Hydrocyclones: Alternative Devices for Sediment Handling in ROR Projects

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ABSTRACT

The incessant and stochastic character of rainfall in young and fragile mountain catchment generates enormous amount of sediment in Himalayan rivers. Irregularity in plan and bed forms, heterogeneity in bed and suspension loads, debris and mudflows make hydraulics of river channel flow quite complex and withdrawal of sediment free water from these rivers a very challenging task. Consequently, sediment related damages due to wear and tear in most of the hydropower projects, but in medium and high head plants have been found to be quite alarming. The conventional wisdom that particles smaller than 200 micron do not cause wear and tear to the turbines and accessories has been found to be inadequate in this region. Therefore, there is a need of excluding most of the sand particles from the flow. However, due to topographical limitations as well as higher cost of the gravity settling basins, construction of bigger settling basins is often impossible. Therefore, there is a need of different approach to be adopted to exclude fine sediment in such cases. This paper puts forth centrifugal acceleration technique and particularly the use of hydrocyclones for particle separation.

Experimental investigations on hydraulic and particles separation efficiency of 224 mm and 380 mm dia hydrocyclones are reported. The performances have been compared among the hydrocyclones and the settling basins. The particles removal efficiency of hydrocyclones, especially of finer particles have been found to be much higher than that of gravity settling basins.

1 INTRODUCTION

Land erosion is the inherent natural phenomenon occurring in most of the catchments of the river basins around the world. Himalayan river basins, which are characterized by young and fragile geology with steep catchment are very prone to such phenomenon. The inherent incessant and stochastic character of rainfall in this region generates extreme sediment load in these rivers due the erosion of catchment, bank and bed. Sediment load as high as 25,000 ppm are regularly recorded on major rivers such as the Narayani in Nepal (Carson, 1985). Even higher loads as high as 50,000 ppm have been observed annually on smaller rivers such as the Jhimruk (Basnyat, 1997, BPC, 2004). Therefore, only the Run-of-River (RoR) hydropower projects are viable alternatives in most of the stretches of the Himalayan rivers due to enormous sediment load and topographical limitations (Stole,1993).

Depending upon the sediment characteristics in the river and degree of removal required, the entry of sediment into the offtaking canal in a water project is usually controlled using tunnel type excluder, settling basins, vortex chamber type extractor (Ranga Raju et al. 1999, Paul et al.,1991, Garde and Ranga Raju, 2000). Among them settling basins are more common in a typical RoR plant. The conventional design practice is to trap most of the particles coarser than 200 µm in the settling basin to avoid appreciable wear and tear of hydro-mechanical equipment and accessories.

However, hard particles such as quartz and feldspar being the chief constituents in most of the Himalayan rivers, there are ample examples that even the particles finer than 200 µm have been found to cause
enormous wear and tear in hydro-mechanical equipment, especially, in medium and high head power plants. Severe erosion followed by cavitation for a high head (920 m) Pelton turbine shortly after 600 hours of operation was observed in a plant subjected to 77 % particles finer than 63 µm and 99 % finer than 125 µm (Brekke et al., 2002). Severe wear and tear of turbines and accessories are experienced in each summer season in Jhimruk power plant, Nepal, where more than 80% particles finer than 90 µm have been observed (Basnyat, 1997). Recent research carried out by Biswaswarkarma (2006) has indicated that sediment load is also one of the major factors for such wear and tear. Not only it involves a huge annual repair/maintenance and periodic replacement cost but also the appreciable revenue loss resulting from outage and decreased efficiency of equipment (Naidu, 1996, Basnyat 1997, Hydro Lab, 2004). As the terminal fall velocity of silt and fine sand particles is relatively small, huge basin is usually required to address these problems. Not only it involves huge chunk of the project cost, but also the layout possibility of longer/wider basin is often ruled out due to the topographical and geo-technical limitations in Himalayan region. This has given rise to the necessity of the alternative methods in handling suspended sediment particles in hydropower plants, especially in the medium and high head ones.

Centrifugal separation has been applied to exclude fine particles in many fields such as water supply and wastewater engineering, mineral processing, chemical engineering and coal refineries. Although the devices used differ from one field to another, centrifugal acceleration is utilized for particles separation in all the devices. A higher velocity flow stream is introduced tangentially into a cylindrical body having orifices at the center of its two ends (Fig. 1). This gives rise to Rankine type vortex conditions with forced vortex forming near the center and free vortex forming in the outer region toward the periphery. As a result, sediment concentration gradient builds up across the vortex and a diffusive flux proportional but opposite to the centrifugal flux is induced (Julien, 1986). Materials that are denser than the carrier medium are separated from the stream during this downward flow and can be removed through the outlet at the bottom of the cone. The sediment particles present in the flow move along a helicoidal path toward the orifice, thereby obtaining a long settling length compared to the dimensions of the separators. The sediment approaching the center is flushed out through the orifice continuously.

The efficiency of a vortex settling basin has been found to be much better compared to classical settling basin (Paul et al.1991, Dhillon, 1996 and Sahuja, 1996). Better geometry of the basin was found by Athar et al.(2002). Satisfactory results have been observed from field applications (Sahuja, 1996). However, despite their higher efficiency for coarser particles, the degree of removal of coarse silt/fine sand desired in most of the plants can not be achieved by vortex settling basins owing to the weaker centrifugal acceleration compared to the devices such as hydrocyclones.

There are basically two well-known families of geometrically similar hydrocyclones for handling the fluid mixture. These are due to Rietema(1961) and Bradley (1965). While the sharpness of separation has been found to be better in Rietema’s geometry with better performance for coarser particles, the higher separation efficiency of finer particles has been observed in Bradley’s geometry due to the long conical section. Krebs Engineers (2000) combined both of these properties by using sharper upper cone to accelerate tangential velocity and then a gradual tapering lower cone to provide residence time for a finer separation resulting in a new geometry (gMax) and better separation efficiency (Turner et al., 2001).

Despite their excellent removal efficiency, hydrocyclones are often criticized for the huge amount of energy they require for processing the flow. Moreover, the available head for such a purpose is often a limitation in many water projects. The short circuiting of flow near the inlet resulting in bypassing of coarser particles directly to overflow is yet another criticism. The significant energy loss incurred in the hydrocyclone has been observed near the inlet and outlet (Boadway, 1984). The migration of coarse particles due to short circuiting is also believed due to the excessive turbulence near the inlet. Keeping the above facts in mind the present study was intended to assess the performance of existing geometry, identify a new geometry minimizing the weakness and assess the removal efficiency with respect to conventional settling basins.
2 MATERIALS AND METHODS

2.1 Experimental Investigations

The outcome from the research work being reported herein is a part of a major program on the study of a cyclone type separator for particles separation. Details of the study will be published in a PhD thesis in a later stage. Hydrocyclones with two different diameters and geometries were considered. A 224 mm dia hydrocyclone, close to Rietema’s geometry (Fig. 2) was investigated at Hydraulics Laboratory of Institute of Engineering (IOE), Nepal. Whereas the experimental work of a 380 mm diameter cyclone with a double cone configuration (Fig. 3) was carried out in the Hydraulics Laboratory of Norwegian University of Science and Technology (NTNU). The test rig for the 224 mm hydrocyclone (Fig. 2) was designed primarily to study the performance of the cyclone. The hydraulic and sediment separation efficiency of the hydrocyclone for different operating conditions were studied. The strength and weakness of the cyclone were identified, which served the basis of the study of the 380 mm dia hydrocyclone.

2.2 Experimental Setup

The experiment was carried out in a fully pressurized system comprising hydrocyclones having a cylindrical chamber connected to a conical bottom (Fig. 2 & 3). The sizing and proportions of the hydrocyclone was carried out based on the information provided by Bradley(1965), Rietema(1961) and commercial cyclone manufacturers such as Krebs Engineers. The hydrocyclones were kept vertical throughout the experiment. The whole part of the 224 mm dia hydrocyclone and the conical part of the 380 mm dia hydrocyclone were fabricated from fiberglass whereas the cylindrical chamber including the inlet and outlet part of the larger hydrocyclone were made up of perspex sheet. The size of the hydrocyclone as well as the test rig was defined considering the available static head, discharge and space availability in the laboratory. The details of the geometry of the hydrocyclone and the arrangement of the test rig are presented in Fig. 2 & 3 and Table 1.

Inlet and outlet arrangement:

The flow into the hydrocyclone chamber in the first test rig was admitted tangentially through an inlet conduit of 0.063 m without any acceleration. The overflow was discharged to the collection tank without any deceleration of the flow. The flow in the second setup however, was gradually accelerated from the normal velocity at the bifurcation point to the maximum velocity near the inlet of the hydrocyclone. An involute type of inlet geometry (Fig. 3) was identified to streamline and guide the flow inside the hydrocyclone. The high velocity at the outlet was decelerated to the normal velocity. The experiment was carried out by receiving the outflow from the hydrocyclone both axially as well as tangentially.

2.3 Sediment feeding arrangement

The sediment into the system in the first setup was fed manually through a pipe from the top almost keeping a constant feeding rate. A sediment-feeding device consisting of a hollow circular PVC pipe of 63 mm diameter connected to a funnel was used for feeding sediment (Fig. 2). However, in the second setup it...
was injected through a sediment feeding box. Constant pressure was maintained in the sediment tank to secure a steady flow in the system. A differential pressure was created in the box and the test rig connecting the sediment feeding box to the city water supply system, operating under a pressure head of 800 kPa.

The particles having a \(d_{50}\) ranging from 76 µm to 397 µm and a specific gravity of bulk feed varying from 1.99 to 2.68 were used as feed sediment. The specific gravity of finer particles alone however varied from 2.5-2.7. Although the rate of injection of particles during a particular test was kept constant, it varied in each test.

2.4 Flow arrangement in the system

The discharge to the smaller hydrocyclone was supplied by a water pump. The discharge in the system could be varied by adjusting the gate valve installed just downstream of the pump. The pump received required amount of flow from nearby tank with fairly constant water level. Three gate valves were used to control the discharge in the system. The first gate valve was installed at the discharge exit of the pump. Whereas the second and third gate valves were installed at the exit points of overflow and underflow conduits to regulate the discharge passing through the respective outlets.

The discharge to the second rig was fed from the hydraulic system of the Laboratory equipped with overhead tanks with fairly constant level. The discharge to the larger rig was admitted through a pipe 0.20 m in diameter to a conduit 3.0 m in length, 0.26 m in width and 0.26 m in depth. From the center of the box the discharge was diverted to the hydrocyclone through a pipe 0.15 m in diameter. A control gate was installed at the end of the feeding conduit to control the proportion of the splitting. The discharge from the overflow was received in a conduit, identical to the feeding conduit. A gate valve was provided at the end of the receiving conduit to control the flow and maintain the desired pressure in the system.

2.5 Flow and Sediment Monitoring Mechanism

Discharge from the underflow and overflow conduits were noted at the beginning of each test run. The weight of the sediment was also recorded before feeding. The sediment in the system was fed once the steady flow in the system was maintained. Piezometers were installed near the inlet, outlet and along the conveyance conduits to measure the pressure head during each test run (Fig. 2 & 3). The flow in the larger test rig system was monitored by two electronic flow measurement valves (EMV) installed one at the beginning of the system to record the total inflow and the other one just before the receiving conduit to monitor the overflow discharge. The discharge passing through the underflow was worked out from a rating curve established for the respective collection tanks.

The sediment removal efficiency of the hydrocyclone was studied for different flow conditions by systematically varying inlet, overflow and underflow discharge. Similarly the sediment concentration was varied for each test. Attempts were made to maintain a fixed concentration in both the rigs; by feeding with constant rate in the first rig and by applying a constant pressure in the sediment feeding box, fed with a fixed amount of sediment.

The samples were collected from each discharging units before the discharge was admitted to the respective containers. The discharge together with the sediment passing through the underflow and overflow conduits were collected in separate tanks and allowed to settle for some duration. Clear water was drained out and the sediment settled in the respective tanks was collected. The samples thus collected were properly dried and weighed. Sieve analysis of the samples from each test was carried out to find out the grain size analysis and to ascertain the removal efficiency. The PSD analysis of fine particles, especially in the silt and clay range obtained from larger test rig was carried out using Coulter LS 230, a device working on Laser diffraction principles. The data obtained from PSD analyzer were verified by sieve analysis as well.

Although the PSD of the feed sediment was quite fine, all the sediment fed in the system, especially the coarser particles in some of the tests were not reported to the discharging outlets, the transport capacity being lower than required. Therefore, the total sediment received in the respective outlets was considered to be the total amount of sediment injected in the system. Whereas the total sediment intercepted by
overflow and underflow was considered to be the total input to the hydrocyclone. Therefore, the feed concentration and sediment removal efficiency was worked out using the following relationships

\[ c = \frac{q_u + q_o}{Q} \quad (1) \]

\[ \eta = \frac{q_u}{q_u + q_o} \quad (2) \]

where, \( c \) = sediment concentration (ppm), \( \eta \) = separation efficiency of hydrocyclone, \( q_u \) and \( q_o \) = amount of sediment received in underflow and overflow per unit time (mg/s); and \( Q \) = total flow processed by the hydrocyclone per unit time.

### Table 1. Range of data collected in the present investigation with different hydrocyclones

<table>
<thead>
<tr>
<th>No</th>
<th>Parameter</th>
<th>Unit</th>
<th>Symbol</th>
<th>224 mm dia</th>
<th>380 mm axial outlet</th>
<th>380 mm tangential outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diameter of hydrocyclone</td>
<td>mm</td>
<td>( D_c )</td>
<td>224</td>
<td>380</td>
<td>380</td>
</tr>
<tr>
<td>2</td>
<td>Height of cylindrical part</td>
<td>mm</td>
<td>( h_{Dc} )</td>
<td>440</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>First Cone angle</td>
<td>deg</td>
<td>( a_1 )</td>
<td>22</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>Second Cone angle</td>
<td>deg</td>
<td>( a_2 )</td>
<td>NA</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>Height of first conical part</td>
<td>mm</td>
<td>( h_{c1} )</td>
<td>440</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>6</td>
<td>Height of second conical part</td>
<td>mm</td>
<td>( h_{c2} )</td>
<td>NA</td>
<td>1350</td>
<td>1350</td>
</tr>
<tr>
<td>7</td>
<td>Inlet discharge</td>
<td>l/s</td>
<td>( Q_i )</td>
<td>0.30-7.81</td>
<td>10.4 – 19.9</td>
<td>15.0-23.70</td>
</tr>
<tr>
<td>8</td>
<td>Underflow discharge</td>
<td>l/s</td>
<td>( Q_o )</td>
<td>0.03-48</td>
<td>0.7-3.5</td>
<td>0.45-2.8</td>
</tr>
<tr>
<td>9</td>
<td>Underflow/inlet discharge</td>
<td>%</td>
<td>( R_f )</td>
<td>0.48-18.63</td>
<td>3.5-25.5</td>
<td>1.12-25.50</td>
</tr>
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<td>10</td>
<td>Headloss</td>
<td>m</td>
<td>( h_L )</td>
<td>0.03-3.0</td>
<td>1.16-3.94</td>
<td>1.6-3.8</td>
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<td>11</td>
<td>Feed concentration by (w)</td>
<td>ppm</td>
<td>( C_i )</td>
<td>1287-5092</td>
<td>97-4295</td>
<td>65-7618</td>
</tr>
<tr>
<td>12</td>
<td>Overflow concentration by (w)</td>
<td>ppm</td>
<td>( C_o )</td>
<td>8-942</td>
<td>28-93</td>
<td>53-238</td>
</tr>
<tr>
<td>13</td>
<td>Underflow concentration by (w)</td>
<td>ppm</td>
<td>( C_u )</td>
<td>734-186116</td>
<td>160-57702</td>
<td>9623-166837</td>
</tr>
<tr>
<td>14</td>
<td>Particles size range</td>
<td>( \mu m )</td>
<td>( d )</td>
<td>65-1000</td>
<td>0.4-1000</td>
<td>I : 0.4-1000 II : 0.4-340</td>
</tr>
<tr>
<td>15</td>
<td>Median Particle size range</td>
<td>( \mu m )</td>
<td>( d_{50} )</td>
<td>76-397</td>
<td>200.4</td>
<td>II : 99.7</td>
</tr>
</tbody>
</table>

### 3 RESULTS AND DISCUSSION

#### 3.1 Performance of Hydrocyclone, dia 224 mm

52 test runs were carried out using cohesion less sediment of different concentration and particle size distribution. The feed sediment concentration in the hydrocyclone varied from 1287 ppm to 5092 ppm, whereas the same for overflow and underflow varied from 8 ppm to 942 ppm and from 734 ppm to 186,116 ppm respectively. Total discharge handled by the hydrocyclone varied from 0.30 l/s to 7.81 l/s whereas the ratio between underflow and total flow varied from 0.48% to 18.6%. The average removal efficiency of the hydrocyclone under different operating conditions varied from 58% to 99%. The range of other data collected in the investigation has been presented in Table 1.

Hydraulic Performance

The discharge handling capacity of the hydrocyclone for a range of headloss is presented in Fig. 8, which resembles a standard rating curve. The hydrocyclone was tested for a headloss ranging from 0.05 m to 3.0 m corresponding to discharge varying from 0.3 l/s to 7.81 l/s. The hydraulic performance of the hydrocyclone has been found to be quite close to that reported by Arterburn, R.A. (2002).
The energy level along the conveyance for a typical flow condition (H=2.73 m and Q = 7.7 lps) is depicted in Fig. 5. Energy profile after the exit point has been found to be much steeper than that before the entry to the hydrocyclone. It indicates that part of the energy available near the exit is not recovered properly. Moreover, a sharp drop immediately after the entry point has been observed corresponding to an energy dissipation of about 30%. The abrupt drop in energy level near the entrance as well as the exit point is believed due to the poor hydraulic conditions. Improvement of hydraulics was therefore one of the objectives of the investigation in a 380 mm dia hydrocyclone.

![Rating Curve for 224 mm dia hydrocyclone](image1.png)

![Energy profile along the conveyance (H= 2.73 m, Q = 7.7 lps)](image2.png)

### Sediment Removal Efficiency

Particle size distributions (PSD) of samples received from overflow, feed and underflow for different operating variables (headloss, total discharge, underflow discharge, feed PSD and concentration) were investigated. Among the operating variables, the headloss across the hydrocyclone and ratio to underflow to total discharge ($R_f$) were found to play a decisive role (Fig. 6) on sediment removal efficiency of the hydrocyclone. In case of weak centrifugal field the removal efficiency, especially, of finer particles ($d< 200 \mu m$) was found to have strong dependency on underflow discharge (Fig. 6.a) and not on headloss across the hydrocyclone. However, it was just opposite in case of stronger centrifugal field (Fig. 6.b).

Although the removal efficiency has been found to be quite high for various flow conditions, some of the coarser particles also have been reported to the overflow (Fig. 6). This migration of coarser particles to the overflow is believed due to short circuiting, which was aimed to minimize in 380 mm dia hydrocyclone.

![Removal Efficiency (Actual recovery) curves: a) with smaller headloss b) with higher headloss](image3.png)
3.2 Performance of Hydrocyclone, dia 380 mm

42 test runs were carried out using two types of cohesion less sediment of different concentration. The feed sediment concentration in the hydrocyclone varied from 65 ppm to 7616 ppm, whereas the same for overflow and underflow varied from 28 ppm to 238 ppm and from 160 ppm to 16,837 ppm respectively. Total discharge handled by the hydrocyclone varied from 0.0104 m³/s to 0.0237 m³/s whereas the ratio between underflow and total flow varied from 1.12% to 25.5%. The average removal efficiency of the hydrocyclone under different operating conditions varied from 66% to 98.8%. The range of other data collected in the investigation has been presented in Table 1.

PSDs of the samples collected from overflow, underflow and feed for different typical cases are presented in Fig. 7. Underflow PSDs in these cases have been overlapped with that of feed, which indicates most of the feed is intercepted by the underflow. Higher removal of efficiency has been demonstrated through actual recovery curves as well (Fig. 8). The removal efficiency has been found to be quite high in both the outflow setups and is almost equal for the given range of operating variables. However, a marked difference from the behavior of other sediment exclusion devices such as settling basins could be observed. The removal efficiency of finest particles is extraordinarily high. These particles in hydrocyclones have higher removal efficiency than can be expected when considering the theory of a single particle sedimentation resulting in a curve observed in the form of ‘fish-hook’ shape (Plitt, 1971, Nageswararao, 2000 and Majumder et al., 2003). The entrainment of finer particles into the zone of coarser particles leading to higher removal has been argued by Neesse et. al. (2004).

Fig. 7: PSD received from feed, overflow and underflow: (a) with axial outflow setup (b) with tangential outflow setup

Fig. 8: Removal Efficiency (Actual recovery) curves obtained (a) with axial outflow setup (b) with tangential outflow setup
3.3 Comparison of removal efficiency of 224 mm and 380 mm dia Hydrocyclones

Although the sediment removal efficiency for coarser particles of both the hydrocyclones have been found to be quite high, the same for finer particles also have been found to be relatively high in the larger hydrocyclone. For almost the same flow parameters (head as 2.23 m against 2.35 m and \( R_f \) as 5.3% against 5.98%) removal efficiencies of corresponding particle sizes; 106 µm, 125µm and 150 µm are 85%, 91.8% and 96.3% as against 97.5%, 98.5% and 99.1% respectively. Despite G Force (Centrifugal force/wt of particle) being 4.2 times higher, the removal efficiency for the same particle sizes and characteristics have been found even better in the larger hydrocyclone. From this discussion and other data presented in Fig 6,7,8, it can be concluded that overall geometry and the hydraulics of the system which enable sufficient residence time is more important than the headloss across the cyclone to have desired level of efficiency.

3.4 Comparison of removal efficiency of Hydrocyclones and settling basins

The removal efficiency of hydrocyclones has been compared with the trapping efficiency of existing basins; two numbers, 42 m long, 5.5 m wide as well as two additional settling basins; 120 m long and 12 m wide (Hydro Lab 2003) proposed in Jhimruk Hydropower plant, Nepal (Fig. 9). The data presented for 380 mm dia hydrocyclone were directly monitored in the laboratory, whereas the data for 1.0 m dia hydrocyclone were generated according to scaling laws.

Very low removal efficiency of gravity settling basins can be noticed as compared to that of hydrocyclones. Despite the addition of two large settling basins to existing basins, overall efficiency of trapping has reached just 32.5% from 17% as against more than 90% with the hydrocyclones. Although the removal efficiency of coarser particles has been improved drastically with the addition of two basins, the trapping efficiency of finer particles did not increase significantly. On the contrary, the hydrocyclones have excellent removal efficiency for finer particles as well due to the fish-hook effect as discussed earlier.

![Comparison of removal efficiency (Actual recovery) curves obtained by hydrocyclone and settling basins](image)

Fig. 9: Comparison of removal efficiency (Actual recovery) curves obtained by hydrocyclone and settling basins

4 CONCLUSIONS

The investigation for hydraulic and sediment separation efficiency of 224 mm and 380 mm dia hydrocyclones with different geometries was carried out. With the modification of the geometry, the performance of the 380 mm dia hydrocyclone has been improved significantly. The hydrocyclones have been found highly efficient in terms of particles separation, especially for finer particles compared to settling basins. Based on the findings above, hydrocyclone can serve as an alternative and effective device
to exclude suspended sediment in water projects, especially high and medium head hydropower plants located in Himalayan river basins.

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