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University of Technology
Department of Civil Engineering
Institute of Water and Environmental Engineering
Postgraduate Course in Water Supply and
Sanitation 1986-88
in co-operation with
Finnish International Development Agency
FINNIDA

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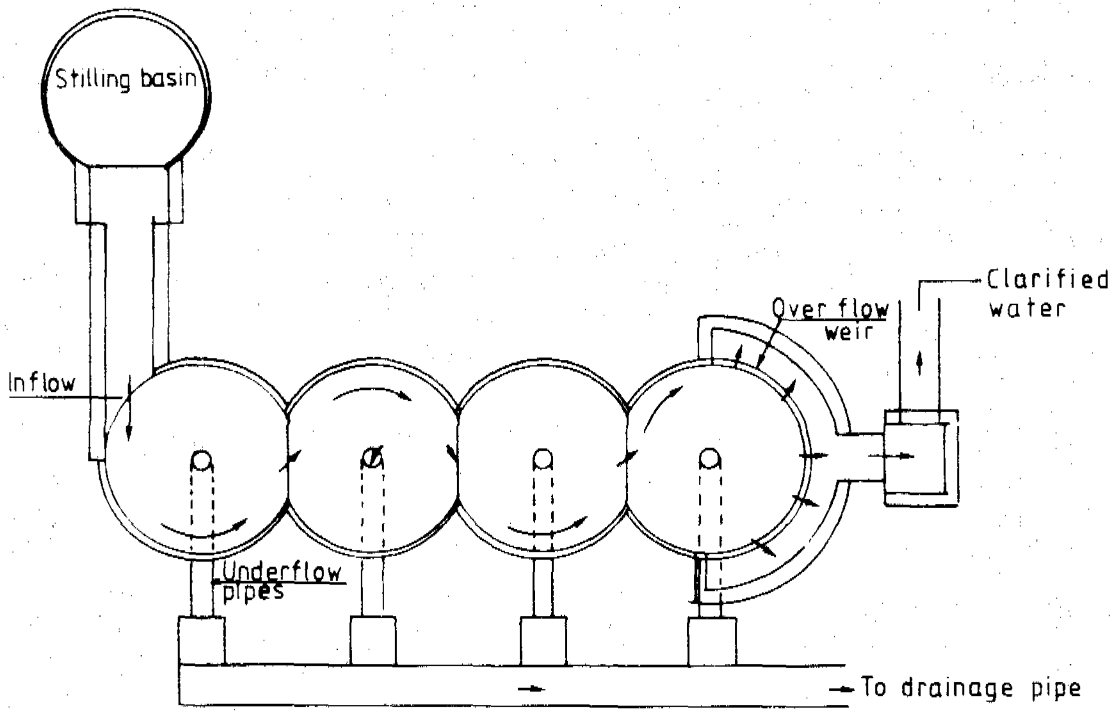

Tampere 1988

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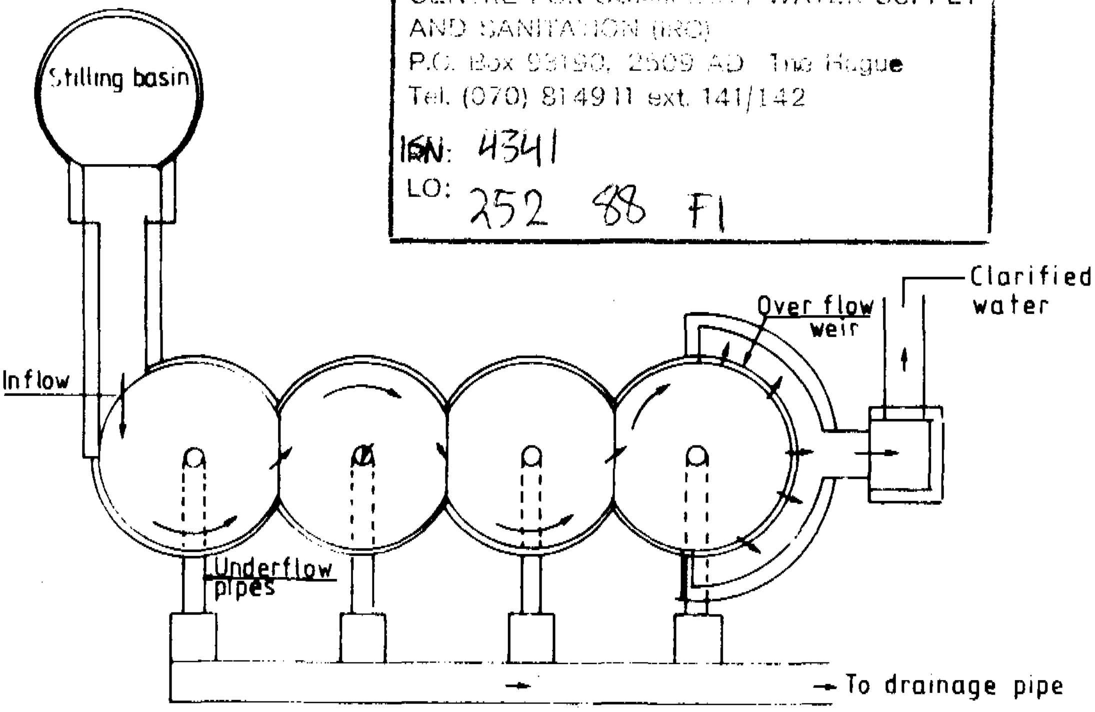

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FIELD TESTING OF THE PERFORMANCE OF MULTI-STAGE SWIRL SEPARATOR

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ABSTRACT

The multi-stage swirl separator is a device which consists of circular basins (4 stages) connected in array to use effectively the swirl motion to separate solids from liquid and possibly solids from solids of different particle sizes or densities in liquid suspension.

Volumetric measurements of the concentration of sediments were carried out to evaluate the performance of the multi-stage swirl separator. From the experiments it was verified in the field that the multi-stage swirl separator has high potential in solids separation.

With the present configuration (referring to the overflow weir) approximately all particles bigger than 0.04 mm in diameter were removed completely corresponding to 1.5 times of an ideal tank. Quadrupling the flow rate, the reduction in removal efficiency was about 10 % maintaining consistent removal efficiency over a wide range of flow. This was possible by increasing the weir height (width of the basin/weir height = 3).

Another interesting finding is the radial clarification in the 3rd and 4th stages which showed the utmost prospect in improving the present configuration. As high as 100 % removal efficiency for sediment particle sizes bigger than 0.02 mm was recorded in the clarified zone for a wide range of flow. In radial clarification inertial separation is supposed to have equivalent importance as gravity separation, which otherwise is more dominant. In this respect it was noticed that the prevalence of free vortex could be used to increase the removal efficiency of the multi-stage swirl separator.

LIST OF SYMBOLS

A	Area
C	Vorticity
C_D	Drag coefficient
C_i	Gravimetric concentration of particles in inflow water
C_d	Discharge coefficient
C_o	Gravimetric concentration of particles in overflow water
D_1	Width of inlet apperture
D_2	Diameter of a chamber
D_3	Diameter of an overflow weir
D_4	Diameter of an overflow shaft
D_u	Diameter of an underflow pipe
d	Diameter of a particle
F	Force
F_D	Drag force
Fi	Impelling force
g	Gravitational acceleration
h	Water depth above weir crest
H	Tank depth
H_b	Water depth in a basin
H_i	Weir crest height from the floor of a basin
H_u	Water depth at the underflow pipe
H_w	Water depth at the wall of a basin
M_i	Mass of particles in inflow water
M_o	Mass of particles in overflow water
M_u	Mass of particles in underflow water
Q	Flow rate
Q_i	Inflow rate
Q_o	Overflow rate

Q_u	Underflow rate
R	Radius
R_b	Radius of a basin
R_c	Radius of the basin at critical point
Re	Reynolds number
R_u	Radius of underflow pipe
T	Time
T_o	Time related with surface load
u	Radial velocity of water
u_s	Radial velocity of a particle
v	Tangential velocity of water
V	Volume of a particle
V_i	Volume of particles in inflow water
V_o	Volume of particles in overflow water
v_s	Tangential velocity of a particle
w	Vertical velocity of water
w_s	Vertical velocity (settling velocity) of a particle; surface load
ν	Kinematic viscosity
$\delta\omega$	Density of water
δs	Density of particles
ω	Angular velocity

1 INTRODUCTION

Ethiopia is a mountainous tropical country. Besides the natural conditions of erosion which contribute to sediment concentration in streams and rivers, human activities and particularly deforestation have profound effects. Thus erosion, entrainment, transportation, deposition and the compaction of sediment has become a formidable challenge for water engineers.

Although groundwater is the foremost source to be exploited for water supply, now and then, the abstraction of river water is unavoidable, where groundwater is scarce and insufficient to cater for the demand.

To protect pumps and the transmission main and to prolong the running time of the treatment units, the exclusion of sediment is indispensable. It is preferred to control sediments at the source, whereby it is necessary to provide the intakes with a sediment controlling structure.

In Ethiopia most of the intakes are provided with a drop intake. Mashauri (1981) noted that the drop intake is one of the effective sediment controlling structures in mountain streams. On the contrary, during the rainy seasons repeated blockage of intake units and pump failures are encountered. This shows that for Ethiopian conditions a highly efficient sediment controlling method is required.

Frontal intake (Cecen, 1973), drop intake with separation chamber (Salakhov, 1975), and curved channel intake (Novak, 1983) are but a few sediment controlling structures which are satisfactorily applied in irrigation and hydropower. Astonishingly there is no single report of their application for water supply intakes which shows that the technology transfer is lacking. It could be due to the investment costs or due to higher clarification requirement for water supply.

In the course of investigation, to evaluate its performance the multi-stage swirl separator was found more attractive for testing in the field conditions as a part of an intake structure.

Primarily, it was necessary to design the multi-stage swirl separator which fits the field conditions. Followed by the manufacturing and installation, it was expected to undertake the experiments in the rainy season when actual problems exist with sediments. Due to lack of experience and the type of construction material selected (prefabricated steel basin(s)) it was not possible to run the tests according to schedule and under expected conditions. However, it was possible to simulate flood conditions by causing disturbance in the stream or by adding excavated soil into the stream.

Due to the location of the site and the limited time the simplest experimental methods were selected. The efficiency of the multi-stage swirl separator was evaluated in terms of volumetric concentration of sediments. Turbidity measurement was also carried out to see the correlation between sediment concentration and turbidity.

Since the application of the multi-stage swirl separator is not restricted as a sediment controlling structure or 'grit chamber' it was necessary to weigh its capacity or potential with other contemporary solids separation devices.

2 GRAVITY AND ROTATIONAL SOLIDS SEPARATORS

Tropical rivers contain a considerable amount of suspended solids and high turbidity. During floods 4 000 mg/l of suspended solids are recorded at the Blue Nile in Egypt (Fahmy and Gassar, 1975). By and large silt concentration at 1 000' s of mg/l are not uncommon during floods for rivers throughout the world (Schulz and Okun, 1984).

River water abstracted for water supply is subjected to treatment by passing through different processing units depending on the quality of water, selected method of abstraction and treatment.

The removal of a high percentage of suspended solids is attained by gravity separation, referred as plain sedimentation. Gravity separation is also applied in chemical treatment to separate flocs, after coagulation and flocculation, a process which is used to separate dissolved solids and colloids which contribute highly to the turbidity of river water.

2.1 Discrete Settling in Fluid Suspension

Solid separation is achieved in fluid suspension by settling discretely or due to the effect of flocculation depending on the properties of the particles in suspension.

In falling freely through a quiescent fluid, a discrete particle accelerates, until the frictional drag of the fluid equals the impelling force acting upon the particle, after which the particle will fall at a constant velocity which is called the terminal velocity of the particle (Fair et al, 1968; Huisman, 1972; Amin, 1976). The settling velocity of a particle directly characterizes its reaction to flow and ranks next to size in importance (Vanoni, 1977; Fair et al, 1968).

2.1.1 Settling Velocity of Discrete Particle

In a settling process a discrete particle does not change its size, shape or weight. Because the impelling force equals the effective weight of the particle, namely, its weight in the suspending fluid,

$$Fi = (\delta s - \delta\omega)gV \qquad (2.1)$$

where Fi is the impelling force, s and are the mass densities of the particle and water respectively, g is the gravity constant and V the volume of the particle.

The frictional drag force according to Newton is expressed as

$$F_D = C_D \frac{\delta\omega}{2} w_s{}^2 A \qquad (2.2)$$

where F_D is the drag force, C_D a dimensionless number (steady-state drag coefficient), w_s the terminal settling velocity of the particle and A its projected area in the direction of motion.

A general relationship can be established for the settling of a discrete particle by combining equations 2.1 and 2.2. Thus

$$w_s = \left(\frac{2}{C_D} \; \frac{\delta s - \delta\omega}{\delta\omega} \; g \; \frac{V}{A} \right)^{0.5} \qquad (2.3)$$

or, for spherical particles,

$$V = \frac{\pi d^3}{6} \quad \text{and} \quad A = \frac{\pi d^2}{4},$$

$$w_s = \left(\frac{4}{3\,C_D} \; \frac{\delta s - \delta\omega}{\delta\omega} \; gd \right)^{0.5} \qquad (2.4)$$

The value of C_D is not constant and depends on the magnitude of the Reynolds number for settling (Figure 2.1) (Graf, 1984; Huisman, 1972; Amin, 1976).

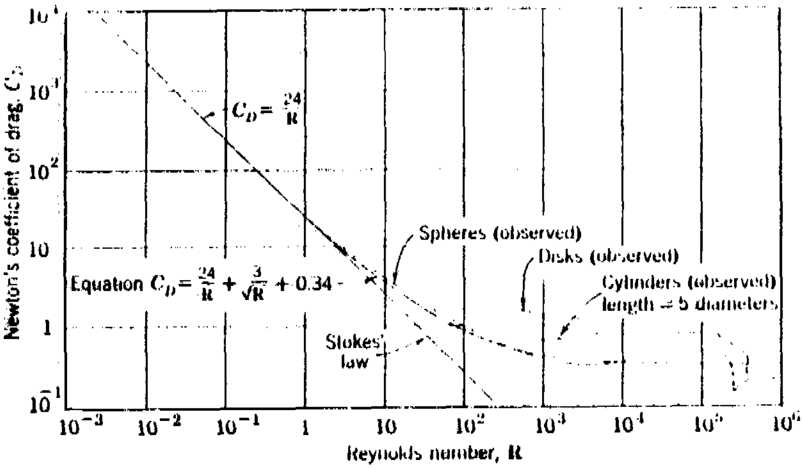


Figure 2.1 Drag coefficient of spheres as function of Reynolds number. (Camp 1946; cited by Fair et al, 1968).

For spheres, this relationship may be approximated (refer to Figure 2.1) as follows:

1. Re < 1 — The frictional resistance is only due to viscous forces as the upward flow of water along the downward moving particle occurs under stream line

conditions. Hence C_d varies inversely proportional to Re,

$$C_D = 24/Re \qquad (2.5)$$

2. Re > 2000 — Turbulent flow conditions occur along the settling particle. Compared with the eddying resistance the viscous forces are negligible and C_d is constant. For spheres and upto Reynolds numbers of 10^5

$$C_D = 0.4 \qquad (2.6)$$

3. 1 < Re < 2000 — The eddying resistance and viscous force are of equal importance being a transition region. An exact formula for C_d can not be given but a good approximation, may be had with

$$C_D = 24/Re + 3/\sqrt{R} + 0.34 \qquad (2.7)$$

Sediment grains are never truly spherical and their shape varies over a wide range from rodlike to spherelike to disklike. With the same volume and weight this means a larger projected area in the direction of motion and a higher value of the drag coefficient C_D under turbulent flow conditions. By both phenomena, the settling rate will be smaller than follows from the formulae given above. In real condition not only the shape of a particle has effect on the settling velocity, but, also boundary conditions, multiparticle influence, particle rotation and roughness, turbulence and combination of these (Graf, 1984).

2.1.2 Ideal Settling Tank

Based on the principle of discrete settling in still fluid suspension and introducing simplifying assumptions of the concentration and distribution of solid particles, the flow condition and removal of solid particles, the settling phenomena of discrete particles in ideal tank can be analyzed. Theoretically, it can be shown that the efficiency of a continuous horizontal flow settling basin solely depends on the surface area A and the flow rate Q, which together constitute surface loading or overflow rate w_s.

$$w_s = Q/A \qquad (2.8)$$

The efficiency is independent of the depth of the basin and the detention time. While this holds true for discrete settling, Huisman (1972) showed that for flocculent settling the efficiency of the basin is a function of both of the overflow rate w_s and the detention time T_o which together constitute the tank depth (H).

$$H = w_s T_o \qquad (2.9)$$

Sedimentation devices can differ widely in size and configuration. Normally, however, they comprise the following elements (Figure 2.2):

1. Inlet Zone:
A system for introducing the feed and direct it into flow paths that will make effective use of the basin volume and area.

2. Settling Zone:
A tank to provide volume and area needed for sedimentation.

3. Sludge Zone:
A zone which collects settled particles with a mechanism to convey settled solids to a discharge point.

4. Outlet:
An overflow collecting system for gathering the clarified effluent in a way that will induce an effective flow pattern (Purchas, 1977; Huisman, 1972; Schulz and Okun 1984; Fair et al, 1968).

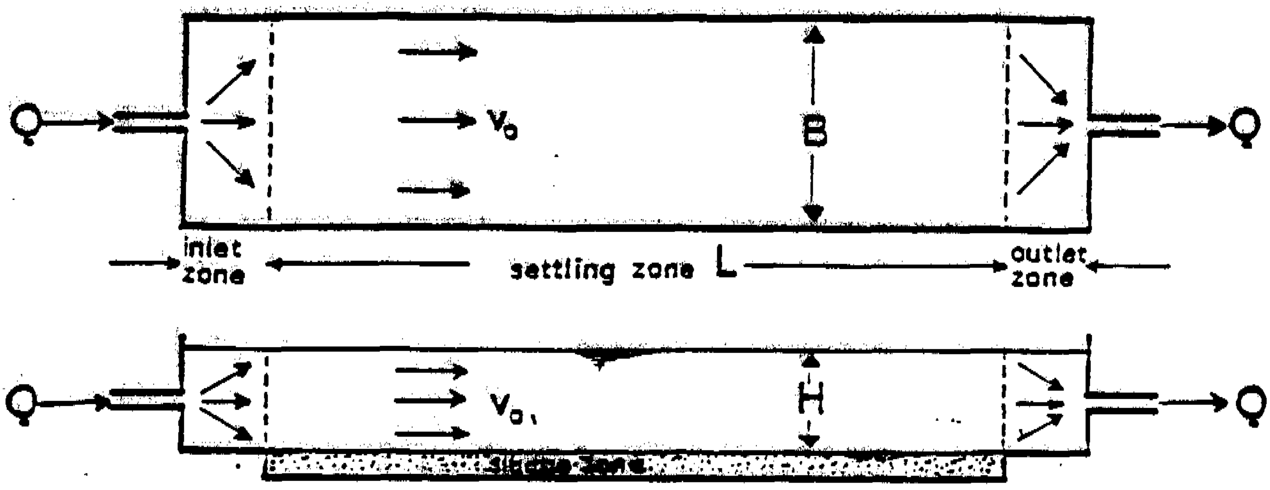


Figure 2.2 Basic configuration of sedimentation devices (Huisman, 1972).

In practice in the field of water engineering the sedimentation process is affected by the turbulent flow of water, scour, instability and short-circuiting (Huisman, 1972; Montgomery, 1985). These conditions can be controlled by the proper design of the above elements for the respective type of solids separators.

2.2 Conventional Solids Separators

Conventionally solids separators are designed in different forms being rectangular, square or circular in plan. The raw water is fed continuously to flow horizontally or vertically depending on the type of sedimentation.

The basic design criteria for the design of a conventional settling tank are

(1) surface loading (overflow rate),
(2) mean horizontal flow velocity
(3) effective depth (floc settling)
(4) detention time (floc settling)
(5) launder or through weir loading rate.
(Montgomery, 1985)

In a rectangular tank the raw water is fed at one end and overflow at the other end, while in a square and circular tank the feed can be central or peripheral. At the inlet, provision should be made to distribute the incoming water throughout the cross-section of the basin and to dissipate the energy of the incoming water in order to have constant velocity in the settling zone.

At the outlet water leaving the settling zone should be collected uniformly across the width of the basin.

The sludge collected at the bottom of the basin is flushed manually or in large treatment plant plowed by a mechanical scraper to a sump, hopper or concentrator to be discharged by gravity, pumping or hydrostatic pressure of water in the settling tank.

From experience the depth of the rectangular basin varies from 2 to 5 m, the average being 3 m. Rectangular tanks may be up to 30 m long and 10 m wide, the width-length ratio being in the range of 1 : 3 to 1 : 5. The length of the square tank may be upto 25 m and of the circular tank may be up to 60 m (Al-Layla et al, 1978; Montgomery 1985; Fair et al 1968).

2.2.1 Improving and Upgrading the Conventional Solids Separators

The basic parameters in the design of conventional solid separators are, the flow rate, the surface load and the surface area of the basin (Equation 2.8). Under ideal conditions, particle removal efficiency is linearly proportional to the surface area regardless of the water depth (El-Baroudi and Fuller, 1973).

Based on this consideration, the settling surface area can be proportionally increased by inserting plate(s) or tray(s) in the settling zone in the conventional tanks, thus having a lower surface load or higher flow rate. Not only due to the increase of surface area high efficiency is achieved, but also other prominant factors, such as turbulence which is related to Reynolds number and instability which is related to Froudes number are substantially controlled in such system (Huisman, 1972; El-Baroudi and Fuller, 1973). Hence the application of tray settlers (Figure 2.3) emerged enabling to pack enormous capacity in a small volume; while the additional cost of installing the trays is small. The main problem in such system is the removal of sludge. Consequently, to avoid the difficulty in sludge removal inclined plate settlers with 60° inclination to horizontal came into use (Figure 2.4).

Further modification of tray settlers gave way to the application of tube settlers : essentially horizontal tube settlers (5° inclination to horizontal) and inclined tube settlers (60° inclination to horizontal) (Figure 2.5) (Yao, 1973).

According to Amin (1974) a reduction of turbidity to 5NTU can be achieved by using 60° tube settlers. However, it is reported that the removal efficiency is dependent on the turbidity of the water (Yao, 1973; Amin, 1974).

The existing conventional tanks can be upgraded by inserting inclined tube or plate settlers. The application of the plate or tube settlers is limited in floc separation, whereas their application in presedimentation needs due consideration (Yao, 1975).

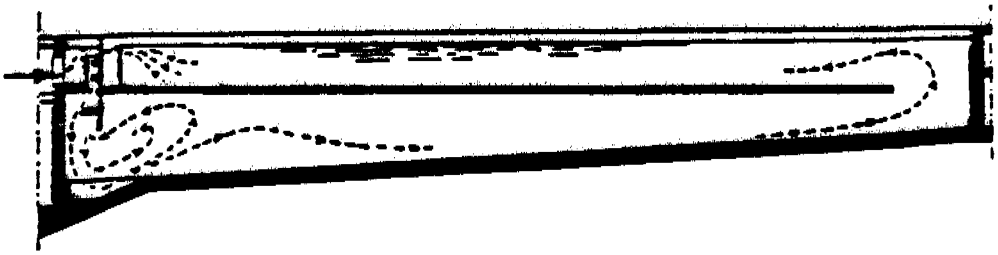


Figure 2.3 Tray settling tank (Huisman, 1972).

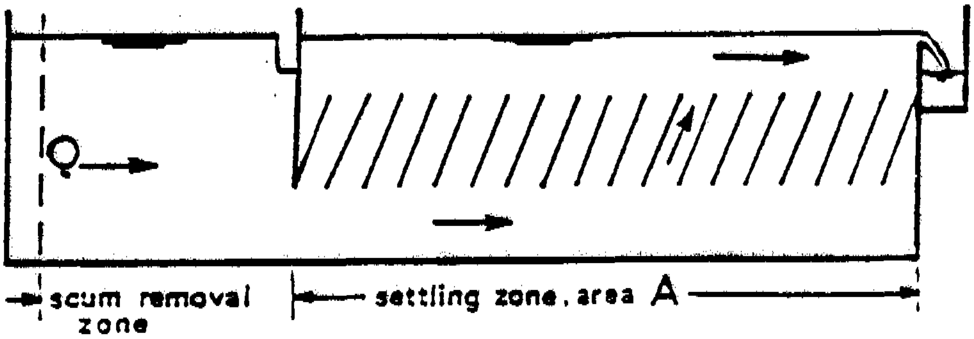
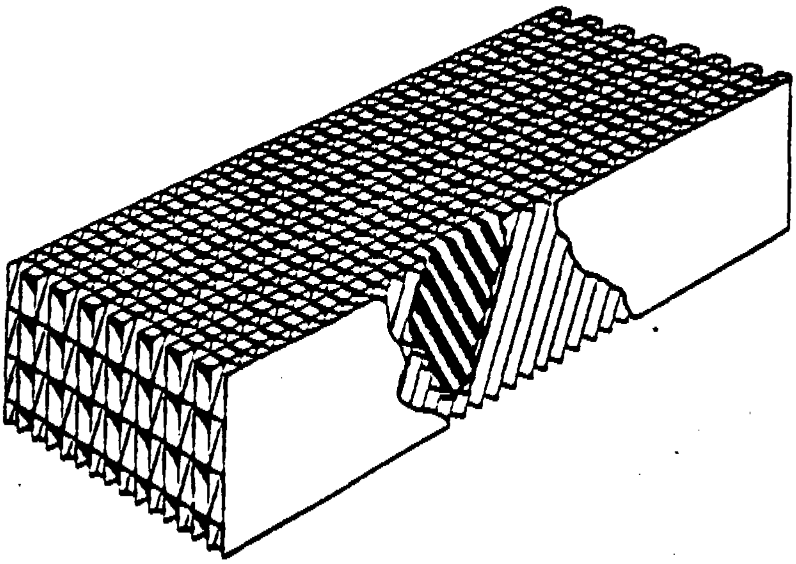
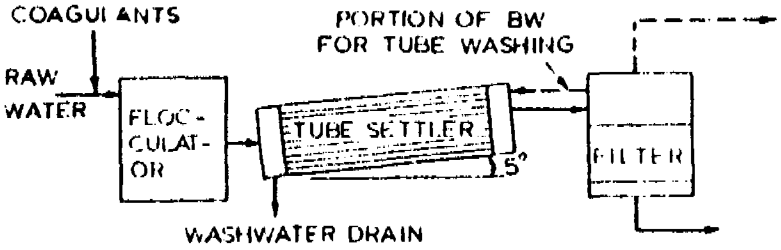


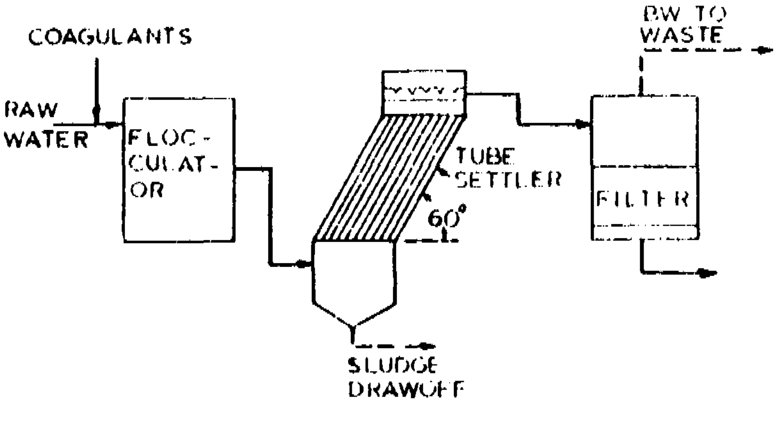
Figure 2.4 Tilted plate settlers (Huisman, 1972).



a) modules of tube settler.



b) essentially horizontal tube settler.



c) steeply inclined tube settler.

Figure 2.5 Tube settlers (Huisman, 1972).

2.3 Swirl Separators

The term "swirl" is used for all gravity rotational separators. The term "vortex" is also commonly used to describe the same device. APWA (1972) discriminately used "swirl" as he attributed the separation of solid particles to the swirl action of the flow rather than the vortex flow. The correction was given also to the vortex separator designed by Smisson (1967) which is the basis for the development of APWA's swirl separators. Teizazu (1986) tried to categorize the gravity rotational separators according to the definition of each researcher but there was overlap in the application of the terms. Mashauri (1986) referred to the swirl/vortex separators after each researcher, such as Sullivan-type vortex settlers, Cecen-type vortex settlers, etc.

Since the fundamental features and solids separation phenomena involved are closely identical of all gravity rotational separators, and there is no definite variation, the term "swirl" is mainly used in this context, keeping in mind that "vortex" is an alternative wording. The term "vortex" is used according to the citations. Similarly instead of "separator", "settler" and "concentrator" are used to describe the same phenomena and they are applied indiscriminately. The term "separator" is mainly used to conform with the heading of the topic while the others are used according to the citations.

2.3.1 Development of Swirl Separators

Gravity solids separators are used either for discrete settling (plain sedimentation) or floc settling (clarification). Although the concept of discrete settling is the basis for both types of solids-separation there is a major difference in the overall hydrodynamics and hence having different design approach.

Conventional horizontal flow circular tanks are applied for floc settling as they are more attractive in constructional and operational considerations than the rectangular tanks. However, they have inherent hydraulic problems such as unstable flow conditions which produce eddy current resulting in poor performance (Chui, 1974; Amin, 1976).

Consequently, starting from the quarter of this century many researchers focused their attention on improving the performance of circular settling tanks. Various types of inlet and outlet arrangements with different flow conditions have been tried. In most cases the improvement in performance was limited for that particular situation in which the research was carried out. After investigating the approaches and results of different researchers Amin (1976) noted that the forced vortex flow in central-feed horizontal flow circular tank can improve the performance of the basin for floc settling. This is achieved by rotating the content of the tank by paddles.

But Walton and Key (1939) claimed that after trying different inlet and outlet arrangements a circular tank with a tangential inlet and peripheral overflow (Figure 2.6) has worked at 90 % removal efficiency of suspended solids of the Blue Nile with various flow conditions and suspended solid concentrations.

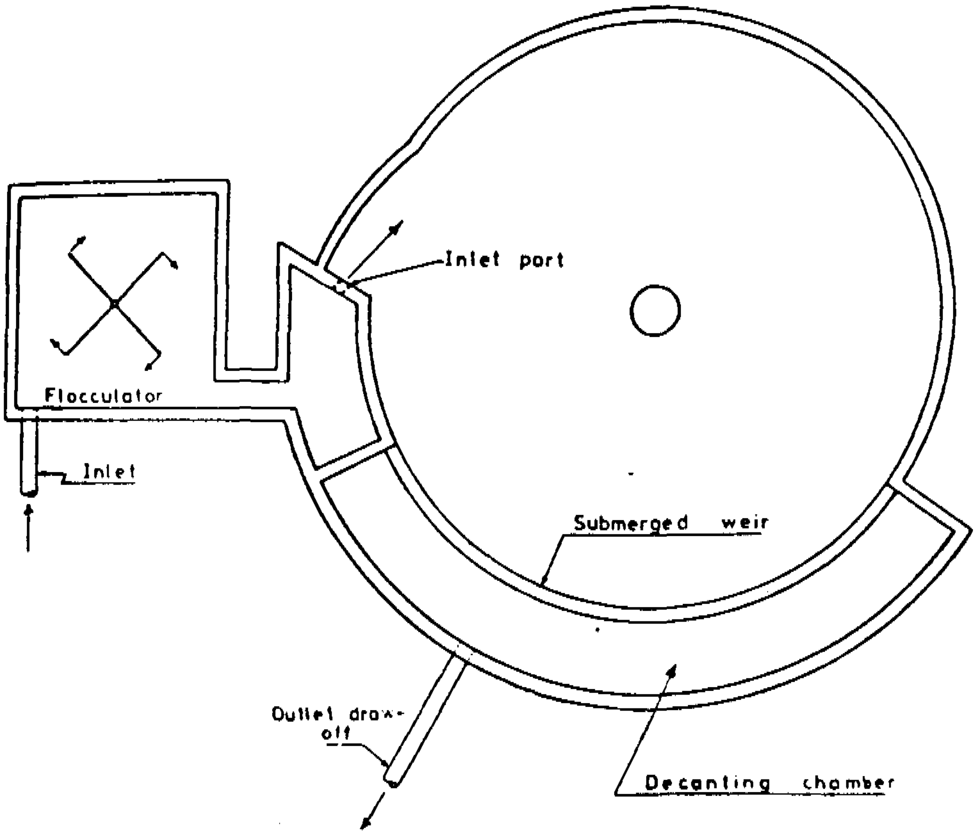


Figure 2.6 Early application of gravity rotational solids separation (Walton and Key, 1939).

A considerable time elapsed before due attention was given to Walton's and Key's type of circular tank design. Eventually in the seventies and eighties the application of vortex separators with tangential inlet, central or peripheral overflow and central underflow for continuous drainage of sludge is reported by Smisson (1967), Cecen and Bayazit (1975) and Salakhov (1975) in different field of water engineering for discrete particle separation. These devices are closely similar to Walton's and Key's design mentioned above. In the field of waste water they are applied as solids concentrator and degritter in the combined sewer system (APWA, 1972; Sullivan et al, 1974 a, 1982) and primary separator at waste water treatment plant (Sullivan et al, 1978, 1982)

During this time because of satisfactory results obtained from the physical models and practical application of swirl separators, researchers formulated mathematical models which are used as a tool to design the separators and to predict their efficiency (APWA, 1972; Cecen, 1975; Mashauri, 1986). However, due to the complexity of hydraulic phenomena involved in the separation of solids and the simplifying assumptions made in the formulation of the mathematical models there is discrepancy in predicting the performance of the swirl separator. Thus there is still a need for further refinement of these mathematical models.

The application of the swirl separators is confined in the separation of medium size particles or larger and settleable solids with the same settling velocity. In order to further improve the efficiency of swirl separators and extend their application to the finer sediment particle, the multi-stage swirl separator evolved. In the experimental stage, the results were satisfactory achieving the purpose (Teizazu, 1986; Häkkinen et al, 1987). The multi-stage swirl separator consists of four circular chambers (stages) connected in series, maintaining similar hydraulic characteristics and operation of the single-stage (chamber) swirl separator.

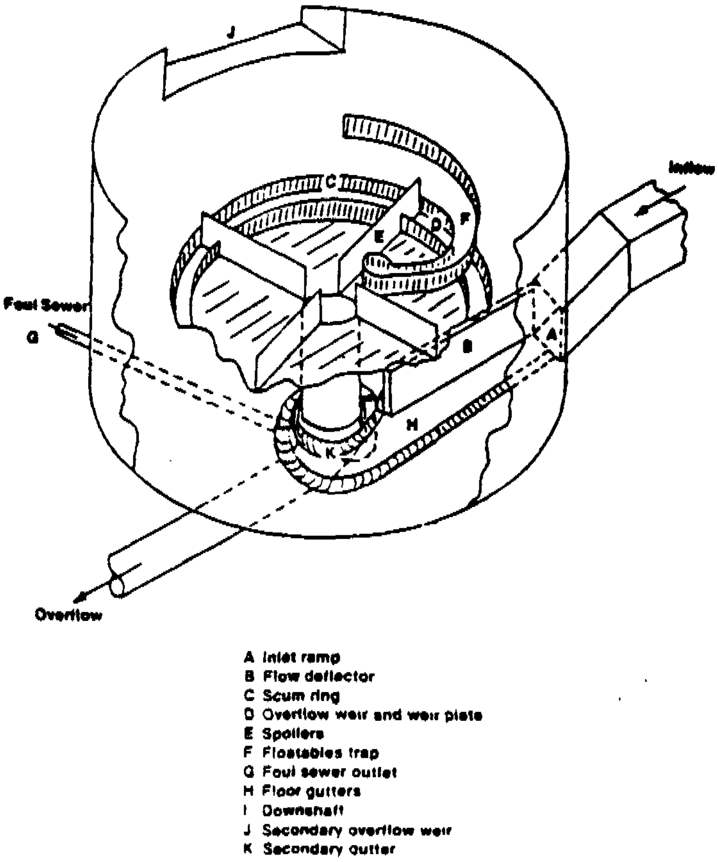


Figure 2.7 Swirl concentrator (APWA, 1972).

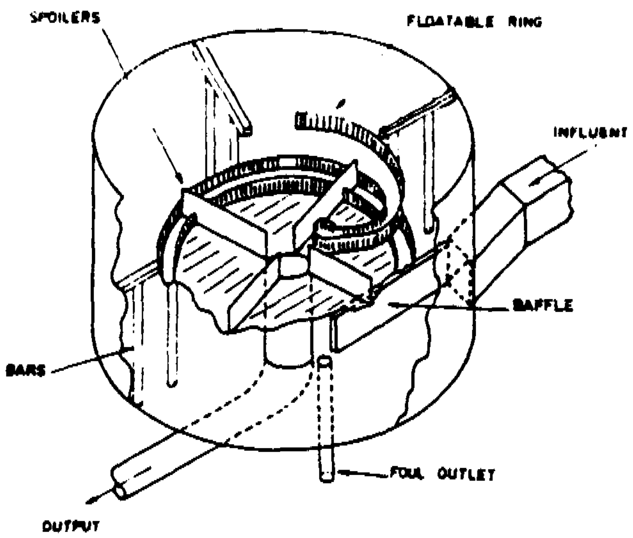


Figure 2.8 Swirl concentrator with eddy structure (Alquier et al, 1982).

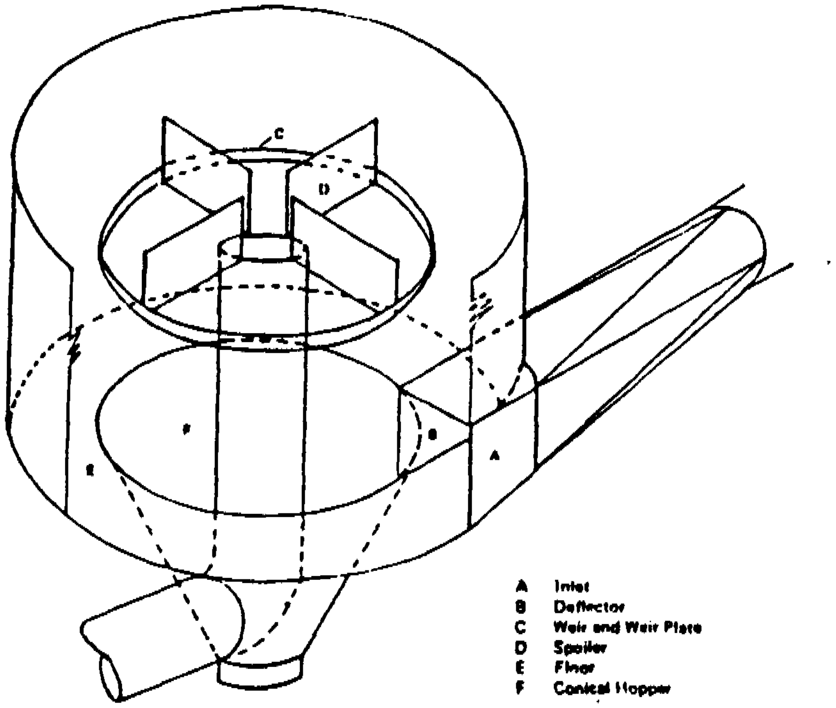


Figure 2.9 Swirl degritter (Sullivan et al, 1974 b).

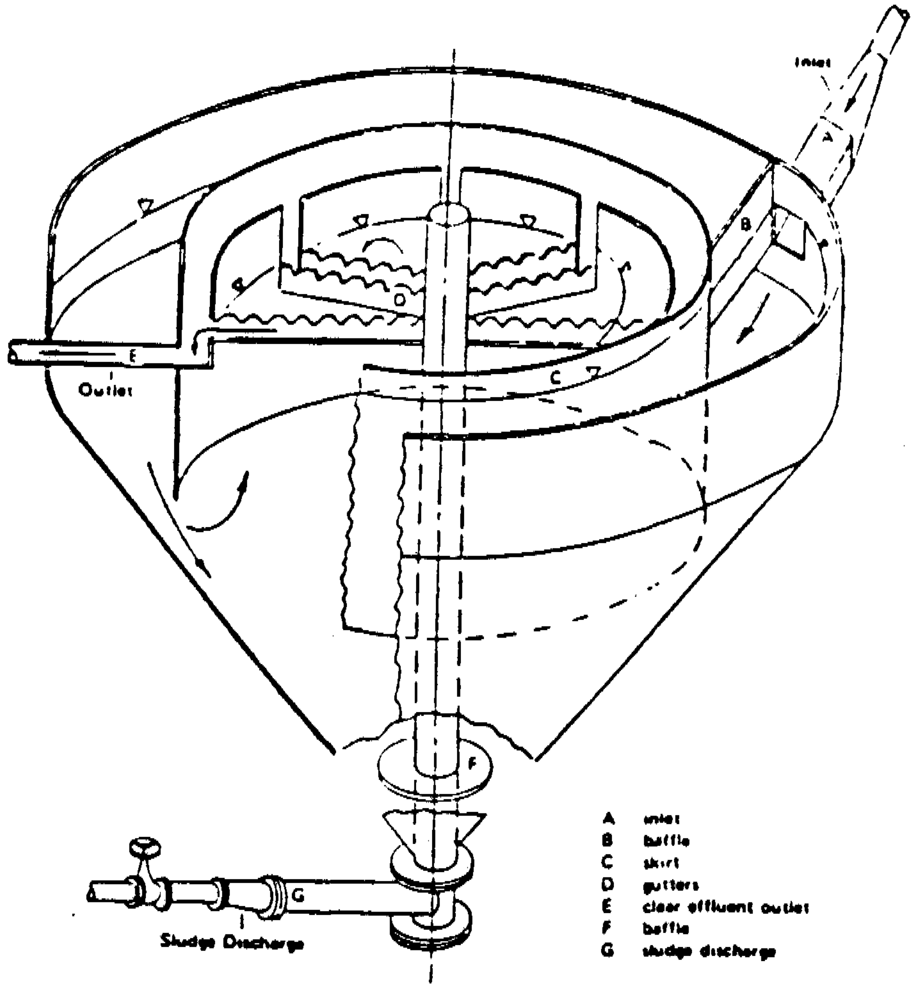


Figure 2.10 Swirl primary separator (Sullivan et al, 1978).

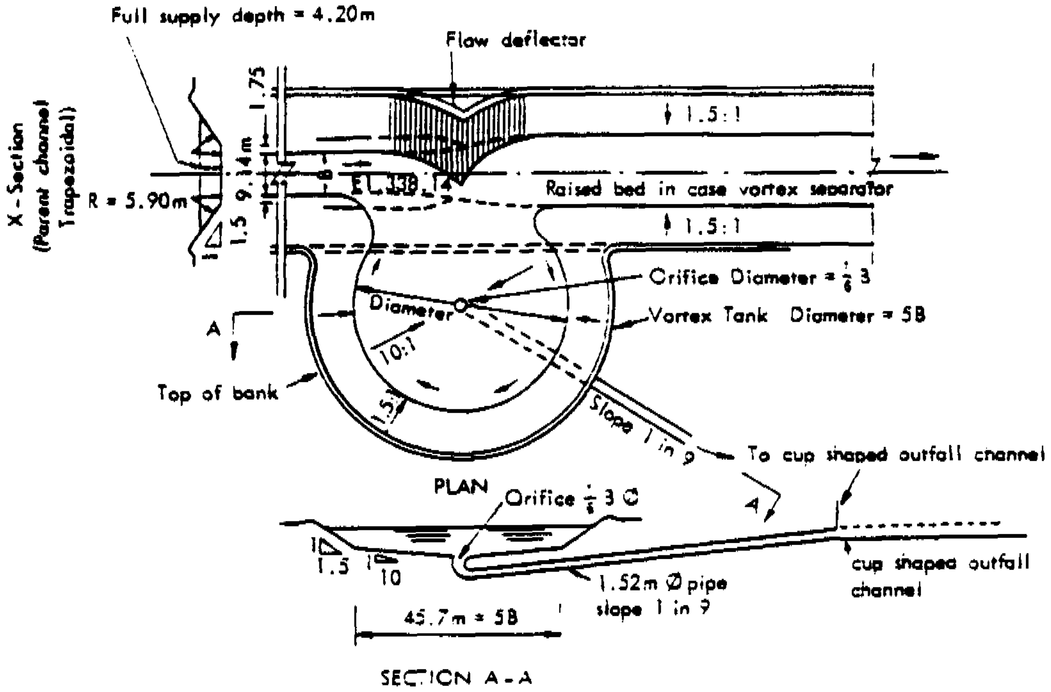


Figure 2.11 Vortex separator with tangential overflow (Dhillon et al, 1981).

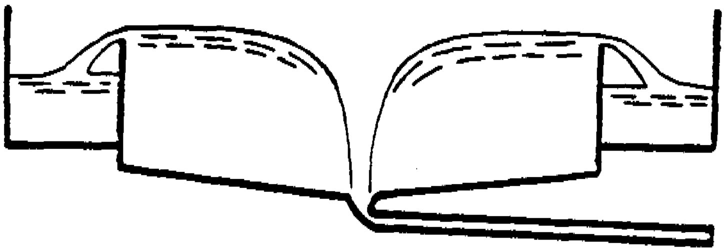


Figure 2.12 Vortex separator with peripheral overflow (Salakhov, 1975).

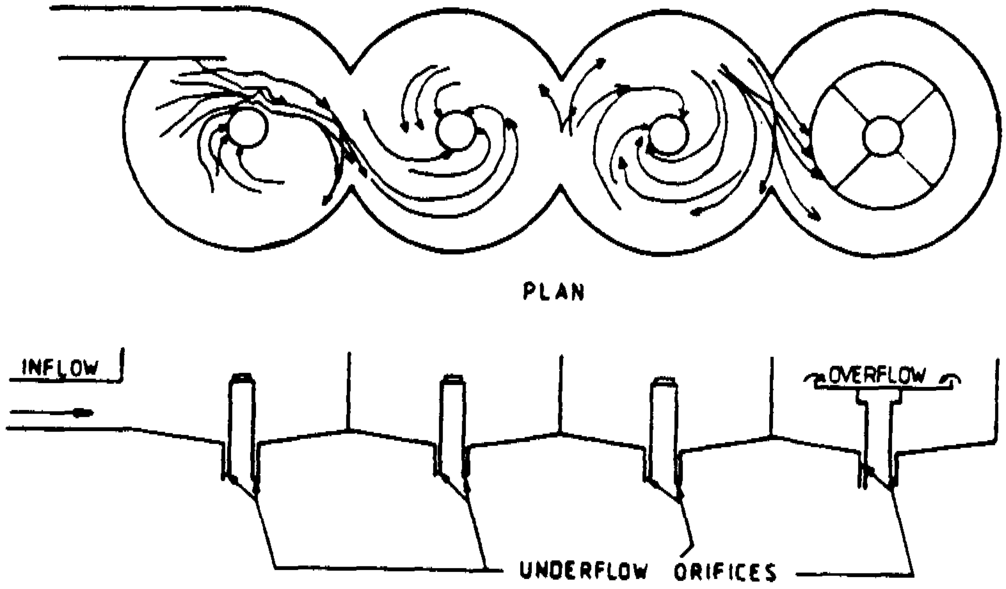


Figure 2.13 Multi-stage swirl separator (Teizazu, 1986).

2.3.2 Prominent Features of Swirl Separators

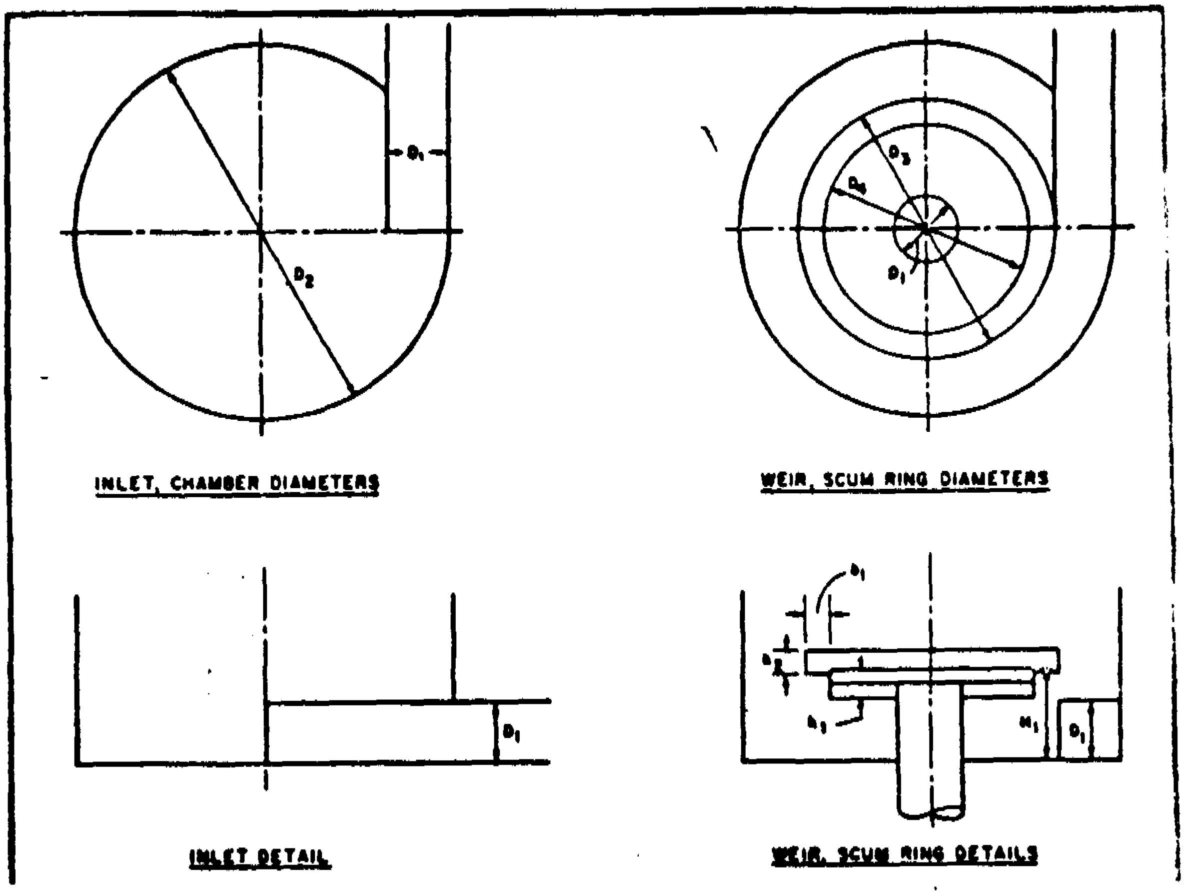
Notwithstanding the differences in terminology and some appurtenances (they can be essential parts for specific condition), the swirl separators have common basic elements (Figure 2.7 - 2.13).

Circular chamber (s)

To induce swirl flow and effectively use the whole volume of the basin, the swirl separators are made circular in plan.

There can be various configuration width (diameter D_2) and depth (overflow weir height from the floor, H_1) of swirl separators for a flow rate and removal efficiency for a specific solid particle size within the design consideration. Larger depth and width reduce the energy for sweeping settled solids to the underflow which may result in shoaling problems with coarse or heavier solids. Smaller depth and width of the chamber will have the converse effect, heavier material will be directed to the underflow, shoaling will not be a problem but fine materials will not settle and will be lost to overflow (APWA, 1972).

Sullivan et al, (1974 b) recommended for swirl separators width to depth ratio to be four (Figure 2.14) as an optimum figure based on extensive research. But it is not uncommon to find different figures suggested by other researchers or designers. For instance as high as ten, width to depth ratio is used in Indian Practice (Dhillon et al, 1981) (Figure 2.11). Salakhov (1975) suggested the width to depth ratio to be six.



$D_2 = 6$ to $12\ D_1$

$H_1 = D_2/4$

$h_1 = D_1/2$

$D_3 = 2/3\ D_2$

$b_1 = D_2/18$

$D_4 = 5/9\ D_z$

$h_2 = D_1/3$

Figure 2.14 Relationship between different elements of swirl separator (Sullivan et al, 1974 b).

The floor of the basin also needs design consideration. Even though, the sweeping and collection of the settled solid particles is attained by the secondary flow. To enhance this, sloping bottom is preferred to the flat bottom. A slope of 10 % is adopted (Mashauri, 1986). Cone-shaped (Figure 2.10) or a combination of flat and cone-shaped (Figure 2.9) are used to fit specific circumstances. During the monitoring period the swirl degritter with flat and cone-shaped floor with an inclination of 60 to the horizontal is reported to have a bridging problem and it is suggested that the slope must be reduced to avoid the problem (Pisano et al, 1984). This shows the gain in self-cleansing by increasing the bottom slope could be hampered which requires due consideration in selecting the optimum slope for a particular application.

Inlet

The inlet of a swirl separator can be a conduit or a channel which is connected to the circular chamber tangentially, a prerequisite configuration in order to induce swirl flow. Frequently, due to constructional simplicity a straight inlet conduit or channel in used. In an exceptional case a curved channel is used (Figure 2.11).

The aperture of the inlet can be square or circle for conduit and for a channel inlet the aperture can take the shape of a supply channel; trapezoidal or rectangular.

The flow in conduit inlet is introduced at the bottom of the basin. This is required to feed the solids at as low a position as possible (APWA, 1972). On the contrary in an open channel inlet the flow is fed in full depth and the basin performed satisfactorily (Figure 2.11) (Dhillon et al, 1981).

A relationship between the width of the basin and the inlet has been established. Various design figures are adopted by different researchers. According to Sullivan et al (1982) the optimum figure for the ratio of the width of the basin and the inlet apperture is six. A figure as high as twelve can be used. From Figure 2.11 for channel inlet smaller width/inlet ratio is adopted, that is five. Salakhov (1975) suggests the ratio to be 10 - 15.

Overflow

The overflow weir can be arranged in three possible locations. Central overflow weir is used in waste water treatment swirl separators (Figure 2.7 - 2.10). The same configuration is adopted for multi-stage swirl separators (Figure 2.13). Salakhov (1975) adopted a peripheral overflow weir in hydropower and irrigation vortex separators (Figure 2.12). Tangential overflow is used in Indian practice (Figure 2.11) and Mashauri's (1981, 1986) research work. No optimization is made on the three types of overflow weir arrangement. However, Mashauri (1986) tentatively suggested that the semi-circular peripheral overflow weir may show better performance than the tangential overflow weir. Smisson (1967) experimented on bell mouthed and flat bottom central overflow weirs and found out that the flat bottom overflow weir is more effective than the bell mouthed overflow weir. APWA (1972) has also found out that the width of the flat bottom central overflow weir has an effect on the removal efficiency; 2/3 of the diameter of the basin is the optimized figure for the width of the central overflow weir.

In most cases the central overflow weir is connected to central shaft to discharge the effluent and the dimension of the shaft is given to be the same at the aperture size of the inlet (APWA, 1972). In a primary separator a different type of central overflow weir with a side effluent outlet is adopted after trying a variety of possibilities (Sullivan et al, 1978).

Underflow

The underflow is positioned at the center of the basin to discharge the settled solid particles continuously with same amount of water loss; say from 3 % to 10 % of inflow rate (APWA, 1972; Salakhov, 1975). It is centered because of the collection of settled solid particles at the center of the basin by the secondary flow which is referred to as "tea-cup phenomena". Nevertheless the collection is not necessarily attained at the center and the underflow can be offset and positioned at the point of maximum concentration of the settled solid particles (Figure 2.7 and 2.8).

The ratio of inflow to underflow is a function of the ratio of the diameter of the basin to the underflow. The underflow discharge is almost constant for the ratio of the width of the basin. The underflow opening is between 30 and 60 and the underflow discharge is very high for if the ratio D_2/D_u is less than 30 (Mashauri, 1986). The suggested figure for the ratio is between 30 and 40 which is big enough to avoid clogging.

2.3.3 Auxiliary Parts of Vortex Separators

Depending on the application of the swirl separator auxiliary parts (Figure 2.7 - 2.10) can be incorporated in the swirl separator.

Flow deflector is an extension of the interior wall of the inlet to the point of tangent. The flow deflector deflects inwards a flow which is completing its first revolution, forming an interior water mass which makes a second revolution in the chamber, thus creating high velocity in the center which avoids the formation of free vortex (APWA, 1972).

Spoilers are radial flow guides, vertically mounted on the weir plate. Spoilers avoid rotational flow of the liquid above the weir plate, thus enhancing the overflow downshaft capacity (APWA, 1972). However, Alquier et al (1982) discouraged the application of spoilers and introduced vertical bars in the basin to form eddy structures which increases the efficiency of the basin. Spoilers are also used to support scum ring. Floatable trap can be inserted depending on the purpose of the swirl separator. Mashauri (1986) incorporated horizontal baffle to provide dividing surface between the inflow and the content of the chamber which completes its first revolution. No appreciable advantage is gained by doing so. The deflector, spoilers and vertical bars can be categorized as pertinent elements for a specific application as they affect the efficiency and hydraulic performance of swirl separators.

2.3.4 Solids Separation Efficiency of Swirl Separators

Solids removal efficiency is used to evaluate the performance of all solids separation devices with no exception. Removal efficiency is expressed as the ratio of the mass of solids settled to the mass of solids fed into the solids separation device. It depends on the type and size (surface area and depth of the basin) of the gravity solids separation devices. The removal efficiency is expressed in relation to the flow rate in the solids separation device or the settling velocity of solid particles.

In extreme end extended plain sedimentation can be applied to remove 97 % of suspended solids with 0.4 m/day surface load, for a water depth of 3 m having the corresponding detention time of 7.5 days (Yao, 1975). However, the relatively larger land area required and the higher expense involved make it prohibitive in many applications. Therefore the comparison of different solids separation devices includes the economical and practical consideration.

The swirl separators are purported so that with smaller size of basin they show higher removal efficiency for a particular solid particles. Salakhov's (1975) vortex separator dealt with bed or near-bottom load and the application of design procedure specified the sediment particle sizes in the range of 0.5 to 1 mm. It is simply stated that this device is effective for the control of both bed and near-bottom loads in the course of water-intake operation. A similar device is applied in India with tangential overflow channel (Figure 2.11) and claimed that it separates the particle size of d_{50} = 0.264 mm, with 64 % removal efficiency (Dhillon et al, 1981).

The swirl concentrator's removal efficiency is reported to be in the range of 40 - 60 % although it is designed for removal efficiency of 80 - 90 % (Pisano et al, 1984). The grit particle size handled in this device is > 0.2 mm.

From the laboratory experiment and theoretical data Mashauri (1986) compiled the results of different researchers as shown in Figure 2.15. It can be noticed that higher efficiency is obtained for particles with higher settling velocities which correspond to the sediment particle sizes greater than 0.2 mm.

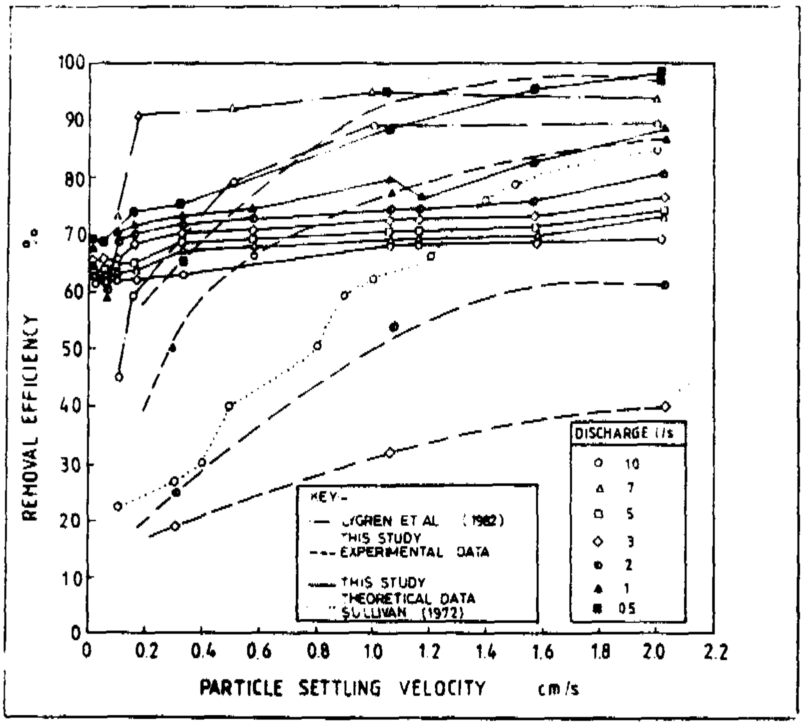


Figure 2.15 Comparison of removal efficiency of swirl separators (Mashauri, 1986).

The swirl separator principle is also applied to primary separation of waste water. To some extent it showed higher efficiency than conventional primary separators (Sullivan et al, 1978). However, the standard of primary sewage treatment could only be obtained at flows of less than 6.5 l/sec. The primary swirl separator is not found useful for removal of more than 50 % of suspended solids due to the size and cost of the required units (Sullivan et al, 1982).

The multi-stage swirl separator from the first laboratory experiment has shown promising results which overcome the drawback of the single stage swirl separators in all respects. Although it is not specifically stated it is claimed to handle finer solid particles with appreciable solids removal efficiency. For polystyrene particles of specific gravity of 1.04 g/cm^3 and particle size of d_{50} = 0.95 mm, the removal efficiency is greater than 90 % (Figure 2.16) (Teizazu, 1986; Häkkinen et al, 1987).

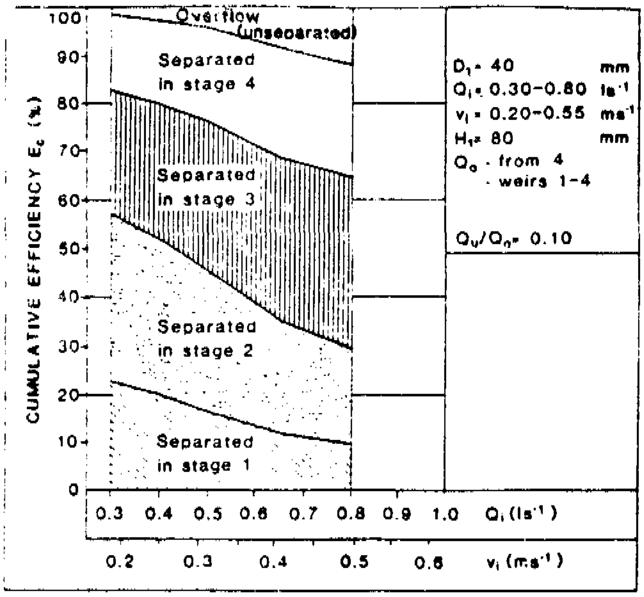


Figure 2.16 Cumulative efficiency when the overflow is taken only from stage 4 (Häkkinen et al, 1987).

Smaller overflow rate could not always give higher efficiency. Pisano et al (1984) reported that the efficiency of the swirl concentrator deteriorated with flows below design flow. Much lower removal efficiency is noted, 5 - 20 %.

In practice, the calculation of removal efficiency for solids separation devices is based on comparison of the gravimetric concentration of solids in the effluent to the concentration in the influent due to the continuous process of solid separation. That is,

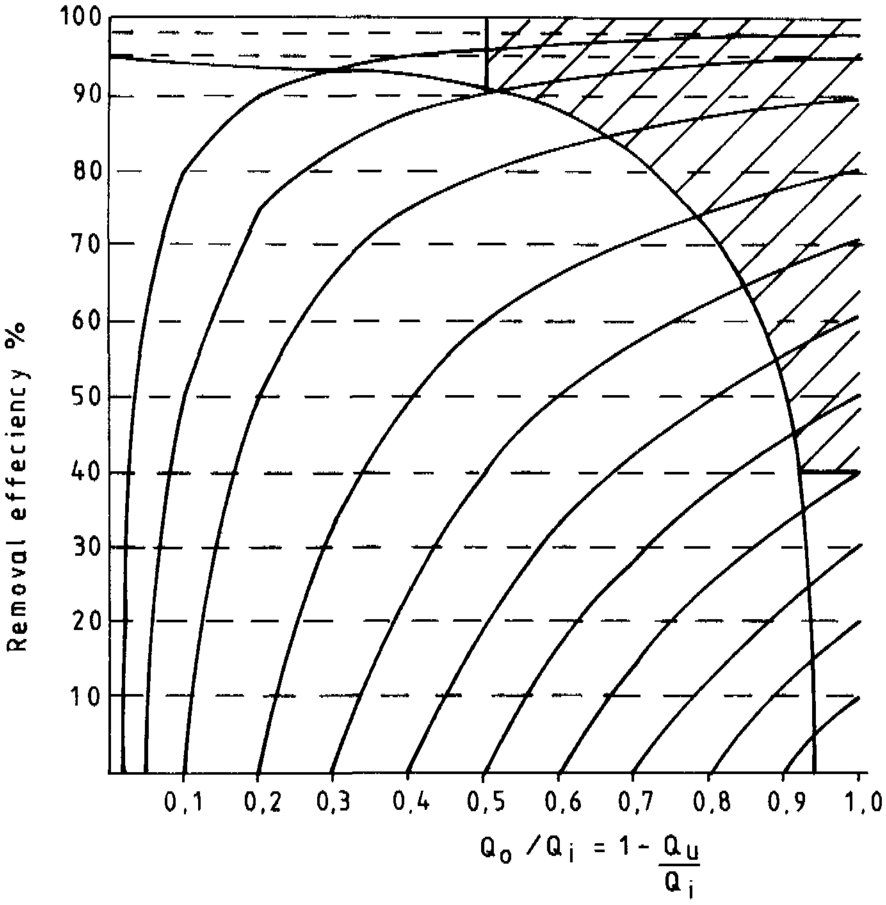
$$\text{removal efficiency } \% = \frac{C_i - C_o}{C_i} \times 100\ \% = \left(1 - \frac{C_o}{C_i}\right) \times 100\ \%$$

where C_i and C_o are the gravimetric concentrations of influent and effluent, respectively.

In the research of swirl separators, due to the possibility of measuring the solids removed with the underflow, the mass of the removed solid particles is compared with the mass of solid particles fed, which is measured at the on set of the experiment (APWA, 1972; Mashauri, 1986; Teizazu, 1986 and Häkkinen et al, 1987). The removal efficiency is the ratio of the mass of particles settled out to the total mass of particles in the inflow.

APWA (1972) proposed this method due to the variation of concentration in the effluent with time. However, the removal efficiency calculated using this method approximates the actual removal efficiency for higher removal efficiency and it diverges from the actual value as the underflow/inflow ratio increased and the removal efficiency decreased. Figure 2.17 depicts the divergence from actual removal efficiency using the mass method for evaluating swirl separators with various underflow/inflow ratio.

Even though, for practical purpose less than 10 % underflow/inflow ratio is recommended, there are times for practical or experimental purpose, when the increase of the underflow/inflow ratio is needed. Therefore, it is suggested that the mass to mass comparison should be applied judiciously in evaluating the performances of swirl separators; better to apply correction factor according to the underflow/inflow ratio as shown in Figure 2.17.



— — $\text{eff} = 1 - M_o/M_i = \frac{M_u}{M_i}$

—— $\text{eff} = 1 - \frac{M_o/M_i}{Q_o/Q_i} = 1 - \frac{M_o}{M_i}\,\frac{Q_i}{Q_o} = 1 - \frac{C_o}{C_i}$

▨ Both equations indiscriminately can be applied with differences of ≤ 5 % within the practical region

Figure 2.17 The effect of the ratio of underflow rate and inflow ratio on the removal efficiency by using two calculation methods.

2.4 Hydrocyclones

Hydrocyclones are inertial separators in which pressurized inflow is fed tangentially to create rotational motion in a body of liquid, thus generating a centrifugal force several thousands greater than the gravity force that separates the solids from the liquid and then separates coarse particles from fine particles (Layton, 1980; Amin, 1976).

Hydrocyclones have a tangential feed inlet into a closed cylindrical feed section, a conical section immediately adjacent to the cylindrical section and existing slightly below the feed inlet and an adjustable apex valve located at the apex of the conical section of discharging separated concentrate of solid particles (Figure 2.18) (ASCE and WCPF, 1977).

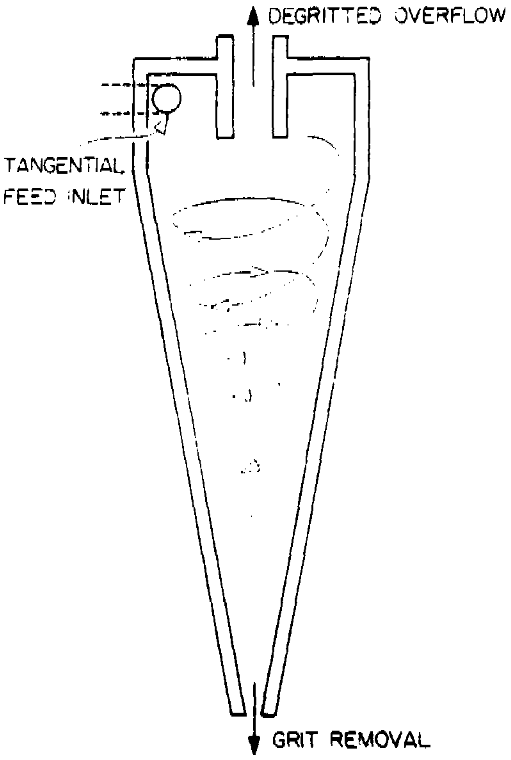
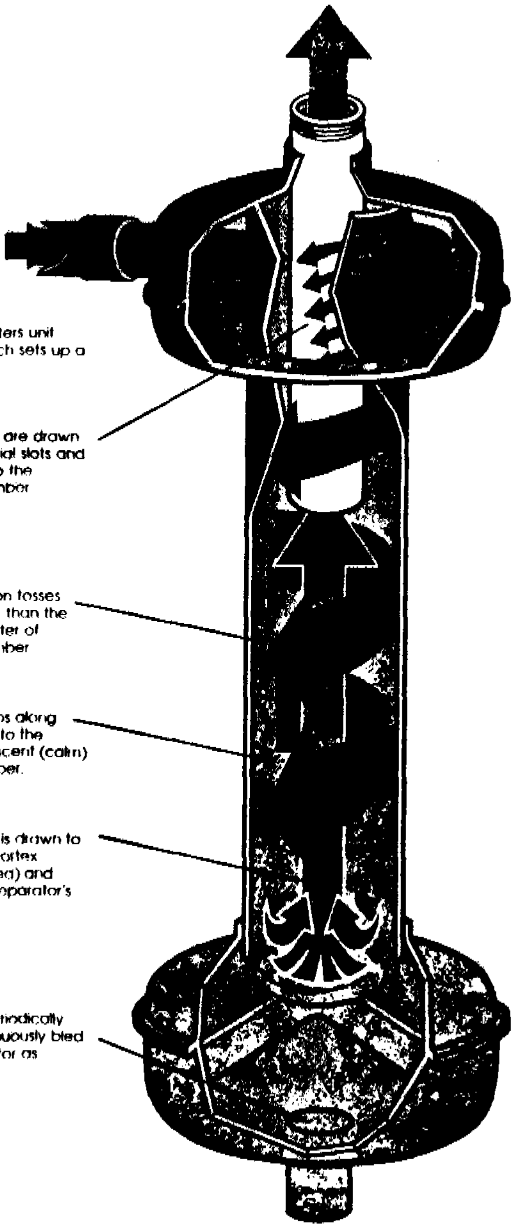


Figure 2.18 Typical cross section of a hydrocyclone (ASCE and WCPF, 1977).

Hydrocyclones can be installed inclined, horizontally or even in an inverted position. This is due to the fact that the dominant factor in solid separation in hydrocyclones is the centrifugal force which throws particles outward against the wall and hence the force of gravity is negligible (Svarovsky, 1984, cited by Mashauri, 1986). This is the basic difference between hydrocyclones and swirl separators in addition to the requirement of differential pressure between feed and overflow. The flow within a cyclone is confined and turbulent. Forced vortex flow prevails in the central core while free vortex flow prevails in the outer annular zone of the cyclone (Dietz, 1981; Reydon and Gauvin, 1981).

Cyclones have wider industrial application (Reydon and Gauvin, 1981). They are also introduced in waste water as degritter to remove grit particle sizes in the 105 to 75 μm range (ASCE and WPCF, 1977). In water supply the use of manufactured hydrocyclones (Figure 2.19) is reported to protect sediment laden river intake pumps, transmission mains and treatment units. These hydrocyclones referred as sand separator function at 98 % efficiency to remove particle sizes of 74 μm (Shulz and Okun, 1984).

The efficiency of the hydrocyclone is affected by the diameter of the particles to be removed which is used to determine the size of the hydrocyclone, the differential pressure between feed and overflow, concentration of solids in the feed, consistency of flow rate, viscosity of the fluid and specific gravity differential (Layton, 1980).



1.
Sandy water enters unit tangentially which sets up a circular flow

2.
Sand and water are drawn through tangential slots and accelerated into the separation chamber

3.
Centrifugal action tosses particles heavier than the water to perimeter of separation chamber

4.
Sand gently drops along perimeter and into the separator's quiescent (calm) collection chamber.

5.
Sand-free water is drawn to the separator's vortex (low pressure area) and up through the separator's outlet.

6.
Sand is either periodically purged or continuously bled from the separator as necessary.

Figure 2.19 Hydrocyclones as sand separator (Schulz and Okun, 1984).

Hydrocyclones are rather small, thus they are more attractive than other solids separation facilities. In general the efficiency is higher as the cyclones become smaller. For instance in waste water application a cyclone of 600 mm in diameter can handle up to 63 l/s of dilute sludge (ASCE and WPCF, 1977).

In developing countries their application for river water treatment is discouraged because of their need of pressure which is mostly attained by pumping (Mashauri, 1986). Additionally they are manufactured in industrial countries and as their on-site production requires skill and sufficient knowhow of the solids liquid separation phenomena involved in the hydrocyclone which is missing to date. However, where the abstraction of raw water from river involves pumping they are claimed to be simple and effective devices for removing sediments (Schulz and Okun, 1984).

3 THEORETICAL ANALYSIS OF SWIRL SEPARATORS

Physical testing of laboratory model and prototype of solid separators gives an insight to hydrodynamics of liquid and separation of solid particles in suspension. An extensive research is required to advance design criteria or procedures. This is excessively expensive work which is most likely prohibitive, unless and otherwise the achievement excels the commitment.

Several types of swirl separators are introduced in different water engineering fields and industrial applications. Although they have similarities in the hydraulics of liquid flow and solid separation, they have a different approach in design procedures which are developed as a result of extensive testing of a model and prototype of swirl separators. These differences are attributed to the variations in the overall arrangement of the essential elements and appurtenances to cater for various purposes.

Another method which is a vital design tool is theoretical prediction with a rigorous theoretical analysis and the subsequent solution of the equations considered to describe the physical situation (Boulton and Evans, 1974). Analytical and numerical models are the two mathematical approaches used to describe the hydraulic phenomena in swirl separators and predict the consequences.

The analytical approach is a simple way of describing the physical situation in a swirl basin using a particular solution of the Euler's equations with measured data. Numerical models are based on Navier-Stokes equations to include turbulent flow (Mashauri, 1986). The innovation of the digital computer made the Navier-Stokes equations applicable which are otherwise time-consuming and impractical (Boulton and Evans, 1974).

3.1 Hydraulics of Liquid Flow and Solids Separation in Swirl Separators

By virtue of structural configuration of swirl separators unlike conventional solids separation units intricate hydraulic phenomena are manifested. These occurrences are manipulated to enhance the solids separation and the collection and removal of particulate at a predetermined location.

The kinetic energy of the inflow which is fed tangentially imparts a slow circular motion in the basin. Consequentially a cross current and secondary flow is created which moves downward near the circular wall to the center along the basin bottom and up again at the central annulus (Figure 3.1) (Mashauri, 1986).

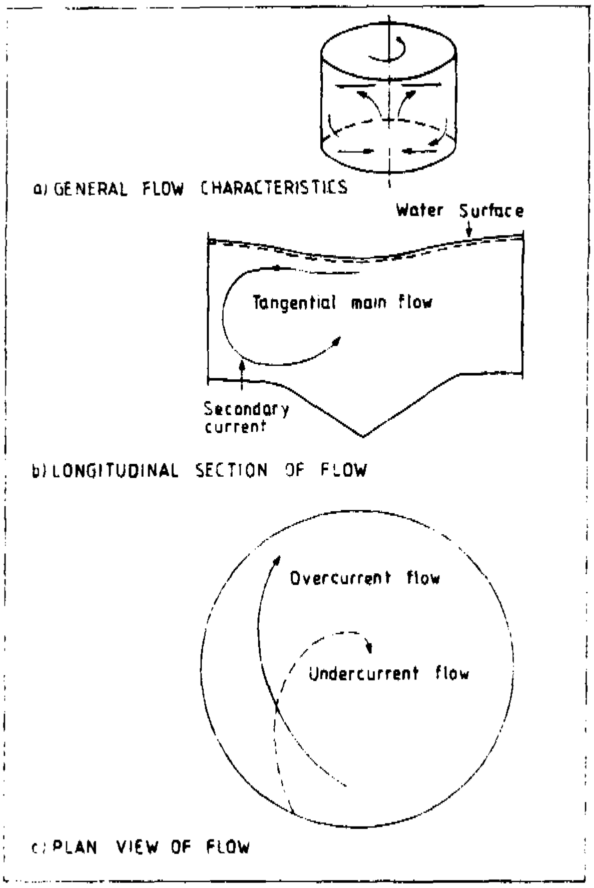


Figure 3.1 Flow phenomena in swirl separators (Mashauri, 1986).

Solids separation is attained mainly due to gravitational settlement. Mashauri (1986) reported that the inertial force in vortex basin is to be much smaller than gravitational force and its effect on solids separation is negligible. While Sullivan et al (1978) stated that in primary swirl separator solids are separated and deposited by inertial and gravity action and agglomeration mechanisms. Furthermore, the vertical velocity of secondary flow could accelerate or deccelerate the rate of settlement. Alquier et al (1982) noticed that the removal efficiency of swirl separator is different for particles of different specific gravity having the same settling velocity. They suggested that the behaviour of solids separation is better characterized by the critical velocity of solid particles rather than settling velocity because of the resuspension of deposited solids.

The description of flow characteristics differs according to the overall configuration of the basin and the observation of researchers. Forced vortex flow and/or free vortex flow are identified in all swirl basins. In Salakhov's vortex basin (Figure 2.12) which is closely similar to 'swirl separator' the dominant flow condition is described to be free vortex (Salakhov, 1975).

In Smisson's vortex basin both types of flow are observed and the effect of free vortex was found to reduce the efficiency of the basin and flow deflector is used to avoid the presence of free vortex (APWA, 1972). Actually the flow condition in a circular basin with a deflector is described as swirl flow. Mashauri (1986) in his study of vortex separator divided the basin into three zones: forced vortex zone, free vortex zone and the underflow zone (Figure 3.2).

Because of the differences in the conception of the physical situation different analytical models are presented by different researchers. Basically the numerical models are the same, except in some variables and boundary conditions due to the configuration of swirl separators (APWA, 1972; Amin, 1976; Sullivan et al, 1978; Mashauri, 1986). To show the general approach only analytical models are presented.

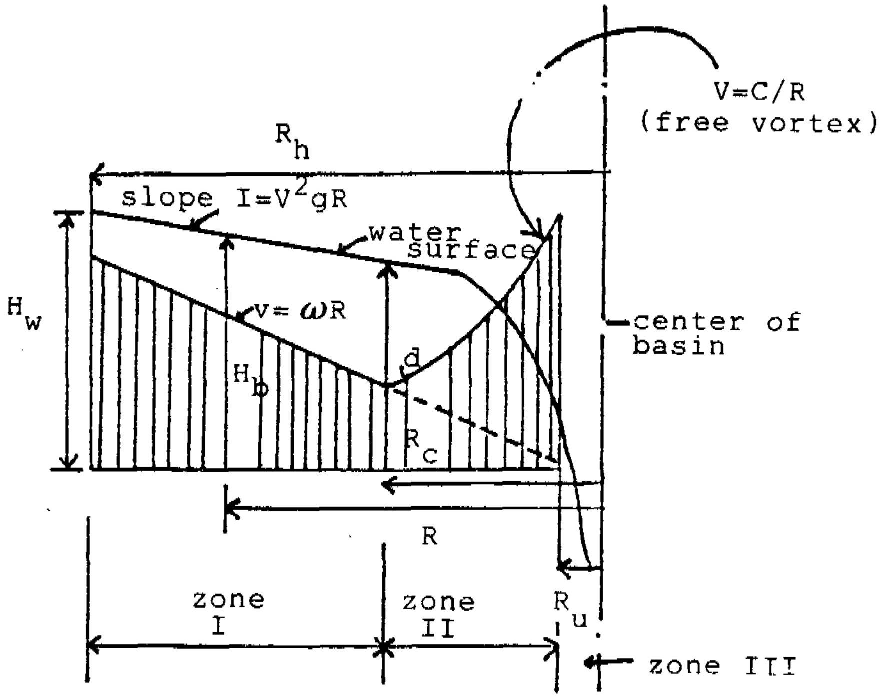


Figure 3.2 Schematic picture of a half-section of vortex basin showing tangential velocity distribution (Mashauri, 1986).

3.2 Analytical Model

Mashauri (1986) has devised an empirical equation (Appendix A) to design a vortex separator based on the analytical approach. The empirical design equations are developed as a result of analytical solutions of fluid flow and solid-particles flow which are treated separately. The solutions are supported by experimental data.

3.2.1 Fluid Flow Equations

According to Cecen and Akmandor (1973) (cited by Mashauri, 1986) the flow in the outer annular section of the vortex basin is forced vortex flow, while the flow in the central core is free vortex flow (Figure 3.2).

In the forced vortex flow condition the fluid rotates as a solid body with constant angular velocity , at any radius R (Douglas et al, 1985). Therefore the tangential velocity at any point R is

$$v = \omega R \qquad (3.1)$$

This shows that the tangential velocity decreases with decreasing radius.

Based on the Bernoulli's energy equation the depth of the water at any point can be equated as follows (Mashauri, 1986).

$$H_b = H_w - \frac{\omega^2}{2g} (R_b^2 - R^2) \qquad (3.2)$$

It is worth noting that the derivation of the above equation is based on the assumption that the radial velocity and vertical velocities are much smaller than the tangential velocity and therefore negligible.

In the free vortex flow condition, it is stated that there is no variation of energy from stream line to stream line (Mohanty, 1986). There is no change of tangential velocity with angular position, and the tangential velocity increases with decreasing radius and practically free vortex changes to spiral vortex. Thus

$$v = C/R \qquad (3.3)$$

where C is a constant known as the strength of the vortex at any radius R (Douglas et al, 1986).

At the intersection of forced vortex flow and free vortex flow the velocity is given as

$$v = \omega R_c = C/R_c \qquad (3.4)$$

The water depth in the free vortex zone can be equated from Bernoulli's energy equation (Mashauri, 1986). That is

$$H_b = H_w - \frac{\omega R_b^2}{2g} \left(1 - \frac{R_c^2}{R_b^2} + \frac{R_c^2}{RR_b}\right) \qquad (3.5)$$

vertical and radial velocities are also assumed to be negligible.

In addition to the two zones there is the underflow zone, where the velocity of flow has radial, vertical and tangential components (Mashauri, 1986). The radial velocity is given as

$$u = \frac{Q_u}{2\ \pi R_u{}^2 H_u} R \tag{3.6}$$

The vertical velocity is given as

$$w = \frac{Q_u}{R_u{}^2 H_u} Z \tag{3.7}$$

The tangential velocity is given as v = C/R (3.8)

3.2.2 Solid Particle Flow Equations

Discrete particle flow condition is assumed in the computation of the flow of the particle. The velocities in radial, angular and vertical directions are given as follows (Cecen and Akmandor, 1973 (Turkish) cited by Mashauri, 1986) in the radial direction

$$\frac{du_s}{dT} - \frac{v_s{}^2}{R} = F\ (u - u_s) \tag{3.9}$$

in the angular direction

$$\frac{dw_s}{dT} + \frac{u_s v_s}{R} = F\ (v - v_s) \tag{3.10}$$

and in the vertical direction

$$\frac{dw_s}{dT} = F\ (w - w_s) \tag{3.11}$$

From these Equations 3.9 - 3.11 the particle trajectories are divided for Zone II (Figure 3.2) assuming there is not slip between particles and liquid. Assuming u_s = dR/dT and the radical velocity u, to be small, Equation 3.9 is written as

$$\frac{d^2R}{dT} - \frac{v_s{}^2}{R} = F \frac{dR}{dT} \tag{3.12}$$

Combining Equation 3.3 in Equation 3.10 and substituting $u_s = dR/dT$ one obtains

$$\frac{d\,(Rv_s)}{dT} = FC - FRv_s \qquad (3.13)$$

Equation 3.11 is also written as

$$\frac{dw_s}{dT} = -Fw_s \qquad (3.14)$$

assuming w to be negligible.

The drag force from F can be written as

$$F = \frac{3}{8}\, C_d\, \frac{\delta s}{\delta \omega}\, \alpha^{-1}\, |u - u_s| \qquad (3.15)$$

where $= A/d^2$

and d and A are the particle diameter and particle area respectively.

Integrating Equation 3.13 by using boundary and initial conditions the tangential velocity is written as

$$v_s = R\,\frac{d}{dT} = \frac{C}{R} + \left[\frac{R_c\, v_{sc} - C}{R}\right] e^{-TFtan} \qquad (3.16)$$

and intergration of Equation 3.14 gives

$$w_s = e^{-TFvert} \qquad (3.17)$$

Combining Equations 3.13 and 3.16 a second order differential equation emerges

$$\frac{d^2R}{dT} + \frac{FdR}{dT} - \frac{1}{R}\left[\frac{C + (R_c v_{sc} - C)e^{-TFtan}}{R}\right]^2 = 0 \qquad (3.18)$$

This equation was solved for a number of varied flow and particle characteristics. The results are shown as functions of dimensionless time $t = TC/Ru^2$ dimensionless radial cordinate $r = R/Ru$ or as a function of the drag force parameter $F = C/Ru^2$. Using the above equations and experimental data one can plot particle trajectories in vortex separator as shown in Figure 3.3 (Mashauri, 1986).

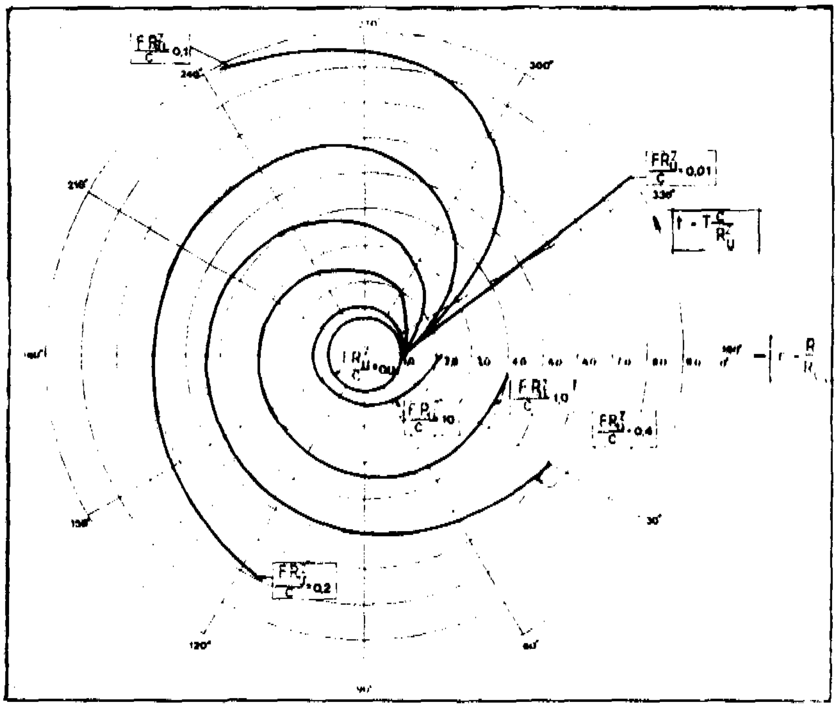


Figure 3.3 Particle trajectories in vortex settling basin (Mashauri, 1986).

4 EXPERIMENTAL INVESTIGATION

The multi-stage swirl separator has shown promising and encouraging results at the first laboratory experiments. Higher surface load could be applied with small size multi-stage swirl separator to separate finer sediment particles. Since many river intakes in Ethiopia faced failure due to a siltation problem the multi-stage swirl separator is found to be one of the attractive sediment controlling devices. Therefore, to foresee the applicability of the multi-stage swirl separator and to procure field data the experiments were carried out in a stream in the vicinity of Jimma town in Ethiopia (Figure 4.1).

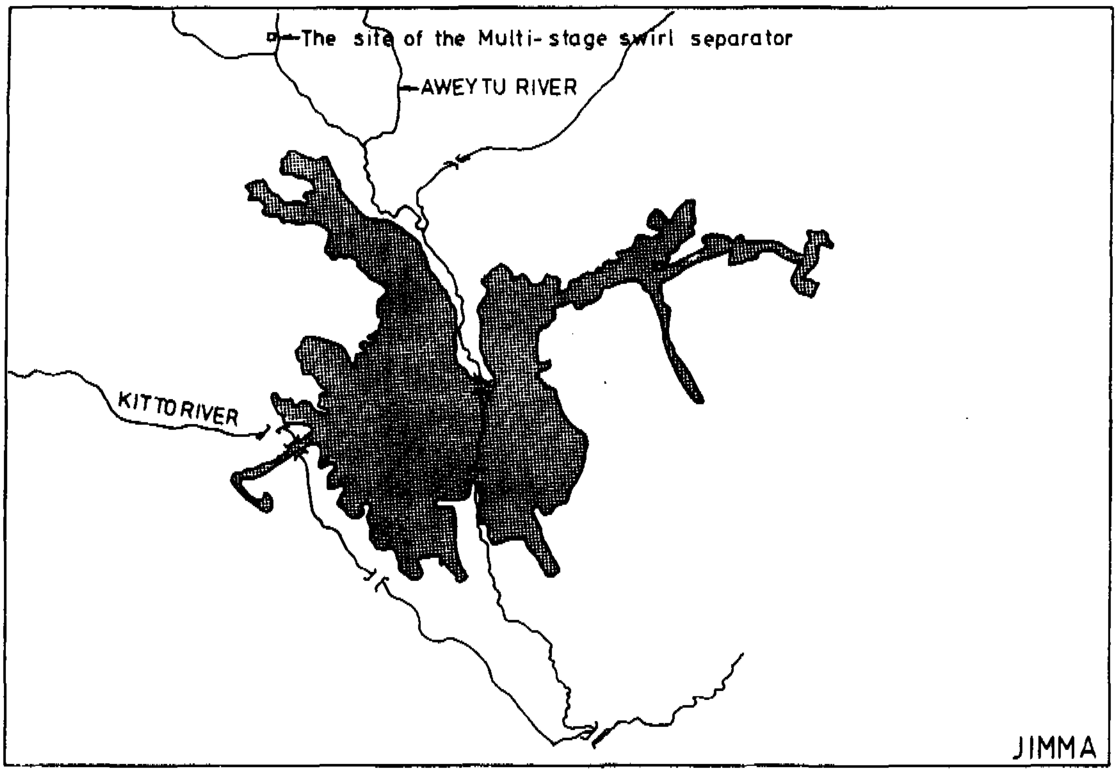


Figure 4.1 Location of multi-stage swirl separator (AESL, 1982).

4.1 Background Information of the Site

The multi-stage swirl separator was installed in a stream at the close proximity of Jimma (Figure 4.1). The dry-weather flow of the stream is approximated to be 25 l/s. During the study the stream flow was in the range of 70 l/s to 500 l/s which was at the end of a rainy season.

Jimma is the capital of Keffa region located 335 km by road southwest of Addis Ababa. The geographical location of Jimma is approximately $7^{o}41'$ 'N latitude and 36^{o} 50' 'E longitude at an average elevation of about 1720 meters above sea level. Jimma is a typically tropical region with an average precipitation of 1 500 mm per annum. The average daily temperature is 19^{o}C while the average maximum is 27 ^{o}C and the average minimum is 11^{o}C (AESL, 1982).

The site was selected on the basis of the future applicability of the multi-stage swirl separator, since Jimma is in extreme shortage of water and the construction of the main water supply projects is to be started in 1988. In the meantime, the construction of an emergency scheme is proposed which consists of a horizontal roughing filter and slow sand filter, and the multi-stage swirl separator will be used as a pretreatment unit before the horizontal roughing filter at the intake site. The site is accessible which facilitated the installation of the prefabricated multi-stage swirl separator.

4.2 Design and Construction of the Separator

The multi-stage swirl separator has originated from the multi-stage hydrocyclone developed by Ryynänen in 1985 (Teizazu, 1986; Häkkinen et al 1987). The first laboratory experiment was carried out in 1986. Because of its originality, the dimensioning of the laboratory model was based on the recommendation of the United States Environmental Protection Agency for single-stage model (Teizazu, 1986).

4.2.1 The Experimental Laboratory Model

The multi-stage swirl separator of laboratory model consists of four equally dimensioned circular chambers arranged in an array. The inflow is introduced tangentially with square conduit at the bottom of the first stage. The flow passes from one stage to the next through a connection opening chord. The opening chord subtends 52^{o} with the center of each basin. Two sets of experiments were carried out: experiments with a circular central overflow weir in each stage and experiments with a circular central overflow weir in the last stage. It was shown that the later type of configuration has higher removal efficiency (Figure 4.2).

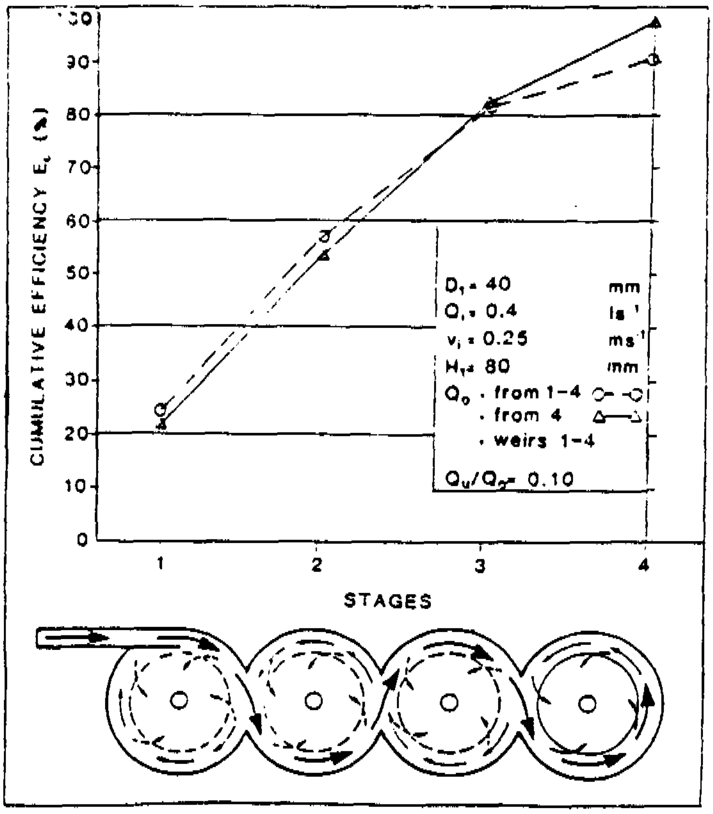


Figure 4.2 Overflow from all stages compared to overflow from the 4th stage only (Häkkinen et al, 1987).

The underflows from each basin are provided at the center of each basin with annular opening around the overflow shaft. The discharge from the underflows was 10 % of the inflow rate. A deflector is introduced only in the 1st stage as an extension of inlet channel.
The overall configuration and dimensions of the laboratory model are shown in Figure 4.3 and Table 4.1.

Table 4.1 Design dimensions of the 1st experimental laboratory model in comparison with the recommendation of EPA (AWPA, 1972; Sullivan et al, 1982).

Design dimensions (1st experimental laboratory model)	Recommended dimension (Figure 2.14)
$D_2 = 5D_1$ and $7.5\ D_1$	$D_2 = 6$ to $12\ D_1$
$D_3 = 2/3\ D_2$	$D_3 = 2/3\ D_2$
$D_4 = 0.75\ D_1$ and $0.5\ D_1$	$D_4 = D_1$
$H_2 = 0.27\ D_2$ and $0.37\ D_2$	$H_2 = 0.25\ D_2$

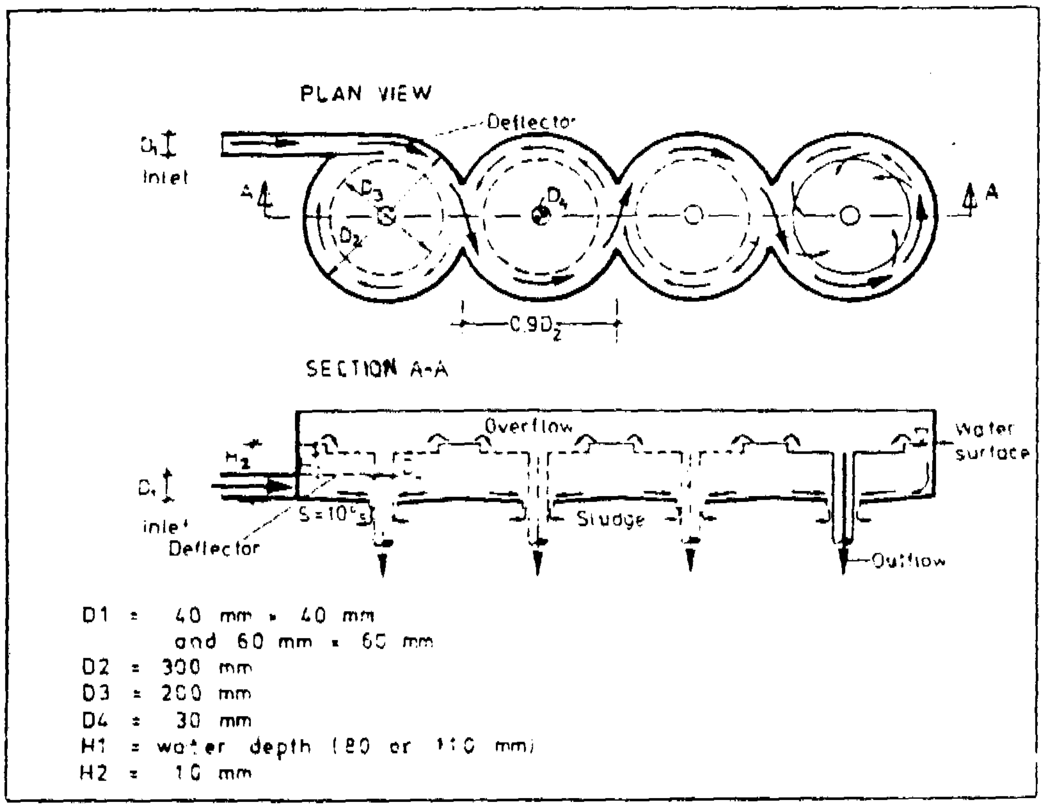


Figure 4.3 The first experimental laboratory model of multi-stage swirl separator (Häkkinen et al, 1987).

4.2.2 Design of the Separator for Field Application

The multi-stage swirl separator is the first of its type to be tested in field conditions. Although it seems a hasty decision to jump directly from the first laboratory test to the practical application, it was done so to substantiate the achievement of the laboratory model and to procure field data which urges the researchers to consider its further development with a concrete design approach and to foresee it's applicability by using the design procedures of the single stage swirl separator.

The design of this multi-stage swirl separator was closely similar to the first laboratory model except for some modifications of the components. The inflow was fed tangentially through an open rectangular channel throughout the depth of the circular basin. The inflow was uniformly distributed throughout the depth of the basin with a minimum inflow velocity. This was done in conformity with the findings of the previous research on the multi-stage swirl separator which indicated that the smaller the inflow velocity the higher the efficiency (Teizazu 1986; Häkkinen et al, 1987).

Based on the suggestion of Mashauri (1986) semi-circular peripheral overflow weir was provided. Two sets of depth of the weir above the floor were tested. Tangential overflow weir condition also simulated for the smaller depth according to the suggestion by Teizazu (1986). Another condition for selecting peripheral weir was its constructional simplicity particularly for an intake structure. The slope of the floor was increased from 10 % to 50 % (30^o inclination to the horizontal) because of the smaller depth of the settling zone.

The deflector in the first stage was avoided because Häkkinen et al (1987) concluded that there was no need to include a deflector. In accordance to the previous experimental laboratory model, the dimensioning was mainly based on the United States Environmental Protection Agency recommendations for the single-stage model (APWA, 1972; Sullivan et al, 1982). The experiences of other researches on the swirl separator are also incorporated. Taking the diameter of the basin as the main parameter the following dimensional relation is used.

D_2 = internal diameter of the swirl basin
D_1 = inlet width
= $D_2/4$
H_1 = height of the overflow weir from the floor
= $D_2/4$ and $D_2/3$

To come out with the design, different design equations and design curves were referred which actually give different dimensions (see Appendix A). The basis for dimensioning the width was the equation suggested by Salakhov (1975). The equation was used also by Mashauri (1986).

The design flow rate was taken as 20 l/s with anticipation of applying higher flow rates. The design sediment particle size was 0.125 mm which is the smallest sediment particle size handled by swirl separators. This size represents very fine sand according to sediment grade scale (Appendix B). The range of sediment particle sizes which could be handled is not given specifically except for the general statement that this device could handle finer particle sizes than other swirl separators (Teizazu, 1986). Because of the multiplication of the circular basin it was also expected to handle finer sediment particles than the design capacity. Finally it was arrived at a preliminary configuration shown in Figure 4.5.

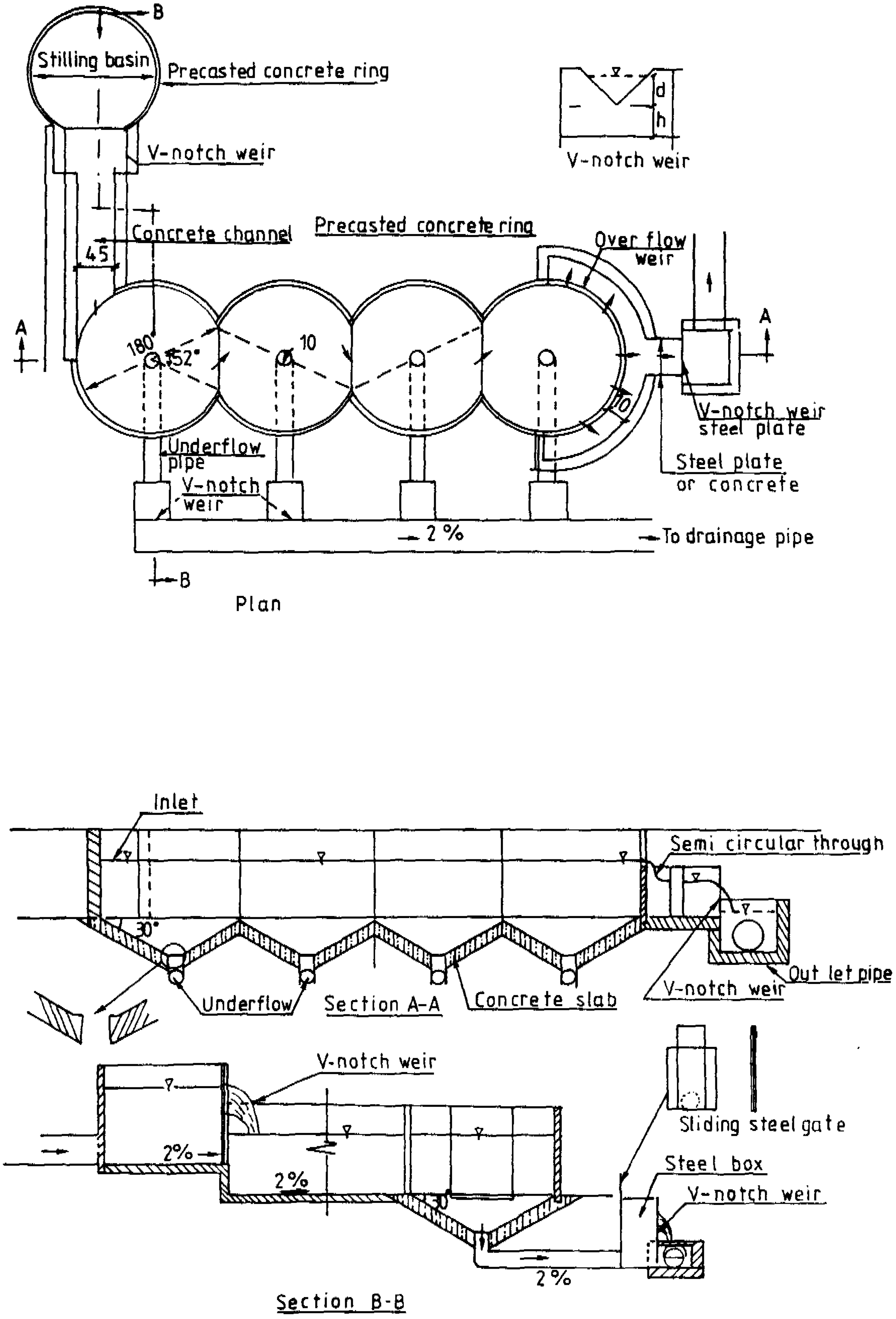


Figure 4.5 Preliminary design of the multi-stage swirl separator (concrete structure).

Initially, because of the limitation of time, it was decided to construct the plant with concrete, the circular compartments being made of precast concrete rings. Steel, brick, hollow block and masonry were taken as alternatives. The engineering department of Water Supply and Sewerage Authority (WSSA) provided the cost estimate of concrete and steel structure with the intention to hasten the construction (Appendix C). The cost estimates were closely the same and finally it was decided to use a steel structure which was found most convenient at that time by the engineering department of WSSA.

4.2.3 Construction of the Separator

The multi-stage swirl separator was manufactured in Addis Ababa in a private metal workshop under the supervision of WSSA. The separator consists of four circular basins (stages) connected in array. The stages and the effluent semi-circular trough were made of 2.5 mm iron-sheet metal. The length including the trough, and the width of the separator is 7 m and 1.8 m respectively (Figure 4.6). Because of the available truck size, to transport the separator the 4th stage was cut and rewelded on site. The vertical underflow G.S. pipes of 80 mm diameter were welded in the workshop. No inlet opening was provided in order to decide the inlet position on site.

The selected site for the installation of the separator was an open sloping land closer to the water source. A cut and refill work was required to install the separator, and one meter high masonry retaining wall was provided on one side to support the stages. The separator could be installed partly or completely in the ground avoiding the masonry work if simple underflow and overflow weir boxes were not required. The topography was convenient to discharge the underflow directly back to the stream. The provision of masonry inlet channel was required to direct the inflow smoothly into the separator. Figure 4.6 to 4.7 show the final configuration and arrangement of the separator.

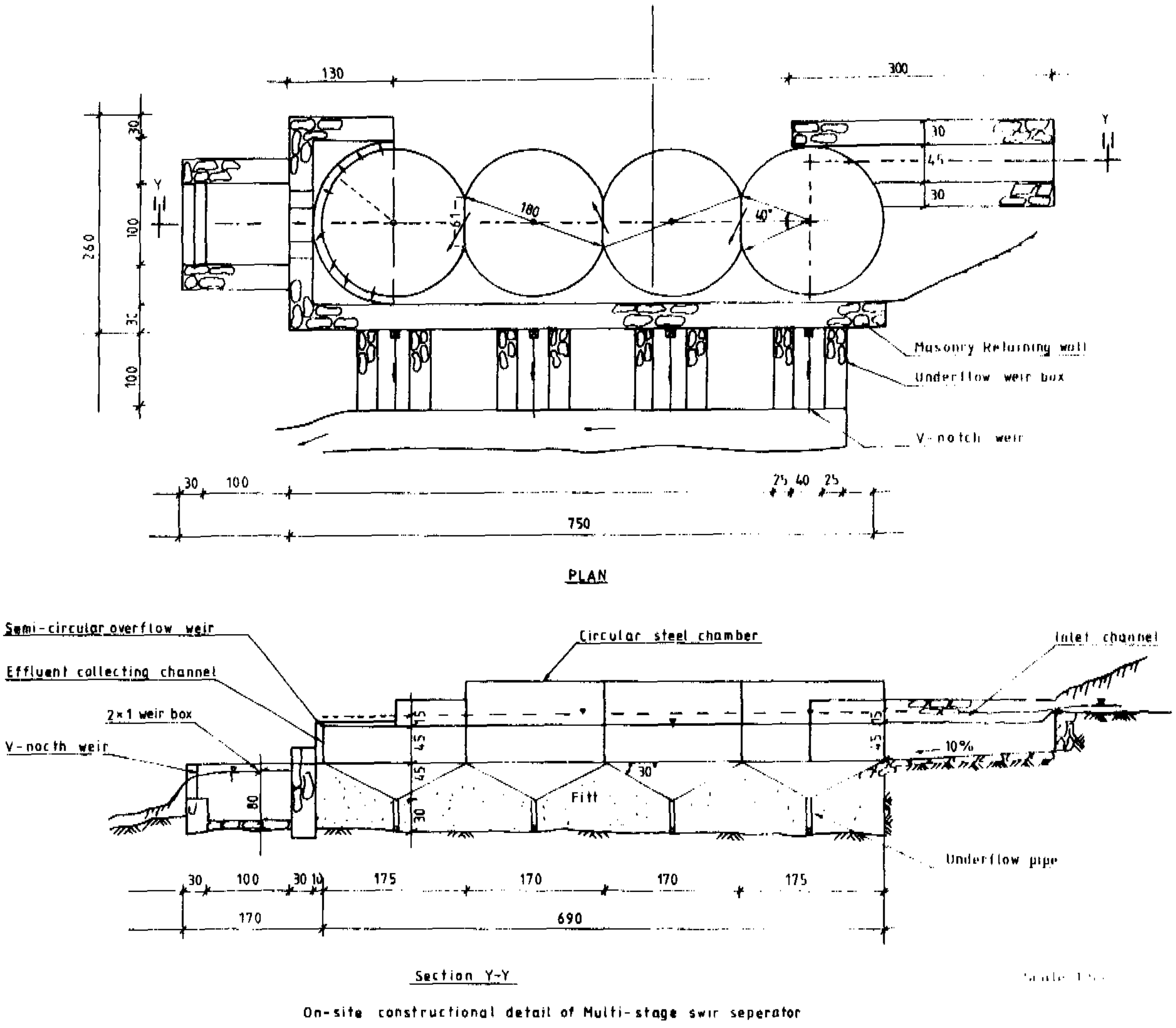
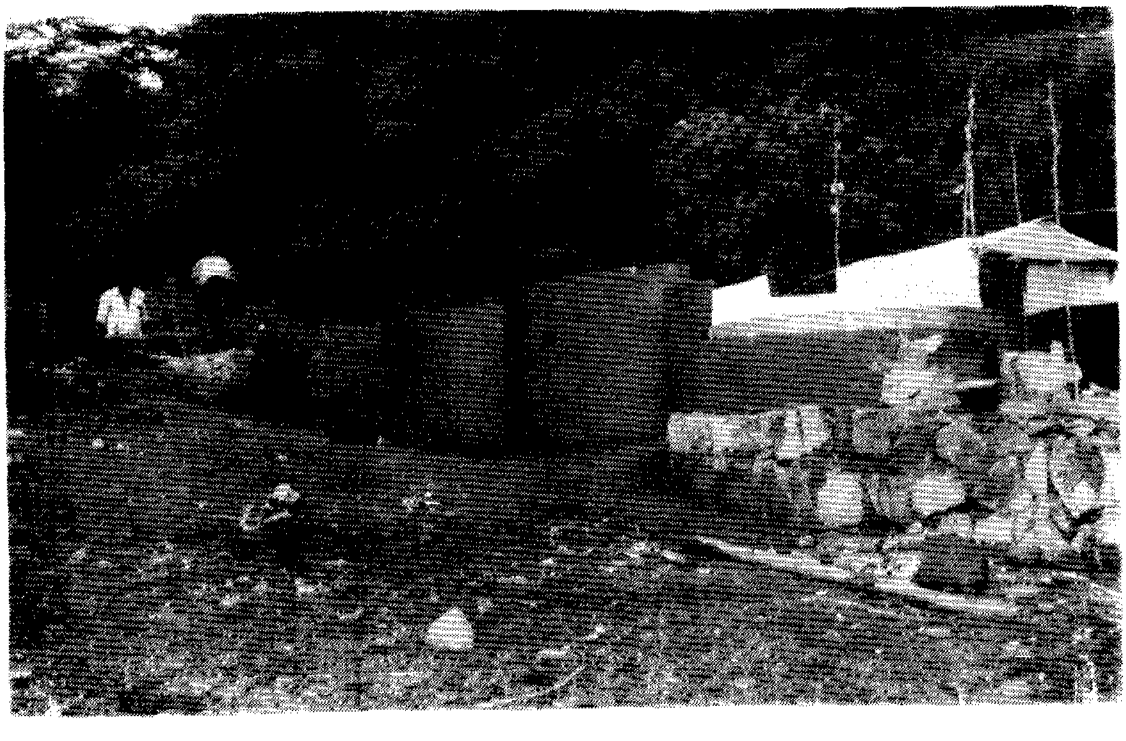


Figure 4.6 As-built drawing of the multi-stage swirl separator.

a) top view



b) side view

Figure 4.7 The multi-stage swirl separator on site.

Despite the fact that there was no previous experience to manufacture the separator, it was possible to weld the separator as designed, except the opening from one stage to the other. The angle substended by the connection chord was made 40° rather than 52° which was taken from the previous design.

The experience with the steel structure which should be mentioned is that due to welding the inside wall and floor of the separator could not be made as smooth as required which otherwise entails additional expenses and time. The rough surface in the basin is shown in Figure 4.8.

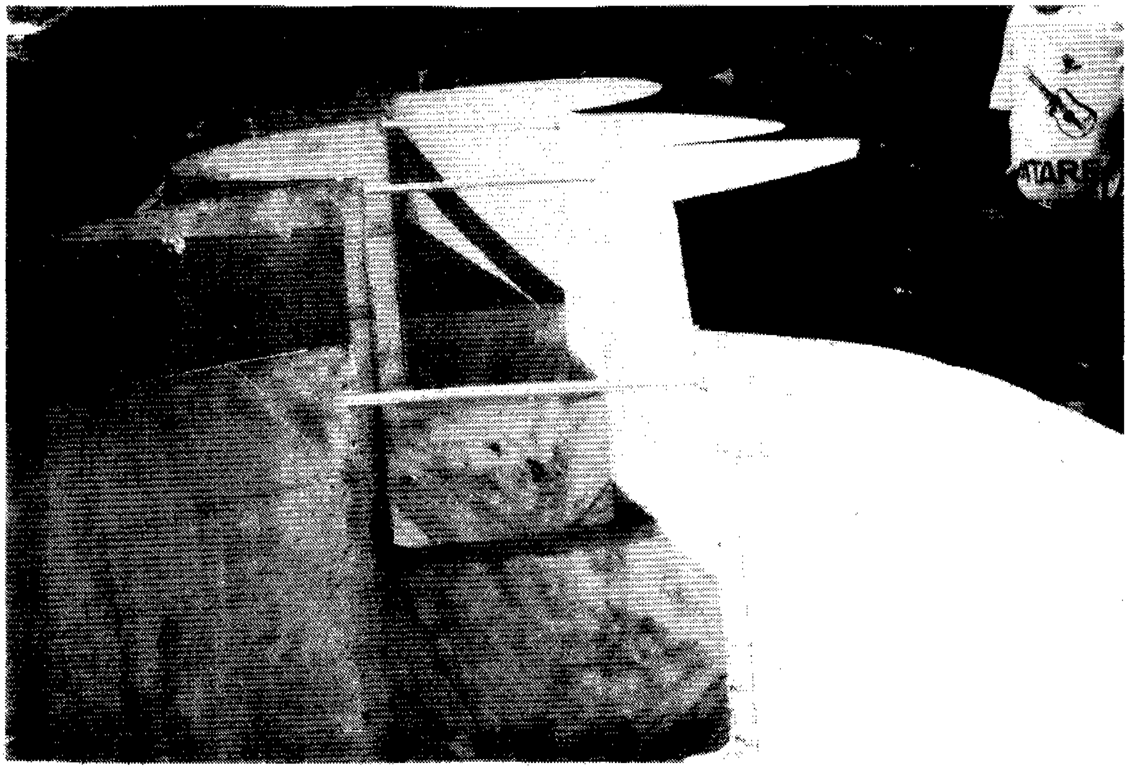


Figure 4.8 View inside the multi-stage swirl separator.

4.3 Type of Tests

One of the criteria in evaluating the performance of a solids-separation device is clarification efficiency. This is expressed as solids removal efficiency or turbidity removal efficiency.

Volumetric or/and gravimetric measurements are used to evaluate the sediment removal efficiency. Inspite of the fact that gravimetric measurement is more reliable than volumetric measurement, the later was used in this study. The main reason is that the instruments for gravimetric measurement were not available: a high precision balance and oven for drying the sample.

Turbidity measurement was carried out to see the extent of turbidity reduction and to relate the turbidity reduction with solids reduction.

4.4 Measuring Apparatus

The types of apparatus used in this study are listed as follows:

1. five sets of Imhoff cones with locally produced wood stand. Capacity = 1 l, height = 40 cm
2. turbidity measuring instrument (HACH portable turbidity meter)
3. five masonry weir boxes with iron-sheet V-notch weir
4. 20 l plastic bucket
5. 3 sets of plastic hose
6. stop watch
7. thermometer
8. 25 ml graduated cylinders
9. sampling plastic bottles for turbidity measurement.

4.4.1 Volumetric Measurement

Volumetric measurement of sediment concentration was carried out by using the Imhoff cones (Figure 4.9). The sediments in the samples from selected specific points were allowed to settle for specific time intervals. Three time intervals were selected: 5 minutes, 10 minutes and 15 minutes. The volumetric concentration of sediment particle is expressed as volume of sediment per volume of suspension in specific time. The time interval is used also to calculate the settling velocity, that is the height divided by the time interval. Using Stoke's equation the particle sizes which have settled in specific time interval were calculated. Because of the effect of viscosity on settling velocity the temperature of the water was measured.

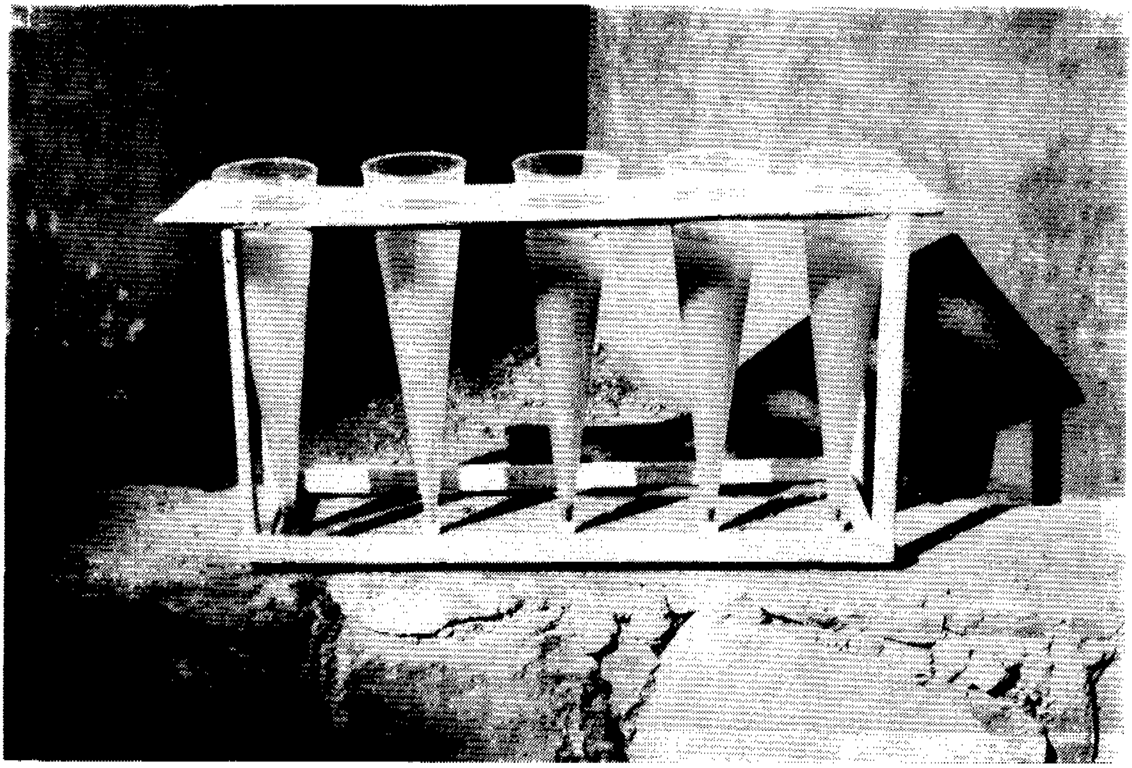


Figure 4.9 Imhoff cones for volumetric measurement of sediment concentration.

4.4.2 Turbidity Measurement

Portable HACH turbidity instrument was used for turbidity measurements. The range of the capacity of the instrument was 0 - 100 NTU. The sample from a selected specific point similar with volumetric measurement was collected and the turbidity measurement was taken on site (Figure 4.10).

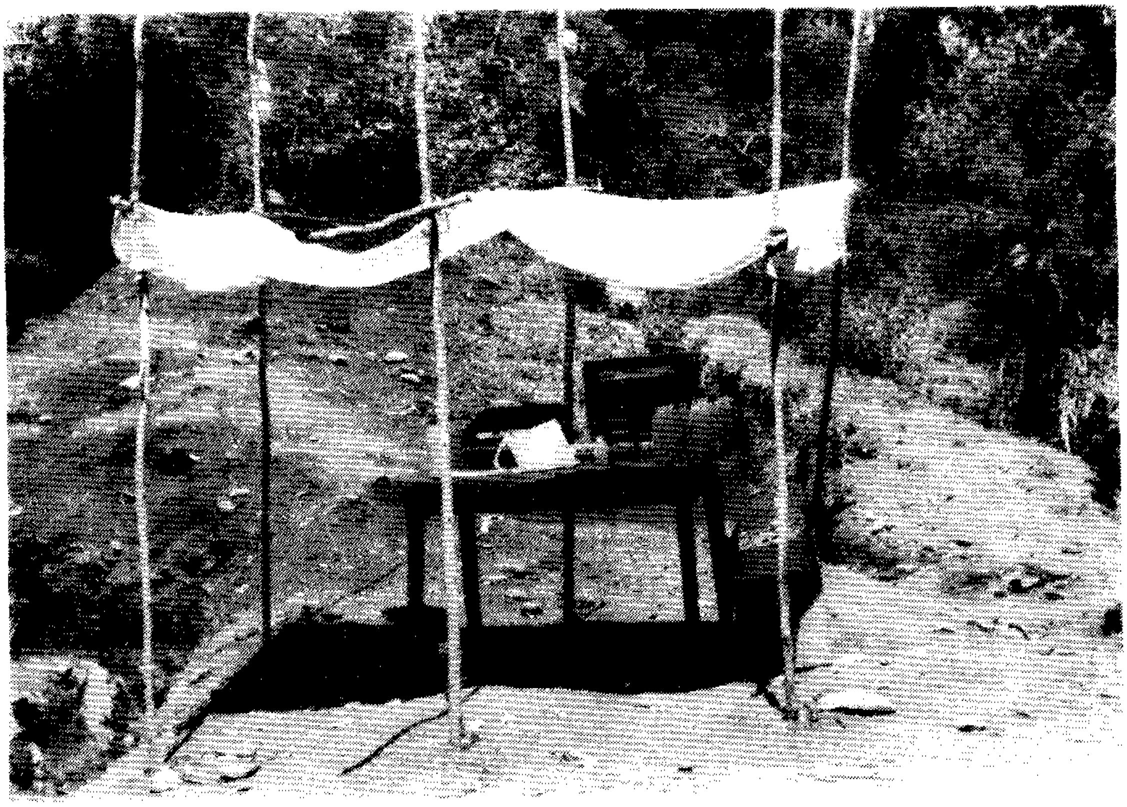


Figure 4.10 Turbidity measurement.

Most of the time the turbidity of the water tested was higher than the capacity of the instrument and hence the measurement was taken by diluting the sample with spring water with turbidity of 1.1 NTU. The spring water (Figure 4.11) was used not only because of its availability at the site but it was also found that it has less turbidity than distilled water available locally.

Figure 4.11 Dilution spring water.

4.4.3 Flow Measurement

The flow measurement was required at six locations: at the inlet, at the overflow and at the underflows (four underflows). Masonry weir boxes with 90^{o} V-notches weir were provided at each location, (Figure 4.6 and 4.12) except for the inlet due to siltation problem upstream of the weir. The inflow rate was measured by closing the underflows, that the inflow rate equals the overflow rate or otherwise by summing up the overflow and underflow rate.

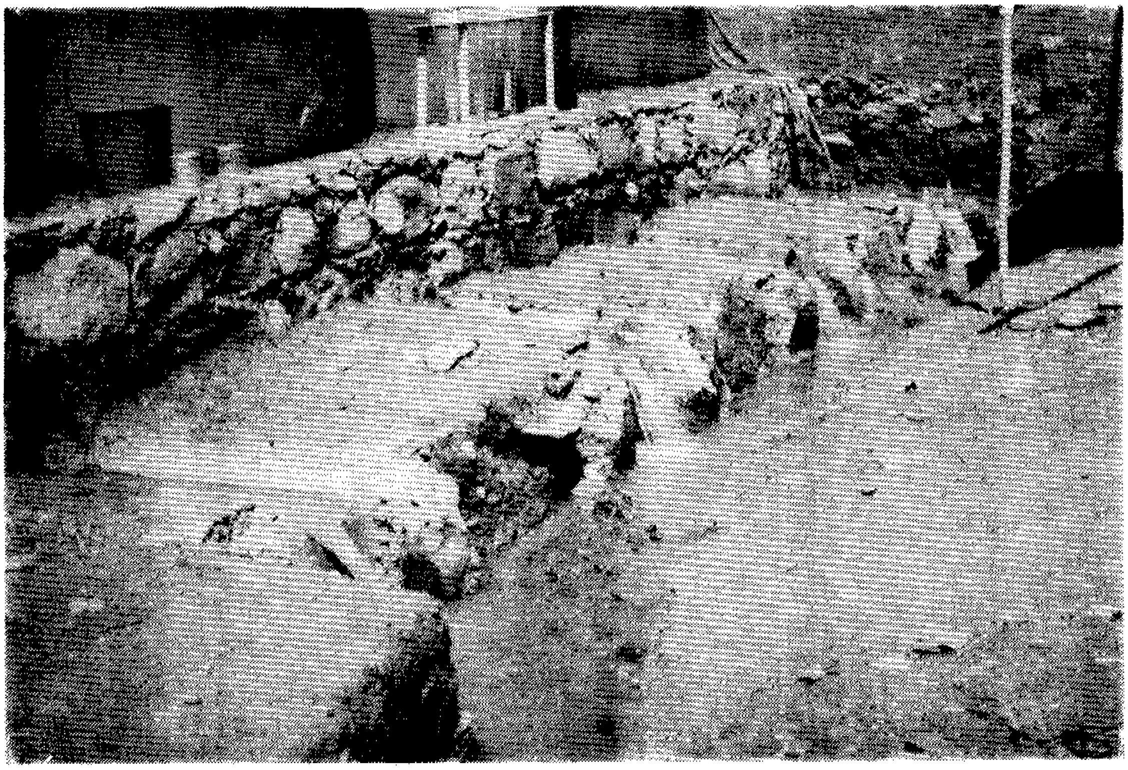


Figure 4.12 Underflow weir boxes in operation.

As the flow rate increases within the acceptable range of approximation because of the weir boxes two values for C_d are used in the discharge equation of 90° V-notch weir. That is 0.65 upto 15 cm depth over the weir and 0.88 above 15 cm depth over the weir. Hence the equation can be written as

$$Q = \frac{8}{15} C_d \quad 2g \quad h \quad \frac{5}{2} \tan\phi$$

$C_d = 0.65 \qquad h < 15$ cm
$C_d = 0.88 \qquad h > 15$ cm
$\tan\phi = 1$ for 90° V-notch weir
$g = 9.81$ m/s

Because of the rough approximation of the above particularly for high flow rate, volumetric discharge measurements were always carried out to cross-check the flow rates, using a 20 l plastic bucket and stop watch.

4.5 Sampling

At the beginning of the test two methods of sampling were used at the inlet to measure the sediment concentration and turbidity of the inflow. The sample water was collected by submerging an Imhoff cone (for volumetric measurement) and a plastic bottle (for turbidity measurement) in the water flowing in the inlet channel. Similarly a plastic bucket was used to draw sample water which was transferred immediately to an Imhoff cone and a plastic bottle. As an alternative plastic hoses were used to collect samples at the inlet. It was tried because of the elevation difference between the working place and the inlet channel. Three 2.5 mm hoses were put inside the channel at random depth and places.

First it was checked if the sampling methods gave similar results. The differences in sediment concentration ranged from 10 - 25 %. The hoses themselves gave different results as they drew water from different depths in the inlet channel. Ultimately the hose method was selected for sampling not only for the abstraction of samples at different depths, but also for its conveniency in the working conditions. The sample water from the hoses was directed at the same time to an Imhoff cone and for turbidity measurement a sample was taken from each hose.

The samples from the overflow were collected directly at the downstream of overflow weir and/or measuring V-notch weir using the Imhoff cone and plastic bottles. The samples from selected specific points were skimmed using an Imhoff cone and plastic bottles.

The inflow rate was regulated using a 2.5 mm iron-sheet metal slide gate which was braced with masonry work. It was installed at the inlet of a diversion channel. Because of its simplicity the slide gate did not give sufficient regulation for the flow rate and the flow rate could not be decidedly adjusted. Hence the flow rate was randomly set by placing the slide gate at random positions. The underflow rate was regulated using 80 mm gate valves fixed on the drain pipes from each stage. At the same time these gate valves were used to regulate the overflow rate.

4.6 Sediment Particle Sizes Studied

Curiously to begin with few test runs were carried out on the particle sizes of 0.011 mm, 0.016 mm and 0.02 mm (medium and fine silt (see Appendix B). Using the volumetric measurement method the efficiency of the basin for the particles of 0.011 mm and 0.016 mm was so small which was not necessary to record. As such in the actual sense, since the volumetric ratio of these sediment particles was so high due to the higher percentage of liquid, the volumetric measurement could not give a real picture of the actual situation for the finest particle sizes. Consequently the study shifted to the particle sizes of 0.02 mm, 0.03 mm and 0.04 mm in the range of medium and coarse silt.

The particle sizes were determined using the simplest method available at hand. It is assumed that the particle which has settled in the Imhoff cone has travelled through the column of water, 40 cm high starting from the surface of the water. By dividing the height of travel (40 cm) to a time interval, the velocity of the particles was calculated. Initially 15, 30 and 60 minute intervals were used and later 5, 10 and 15 min intervals are used exclusively throughout the whole test run. Then using Stoke's equation

$$d = \left(\frac{18}{g} \; \frac{w_s \omega}{\delta s - \delta \omega} \right)^{0.5}$$

the sizes of particles were calculated. To determine the kinematic viscosity the temperature was found in the range of 18 - 20° C during the study. Using the kinematic viscosity (1 mm^2/s) for the 20 °C sufficed the purpose.

The sediment gradation curve could have helped in identifying the weight ratio of each sediment particle size which aids in realistically interpreting the result of the volumetric measurement of the smallest particle sizes. Unfortunately, mainly due to the time limitation and unexpected incidents it was not possible to produce sediment gradation curves.

4.7 Circumstantial Incidences

During the study the main problem encountered was the concentration of sediment particles in the stream. The amount of solid particles in the stream was so small, less that 0.2 ml per litre of suspension except during the rain.

At the outset, it was intended to run the tests in the rainy season which was in vain due to the delay in the manufacturing and installation of the multi-stage swirl separator. Although the rainy season was over during the test run, it was raining intermittently which is actually the climatic condition of Jimma. Another inconveniency was that it was raining in the evening, so that the flash flood effect could not be measured. The site is not accessible when it rains.

The problem was solved by creating disturbance upstream or by using the soil excavated from the diversion channel (Figure 4.13).

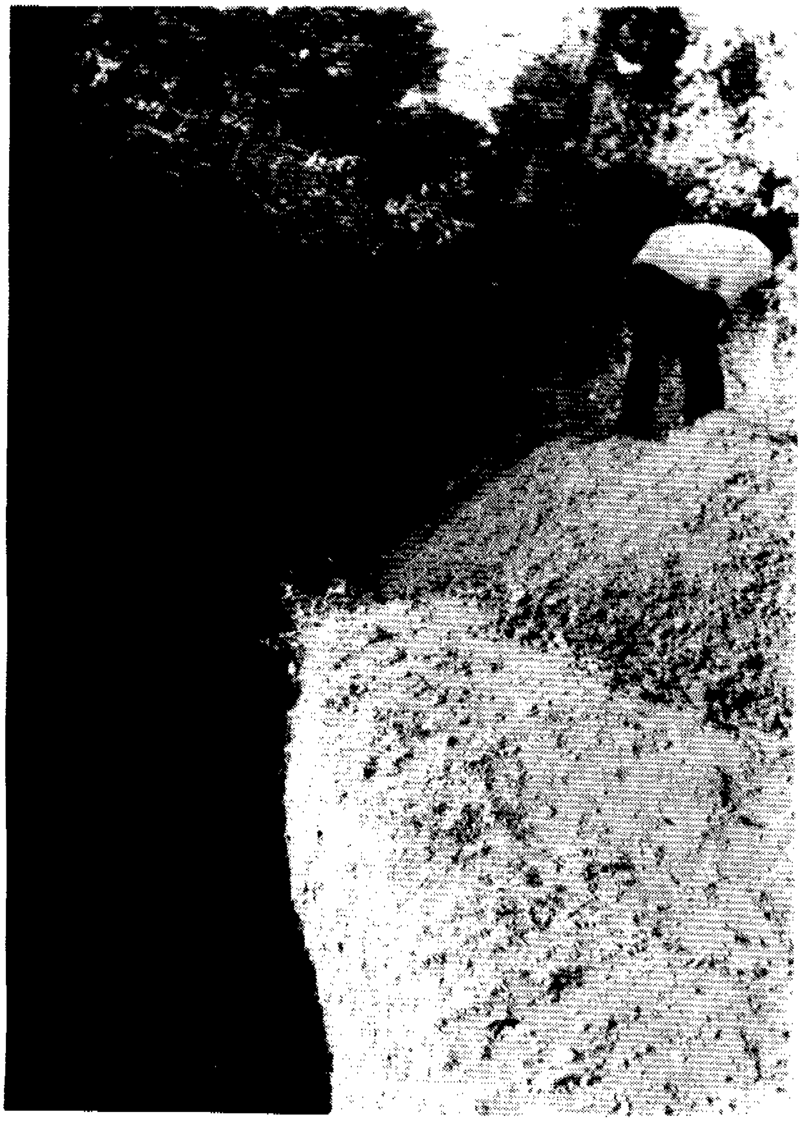


Figure 4.13 Simulation of flood condition.

Therefore it was possible to increase the concentration of sediments simulating flood condition.

The second problem was the clogging of the underflow pipe of the 1st stage when 10 % of the inflow was used for the underflow discharge and equally divided for each stage. It was mainly due to the gravels and floating matters in the stream and secondly the high percentage of solid particles was removed in the first stage. The first condition was solved by providing a screen with mesh wire available locally. But it required incessant cleaning. The second condition was solved by increasing the share of the underflow rate of the 1st stage, mostly 50 % of the underflow. It is observed that the gate valves enhanced clogging when not fully opened.

Simultaneously the total underflow rate was increased depending on the inflow rate. The effect of the increase of underflow rate was evaluated at the same time.

Thirdly about 20 cm drop was provided from the diversion channel to the water surface in the inlet channel (Figure 4.14). This was done to avoid sediment settlement in the inlet channel by creating turbulence. It was observed that its effect did not subside in the 1st stage but continued upto the last stage.

The increase of the basin depth remarkably avoided this problem. Therefore, the gain due to the increase of basin depth examined with this condition.

Figure 4.14 Drop and turbulent flow in the inlet channel.

5 RESULTS AND DISCUSSION

The main objective of this study was to evaluate the performance of the multi-stage swirl separator in the field conditions. During the study the only controllable parameter was the flow rate. Others such as sediment concentration, sediment particle sizes and temperature could not be regulated. However, the sediment concentration of river water was small enough which have no effect on the performance of gravity separators (Mashauri, 1986; Al-Layla et al, 1978). The study was focused on the removal of particle sizes greater than specific sizes rather than total suspended solid particles avoiding the effect of the variation of sediment gradation with time. The water temperature variation was small during the test run. Therefore, the condition was sufficient to evaluate the performance of the multi-stage swirl separator, in terms of inflow rate and specific sediment particle sizes.

Two overflow weir heights, 45 cm and 60 cm and two types of overflow weirs, semi-circular peripheral overflow weir and "tangential" overflow weir were tested. In actual sense tangential overflow channel was not provided. Tangential overflow condition was simulated by reducing the size of peripheral overflow weir. It was expected that the effect to be the same.

As noted it was difficult to adopt constant underflow/inflow ratios. At different times it was tried to see the effect of the ratio of underflow and inflow rate. No significant effect was observed. It is worth noting that due to the difficulties in the working condition, the underflow rate was not shared equally by each stages. Different configuration of the underflow ratio in each stage used makes it difficult to evaluate the effect of underflow/inflow ratio conclusively.

Mashauri (1986) commented that the underflow/inflow ratio has effect on the smaller particles, whereas no effect is noticed in this test, even using higher underflow rate in the last stage. The purpose of minimizing the underflow rate has only practical reasons : to minimize wastage of water, and construction cost of the separator as the design is mainly based on the inflow rate.

It should be realized also that the increased underflow ratio concurrently reduces the effluent, linearly reducing the capacity of the separators, whereas the gain in removal efficiency, if there is any, should exceed this effect.

5.1 Solids Removal Efficiency

The capacity of a solids separation device is expressed in terms of flow rate and solid removal efficiency for that particular flow rate, for specific sediment particle size. This is a widely practiced method and is applied in evaluating the performance of multi-stage swirl separator under consideration. Furthermore the effect of other parameters such as inlet velocity, resuspension and underflow rate v/s radial clarification is investigated.

The solids removal efficiency is expressed as the ratio of the volume of sediment particles removed to the volume of sediment particles introduced per volume of suspension. One litre suspension is used in the experiments. Thus,

$$\text{solids removal efficiency} = 1 - \frac{V_{so}}{V_{si}} \times 100\ \%$$

where V_{so} and V_{si} are volumes of effluent solids particles and influent solid particles per litre suspension respectively.

5.1.1 Experiments on Initial Design: Semi-circular Peripheral Weir, $D_2/H_1 = 4$

The first set of experiments were carried out on fine and medium coarse silts of 0.011, 0.016 and 0.02 mm particle sizes. This was done to see the extent of particle sizes which could be removed by multi-stage swirl separator.

The efficiency for the two smaller sediment particle sizes was too small to be recorded. The removal efficiency for the larger particle $\geq$ 0.02 mm is shown in Figure 5.1 on the lower and right side parts of the figure.

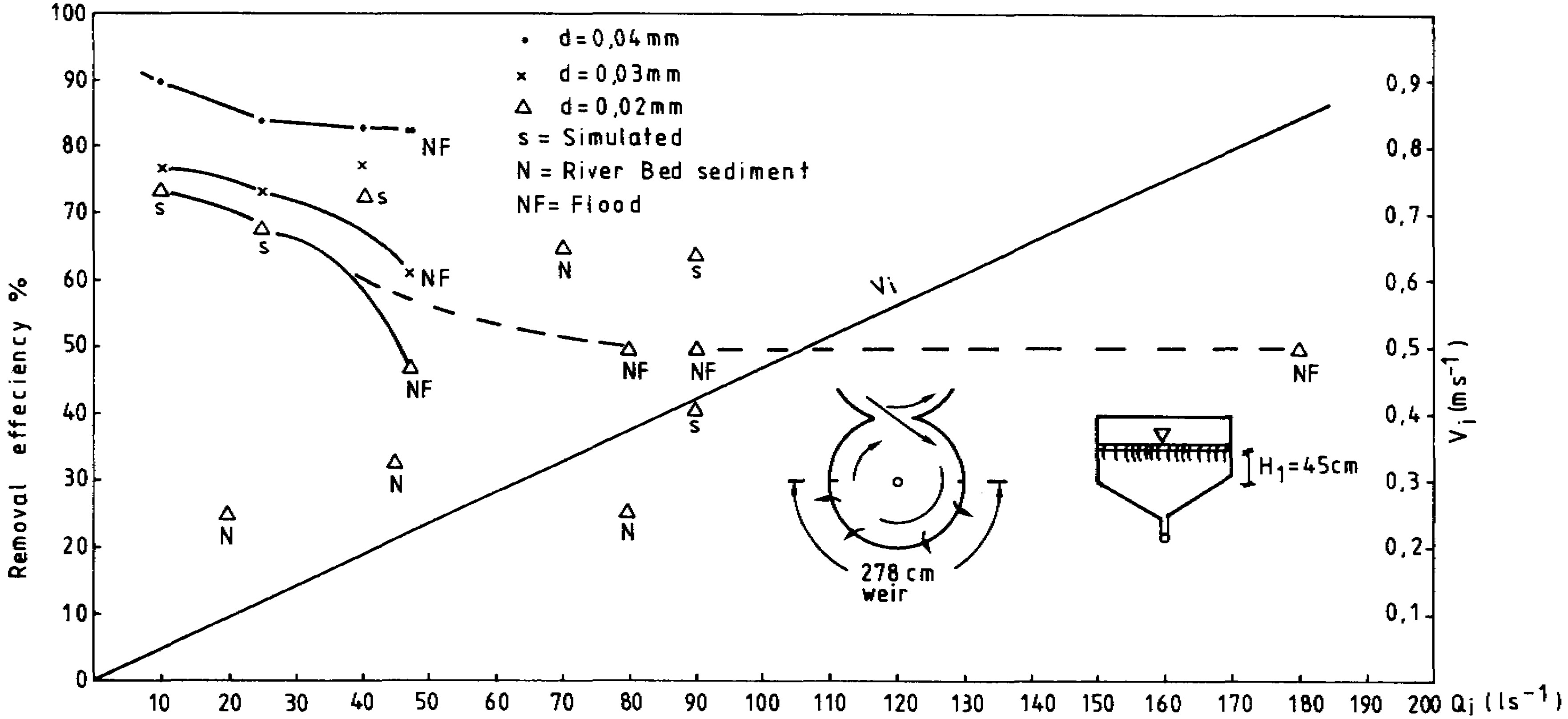


Figure 5.1 Removal efficiency of semi-circular overflow weir, $D_2/H_1 = 4$
weir height = 45 cm
weir width = 2.78 cm

Because of general disagreement between the points, the study was shifted to larger sediment particle sizes, 0.02 mm, 0.03 mm and 0.04 mm, still being in the range of silt. Also it is found necessary to raise the concentration of sediment in the stream, by causing disturbance in the stream or by adding excavated soil. In effect the results on the upper left side of Figure 5.1 is obtained.

Analyzing the overall results, it is possible to match the results of the simulation and flood condition, which are in satisfactory agreement. As stated earlier, the volumetric measurement is unreliable for the lower sediment concentrations and the results of the natural stream condition could be ignored (Figure 5.1).

Using this configuration of the multi-stage swirl separator, it was found that the removal efficiency is high enough for larger sediment particle sizes ($\geq$ 0.02 mm). The removal efficiency was drastically reduced for the smallest particles as the inflow was doubled from 20 ls^{-1} to 40 ls^{-1}, and surprisingly straighten even for the largest possible inflow measured. This shows that for particle sizes in the sand range say $\geq$ 0.06 mm, the efficiency could be approximately higher than 70 % for the largest inflow test, and still the inflow rate could be increased without any significant efficiency loss.

In examining the removal efficiency of the multi-stage swirl separator, the effect of the hydraulic characteristics which could be possibly involved is incorporated. At this instance which need to be mentioned is the effect of turbulent inflow condition which propagated upto the last stage which eventually led to the 2nd set of experiments.

5.1.2 Experiments on Increased Overflow Weir Height; Semi-circular Peripheral Weir, $D_2/H_1 = 3$

The increase in weir height increased the depth of water surface at the inlet channel whereby the turbulency which was caused due to the drop is significantly reduced. At the same time the cross-sectional area of the inlet channel was increased, decreasing the inflow velocity for the same flow rate of the previous experiments.

The test was carried out similarly on particle sizes of 0.02 mm, 0.03 mm and 0.04 mm. The inflow was varied from 20 ls^{-1} to 100 ls^{-1}. Mostly the tests were run under simulated sediment concentration, except when there was sufficient sediment concentration in the natural stream due to flood. The achievement in increasing the overflow weir depth was remarkably higher than the previous test.

The removal efficiency was higher than 85 %, 80 % and 75 % for particle sizes of 0.04 mm, 0.03 mm, and 0.02 mm respectively for an inflow rate upto 60 ls^{-1} (Figure 5.2). Thus it was possible to attain consistent removal efficiency for a wider range of inflow rate.

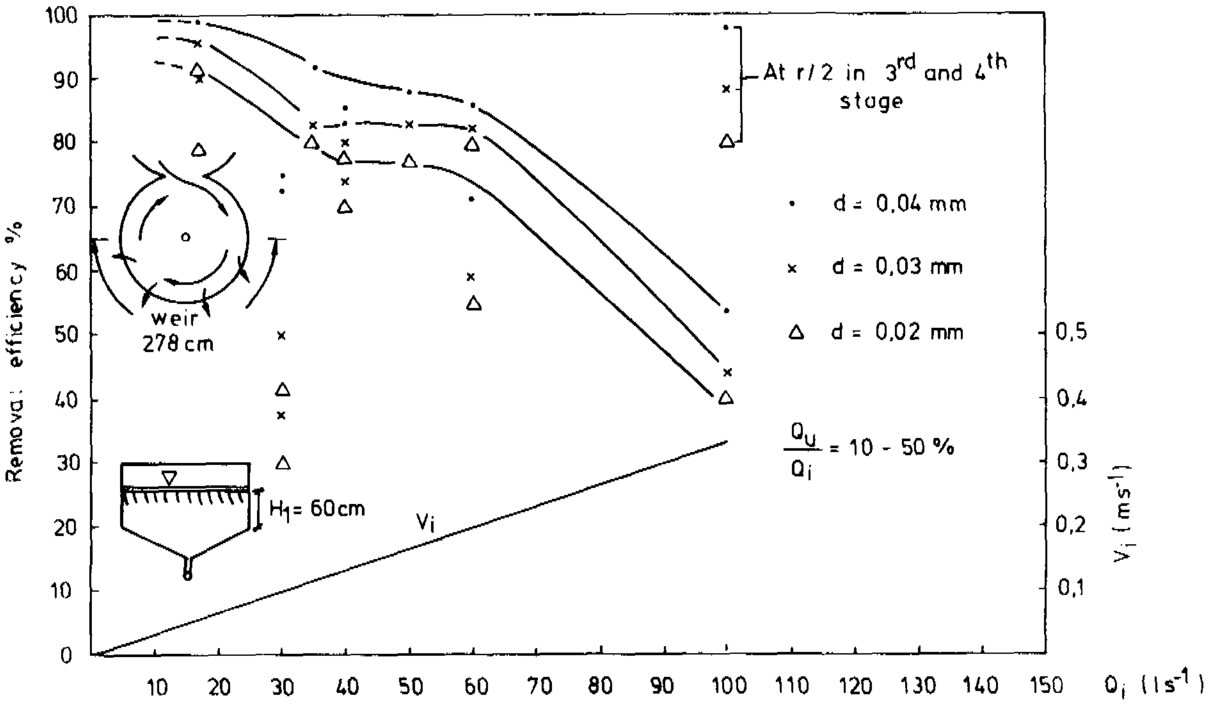


Figure 5.2 Removal efficiency of semi-circular overflow weir;
weir height = 60 cm
weir width = 278 cm
$\frac{D_2}{H_1} = 3$

Here, very interesting questions could be posed. Could the removal efficiency could be attributed to the increase of depth or is it due to the reduction of turbulency at the inlet and decrease of the inlet velocity?

The reduction of removal efficiency due to turbulency in solids separation devices is an established fact. Thus the increase of removal efficiency due to the absence of turbulency though not compeletely is undeniable. The effect of inlet velocity is a reported fact, in the experimental study of the laboratory model of the multi-stage swirl separator (Teizazu 1986; Häkkinen et al, 1987). In this experiment the effect of the reduced inlet velocity, which is either due to the increase of cross-sectional area of the inlet or due to the decrease of inflow rate, is realized. Compare the velocity gradient of Figure 5.1 and Figure 5.2.

APWA (1972) and Sullivan et al (1974 a) reported that there is marginal increase of removal efficiency due to increased depth, which does not justify extra expense for the deeper construction. Similarly Teizazu (1986) observed minimal increase of removal efficiency in the multi-stage swirl separator of laboratory model.

However, on the contrary, it was clearly observed that highly stable hydraulic phenomena was manifested which leads in crediting the increase of depth, higher percentage than the diminished inlet turbulency and reduced inlet velocity. It is not concievable that 50 % increase in inflow rate (compare Figure 5.1 and Figure 5.2) could not be attained simply by avoiding inlet turbulence and decreased inlet velocity. In fact, this is a completely unique device by itself, differing from a single stage. It also has major differences in structural configuration compared to the original design of laboratory model of the multi-stage swirl separator, which needs re-evaluation of all parameters studied in the previous swirl separators.

Considering the above condition in the practical sense, the overflow weir depth is the simplest possible means which provides regulation of turbulence flow and inlet velocity considering the configuration of the multi-stage swirl separator experimented. The jump could be simply avoided which has no significance in the setup of the multi-stage swirl separator. Another way of tackling this problem is that inlet velocity and turbulent flow can be regulated by playing with the dimensions of the aperture of the inlet channel. The depth of the inlet is the same as the depth of the overflow weir, hence it is fixed.

The width of the inlet is the only possibility which gives the flexibility. The width has already been made 0.25 of the diameter of the basin, the largest inlet/basin, width ratio ever to be applied (see 2.3.2).

It is not yet known if the increase of the inlet/basin width ratio has positive or negative effect, and it is clear that the inlet/basin width ratio can not be greater than 0.5. The optimization of the inlet size is only possible upto this ratio.

Since the comparison is focused on the practical situation, the increase in width could incur comparable and higher expense than the increase of the overflow weir depth. This shows that the optimization of the multi-stage swirl separator, in this respect, should encompass the expenditure and the practicality besides the removal efficiency.

5.1.3 Experiments on "Tangential" Overflow Weir, $D_2/H_1 = 4$

Teizazu (1986) suggested the possibility of using a tangential overflow weir. On the other hand later Mashauri (1986) after experimenting on a single stage swirl separator, preferably suggested a semi-circular overflow weir. This shows a tendency of shifting from one possibility to the other, and previous investigations should not shun the re-evaluation of all possibilities.

The main factor, in this experiment is its applicability rather than the suggestions. A separator with many possible configurations and flexibility with optimum capacity is the paramount goal to be reached.

The test was carried out, not on a multi-stage swirl separator with tangential outlet channel or conduit, but on a multi-stage swirl separator with a reduced peripheral overflow weir which closely simulates the tangential outlet condition. The overflow weir size was reduced from 278 cm to 78 cm. This constructional possibility was attained by increasing the overflow weir depth (Figure 5.3).

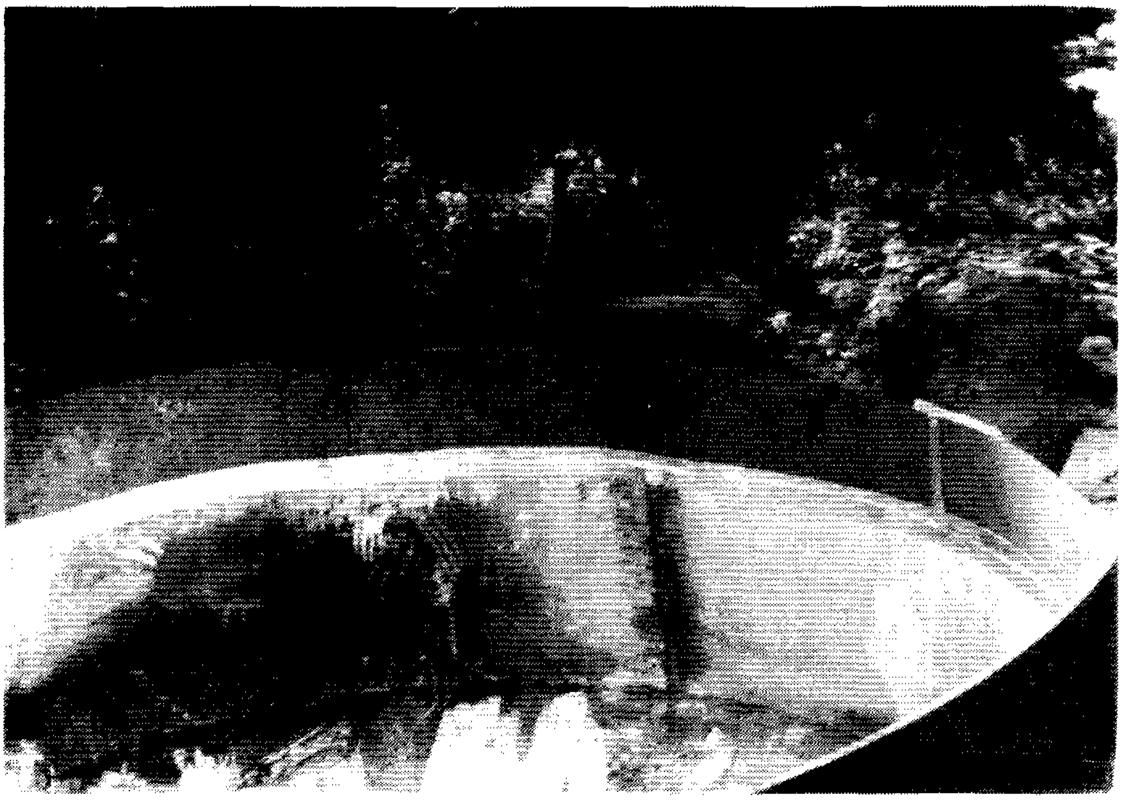


Figure 5.3 Simulation of "tangential" overflow.

Even though only few tests were carried out, the results give good indication for the behaviour of tangential overflow due to the increased inflow rate. Figure 5.4 shows that at lower inflow rate, higher removal efficiency, similar to the increased depth (Figure 5.2), for all particle sizes was achieved. This effect could be attributed to the location of the overflow weir, whereby sufficient length is provided for sediment particles to settle after entering the last stage.

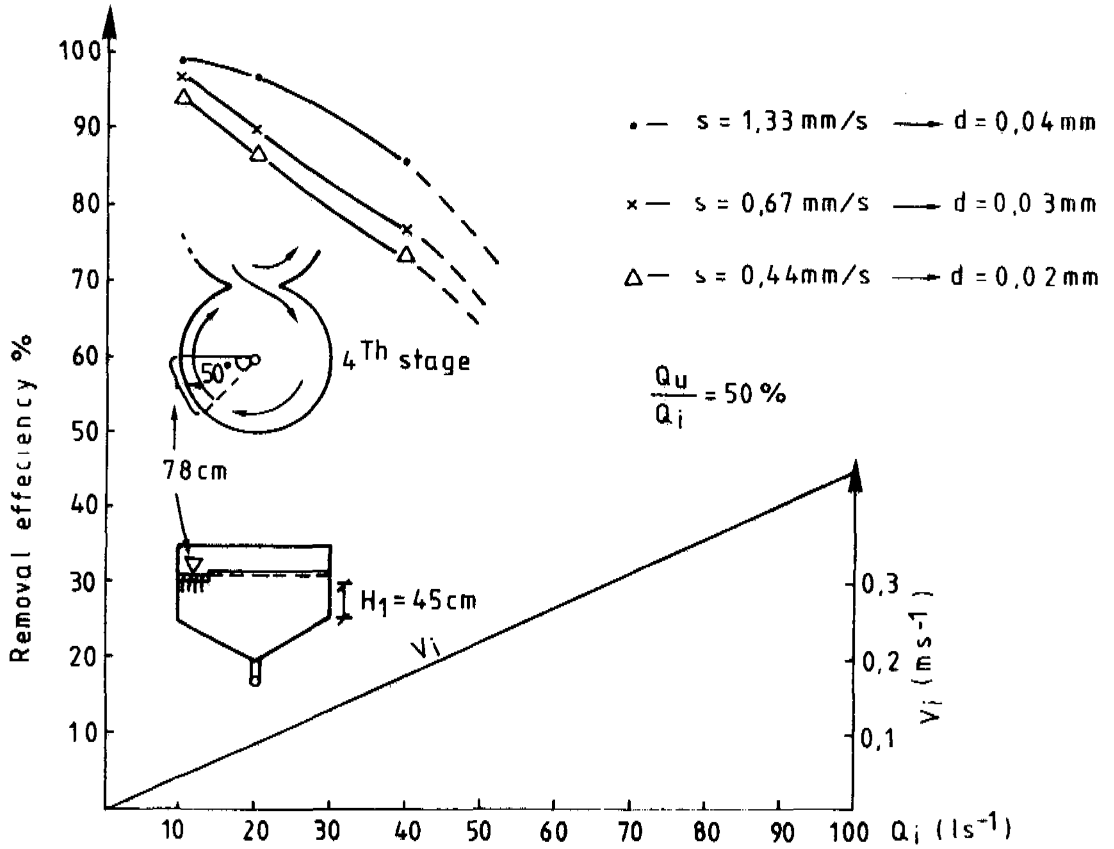


Figure 5.4 Removal efficiency of "tangential" overflow weir;
weir height = 45
weir width = 78 cm
$\frac{D_2}{H_1} = 4$

For small increase in inflow rate (which corresponds to overflow rate if underflow rate is held constant) the gain is immediately lost, with steep decrease of removal efficiency. As the flow rate increases, it could be extrapolated from the graph, the curve could assume steep gradient with a fast reduction of removal efficiency.

The cause for this phenomena is most likely the overflow velocity. The size of the overflow weir is reduced to 0.28 of the semi-circular overflow weir proportionally increasing the overflow velocity. It has resuspending effect on the settling particles and possibly of the settled particles as the depth of the basin is comparatively small. This possibility is also investigated in other direction as will be shown later.

Notwithstanding, the discouraging effect of the application of tangential overflow from this experiment, it is possible to optimize the tangential overflow for a particular situation by increasing the width of the overflow channel or conduit.

5.2 Turbidity Removal Efficiency

For a particular circumstances an empirical correlation between suspended solid concentration and turbidity can be established as shown in Figure 5.5 (Yao, 1975). Schulz and Okun (1984) noted also the turbidity removals are very much a function of particulate size distribution.

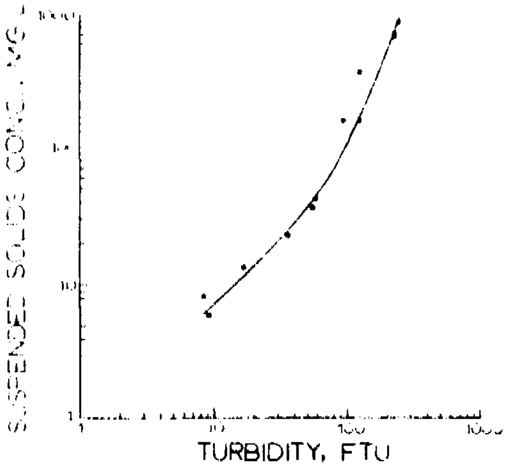


Figure 5.5 Turbidity versus suspended solids concentration (Yao, 1975).

In this study, similarly to see the order of magnitude of correlation between the two parameters and evaluate the performance of the multi-stage swirl separator on site, turbidity measurement was taken using portable HACH turbidity measurement instrument, simultaneously with the volumetric measurement of suspended solids.

As a result definite correlation could not be established and the turbidity removal efficiency was found to be very small as low as 5 % and increases with the increase of turbidity in the influent with no definite relationship with inflow rate and solids removal efficiency.

The cause for such poor result could be enumerated as follows:

1. The range of turbidity measurement taken was small, and even there was a considerable increase due to simulation, it was found that higher percentage of turbidity was caused of colloidal particles rather than suspended solids. Even for the highest solids removal efficiency there was no appreciable turbidity removal.

2. With the volumetric measurement it was not easy to formulate correlation of the two parameters. Total suspended solids measurement would have given better result.

3. The accuracy of turbidity measurement was not satisfactory, mainly due to the dilution water which

contain turbidity of 1.1 NTU, whereas the requirement is turbidity free which was not locally available. the process of dilution contributed also to the inaccuracy in the turbidity measurement.

4. Eventhough the sample for turbidity measurement and volumetric measurement are taken in a short time interval, there could be higher difference as the solids removal efficiency is time dependent as noted by APWA (1972).

Ultimately, it appears that there is a tendency of increasing turbidity removal efficiency with increasing turbidity in the influent, that is with turbidity greater than 200 NTU.

Since the results of turbidity measurements are inconclusive for all cases, further discussion concerning turbidity is avoided.

5.3 Evaluation of Other Hydraulic Characteristics of Multi-stage Swirl Separator

5.3.1 Resuspension Due to Overflow Velocity

The effect of overflow velocity was examined indirectly by measuring surface water volumetric concentration of solids in each stage at the connection chords and overflow weir. The result is shown for different inflow rate for each stage in Figure 5.6.

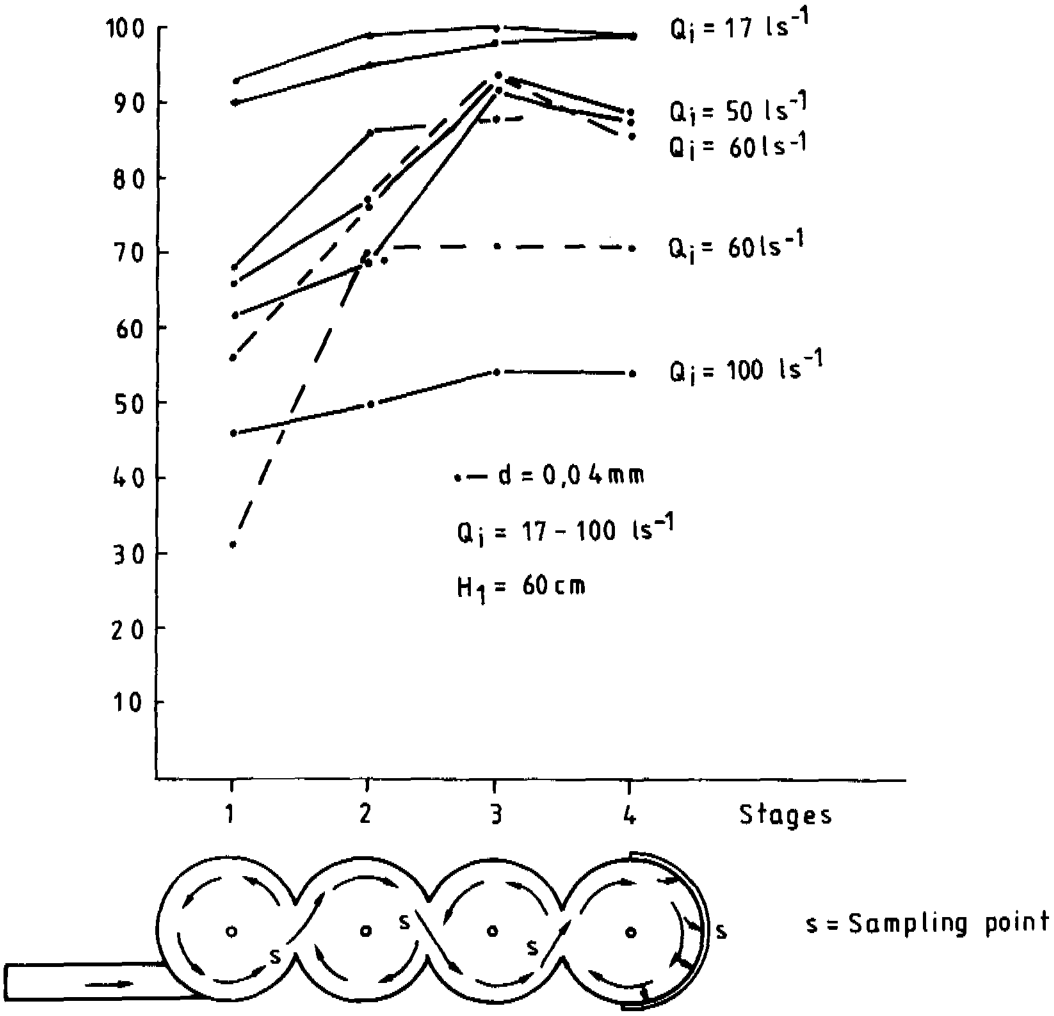


Figure 5.6 Effect of resuspension at the overflow weir.

Even though the solids removal efficiency is plotted for each stage, it does not show the actual solids removal efficiency of each stage, which have been studied in the previous research (Teizazu, 1986; Häkkinen et al, 1987).

Actually from Figure 5.6, it is likely one may conclude that for higher solids removal efficiency the multiplication of the stages above two is not required. It could be crucial and contraversial question, whether the increase and reduction of the number of stages could result in appreciable solids removal efficiency with economical and practical consideration.

While this remains unanswered question, in this investigation, the effect of another parameter of vital consideration is discernable. By investigating the solids removal efficiency of the third and fourth stages one can directly attribute the effect of the same or reduced solids removal efficiency in the two last consecutive stages to the overflow velocity. Due to the effect of relatively small depth, the overflow velocity could easily resuspend solid particles which are settling as well as the settled ones.

It is worth noting that this experiment was carried out with increased depth, in which the effect of overflow velocity is still unavoidable. This finding also supports the requirement of increased depth which could possibly reduce the effect of overflow velocity. Similarly it strengthens the conclusion in the third experiment with tangential overflow.

5.3.2 Radial Clarification in the 3rd and 4th Stage

In the course of events of experimental test runs initially it was observed visually that there exists a relatively clarified annular zone in the 3rd and 4th stage. Preliminary tests showed this annular zone was unbelievably sediment free zone, which led to the investigation of optimum condition which yields sediment free zone and the possibility of abstracting water from this zone.

Since the phenomena in the 3rd and 4th stage in the annular zone was similar the annular zone of 4th stage was experimented and samples randomly were taken from the 3rd stage to cross check the correspondence of the situation. It was found that the clarification and location of annular zone is dependent on the underflow rate in the stage in concern.

Because of limitation of time this test was carried out simultaneously with other experiments mainly with the 1st experiments and it was not possible to establish definite relationship between the clarification efficiency and the underflow rate.

But from the experiments a generalizing relationship is drawn as shown in Figure 5.7 (see also on the right upper side of Figure 5.2)

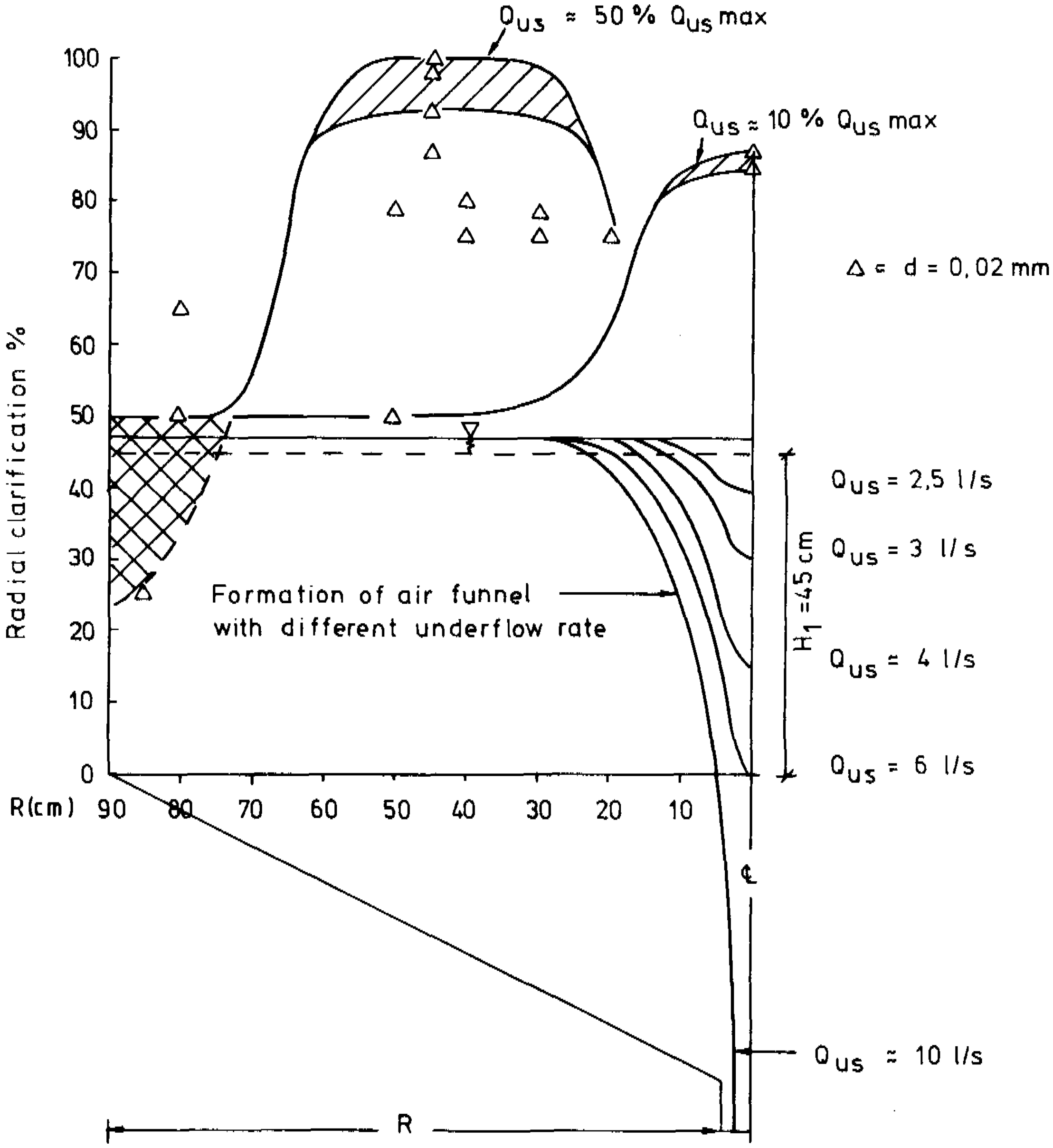
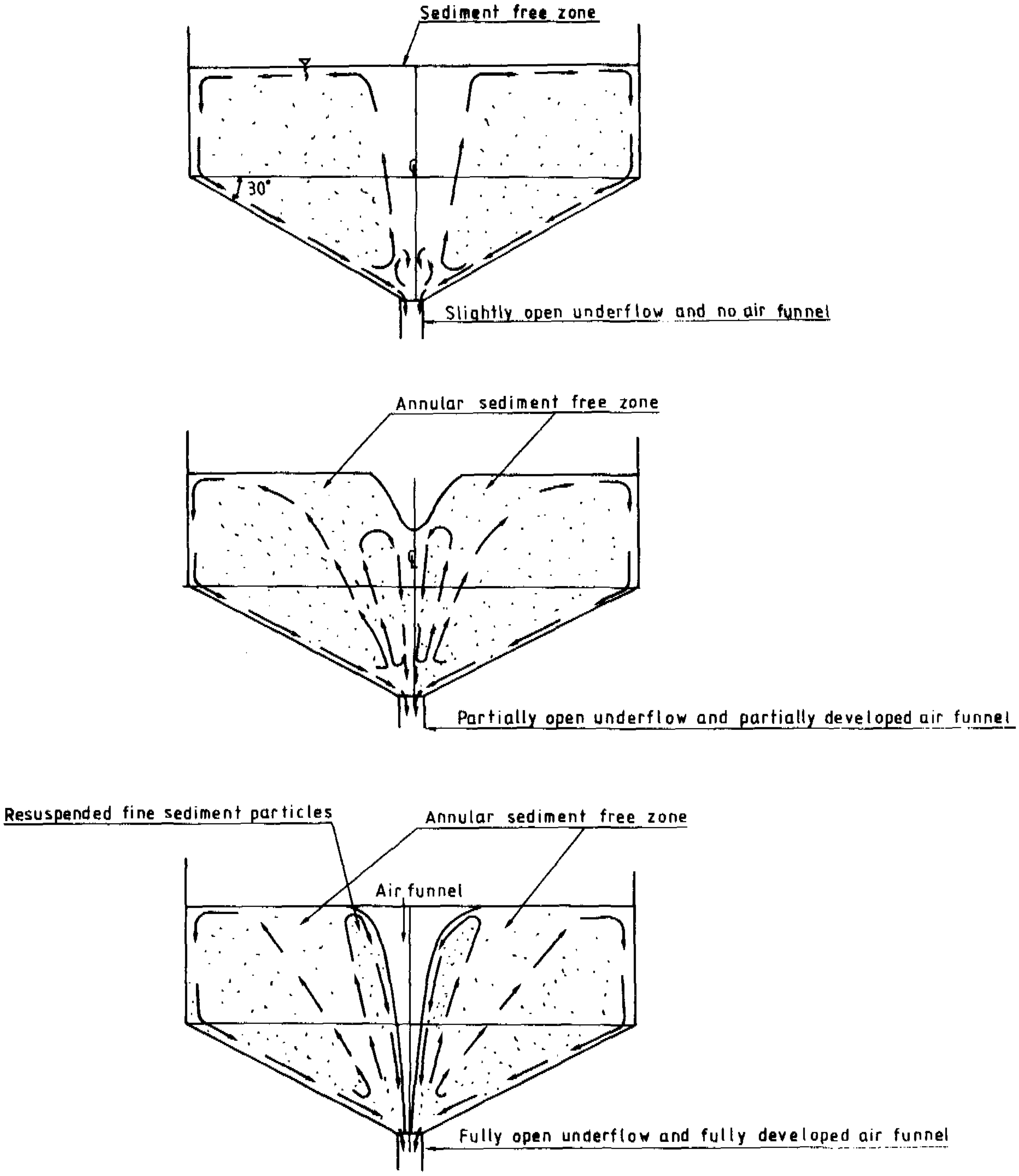


Figure 5.7 Effect of underflow rate on radial clarification in stage 3 and 4; semi-circular weir H_1 = 45 cm $Q_i = 20 - 90\ ls^{-1}$

With small underflow rates the clarified zone formed a circular zone in the center of the basin having sufficiently higher solids removal efficiency than the effluent. As the underflow rate was increased the clarified zone spread out and formed annular zone with larger surface area depending on the intensity of the underflow rate. The clarification efficiency increased to a maximum point as the underflow rate increased, and fell back as the underflow reached its full capacity. It appears there is an optimum underflow rate which yields surprizingly clarified zone with almost sediment free zone for a very wide range of inflow rate. At present situation, examining the results the optimum condition could be attained when 50 % of the maximum underflow rate is used in the stages (3rd or 4th stage).

The decrease in clarification of the annular zone as the underflow increased over the optimum value was due to the resuspension of settled fine solid particles due higher upflow and downflow at the center of the basin as depicted in Figure 5.8



Observed flow condition and sediment concentration in the 3rd and 4th stage.

Figure 5.8 Cross-sectional flow characteristics and sediment resuspension.

Another interesting phenomenon was, in addition to the increase or decrease in clarification intensity in the annular zone, that there was no change on the removal efficiency of the effluent. This could be due to the resuspension at the overflow weir or there was no crossflow between the clarified zone and the outer peripheral zone, and if there is, it could be of negligible magnitude. The highly steep gradient of solid removal efficiency (Figure 5.7) between the two zones justifies this assumption.

This implies also that the clarified zone was a dead zone or the clarified water from the annular zone was sacrificed as underflow. Visual observations and experimental data stand against the first assumption that the clarified zone was a dead zone and support the second assumption, which brings into light the possibilities of abstracting highly clarified water from the 3rd and 4th stage.

This phenomenon could be related to the hydraulic characteristics prevailing in the basin. The clarified zone lies at the intersection of forced vortex and free vortex where tangential velocity is minimum (Figure 3.2) and shifts to the center as the effect of free vortex diminishes due to the reduction of underflow rate. The manifestation of the clarified zone in the 3rd and 4th stage is attributable to stability of flow attained, which otherwise easily affected by the kinetic energy of the influent which is observed in the 1st and 2nd stage.

From the findings it appears that the prevalence of free vortex in swirl separator can be used to achieve higher efficiency, which is contrary to the previous suggestions that free vortex has insignificant effect in removal efficiency (APWA, 1972).

Further research is needed to justify the possibility of abstracting water from the clarified zone. All configurations of central overflow weir should be tested, to identify the type and size of the central overflow weir, which yields optimum clarification without disturbing the stable condition observed in this study. To suggest few, the type of weirs used in Figure 2.7 and 2.10, bell mouthed weirs (although discouraged by Smisson, (1967)) are the possibilities. Siphonage could be another alternative.

The future study should also focus on the utilization of the clarified zone of the 3rd stage simultaneously with the 4th stage; thereby reducing the load on the weirs which could possibly show higher removal efficiency with larger effluent. This suggestion favours also the possibility of increasing the number of stages to optimize the application of swirl flow in solids separation (Figure 5.9).

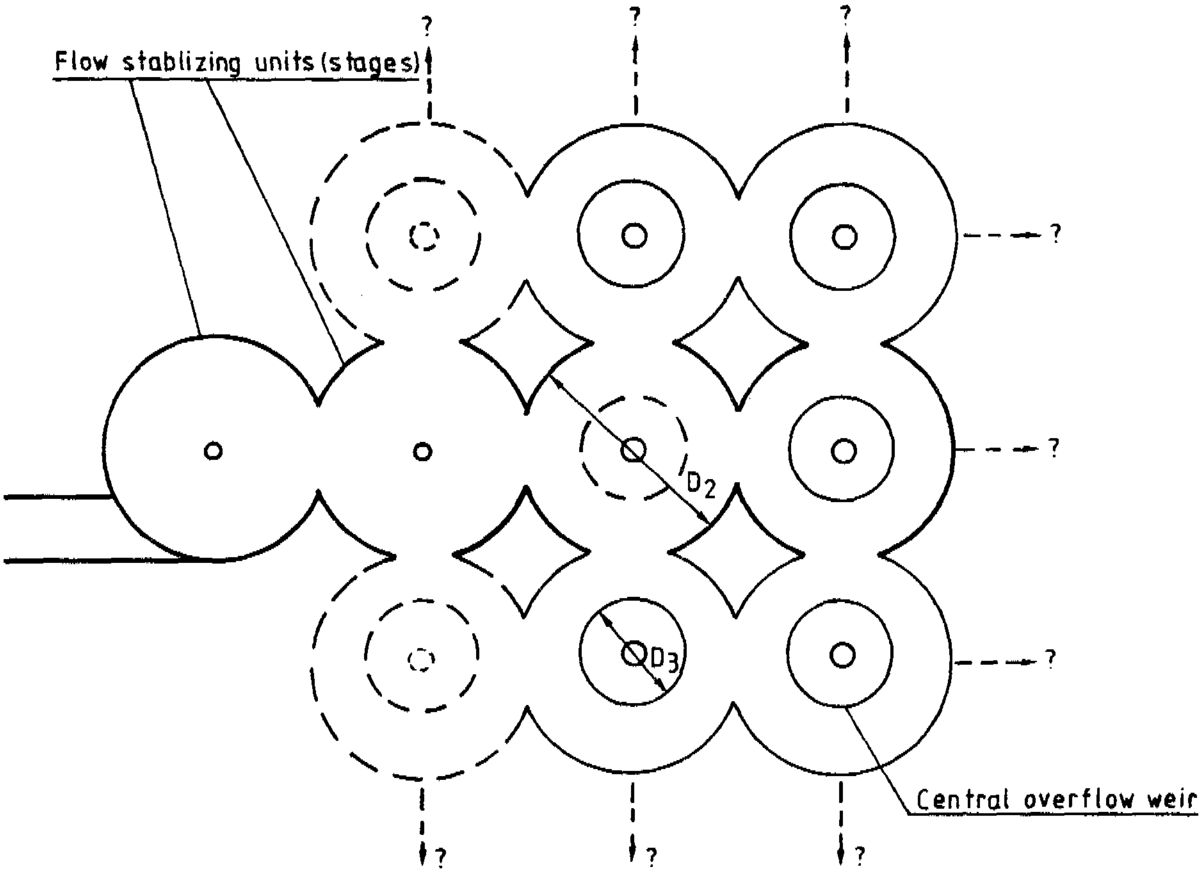


Figure 5.9 Optimizing the possible configuration of multi-stage swirl separator.
What is the optimum configuration, which is economical and practical?
$D_2 > 2D_3$?
What is the optimum ratio?

With this type of multi-stage swirl separator, the effect of inertial separation is expected to be as important as gravity separation, which requires due consideration in analyzing the solids separation process. Besides as reported by Alquier (1982) the critical velocity which resuspend the settled particles needs due attention and be considered in the analysis of solids separation.

5.4 Comments on Some Structural Aspects in Relation with the Removal Efficiency

5.4.1 Connection Chords

The width of connection chords between two consecutive stage was reduced from 79 cm to 60 cm. As the original angle substended by the connection chord is a random intuitive figure, the effect of constructional angle could not be realized. However, from visual observation it seems that the size of the connection chord could possibly affect the radial clarification. When central overflow weir is used these may require attention to get optimum effect.

5.4.2 Floor Slope

In the present experiment the effect of floor slope on the removal efficiency could not be recognized. However with the present configuration with 30 inclination to horizontal structurally it has big effect. That is the depth required for the sloping section is equal to the settling water depth. Therefore the total depth was 0.5 D_2. As the diameter increases it incurs more expenditure than smaller slope and larger depth requirement in some circumstances may hinder the realization of multi-stage swirl separator. Therefore it could be suggested smaller slope can be applied without affecting the drainage system.

5.4.3 Inner Rough Surfaces

The removal efficiency achieved should be weighed in the working of the multi-stage swirl separator, which brings the recognition of the affect of rough surfaces. Although the effect could not be measured, it is likely that it had to some extent a reducing effect on the removal efficiency.

5.5 Visual Observations

5.5.1 Flow Characteristics in the Multi-stage Swirl Separator

The complexity of flow phenomena in the multi-stage swirl separator duplicates with the number of stages. However a generalizing description of flow condition could be given.

In the multi-stage swirl separator the flow is predominantly forced vortex flow when the underflow rate is small and when the surface water level is the same throughout the cross section of the stages. As the underflow rate is increased the water level at the center of the basin drops with a concave shape and gradually the air funnel shows up when the underflow is fully opened. Under such condition the free vortex fully develops in the central annulus region, while forced vortex prevails on the outer section. This is similar to the flow condition shown in Figure 3.2.

It is possible to have various configuration of underflow rates from each stage having several types of flow condition in each stages (Figure 5.10 and 5.11).

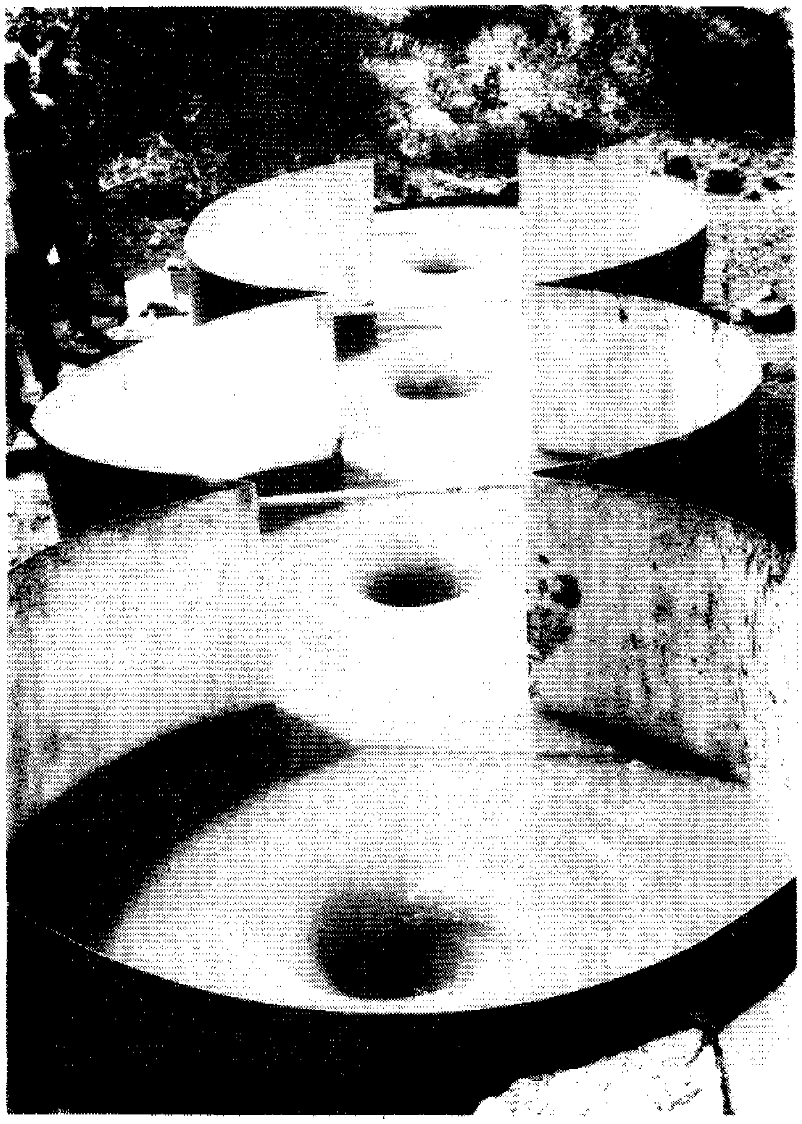


Figure 5.10 Flow condition with full underflow opening in all stages.

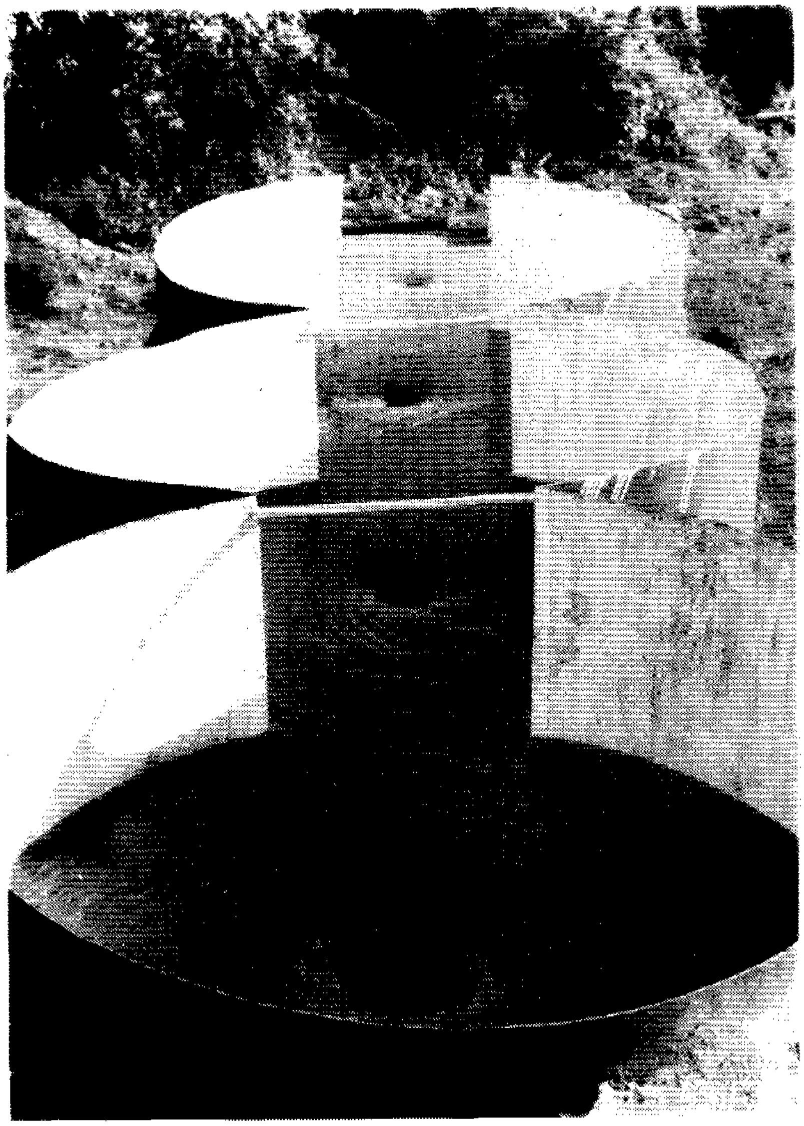


Figure 5.11 Flow condition with successively reduced underflow rate.

It was noticed that the intensity of air-funnel formation (free vortex flow) in a stage has a cross effect on the adjacent stage. That is to say when the underflow rate increased or decreased in a stage, it was possible to see simultaneously the change in the adjacent stage.

With increased depth, it could be easily felt that stable hydraulic condition was attained. The surface wave which was formed due to cross-current and propagation of turbulency at the inlet was considerably reduced maintaining high inflow and/or underflow rate (compare Figure 5.12 and 5.13). Even with highest underflow rate the formation of surface wave was small with larger depth.

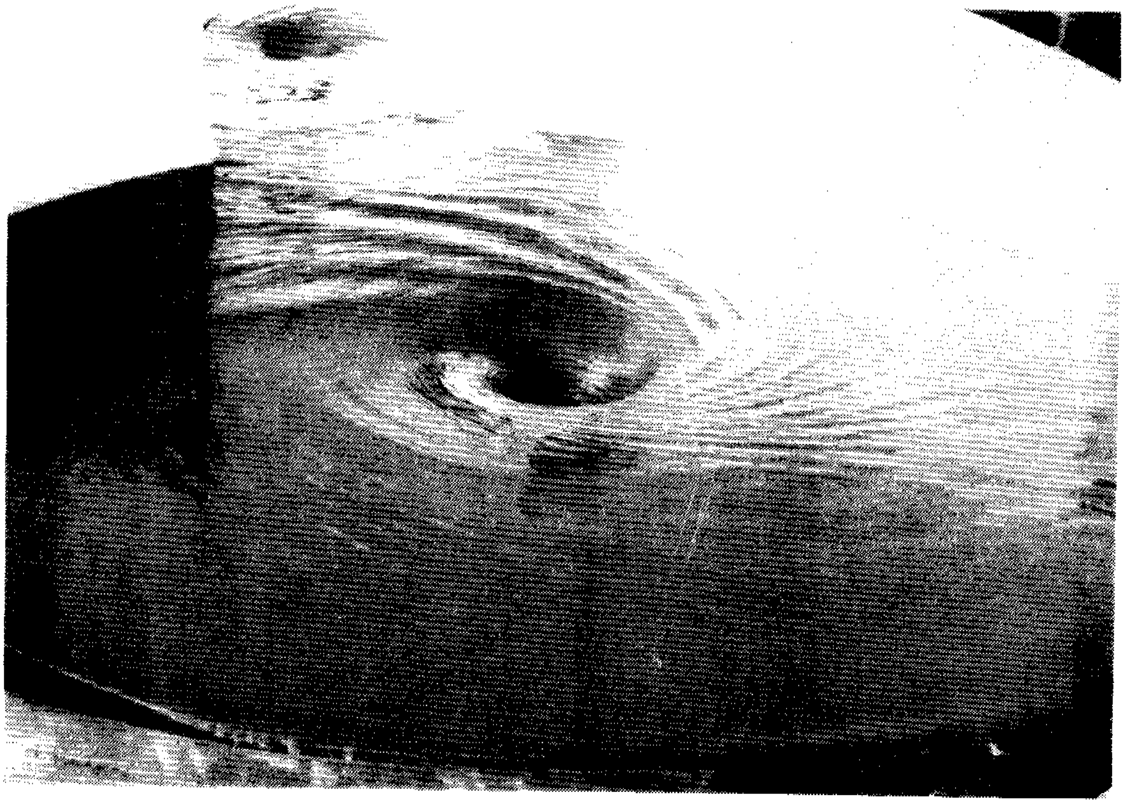


Figure 5.12 Surface wave in the 4th stage H_1 = 0.45.

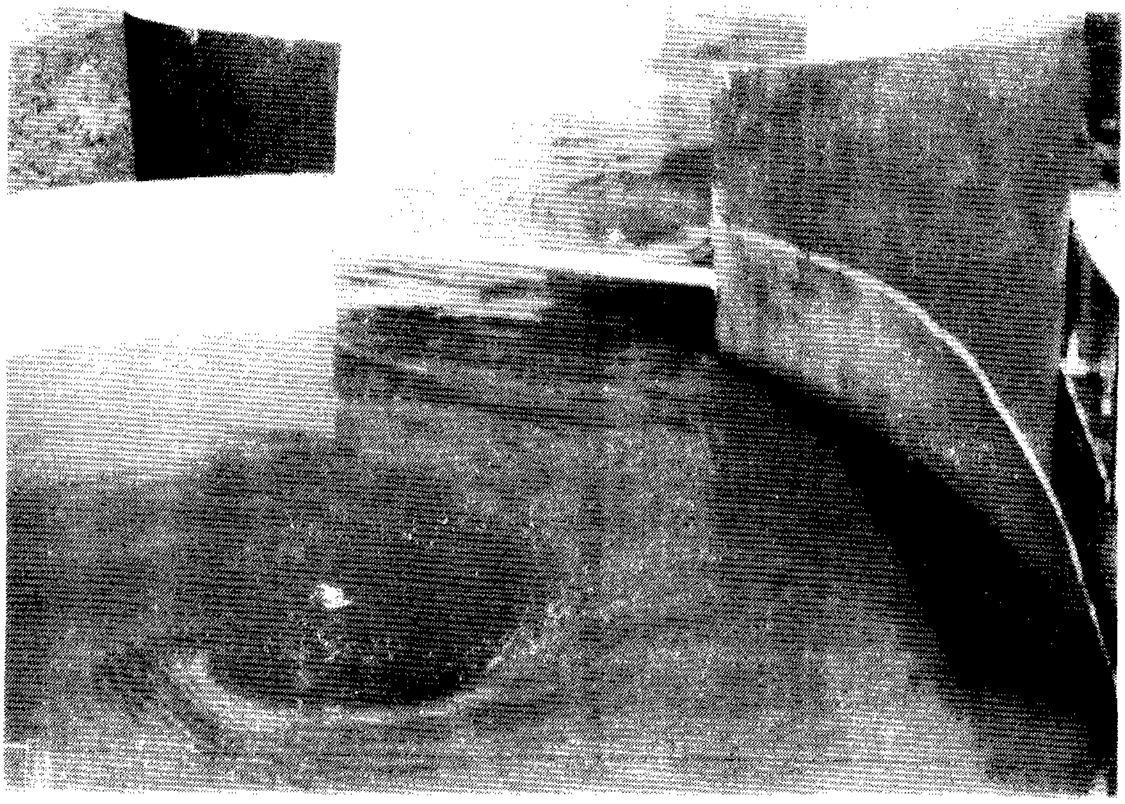


Figure 5.13 Surface wave in the 4th stage H_1 = 0.60 m.

By looking at the surface flow condition it is possible to infer the removal efficiency of the separator. With non-existence of surface wave in the 4th stage it is most likely to get higher removal efficiency (Figure 5.14 and 5.15).

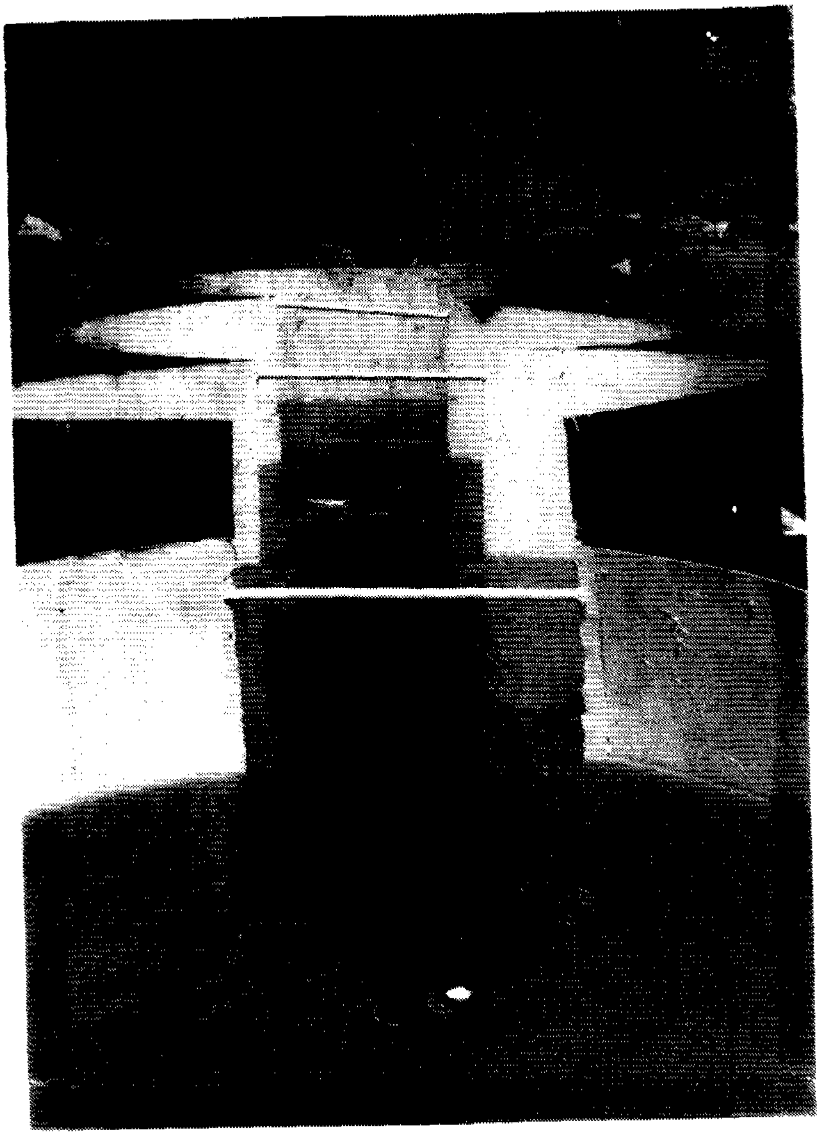
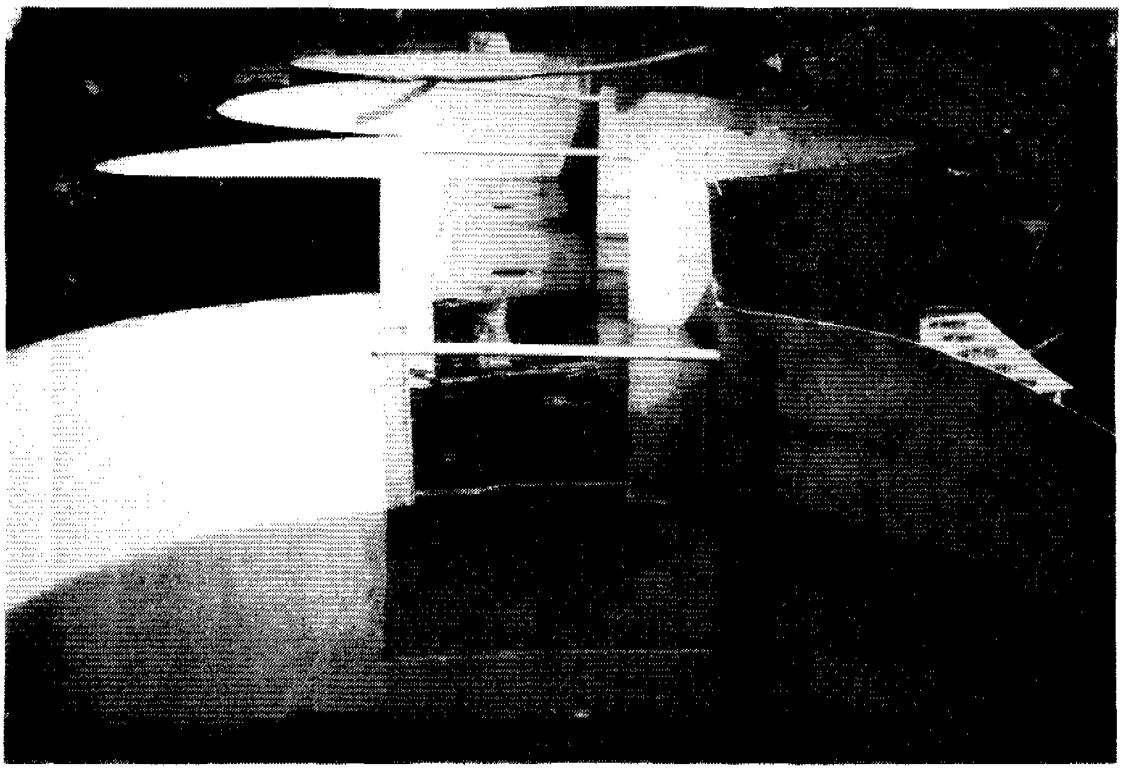
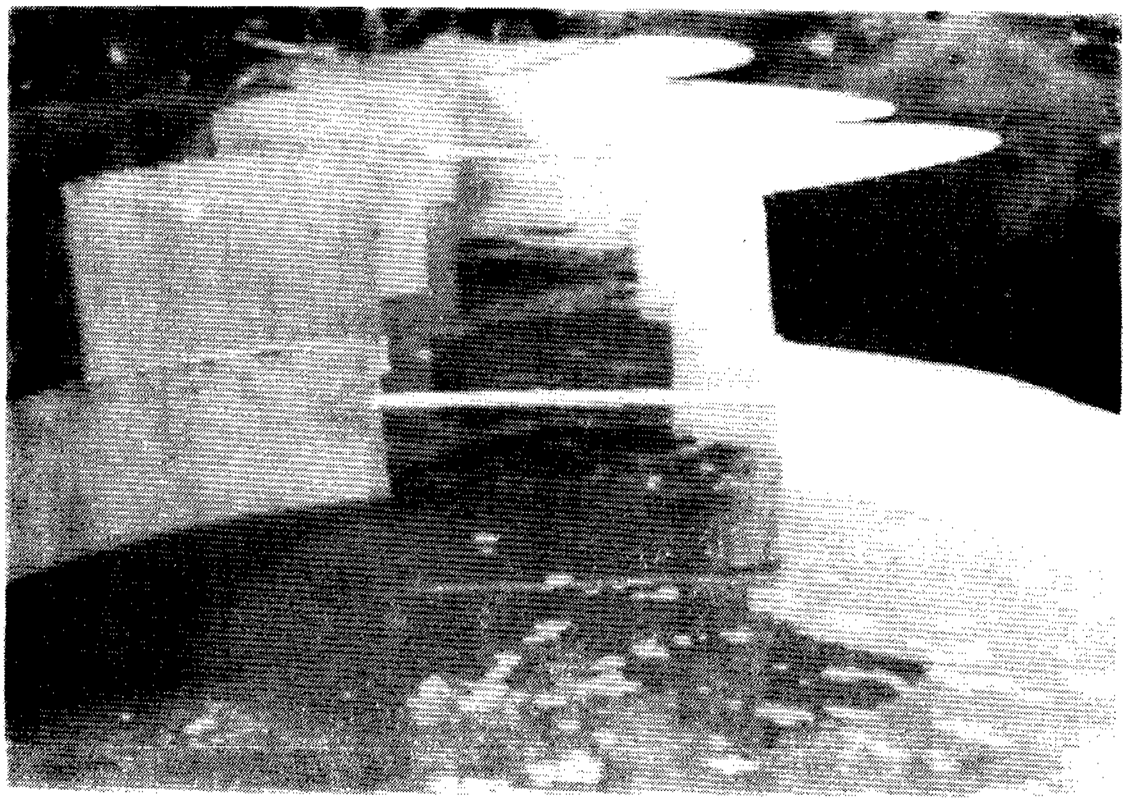


Figure 5.14 Surface wave formation indicating lesser solid removal efficiency $H_1 = 0.45$ m.



a) tangential overflow, H_1 = 0.45 m.



b) semi-circular peripheral overflow weir H_1 = 0.60 m.

Figure 5.15 Non-existence of surface wave indicating higher solids removal efficiency.

5.5.2 Settling Behaviour of Solid Particles in The Imhoff Cones Used for Volumetric Measurement

Within the time intervals selected, it was possible to recognize the settling behaviour of the solid particles and relate with the calculated result (the sediment particle sizes).

In the time interval of 5 min in all tests without exception, the particles settled discretely and holding the bottom of the cone compactedly. In the time interval of 5 min to 10 min in most cases the particles settled discretely and coalescing with each other. After 10 min the particles settled completely coalescing with each other. The particles settled after 5 min formed a sludge with very high percentages of water. These observations simply describe the behaviour of silt which is in agreement with the calculated values.

In comparing the volume of settled particles of influent and effluent water, it was observed that particle sizes $\leq$ 0.04 mm were not separated with the overflow weir height, H_1 = 0.45 m and were partly removed with the overflow weir height H_1 = 0.60 when the removal efficiency was approximately greater than 90 % for all sediment particle sizes studied.

But in the clarified annular zone, it was noticed that 100 % removal efficiency (Figure 5.7) could be attained for particle sizes $\geq$ 0.02 mm. It is also measured that there was a considerable reduction of turbidity in this zone.

5.6 Economical Comparison of the Multi-stage with Single Stage Swirl Separator

Presently it is not simple to make cost comparison of the two devices. The cost estimate of the multi-stage swirl separator is given in Appendix C. The investment during construction was in the same range without including the labour and transport cost provided by WSSA. If locally available construction material, such as brick, hollow block or masonry was used instead of steel structure, it is most likely about 50 % saving would have been possible. This is not sufficient to make a basis for cost comparisons.

Instead of cost comparison, single constructional comparison is made which sufficiently show the economical gain of the multi-stage swirl separator with its present configuration.

In constructing the two types of separator, the investment on the floor, wall and 'roof' comprises a higher percentage of the overall investment and at the same time these parts contribute highly for the differences in the investment.

In the present comparison, even though there are differences in inlet, outlet, underflow they are not included. The effect of connection chords is not included to simplify the calculation and with the present configuration it can be shown that their effect in negligible.

The total area required for 'flat' floor, and roof and wall for single stage swirl separator is

$$A_{ss} = (1 + 2x)D^2{}_{2ss}/2$$

and for multi-stage swirl separator

$$A_{ms} = (1 + 2x)D^2{}_{2ms}/2 \times S$$

whereas

A_{ss} = $A_{floor} + A_{roof} + A_{wall}$ of single stage swirl separator

a_{ms} = $A_{floor} + A_{roof} + A_{wall}$ of multi-stage swirl separator

x = the ratio of $H_1/D_2 = 0.25$

D_{2ss} = diameter of the single stage swirl separator

D_{2ms} = diameter of the multi-stage swirl separator

S = number of stages

Therefore, the multi-stage swirl separator is economically feasible when it is possible to show

$$\frac{A_{ms}}{A_{ss}} < 1$$

for the same flow rate and efficiency.

From this relationship for the multi-stage swirl separator (4 stages)

$$\frac{D_{2ms}}{D_{2ss}} < 0.5$$

as shown in Figure 5.16. It is shown also that as the number of stages increased

$$\frac{D_{2ms}}{D_{2ss}}$$

decreases to be economically feasible. The attitude of increasing the number of stages should give also attention to this requirement, even though it is a simplified approach.

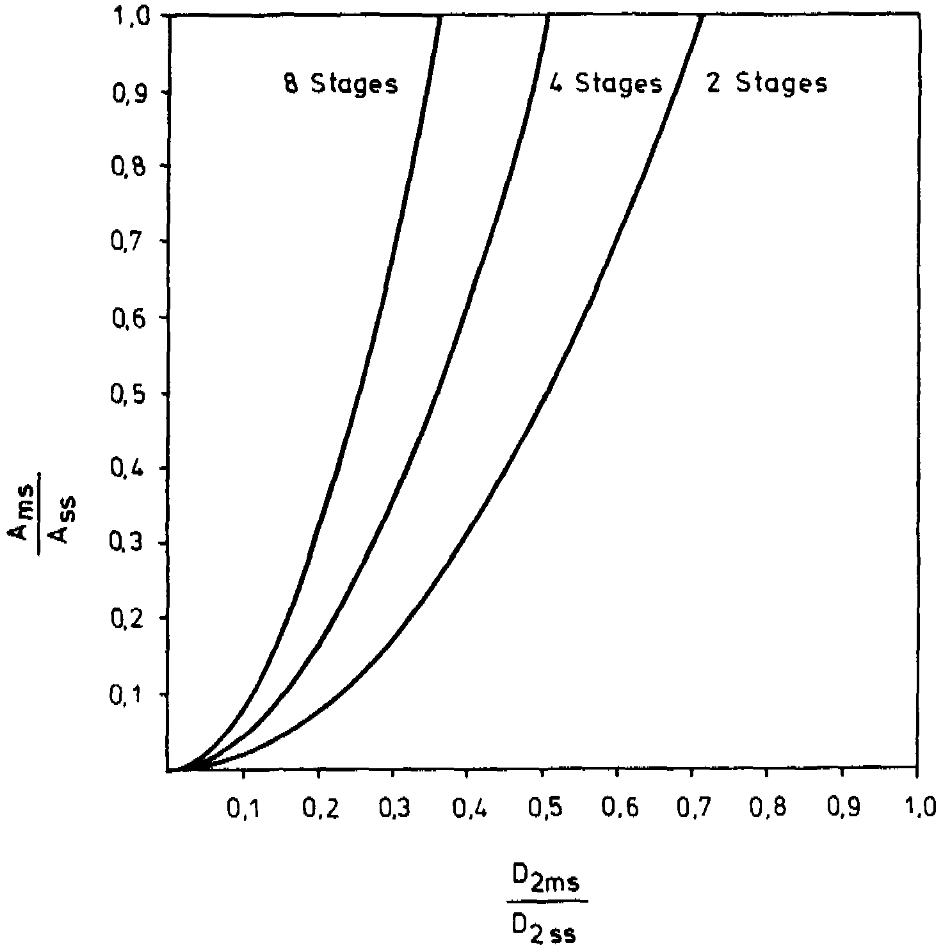


Figure 5.16 Comparison of constructional area of multi-stage with single-stage swirl separator.

Coming back to this experimental device it is shown that using the design approach of single stage swirl separator, higher removal efficiency could be attained using the multi-stage swirl separator. Confidently with the present dimension of the multi-stage swirl separator, it could be stated, approximately 100 % removal efficiency for sediment particle size 0.04 mm can be reached with a flow rate of 20 l/s. Ideally the surface area required to remove particle size ≥ 0.04 mm and with a settling velocity ≥ 1.3 mm/s is about 15 m^2 whereas the surface area of the multi-stage swirl separator is about 10 m^2, 1.5 times higher than ideal settling tank. For instance if we consider Salakhov's equation (Appendix A) 1.6 times larger area is required than ideal tank, similarly using other design approaches still larger area will be required.

Hence, without hesitation, it could imply

$$\frac{D_{2ms}}{D_{2ss}}$$

is much smaller than 0.5, and the multi-stage swirl separator is economically more feasible than the single-stage swirl separator.

6 CONCLUSION

The multi-stage swirl separator was proved to be a gravity rotational separator which effectively utilizes the swirl motion induced by the kinetic energy of flow.

It was verified that it can remove completely all particle sizes greater than 0.02 mm. It could be used also to separate all suspended particles if the water in the clarified zone in 3rd and 4th stages could be abstracted without affecting the hydraulic characteristics observed.

The open channel inlet is more preferable than a closed conduit. The open channel inlet feeds the inflow with less turbulence and smaller velocity.

The weir height has shown significant effects on the removal efficiency and the capacity of the separator. As a guide, basin diameter/weir height ratio D_2/H_1 = 3 rather than 4 can be suggested. Nevertheless the optimization of D_2/H_1 ratio is required as it affects the construction cost and the performance of the separator.

A semi-circular peripheral weir was found to be more effective than tangential outlet.A central overflow weir could be more efficient if the clarified zone could be intercepted. However, the selection depends on the application of the multi-stage swirl separator, the solid removal efficiency required and the location of the site.

For practical purposes, the underflow discharge is recommended to be less than 10 % of the inflow rate. It was found that conforming to this requirement resulted in clogging of the underflow pipes mainly the underflow pipe of the first stage. This was related to the capacity of the separator and the underflow pipes. The type of valves also contributed to this difficulty. It is shown that the capacity of the separator was underestimated. By augmenting the separator's capacity it is possible to have underflow discharge less than 10 % of the inflow whereas the underflow pipes discharge fully opened. This could also possibly avoid the need of valves for practical situation. The size of the underflow pipes requires consideration. The dimensional relationship of the underflow pipes with other dimensions of the separator should be established. Mashauri's (1986) suggestion could be applied. That is D_2/D_u = 30 - 40; preferably the highest value could be used. In conjunction the effect of the floor slope and the length of the vertical pipe of underflow should be realized.

The applicability of the multi-stage swirl separator as a part of the intake structure to exclude deleterious sediment particles was unquestionably verified. It is comparatively small and compact. It is completely free of mechanical equipment. It has constructional flexibility. It has a continuous desludging mechanism requiring less attendance.

In addition to the above-mentioned inherent practical aspects, the ability of the multi-stage swirl separator to remove finer sediment particles could make it competitive with other solids separation devices in various water and wastewater treatment processes.

However, design procedure is lacking which hampers the application of the multi-stage swirl separator. It is possible on the basis of this experience to use conservatively the design procedures of the single-stage swirl separator. That means the diameter of the multi-stage swirl separator (4 stages) could be taken 25 - 50 % of the calculated single-stage separator.

This could not be taken for granted. It is proven that the multi-stage swirl separator has its own unique characteristics, which require optimization of the overall configuration of the separator.

This study has shed light on the perspective in optimizing the multi-stage swirl separator. It was possible to observe the effect of the free vortex in forming the clarified zone the highest removal efficiency attainable by the multi-stage swirl separator.

Therefore future study should focus on the possibilities of abstracting water from the clarified zone in the third and fourth stages using the same number of stages (4 stages). This could pave the way in using cells of stages (Figure 5.9). The re-evaluation of the dimensional relationship, particularly, the ratio of the width of the basin to the weir height is of paramount importance. Simultaneously the development of design procedures and nomographs is essential.

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APPENDIX A

Design equations and nomograph used in the preliminary design of the multi-stage swirl separator.

a) Salakhov's equation

$$D_2 = 1.41 \left(\frac{Q_i}{w_s} \right)^{0.5} \qquad \text{(A.1)}$$

where as

D_2 = width of the basin (m)

Q_i = inflow rate (m^3/s)

w_s = settling velocity of particles to be removed (m/s)

It is applicable for particle sizes $d \geq 0.5$ to 1 mm. Used by Mashauri (1986) for smaller particle sizes.

b) Mashauri's equation

$$D_2 = \left[\frac{56.51}{2} \right]^{0.5} \left(K_1 K_2 \; U_* / v_i \right)^{0.25} \left(\frac{Q_i}{w_s} \right)^{0.5} \qquad \text{(A.2)}$$

K_1 = mobility factor (dimensionless)

K_2 = settling coefficient of sediment

U_* = shear velocity (m/s)

v_i = inflow velocity (m/s)

$$H_1 = w_s D_2 / K_2 v_i \qquad \text{(A.3)}$$

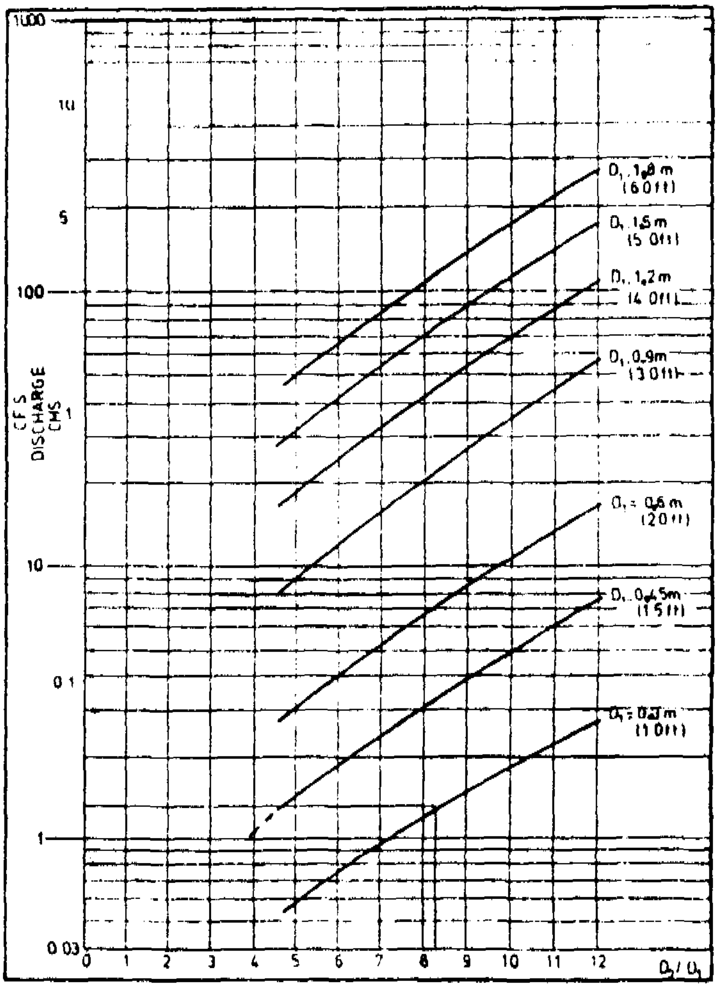
These equations are similar with Cecen's equation (1975)

$$D_2 = 5.274 \; (U_*/v_i)^{0.25} \; (K_1 \times K_2)^{0.5} \left(\frac{Q_i}{w_s} \right)^{0.5} \qquad \text{(A.4)}$$

$$H_1 = K_1 U_* D_2 / K_2 v_i \qquad \text{(A.5)}$$

$$K_1 = \frac{w_s}{U^*} \qquad \text{(A.6)}$$

APPENDIX A



c) Design nomograph for 100 % removal efficiency (Sullivan et al, 1982).

APPENDIX B

Sediment Grade Scale (Vanoni, 1977).

	Size range		
	Millimeters		
Class name			Microns
(1)	(2)	(3)	(4)
Very large boulders		4,096 - 2,048	
Large boulders		2,048 - 1,024	
Medium boulders		1,024 - 512	
Small boulders		512 - 256	
Large cobbles		256 - 128	
Small cobbles		128 - 64	
Very coarse gravel		64 - 32	
Coarse gravel		32 - 16	
Medium gravel		16 - 8	
Fine gravel		8 - 4	
Very fine gravel		4 - 2	
Very coarse sand	2 - 4	2.000 - 1.000	2,000 - 1,000
Coarse sand	1 - 1/2	1.000 - 0.500	1,000 - 500
Medium sand	1/2 - 1/4	0.500 - 0.250	500 - 250
Fine sand	1/4 - 1/8	0.250 - 0.125	250 - 125
Very find sand	1/8 - 1/16	0.125 - 0.062	125 - 62
Coarse silt	1/16 - 1/32	0.062 - 0.034	62 - 34
Medium silt	1/32 - 1/64	0.034 - 0.016	34 - 16
Fine silt	1/64 - 1/128	0.016 - 0.008	16 - 8
Very fine silt	1/128 - 1/256	0.008 - 0.004	8 - 4
Coarse clay	1/256 - 1/512	0.004 - 0.0020	4 - 2
Medium clay	1/512 - 1/1,024	0.0020 - 0.0010	2 - 1
Fine clay	1/1,024 - 1/2,048	0.0010 - 0.0005	1 - 0.5
Very fine clay	1/2,048 - 1/4,096	0.0005 - 0.00024	0.5 - 0.24

APPENDIX C

a) Preliminary cost estimates of the multi-stage swirl separator concrete structure.

Item No	Description	Unit	Quantity	Unit Price	Total Price
1	Dia = 100 cm height = 110 cm stilling basin	m^3	2.35	350.00	322.50
2	Dia = 180 cm height = 110 cm swirl basins	m^3	6.20	350.00	2170.00
3	Dia = 61 cm length = 50 cm (concrete inlet channel)	m^3	0.12	350.00	42.00
4	Dia = 45 cm length = 200 cm (concrete inlet channel)	m^3	0.55	350.00	192.50
5	Semi-circular tank radius = 180 cm height = 45 cm	m^3	0.5	350.00	175.00
6	Square shaped concrete box height = 50 cm width = length = 65 cm	m^3	0.2	350.00	70.00
7	V-notch weirs	No	6	60.00	360.00
8	Underflow pipe DN 100 (PVC)	m	6	30.00	180.00
9	Outflow pipe DN 450 (DCI)	m	1	80.00	80.00
10	Drainage pipe DN 100 (DCI)	m	1	40.00	40.00
11	Sliding steel gates	No	4	85.00	340.00
12	Open channel (6 m length)	LS	-	-	100.00
13	Formwork	LS	-	-	2000.00
	TOTAL				6572.00
	CONTINGENCY (5 %)				328.60
	GRAND TOTAL				6900.60

1 US $ = 2.10 ETB

APPENDIX C

b) Steel structure.

Item No	Description	Unit	Quantity	Price (ETB) Unit Price	Total Price
1	Dia = 100 cm height = 110 cm stilling basin	No	1	510.00	510.00
2	Dia = 180 cm height = 110 cm swirl basins	No	4	1040.00	4160.00
3	Dia = 61 cm length = 50 cm (concrete inlet channel)*	m^3	0.12	350.00	42.00
4	Dia = 45 cm length = 200 cm (concrete inlet channel)*	m^3	0.55	350.00	192.50
5	Semi-circular tank radius = 180 cm height = 45 cm	m^3	1	140.00	140.00
6	Square shaped concrete box height = 50 cm width = length = 65 cm*	m^3	0.2	350.00	70.00
7	V-notch weirs	No	6	60.00	360.00
8	Underflow pipe DN 100 (PVC)	m	6	30.00	180.00
9	Outflow pipe DN 450 (DCI)	m	1	80.00	80.00
10	Drainage pipe DN 100 (DCI)	m	1	40.00	40.00
11	Sliding steel gates	No	4	85.00	340.00
12	Open channel (6 m length)	LS		-	100.00
13	Formwork	LS		-	300.00
	TOTAL				6514.50
	CONTINGENCY (5 %)				325.73
	GRAND TOTAL				6840.23

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* Concrete Made

1 US $ = 2.10 ETB

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