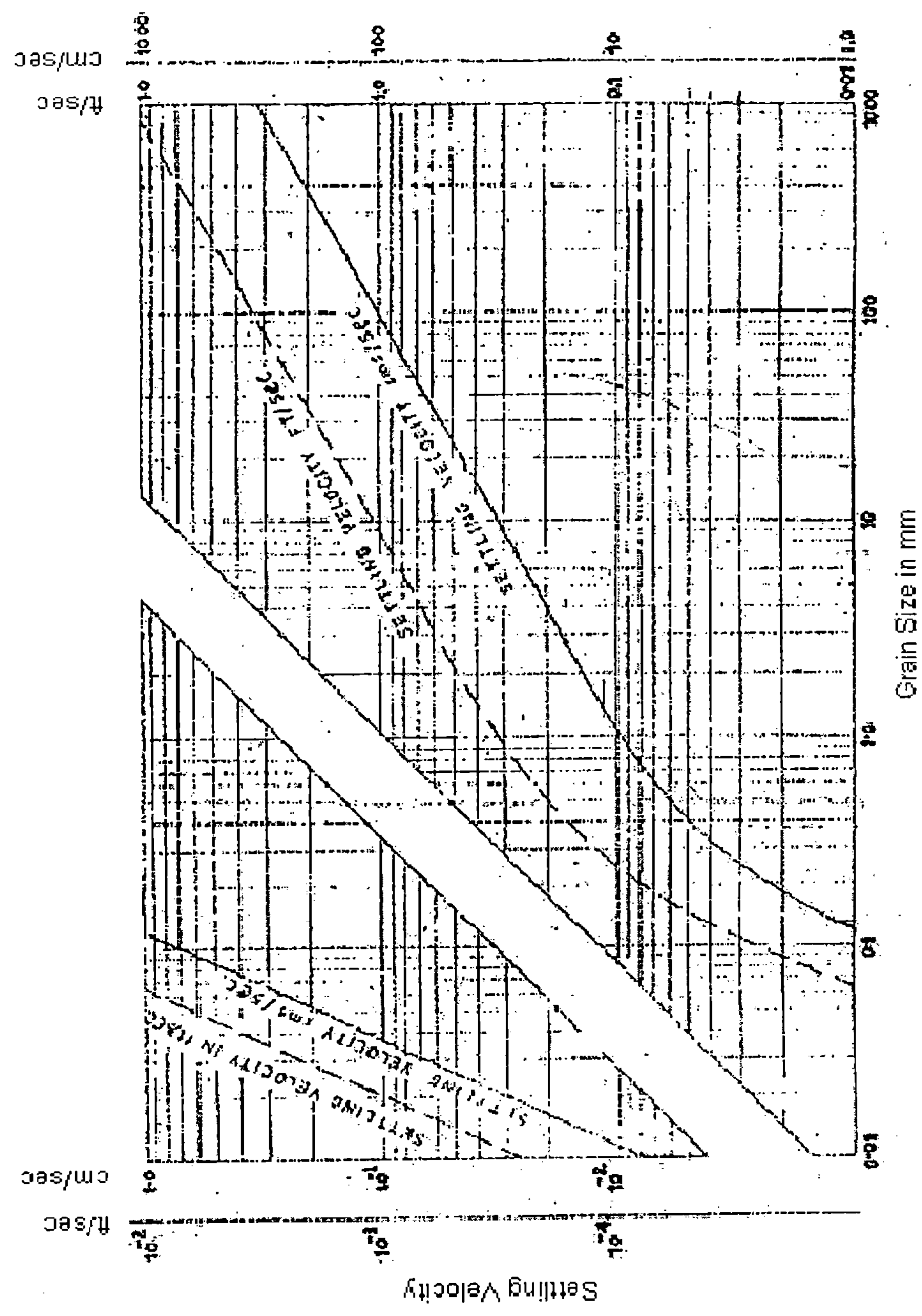


Fig 3.7 Relation between Settling Velocity and Grain Size (Rubey's Curve)

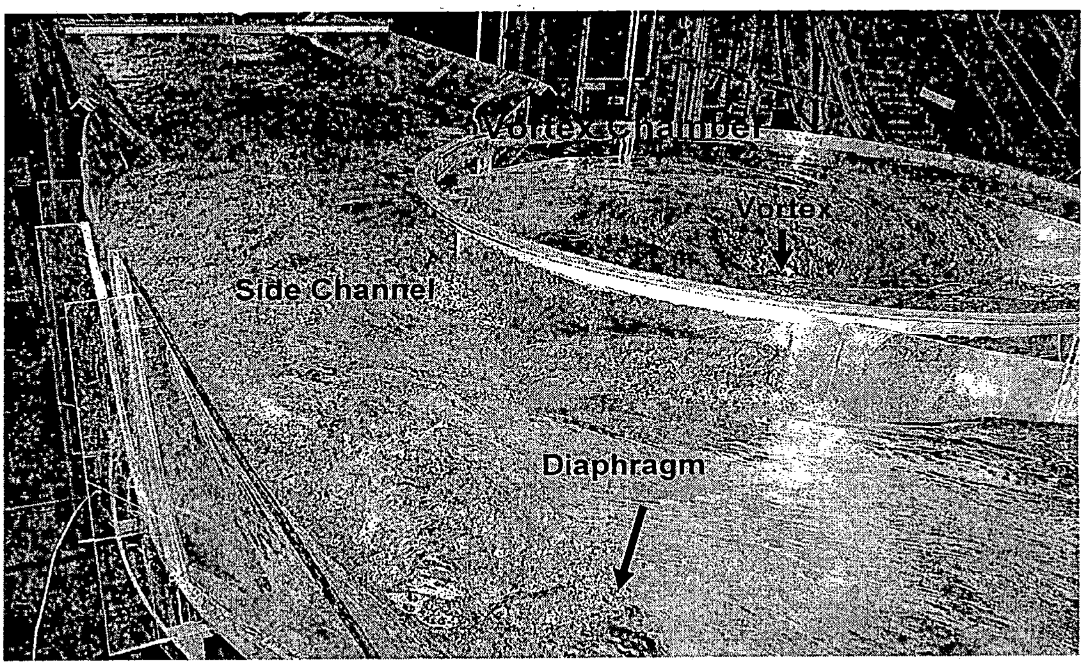


Fig 4.1 : Photographic view showing flow condition at vortex chamber

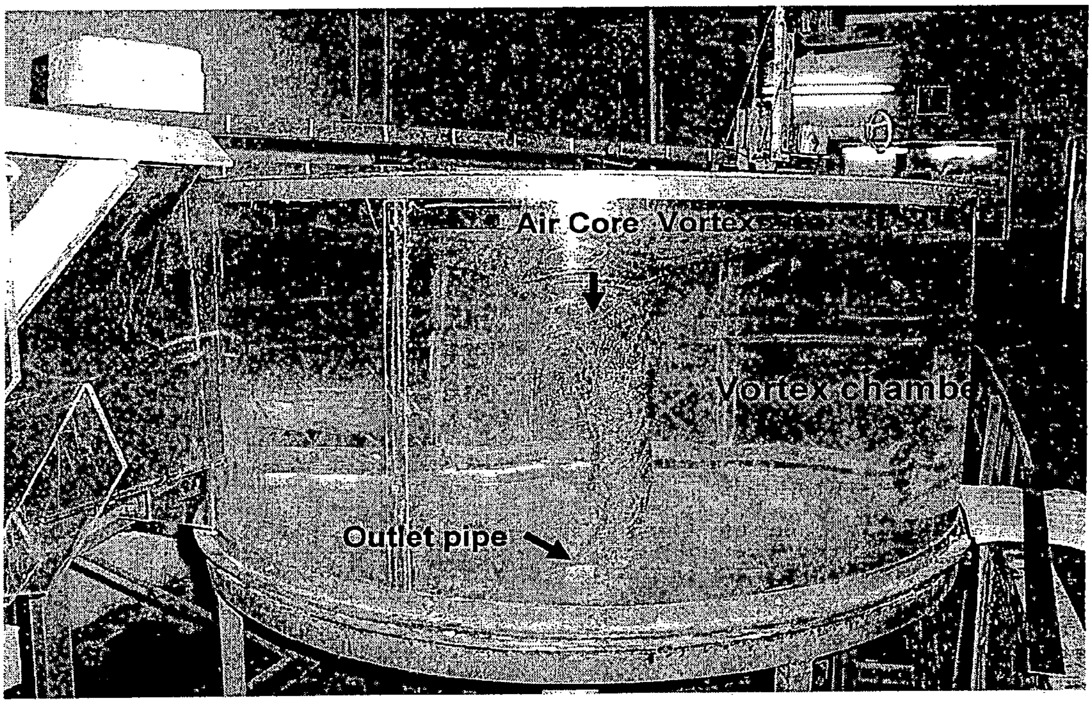


Fig 4.2 : Photographic view showing flow condition at vortex chamber

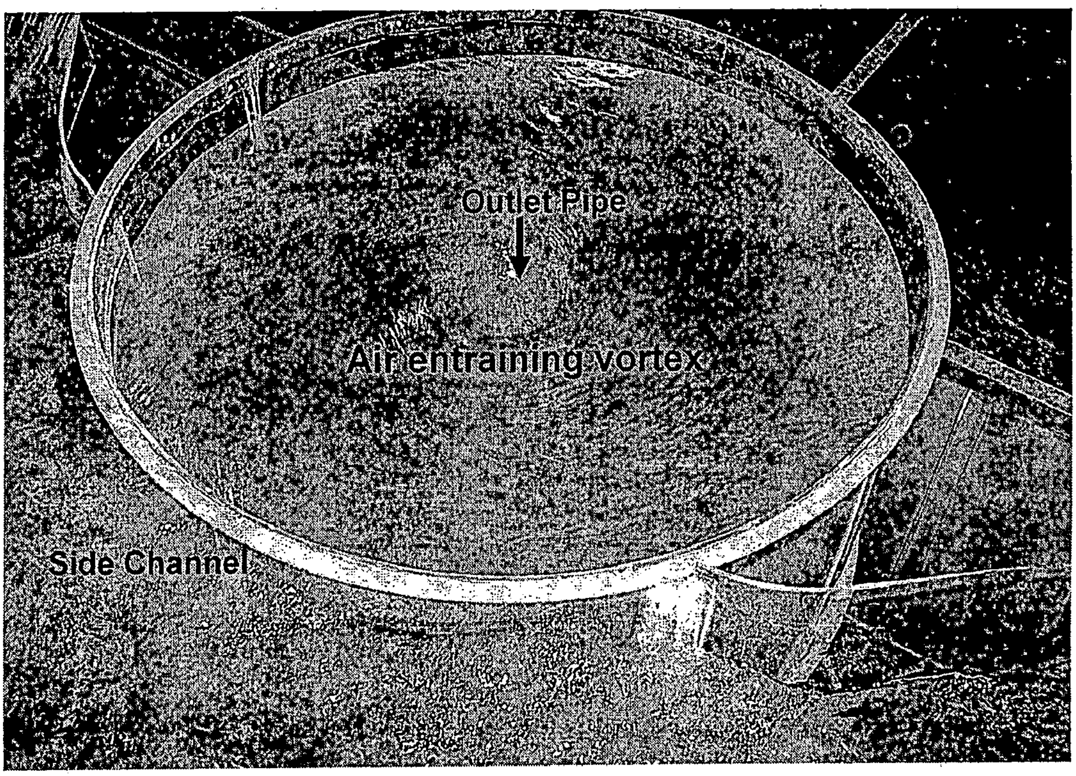


Fig 4.3 : Photographic view showing flow condition at vortex chamber

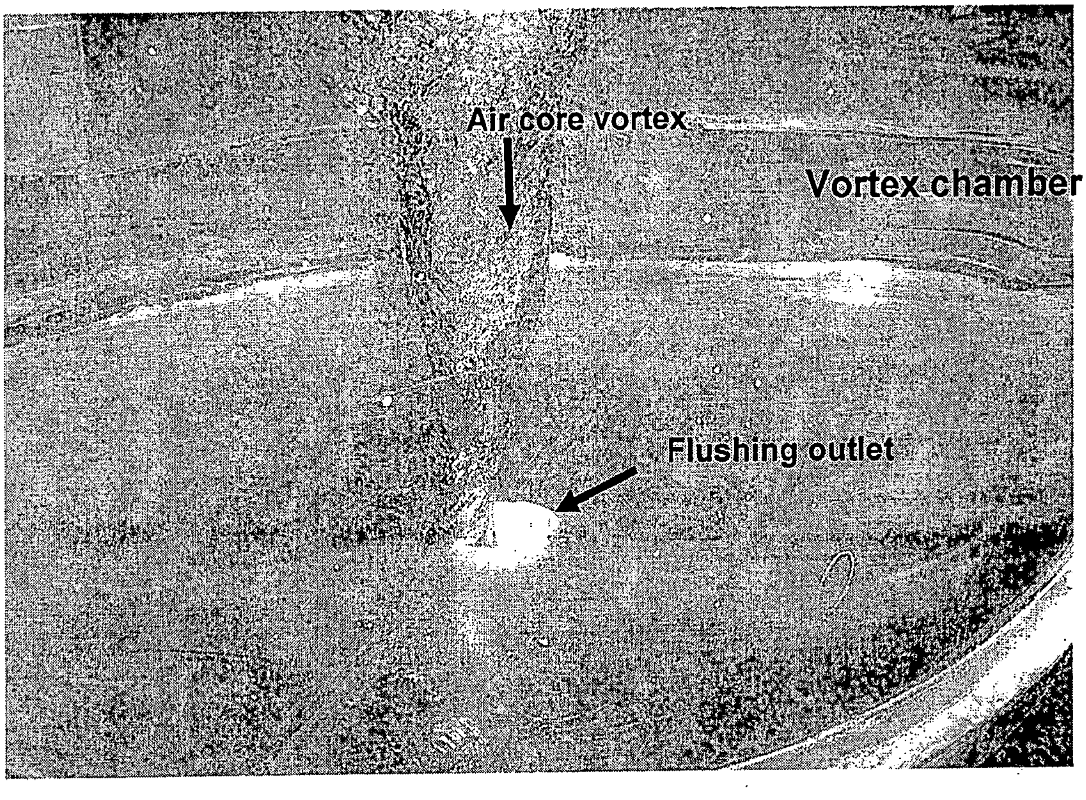


Fig 4.4: Photographic view showing flow condition in vortex chamber

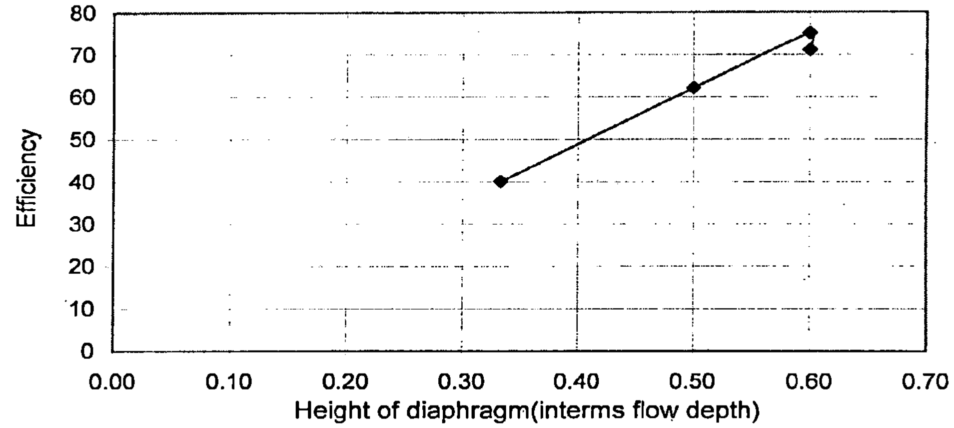


Fig. 5.1: Variation of efficiency with height of diaphragm

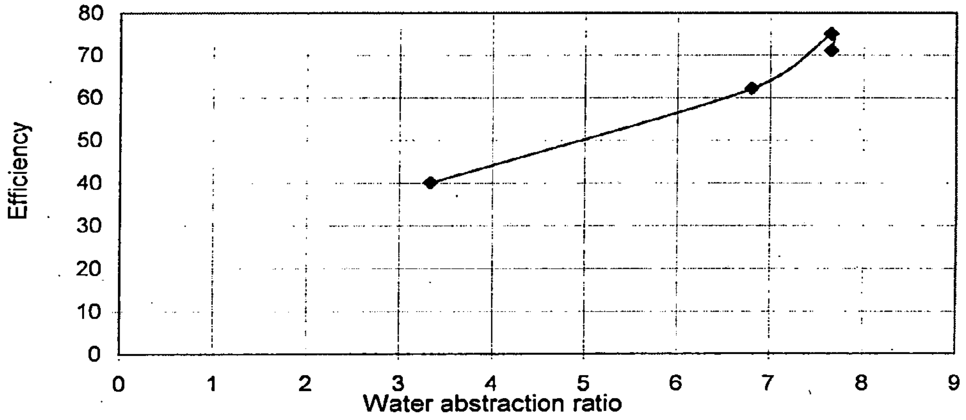


Fig.5.2: Variation of efficiency with water abstraction ratio

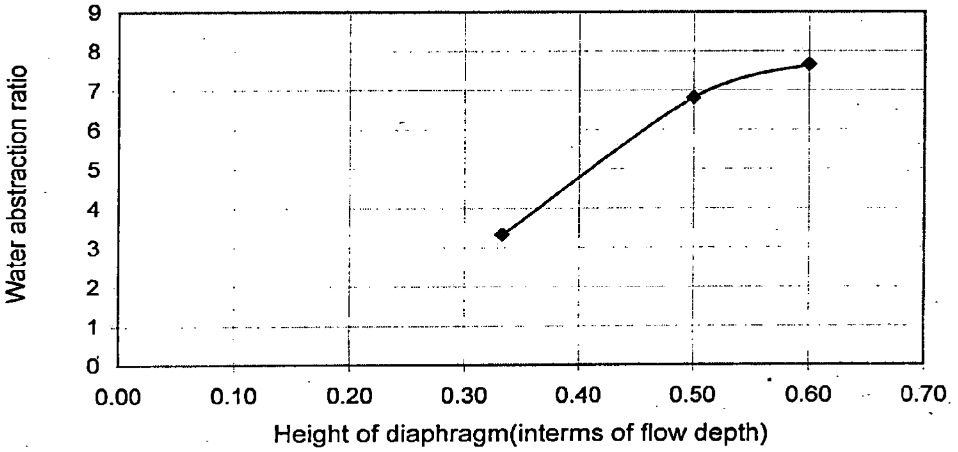


Fig.5.3: Variation of water abstraction ratio with height of diaphragm

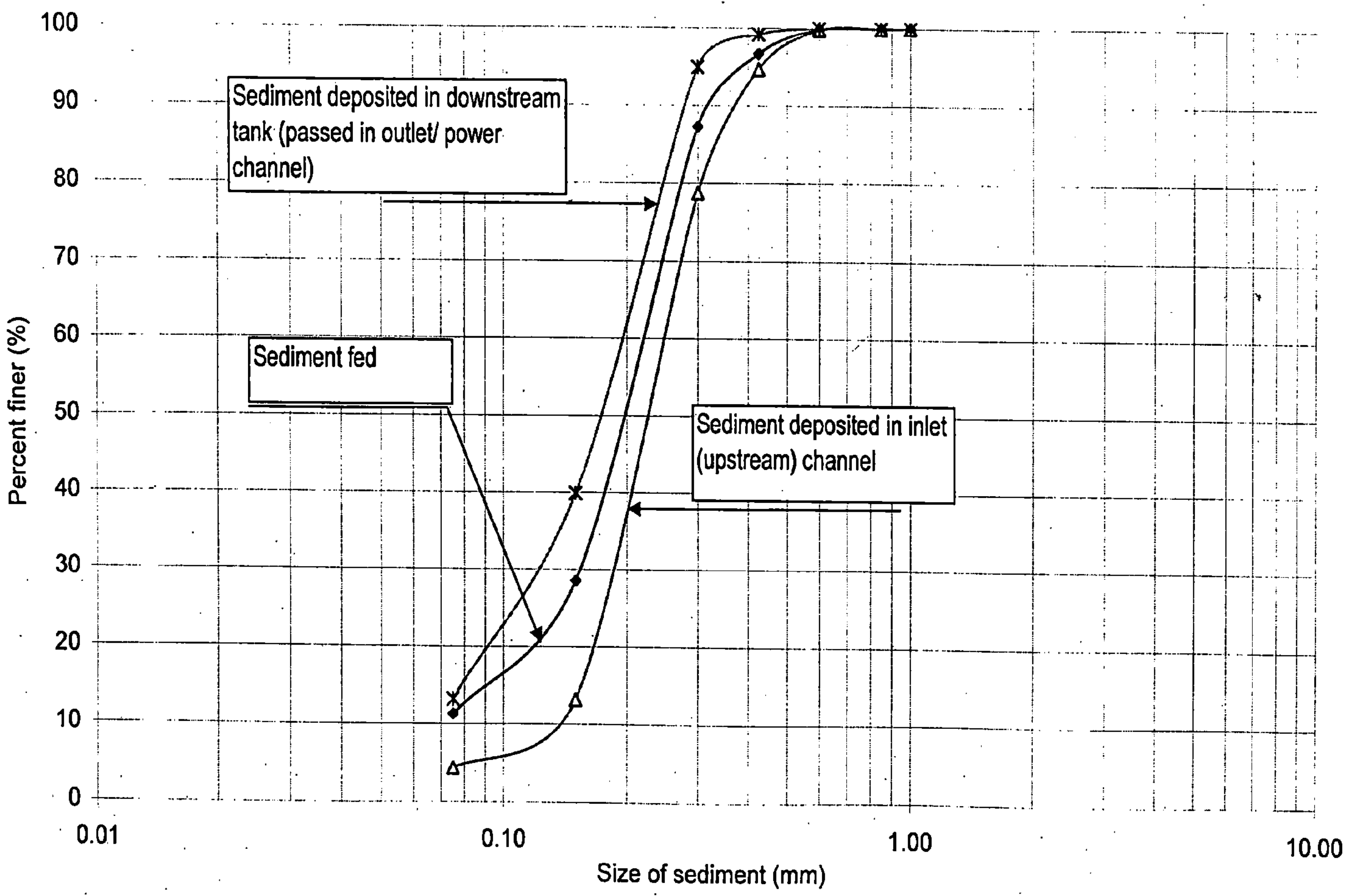


Fig. 5.4: Sediment Gradation Curve for Model Sand

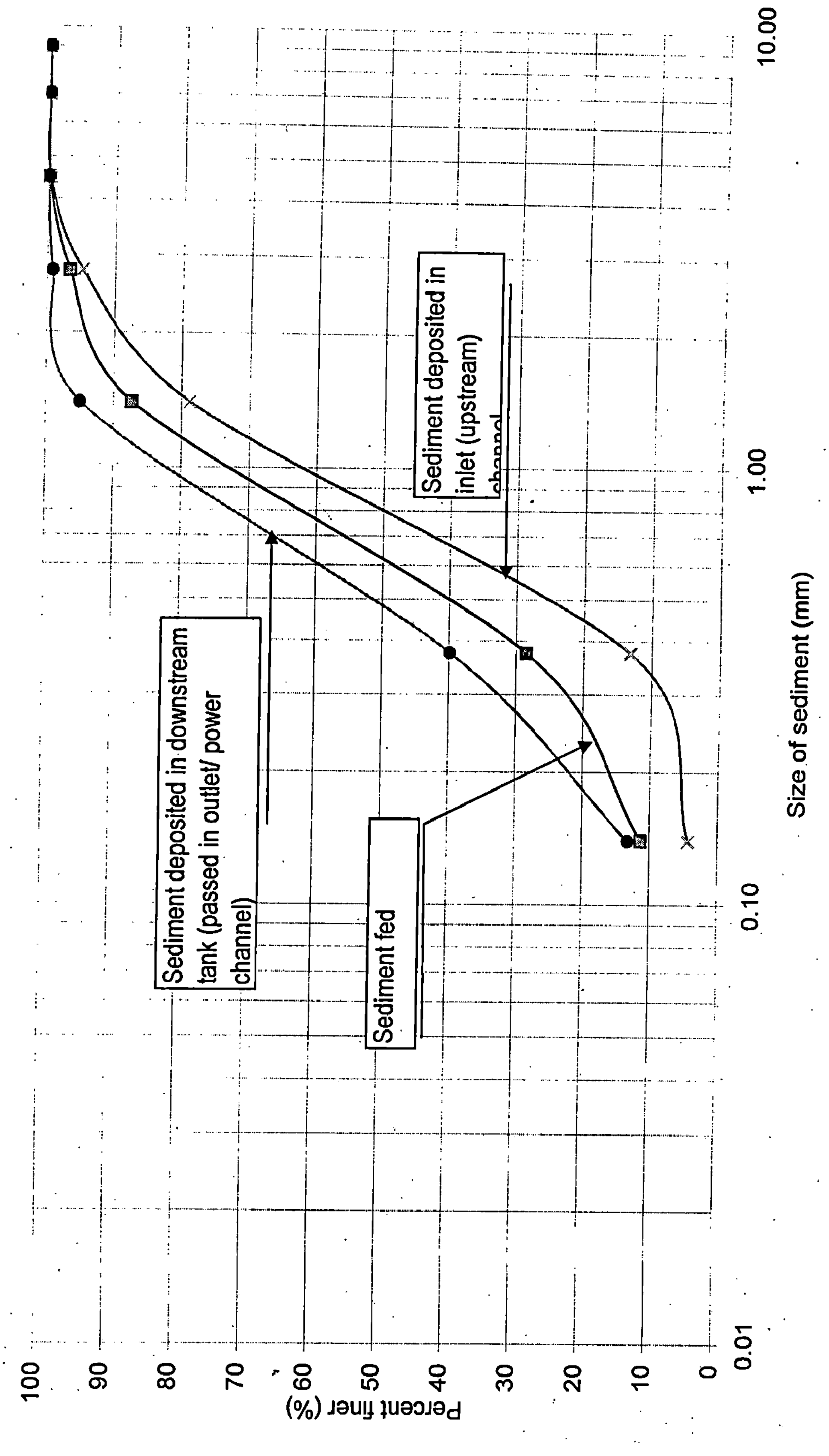


Fig. 5.5: Sediment Gradation Curve for Prototype Sand

a) Design of approach Channel

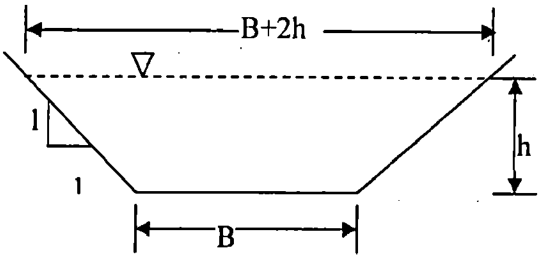
Design discharge of power house = 28.32 m^3/sec (1000 cusec)

Assume flushing discharge = 5% of the total discharge

Then design discharge of approach channel Q_c= 1.05x28.32 = 29.73 m^3/sec.

For concrete tiled lining, the maximum permissible velocity of flow is restricted to be 2.0 m/sec to avoid any danger to the material forming lining.

Assume a trapezoidal channel section with base width 'B' and flow depth 'h'. For an efficient channel section, "The top width of the channel (water surface width) will be two times the length of the sloping side".



Assume a side slope equal to 1:1 (H:V), then the water surface width will be

$$B + 2h = 2\sqrt{(1^2 + 1^2)}h$$

$$\Rightarrow B = 2\sqrt{2}h - 2h$$

$$\Rightarrow B = 0.828$$

$$\Rightarrow h = 1.207B$$

Wetted cross sectional area,

$$A = \frac{B + B + 2h}{2} \times h$$

$$\Rightarrow A = (B + 1.207B) \times 1.207B$$

$$\Rightarrow A = 2.6638B^2$$

From flow continuity equation

$$Q = Av$$

$$\Rightarrow 29.73 = A \times 2.0$$

$$\Rightarrow A = \left(\frac{29.73}{2}\right)$$

$$\Rightarrow 2.6638B^2 = 14.865$$

$$\Rightarrow B = \sqrt{\frac{14.865}{2.6638}} = 2.36m$$

$$\Rightarrow h = 1.207 \times 2.36 = 2.85m$$

There fore channel base width B= 2.36 m and depth of flow h= 2.85 m.

Take free board = 0.60 m

Net depth of channel = 2.85 + 0.60 = 3.45 m

Wetted Area $= \left(\frac{2.36+8.06}{2}\right) x\ 2.85 = 14.848 \quad m^2$

Wetted perimeter $= 2.36 + 2 \times 2.85 \times \sqrt{2} = 10.421m$

Hydraulic radius $R = \left(\frac{wettedarea}{wettedperimenter}\right)$

$$\Rightarrow R = \left(\frac{14.848}{10.421}\right) = 1.425m$$

From Manning's equation

$$v = \frac{1}{n} R^{2/3} S^{1/2}$$

$$\Rightarrow S = \left(\frac{nv}{R^{2/3}}\right)^2$$

$$\Rightarrow S = \left(\frac{0.016 \times 2.0}{(1.425)^{2/3}}\right)^2$$

$$\Rightarrow S = 6.38 \times 10^{-4} = 1:1565$$

Longitudinal slope of channel is 1:1565

The average shear stress τ_0 on the channel bed

$$\tau_0 = \gamma_f RS$$

$$\Rightarrow \tau_0 = 9810 \times 1.425 \times 6.38 \times 10^{-4}$$

$$\Rightarrow \tau_0 = 8.9187 N/m^2$$

The critical tractive shear stress τ_c on the channel bed for d_{50} =0.20mm size is

$$\tau_c = \tau_c^* g \Delta \rho_s d$$

Again $R_1^* = (R_c^*)^{2/3}(\tau_c^*)^{-1/3}$ (R_c^* is dimensionless shear stress parameter=$\frac{u_{*c}d}{\nu}$)

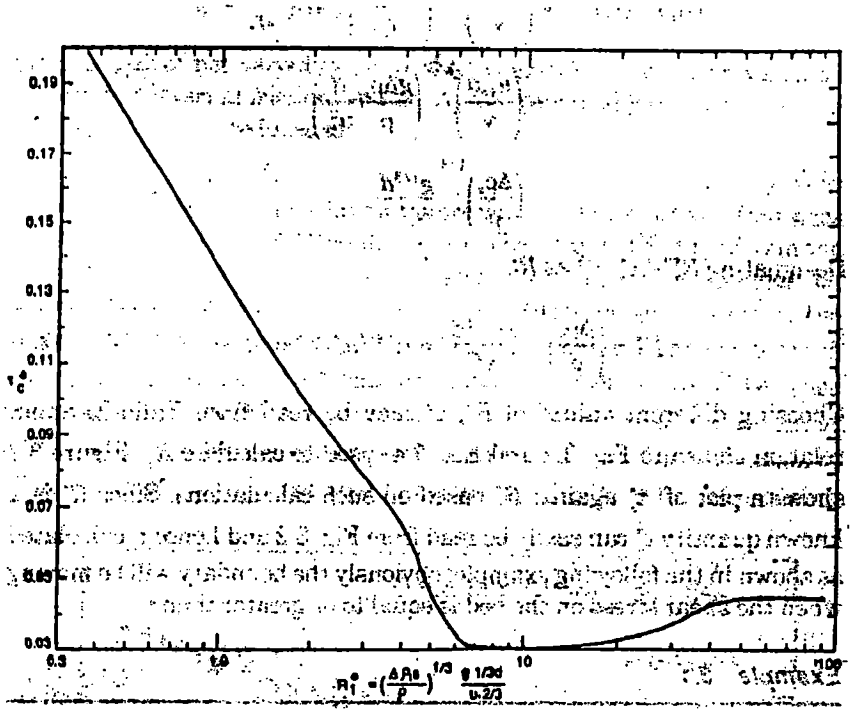
$$\Rightarrow R_1^* = \left(\frac{u_{*c}d}{\nu}\right)^{2/3}\left(\frac{\Delta\rho_s gd}{\tau_c}\right)^{1/3} \text{(Since } \tau_c^* = \frac{\tau_c}{\Delta\rho_s gd}\text{)}$$

$$\Rightarrow R_1^* = \left(\frac{u_{*c}d}{\nu}\right)^{2/3}\left(\frac{g\Delta\rho_s}{\rho}\frac{d}{u_{*c}^2}\right)^{1/3} \text{(Since } \tau_c^* = \frac{\tau_c}{\Delta\rho_s gd}\text{)}$$

$$\Rightarrow R_1^* = \left(\frac{\Delta\rho_s}{\rho}\right)^{1/3}\left(\frac{g^{1/3}d}{\nu^{2/3}}\right)$$

$$\Rightarrow R_1^* = \left(\frac{2650-1000}{1000}\right)^{1/3}\left(\frac{(9.81)^{1/3}\times(0.2\times10^{-3})}{(10^{-6})^{2/3}}\right)$$

=5.059



From Yalin- Karahan plot (τ_c^* vs R_1^*)

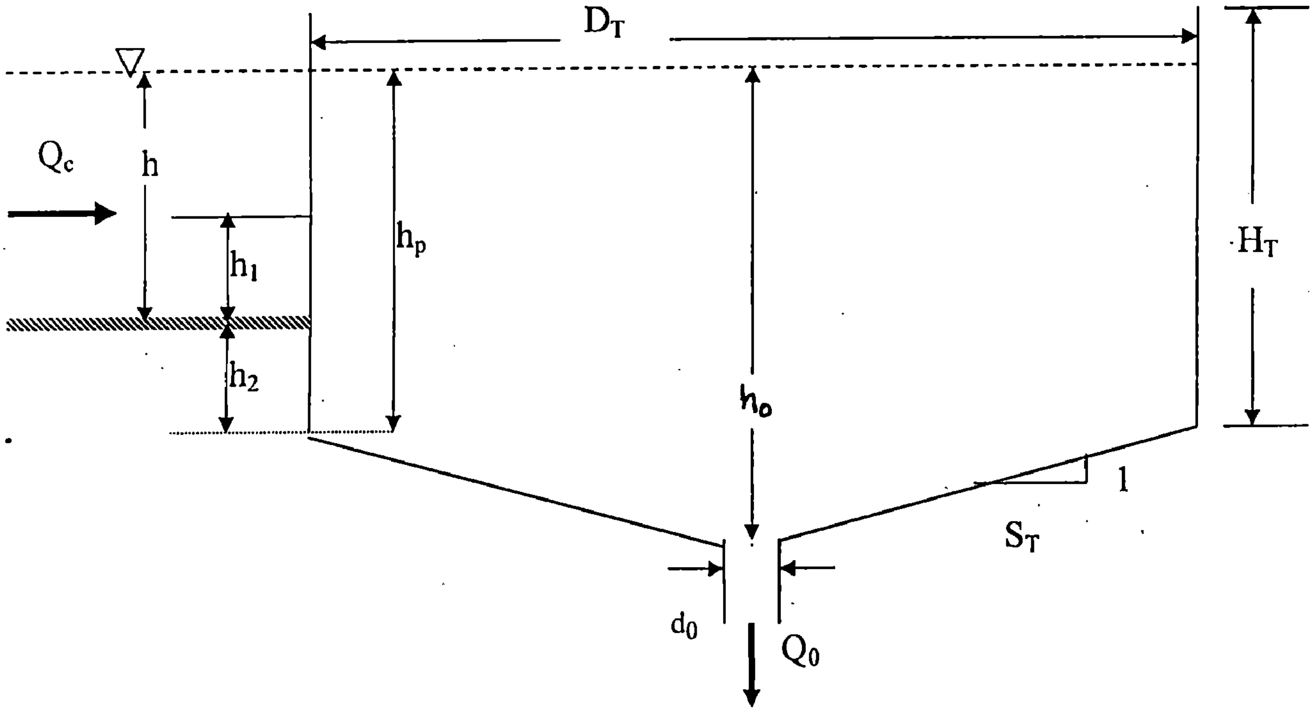
τ_c^*=0.0465

$$\tau_c = \tau_c^* g\Delta\rho_s d = 0.0465\times9.81\times1650\times0.20\times10^{-3} = 0.1505 N/m^2$$

Since $\tau_0(=8.9187)$ > $\tau_c(0.1505)$ all the sedimentary particle having d_{50} size equal to 0.20 mm will be in motion.

b) Design of vortex chamber type extractor

Input Data:	Upstream channel discharge Q_c		= 29.73 m^3/s
	Base width of channel	B	= 2.36 m
	Depth of flow in channel	h	= 2.85 m
	Velocity of flow in channel	v	= 2.0 m/s
	Sediment size (d_{50})		= 0.2 mm



Width of inlet channel, B = 2.36 m

Diameter of vortex chamber, D_T = 5 B = 5 x 2.36 =11.80m

Suppose diameter of flushing pipe, d_o = 0.50 m

Slopping depth of basin $=\left(\frac{11.8-0.5}{2}\right)x\frac{1}{10}= 0.565$ m [assume S_T = 10]

Total depth of basin = (h_p+ 0.565) m

Depth of water in channel,h = 2.85 m.

Depth of diaphragm above channel bed $h_1 = \left(\frac{2.85}{3}\right) = 0.95$ m

Depth of basin (at periphery) below the channel bed h_2 =0.2 h = 0.2 x 2.85 = 0.57m

Depth of basin, h_p = (2.85 + h_2) = 2.85 + 0.57 = 3.42 m

Settling velocity ω_0 of sediment of diameter d_{50}= 0.20 mm is = 2.55 x 10^{-2} m/s

Tangential velocity at the inlet of basin v_{tp}= 2.0 m/s

$$K_2 = \left(\frac{\omega_0 D_T}{v_{tp} h_p}\right)$$

$$\Rightarrow K_2 = \left(\frac{2.55x10^{-2}x11.8}{2.0xh_p}\right)$$

$$\Rightarrow K_2 = \left(\frac{15.04x10^{-2}}{h_p}\right)$$

$$\frac{h_p}{D_T} = 0.262 + \frac{0.0042}{K_2}$$

$$\Rightarrow \frac{h_p}{11.8} = 0.262 + \frac{0.0042}{15.04x10^{-2}} h_p$$

$$\Rightarrow (0.0847 - 0.0279) h_p = 0.262$$

$$\Rightarrow h_p = \left(\frac{0.262}{0.0568}\right) = 4.61 \text{ m}$$

Adopt h_p = max of (3.42, 4.61) = 4.61 m

h_2 = (h_p – h) = 4.61 – 2.85 =1.76 m

h_o = (h_p + 0.565) = 4.61 + 0.565 = 5.175 ≅ 5.20 m

Reynold's number, $R_e = \frac{Q_o}{\nu d_o}$

$$\Rightarrow R_e = \left(\frac{1.408}{10^{-6} d_o}\right)$$

$$\Rightarrow R_e = 2.83x10^6$$

Tangential velocity, $V_{to} = \sqrt{\frac{2gh_o}{3.45}}$

$$\Rightarrow V_{to} = \sqrt{\frac{2x9.81x5.2}{3.45}} = 5.44 m/\sec$$

Circulation number, $N_T = \frac{\pi\, d_o^2 V t_o}{Q_o}$

$$\Rightarrow N_T = \left(\frac{\pi \times 0.5^2 \times 5.46}{1.408}\right) = 3.017$$

Froude's number, $F_d = \frac{4Q_o}{\pi d_0^2 \sqrt{g d_o}}$

$$\Rightarrow F_d = \frac{4 \times 1.408}{\pi \times 0.5^2 (\sqrt{9.81 \times 0.5}} = 3.256$$

Discharge coefficient, $C_d = \frac{0.22 R_e^{0.075} N_T^{0.054} F_d^{0.965}}{\left(\frac{h_o}{d_o}\right)^{0.375}}$

$$\Rightarrow C_d = \frac{0.22 \times (2.83 \times 10^6)^{0.075} \times (3.017)^{0.054} \times (3.256)^{0.965}}{\left(\frac{5.2}{0.5}\right)^{0.375}}$$

$$\Rightarrow C_d = \left(\frac{0.22 \times 3.047 \times 1.06 \times 3.12)}{2.406}\right) = 0.921$$

Flushing discharge, $Q_0 = C_d \pi\, \mathrm{d}_o^2 \sqrt{\frac{\mathrm{g\, h_o}}{8}}$

$$\Rightarrow 1.416 = 0.921 \times \pi \times \mathrm{d}_o^2 \sqrt{\frac{9.81 \times 5.2}{8}}$$

$$\Rightarrow d_0 = 0.44m$$

So, d_o = 0.50 m is O.K.

Length of spill weir crest = 0.16 x Basin Periphery

= $0.16 \times \pi \times D_T$

= $0.16 \times \pi \times 11.8$ = 5.93 m

The output data are:

h_1 = 0.95 m

h_2 = 1.76 m

h_p = 4.61 m

h_o = 5.20 m

D_T = 11.8 m

d_o = 0.50 m

H_T = 4.91 m

Length of spill weir = 5.93 m

CALCULATIONS:

Determination of sediment removal efficiency:

$$\eta_0 = \frac{W_F}{W_V}$$

where, $W_V = W_t - W_i$

$W_F = W_V - W_0$

W_t = Sediment fed through sediment feeder

W_i= Sediment deposited in inlet (upstream) channel

W_0 = Sediment deposited in downstream tank (passed in outlet channel)

i. Height of diaphragm h_1=h/3 (Table 4.1)

W_t=168.00 kg

W_i=(38.20+38.00+37.80)/3=38.00 kg

W_0=(77.00+77.20+77.40)/3=77.20 kg

$W_V = W_t - W_i$ =168.00-38.00=130.00 kg

$W_F = W_V - W_0$ =130.00-77.20=52.80 kg

$$\eta_0 = \frac{52.80}{130.00} = 40.61 \cong 40 \, percent$$

ii. Height of diaphragm h_1=h/2 (Table 4.2)

W_t=168.00 kg

W_i=(40.00+40.25+39.75)/3=40.00 kg

W_0=(49.00+48.75+49.25)/3=49.00 kg

$W_V = W_t - W_i$ =168.00-40.00=128.00 kg

$W_F = W_V - W_0$ =128.00-49.00=79.00 kg

$$\eta_0 = \frac{79.00}{128.00} = 61.72 \cong 62 \, percent$$

iii. Height of diaphragm h_1=0.6h (Table 4.3)

W_t=168.00 kg

W_i=(39.65+40.35+40.00)/3=40.00 kg

W_0=(31.85+31.15+31.50)/3=31.50 kg

$W_V = W_t - W_i$ =168.00-40.00=128.00 kg

$W_F = W_V - W_0$ =128.00-31.50=96.50 kg

$$\eta_0 = \frac{96.50}{128.00} = 75.39 \cong 75\,percent$$

iv. **Height of diaphragm h_1=0.6h and do= 0.085 m (Table 4.4)**

W_t=168.00 kg

W_i=(40.50+39.90+40.20)/3=40.20 kg

W_0=(35.35+35.65+35.50)/3=35.50 kg

$W_V = W_t - W_i$ =168.00-40.20=127.80 kg

$W_F = W_V - W_0$ =127.80-35.50=92.30 kg

$$\eta_0 = \frac{92.30}{127.80} = 72.22 \cong 72\,percent$$