International Conference on Hydropower and Dams Development for Water and Energy Security – Under Changing Climate,
7-9 April, 2022, Rishikesh, India

SEDIMENT MANAGEMENT FOR RESERVOIR BASED HYDROPOWER PROJECTS

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ABSTRACT

The transportation of sediment by rivers is an inevitable phenomenon and the need of sediment management arises due to sediment transportation being intercepted by the hydropower projects. The handling of sediment is one of the major challenges facing the design as well as operation of hydropower projects. The concepts pertaining to origin, transformation and transportation of sediment particles in the hydrological system are important to be realized for development of efficient sediment management mechanisms in the context of hydropower projects. It is therefore worthwhile to relook at the principles of sediment transportation in the rivers and streams.

The sediment management in hydropower stations is either by allowing accumulation of sediment in the dead storage capacity of the reservoir or by removal of sediment by way of large desilting chambers followed by arrangements for silt flushing. The discussion in the paper is limited to sediment management in reservoir based hydropower projects.

The paper revisits some of the phenomena associated to the behavior of naturally occurring sediments under different flow conditions. A commentary on evolving technologies supporting the practices of monitoring and management of sediment in rivers as well as reservoirs is also incorporated. The unique structure developed for sediment management at Kol Dam Hydropower Station has been presented by way of case study.

1. INTRODUCTION

1.1 Interface between Sediment Transportation and Hydropower Projects

Sediment transport is an inherent feature of all rivers across the globe. The quantity and mineralogical composition of the sediments, albeit vary depending upon the flow parameters and catchment characteristics. For instance, the sediment concentration is quite high in Indian rivers, particularly so in Himalayan rivers, wherein major hydropower potential of the country is concentrated. This is because the Himalayan rivers flow through narrow valleys at steep bed slopes. These characteristics result in generation of high velocities which in turn give rise to high rates of sediment transport. Steep overland slopes and fragile Geology contribute to heavy sediment yield from the catchment areas. The sediment in Indian rivers has a significant fraction of minerals like Quartz and Dolomite, which makes the situation more alarming as these sediments are abrasive in nature posing the problem of damage to turbine components in a Hydro Power Plant. Owing to such reasons, sediment management is viewed as the major challenge towards operation of Hydro Power Projects. Conventionally, in the Hydro Power Projects involving large reservoirs, a significant portion of reservoir capacity (dead storage capacity) is dedicated for accumulation of silt during the lifetime of the project. In run-off the river projects, extensive desilting measures are designed for exclusion of silt from the water entering the water conductor system. The guidelines for design of sediment management arrangements have been standardized over the years. However, the underlying principles are important to be studied so that project specific design may be corroborated with the same.

1.2 General Treatment of Sediment

Hydropower projects involving large reservoirs, invariably envisage accumulation of sediment and other water borne material in the dead storage capacity, over the life of the project. The fixation of adequate dead storage capacity is based on the estimated rate of sediment inflow. For this purpose, a dependable data base of observed river sediment inflows is critically important, which is often not available. The design of dead storage based on inadequate data base results in under provisioning of dead storage capacity or wastage useful storage space being assigned for silt accumulation. Salal Hydropower Station on river Chenab comprises of 113 m high concrete dam and 118 m rockfill dam, giving rise to a reservoir of 280.85 MCM storage capacity. The reservoir was silted up fast, losing almost whole of storage capacity in initial five years, due to excessive silt inflow and two high flood events. Therefore, precise long-term observation of sediment data (including bed load) is important to be available at the design stage.

For run-of-the-river projects, large size desilting chambers are usually provided which trap most of the sediment particles and flush them back into the river while silt free water is drawn for power generation. However, due to very large range of particle size distribution of river sediment and also due to temporal variation in the sediment concentration, the design of desilting chambers, particularly silt flushing arrangements needs to be customized for individual case. Special attention is to be paid towards the handling of wash load component.

2. BASIC PRINCIPLES OF SEDIMENT TRANSPORTATION

Equilibrium is the fundamental principle of nature. The transportation of sediment through rivers is also in equilibrium. The phenomenon of aggradation or degradation occur when there is a disturbance to the equilibrium conditions, however, the whole endeavor of the system is to attain a fresh equilibrium. The phenomenon of sediment transportation, therefore, is to be carefully observed and conceived to understand the dynamism of equilibrium. The movement of sediment particles and the flow characteristics in the mobile bed channel are interdependent. A sediment particle comes into motion due to a particular combination of flow parameters and its course of transportation remains dependent on complex interaction between flow characteristics and composition of sediment matrix.

2.1 Incipient Motion of Sediment Particles

The phenomenon of incipient motion, i.e., the transition from a stationary state to a state of initial motion of the sediment particles is in response to an increase in the hydrodynamic forces acting on a bed of loose sediment. Shields (1936) expressed the critical shear stress for the initiation of motion as a relation between the non-dimensional shear stress τ* (Shields parameter) and the grain Reynolds number (R*) based on the shear velocity. Shields Curve for incipient motion is shown in Fig. 1.

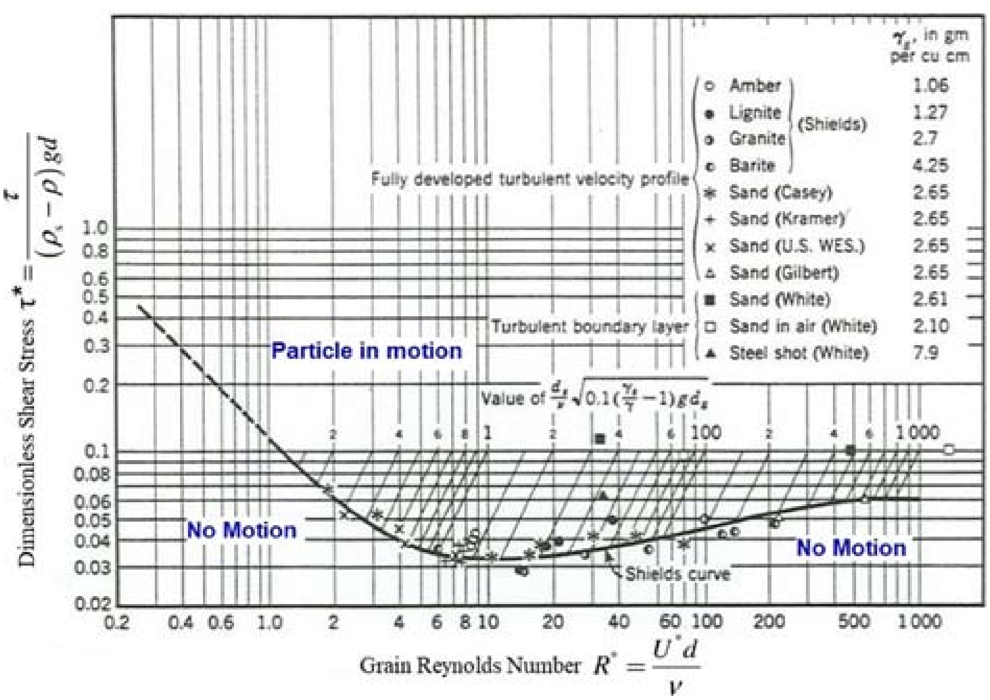

Fig. 1 : Shields' Curve for Incipient Motion of Sediment Particle.

Any particle of size d, plotting below the curve shall be in rest while the particles plotting above the curve is entrained by the flow and comes into motion. Practically speaking, the criterion defines that once the hydrodynamic forces acting on a particle generate tractive shear stress in excess of the submerged weight of the particle, then the particle comes into motion. Over the years there have been certain refinement into Shields' curve, however the same continues to be relevant and reasonably accurate for all practical purposes.

2.2 Modes of Sediment Transport

Once a particle comes into motion it can further be transported as bed load or suspended load. It is to explicitly mention that the bed load and suspended together form "Bed Material Load". This nomenclature evolves from the fact that the bed and banks of a mobile bed channel comprise of the same size fractions as those present in the sediment being transported as bed load or suspended load. Moreover, the particles in motion as bed load or suspended load have continuous interaction and interchangeability with the material present in the bed and banks. The phenomenon of a particular particle being is suspension or moving as bed load or being unable to move due to shadow zone created by surrounding particles is stochastic in nature. Therefore, Lagrangian approach as such is not applicable to the phenomenon of sediment transportation and the sediment transport modelling is based on Eulerian approach.

Apart from the aforementioned bed material load, occasionally some very fine sediment particles from the catchment, find their way into the river. These sizes are not present in the channel bed in normal conditions and get into the river because of a concentrated event of heavy rainfall such as a cloudburst etc. This sediment load is termed as Wash Load and its transportation needs to be dealt differently as compared to bed material load. A conceptual picture of different modes of sediment transport is shown in Fig. 2.

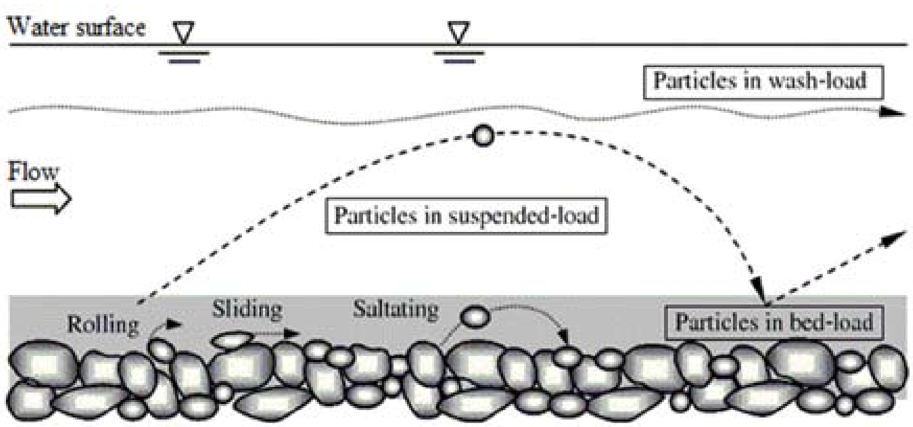

Fig. 2 : Pictorial Representation of Particles in Bed Load, Suspended Load and Wash Load.

(a) *Bed load transport*

The fraction of sediment which travels with the flow either in contact with bed or very close to the bed is termed as bed load. The particles moving as bed load may be rolling or sliding or saltation. Whereas the particles rolling or sliding along the bed are self-explanatory, the particles in saltation are those which are bounced up from the bed and thus intermittently travel short distances in suspension, before being replaced by another particle from the bed material or taking a bump again. The mode of travel of a particle is a primary function of hydrodynamic forces and also governed by the size and shape of the particle under reference as well as the neighboring particles.

(b) *Suspended load transport*

The sediment load which is transported for long distances without interacting with the bed material is termed as suspended load. However, it should be emphasized that the suspended load does have interaction as well interchangeability with the fellow particles in bed material. There is remarkable difference between the movement of a particle in suspension viz-a-viz a particle moving in saltation. The suspended particle once afloat completely loses its contact with the bed, whereas the particle in saltation as a continuous affinity with the bed. It is important to notice that a sediment particle moving as bed load is continuously controlled by its surrounding particles. A particle moving in suspension, has no control of surrounding particles, however the event of a particle coming in suspension or continuing in suspension is greatly influenced by the surrounding particles on the bed.

The computation of the concentration of bed load and suspended load is a matter of complex modelling because of inter-dependency of flow and sediment characteristics. There are numerous methods and equations available for estimation (calculation) of sediment flow rate and these are available in standard literature, however applicability of a particular method must be ascertained before applying the same to a particular case.

(c) *Wash load*

Sometimes due to the event of massive landslide or cloudburst etc, soil particles of in such size fractions are exposed as are otherwise not present in the overland flow from the catchment and therefore not present in the river bed material. These very fine size particles enter the river in large concentration. This sediment load is transported very close to the free surface and without any interaction with the bed material load. It is important to note that presence of wash load has no significant effect on the suspended load transport capacity. Thus, wash load is over and above the normal sediment transport capacity of the river. There is a possibility of deposition of wash load particles due to change in flow parameters or their own concentration exceeding certain threshold value.

2.2 Sediment Non-uniformity and Armouring of river-bed

The sediments occurring in a natural stream are highly non-uniform, both in their shape as well size. This non-uniformity of the sediment particles adds complexities to the mechanics of sediment transportation. For instance, a larger particle amidst relatively fine grained sediment experiences larger drag force compared to what it would have on a bed comprising of similar sized particles. Contrary to this, a smaller particle enjoys shielding effect due to presence of large particles around it. The phenomena of exposure and shielding as presented in Fig. 3, effects the overall rate of transport of a particular size fraction.

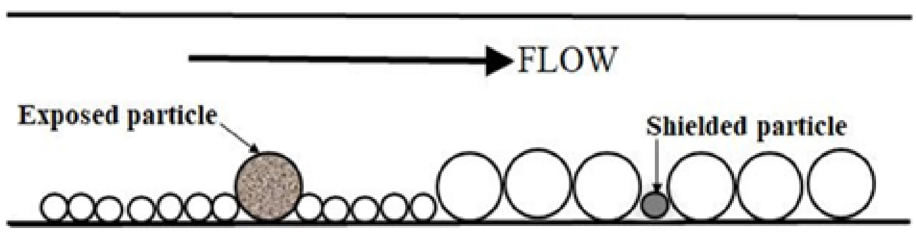

Fig. 3 : The Concept of Exposure and Shielding Effect

Another interesting outcome of non- of sediment particles is the phenomenon of development of armour coat. This is explained by transport of smaller grains in large quantities corresponding to a particular flow velocity, which results in very high fraction of coarse particles in the top layer of the sediment bed. These large particles do not move with the prevailing flow velocity and the finer particles, which are still present in lower layers are not at-all exposed to the flow, so those also do not move. The layer of coarse particles on the top, which acts as a protective shield for the finer sediments beneath it, is called the "Armour Coat". As a consequence of development of the armour coat, the flow of practically clear water takes place over a bed, which has the presence of fine sediment but the same is protected by the armour coat. A pictorial depiction of the phenomenon of armouring is shown in Figure 4.

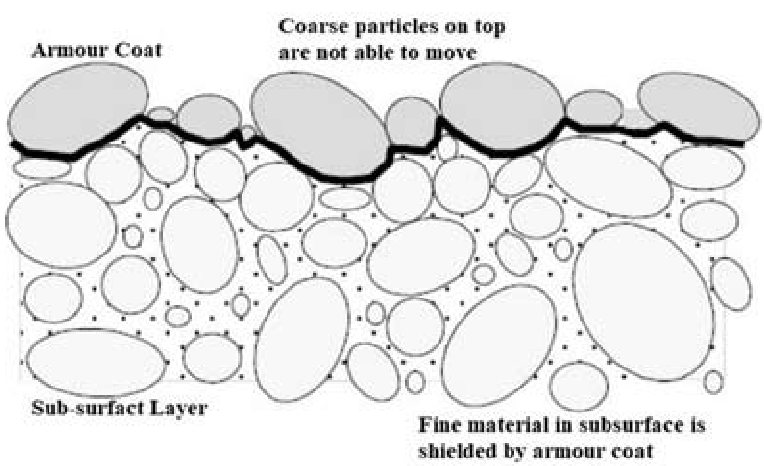

Fig. 4 : Development of Armouring Coat on a non-uniform bed

3. SEDIMENT MANAGEMENT IN RESERVOIR BASED PROJECTS

The hydroelectric projects comprising large reservoirs almost invariably have the provision dead storage capacity for accumulation of sediment throughout the operational life of the project. However, it is important to understand that sediment accumulation is not restricted to the dead storage capacity only. The coarser particles find their way to the reservoir bottom, in the upstream reach of the reservoir, which is at much higher levels compared to the dead storage level. However, even slight increase in depth and resulting slight reduction in the flow velocity is sufficient for the deposition of coarser particles, which reduce the useful live storage capacity. However, the delta of the deposited sediment progressively moves downstream, due to the effect of its own presence on the flow parameters. The reservoir operation near MDDL for longer period of time is an effective strategy is faster movement of the deposited sediment into the dead storage zone, thus transferring the deposited material from live storage to dead storage. Typical movement of deposited sediment towards downstream direction is shown in Figure 5.

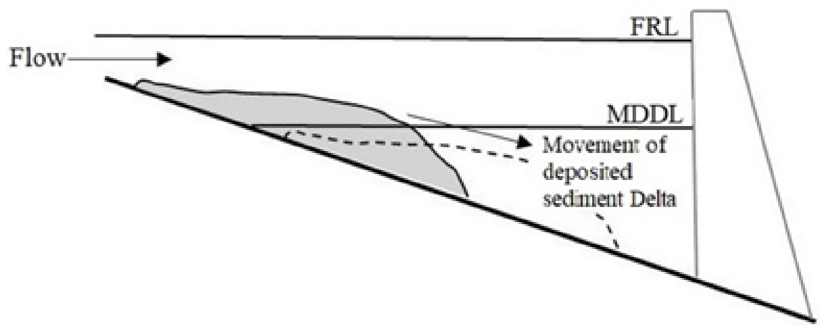

Fig. 5 : Typical Movement of Delta of Deposited Sediment in a Reservoir.

3.1 Special Silt Exclusion Arrangement at Kol Dam Hydropower Station

Kol Dam Hydropower Station is located on River Satluj in District Bilaspur of Himachal Pradesh. The project comprises of a 163 m high earth and rockfill dam, appurtenant structures and power house having installed capacity of 4 x 200 MW, located at the dam toe. The project has been designed to utilize a head of 140 m resulting in 3054 GWh design energy annually. The project is under commercial operation since July 2015. Though the project involves a 163 m high dam, which acts primarily as a lift dam, it operates like a run-off the river scheme. The project is thus a combination of storage and run-off the river schemes. Comprehensive studies were taken-up with a view to evolve an innovative and cost effective technique for silt exclusion, making use of this special feature of the project.

Initially conventional desilting chambers were envisaged to be constructed at Kol Dam project. Subsequently, it was observed that the conventional desilting chambers were designed as a standalone system. It was then pondered upon that since a large reservoir is being created, the same could be utilized for settling of silt particles. The concept is technically valid, as the reservoir eventually does perform the function of a desilting chamber by reducing the flow velocity and allowing the silt particles to settle.

In Kol Dam Project, the earth and rockfill dam gives rise to a vast reservoir having length of nearly 44 km, surface area of 13.02 km2 and storage of 576 MCM at FRL. The crest of the dam is at El 648.0 m, whereas the FRL and MDDL for the project are at El 642.0 m and El 636.0 m respectively. The reservoir has a maximum depth of 142 m at FRL. At MDDL (642 m) the reservoir extends to a length of about 25 km having surface area of 11.57 km2 and storage capacity of 486 MCM. The power intake is at El 606.0 m whereas the spillway crest is at El 625.0 m. It is therefore obvious that reservoir capacity below El 606.0 m only, can be used for accumulation of silt. In order to enhance the silt storage capacity, some mechanism was to be devised for (i) either flushing of silt once it approaches the intake level or (ii) utilizing the reservoir storage above El 606.00 m for silt accumulation. Since there is no low level flushing outlet, the flushing of sediment can be feasible through spillway only. In order to utilize the reservoir storage available between El 606.0 m (intake level) and El 625.0 m (spillway crest) for silt accumulation, a special arrangement has been developed in the form of a silt exclusion chamber or decanting chamber.

The silt exclusion chamber has been designed in the form of a series of submerged weirs, enclosing the power intakes. The weirs have been designed having crest at El 631.75. This allows the drawal of design discharge of 800 m3/s at MDDL as well as FRL. The underlying concept for such a decanting chamber is that the sediment particles shall continue to deposit in the reservoir and the water from the top-most zone of reservoir, above the weir crest shall be drawn for power intakes, which are otherwise located at a much lower level. Since the water in the upper region of the reservoir is devoid of particles of undesirable size, the power intakes draw the desilted water, at the same time fulfilling the water seal corresponding to MDDL. The design of the submerged weirs ensures that the setting of the crest level is such that the particles of size 0.25 mm(+)are excluded from water conductor system. In principle, all the particles above 0.25 mm size settle in the reservoir as the velocities prevailing in the reservoir are extremely low. At the same time, deposited silt can be flushed through spillway, once it reaches upto the spillway crest level of 625.0 m, which is 6.75 m below the drawal level i.e. the crest of submerged weirs. The water to be drawn into the power intakes and water conductor system is thus free from the silt particles coarser than 0.25 mm.

The final design of silt exclusion chamber was evolved based on extensive hydraulic model studies. The typical cross section of Silt Exclusion Chamber is shown in Figure 6 (a) and the final layout in plan is shown in Figure 6(b), whereas Figure 6(c) shows the photograph of the structure during operation.

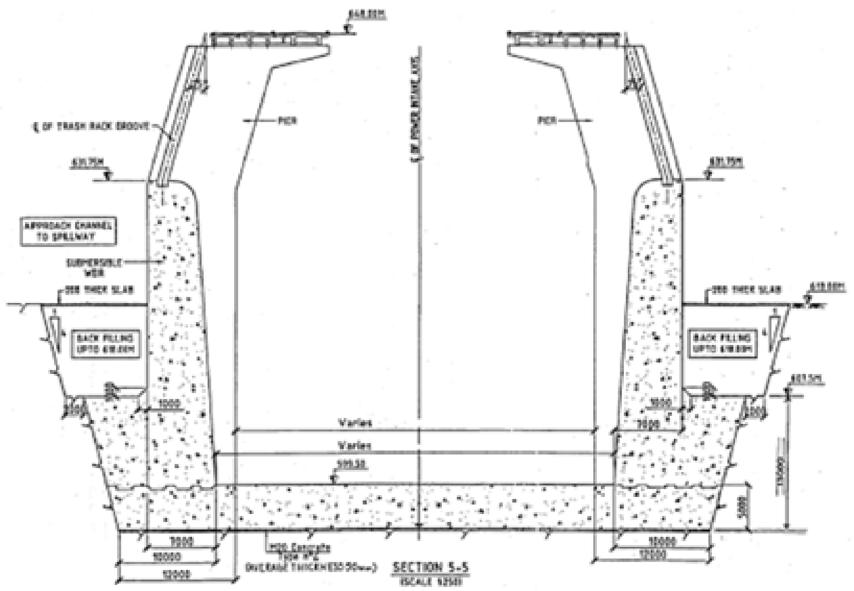

Fig. 6(a) : Typical Cross Section through Decanting Chamber of Kol Dam HPS

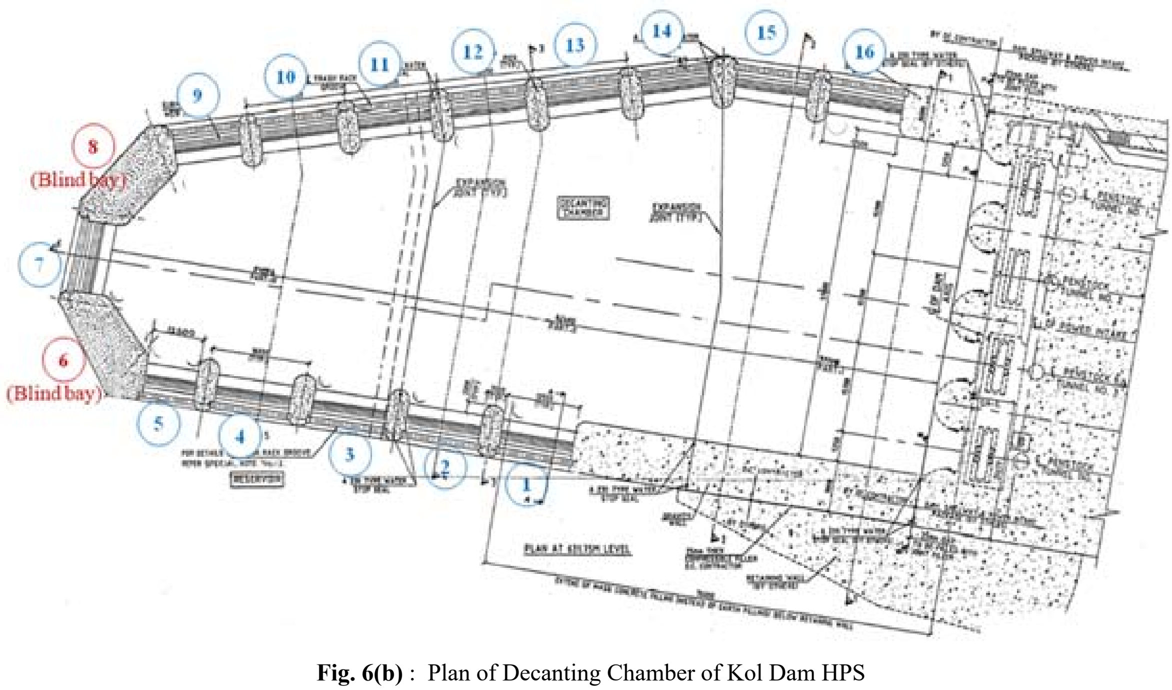

Fig. 6(b) : Plan of Decanting Chamber of Kol Dam HPS

Fig. 6(c) : Pictorial View of Kol Dam Decanting Chamber in Operation

It may be noticed that the chamber comprises of 14 spans of submerged weirs having 12.5 m waterway each. These spans are separated by piers which are 3.5 m thick, except the corner piers. The waterways have been provided with the trash racks to overrule the possibility of floating debris and trash entering into the silt exclusion chamber. A hydraulic trash rack cleaning machine has been provided for mechanical cleaning of the trash racks.

4. MONITORING OF SEDIMENT AND BATHYMETRIC STUDIES

4.1 Sediment Monitoring in River Flow

Major sediment transportation takes place during monsoon period and high flood regime of the rivers. The sampling of sediments is difficult during such challenging situations. Moreover, the concentration of different size fractions demonstrates a huge variation along the depth of flow. Owing to these and many more factors, the reliable measurement of sediment load, particularly the bed-load, in a river is a difficult task. Nevertheless, sediment monitoring is an important aspect and sediment samplers of various types have been evolved over the years.

There are four main types of samplers for suspended sediments:

- integrated samplers,
- instantaneous grab samplers,
- pump samplers,
- sedimentation traps.

The concentration of the coarser fractions of suspended sediment increases towards the bottom of the river channel. Therefore, a depth-integrating sampling technique is used to obtain a sample that accounts for different sediment concentrations throughout the vertical profile of a river. The depth integrated samplers have a water inlet nozzle and an air outlet. The nozzle is designed to permit isokinetic sampling. The size of the water inlet can be changed so as to control the rate of filling of the sampler. The depth-integrating samplers are lowered to the river bottom, then immediately raised to the surface; maintaining the same rate of lowering and raising. Large and heavy samplers are used as the samples are obtained from a bridge, boat or similar situation. In shallow streams, where all points can be reached by wading, a bucket or a small sampler attached to a metal rod can be used. A typical integrated sediment sampler is shown in Figure 7.

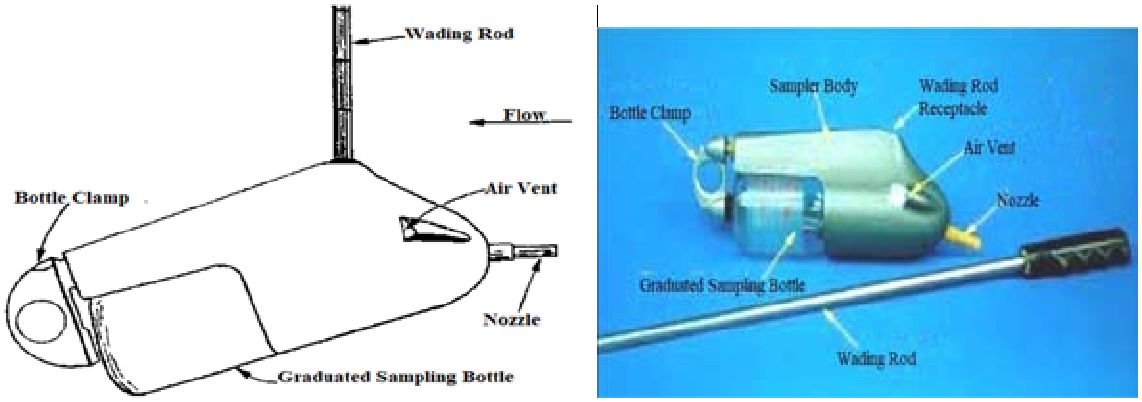

Fig. 7 : Schematic Diagram and Photograph of a Depth Integrated Sampler

Bed-load measurement is a more challenging task. Any sampling from the bed or near the bed, causes interference with the flow parameters, in-turn affecting the rate of bed-load transport. Nevertheless, manual and mechanical samplers for bed-load sampling have been in use. For manual sampling of bed load transport, the pressure difference type samplers are generally used. These samplers comprise of a large sized square intake and a meshed polyester bag for sample collection. The sampler is lowered to be positioned close to bed and the sample is then collected over a defined period of time so as to fill nearly 90% of the sampling bag. A typical pressure difference type sampler is shown in Figure 8.

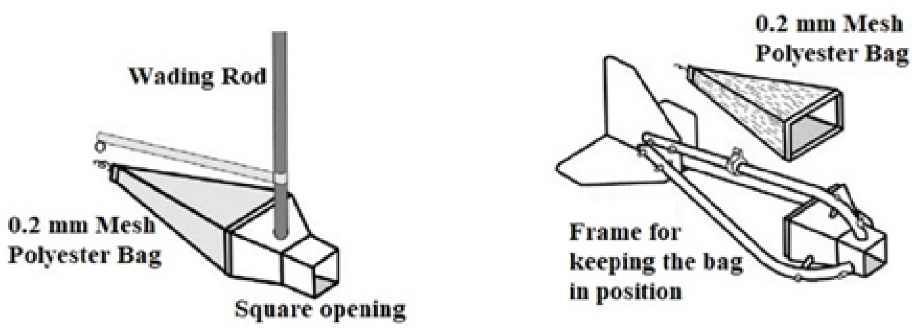

Fig. 8 : Schematic Arrangement of Typical Bed-load Sampler

Detailed description of the manual sediment samplers is available in literature. These techniques of sediment rate measurement are time tested but they have their own limitations. Presently, with the advancement in technology and application of automation advanced sensors have been developed, which are described in subsequent sections.

4.2 Sediment Monitoring in Reservoirs (Bathymetric Studies)

Conventionally, the sediment deposition patters in a reservoir are studied through bathymetric surveys or hydrographic surveys. Imaginary cross section lines are drawn on the reservoir water surface by way of erection of pillars on the banks. Then a survey boat traverses along these cross section lines and eco-sounding technique is used to observe the reservoir bed level at different point along the cross section and then along various cross sections. Based on Bathymetric surveys the deposition pattern of Bhakra Reservoir is shown in Figure 9.

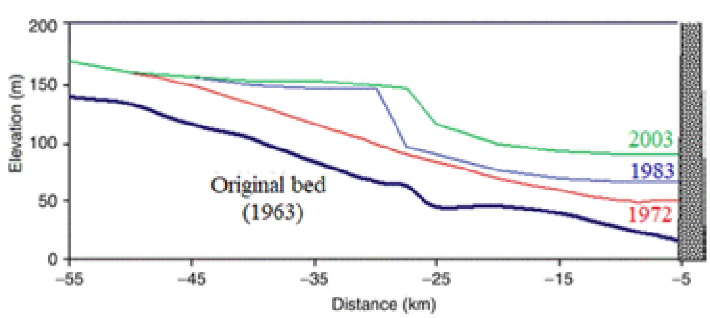

Fig. 9 : Reservoir Bed Profiles of Bhakra Reservoir

Bathymetric surveys using eco-sounding methods yield reasonable results. However, the method involves a lot of back-up desk studies and handling of large volume of data. It is also a challenge to maintain the same traverse of survey boat over the years. Any variation in the traverse path results in inaccurate observations, which are difficult to be correlated to earlier bathymetric surveys. With the present day technology, high resolution sensors carried through unmanned submarines have been developed. These technological nuances have the potential to yield much better data resolution and a far more detailed representation of the progressive deposition pattern.

5. TECHNOLOGICAL ADVANCES IN SEDIMENT MONITORING

As mentioned in the foregoing sections, the conventional methods of sediment monitoring in the streams and reservoirs have their own limitations. In the present day world, rapid evolvement of Artificial Intelligence, Computer Technology and Data Analytics has lead to development of such instruments and techniques, which can make this monitoring more reliable. The human interface, though still required may be reduced to a great extent. Simultaneously, continuous observations may be obtained as against discrete data observed by conventional methods.

5.1. Automated Sediment Monitoring in Rivers

The simplest automatic sampler for suspended sediment measurement is an automatic pump based sampler. In this case, only the nozzle of a suction pump is lowered into the flow and the sample of sediment laden water is collected in a sampler connected to the pump above the water surface. The velocity of sample entering into the water conductor system of the pump is kept equal to the flow velocity and the same is controlled by a computer which controls the rate of pumping. The device is permanently installed at a monitoring station and the sampling process may be completed very quickly. With the application of robotics, a remote operation of sampling system is also possible wherein the replacement of sample collector may be done by a robotic arm.

Apart from the above, a number of automatic sensors are available which are based on surrogate parameters. Pressure-difference is one such surrogate which can be calibrated for yielding the value of sediment concentration. In this technique, simultaneous measurements of hydrostatic pressure are made with the help of extremely sensitive pressure transducers installed at different fixed depths in a water column. The difference in pressure readings is directly convertible to water density from which suspended sediment concentration may be derived.

There are sensors which function on measurement of turbidity which causes light rays to be scattered and absorbed rather than transmitted in straight lines through the sample. These optical sensors operate on either the principle of Transmissometry or Nephelometry. In a Transmissometry based sensor, a light source is beamed directly at a light detector and the instrument function on the measurement of fraction of light that reaches the detector. Nephelometry based sensor functions on the measurement of light scattering usually with a light detector perpendicular to the incident light. Both the aforementioned sensors account for visible spectra as well as infra-red range of light.

Laser diffraction instruments apply the principles of smallangle forward scattering to derive particle size distribution in volumetric terms. Such sensors can be deployed in-situ and they operate unattended. Further, with the help of a data-logger, continuous or short interval records of sediment concentration as well as particle size distribution may be obtained.

Sensors based on hydro acoustics also have a wide applicability. These sensors work on the fundamental principle that sediment particles striking against a surface cause sound waves and the monitoring of the same can be calibrated in terms of number and size of particles, which in turn gives the volumetric concentration of suspended sediment. Various types of instruments have been developed based on various kinds of acoustic transducers.

5.1 Automated Bathymetric Surveys in Reservoirs

The fundamental of automation in the monitoring of sediment deposited on the reservoir bed is that instead of a boat equipped with echo-sounding system traversing on the surface of the reservoir, an Automated Underwater Vehicle (AUV) or unmanned submarine may be deployed for bathymetric survey. A series of sensors and recorders may be installed on this AUV which may range from simple video cameras (with flash lights) to high resolution Sonars, Echo-Sounders, LIDARs, GPRs Laser Instruments and many more as per the specific requirement. The technique is simple, robust, reliable and completes the coverage of vast reservoirs in very short time. Some typical AUVs are shown in Figure 10.

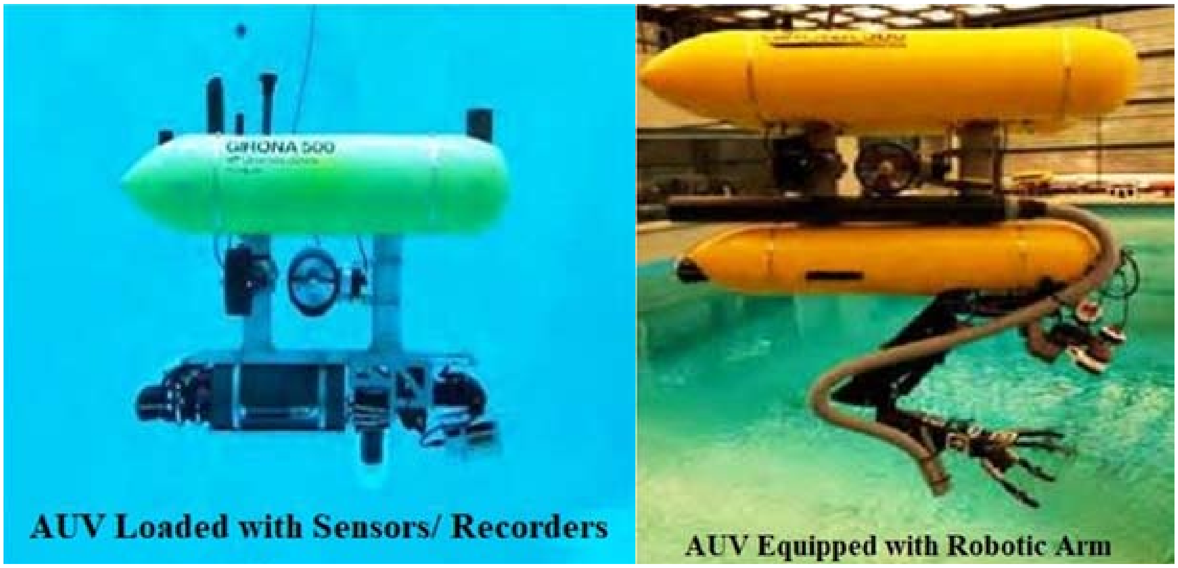

Fig. 10 : AUVs fitted with sensors and Robotic Arm

It is important to mention here that despite the AUV being completely remote controlled and battery powered, it is advisable to keep it connected with a high strength braided steel cable so that the equipment may be recovered in case it is trapped due to some unforeseen underwater feature in deep reservoirs. The data acquired through high resolution sensors may be processed through customized softwares, which may be developed based on specific requirements. A typical contour plan for a small segment of reservoir bed as developed by AUV based Bathymetric Survey is shown in Figure 11. The contour interval may be adjusted as per the requirement.

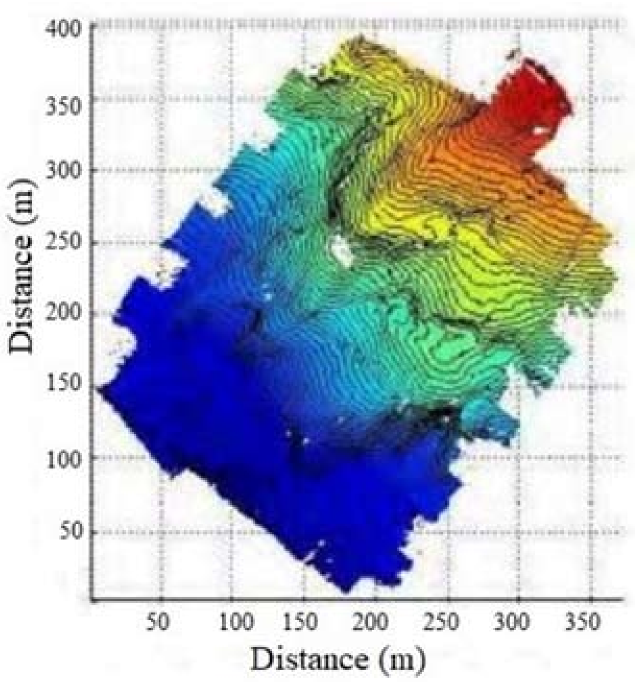

Fig. 11 : A Software Developed Contour Plan Based on Bathymetric Survey by AUV

6 CONCLUSIONS

The classical principles of sediment transportation have been revisited in the present article, alongwith a brief commentary on the evolving technologies relevant to monitoring of sediment in the streams as well as in the reservoirs. The following points emerge from the aforesaid discussion:

(i) The characteristic parameters pertaining to sediment transportation need to be thoroughly and patiently studied so as to evolve site specific solution for sediment management for a particular hydropower project. This would result in more efficient and cost effective solution as compared to indiscriminate application of design guidelines.

(ii) A detailed insight into special characteristics of the reservoir parameters has resulted in an innovative scheme of silt exclusion at Kol Dam Hydro Power Station. This has proven to be a technologically advanced solution apart from huge cost savings.

(iii) Finer aspects of the mechanics and kinematics of sediment transportation need to be conceived so as to develop effective solution for reducing the sediment volume reaching the project site. Even a marginal reduction in the quantity of sediment to be handled helps increase the operation life of the project, resulting in huge socio-commercial benefits. Construction of low height check dams in the catchment as well as upstream reach of the main reservoir helps in extending the life of main reservoir. These small check dams are easy to be dredged by mechanical means at regular intervals.

(iv) Attention should also be paid in change of morphological regime of the river, downstream of the dam, because the water released from the power house is devoid of the sediment. This demands a fresh equilibrium in the downstream reaches of the river which is achieved by long distance progressive degradation, endangering the existing and upcoming hydraulic structures in the downstream reaches.

(v) Hydropower projects need to be designed based on reliable long-term hydrological and sediment flow data. Deployment of automatic sensors, yielding continuous and accurate monitoring of the sediment transport rate in rivers is need of the hour.

(vi) Hydropower projects are Engineering marvels and are developed over long period of time. These are not only commercial establishments but also institutions of learning for future generation of Engineers. Precise monitoring of reservoir sedimentation is one of the important activities to help enlighten the Engineering fraternity and evolve better solutions for forthcoming projects. Automatic Underwater Vehicles loaded with advances sensors and recorders are available. It is high time that such technologies should be implemented on large scale to bring about long-pending sophistication in Bathymetric Recordings.

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