A General Review on Methods of Sediment Sampling and Mineral Content Analysis

R. Awal¹, P. Sapkota ¹, S. Chitrakar¹, B.S. Thapa¹, H.P. Neopane¹*,B. Thapa¹
¹Department of Mechanical Engineering, KU
*Corresponding author (hari@ku.edu.np )

Abstract. Sediment erosion is a major problem in hydropower plants of Himalayan and Andes region which causes frequent breakdown of electromechanical parts in contact with sediment laden water demanding regular maintenance. Sediment suspended in water with high velocity has higher potential to erosion of the turbine parts. Studies show that sediment erosion can be minimized to some extent if modifications in the design, use of erosion resistant material as well as application of erosion resistant paints are carried out on those components. Besides, thorough understanding of sediment by proper analysis is important for designing and making components less prone to sediment erosion. The efficiency of sediment analysis depends on the sampling method and the method used for particle size distribution (PSD) analysis and mineral content (MC) analysis. Depending on the nature of the stream, a different method should be adopted. This paper presents a general overview of the method of sampling, method of PSD and MC analysis.

Keyword: Sediment Erosion, Sampling Method, Particle size distribution, Mineral Content

1. Introduction
Sediment is solid particles produced by the natural process of weathering and erosion, transported to other locations by the actions of wind, water, and glacier. Among different means of sediment transportation, river is an important and major one. About 15 to 30 billion tons of sediment are loaded annually, out of which south Asia alone contributes to a two-third portion of sediment transport. Among the main rivers around the world, Amazon deposits mean sediment load of 1200 million tons per year, Magdalena, Orinoco and Mississippi rivers deposit mean sediment of 143, 105 and 157 million tons per year respectively [1].

Every hydropower has provisions for settling down the sediment carried by the river. However, sediment of less than 200 micron size is difficult as well as not feasible to settle down. Electromechanical components like runner, guide vane and draft tube which come in direct contact with water is susceptible to erosion. Neopane [2] observed that at higher velocity, even fine sediment has greater potential to permanently damage these components. Sediment erosion on hydraulic turbines is a complex process which depends on sediment characteristics like shape, size, concentration and mineral contents. In addition to these, flow rate, head, rotation speed, velocity, acceleration, turbulence, impingement angle and materials used in the turbine will have a significant influence in sediment erosion [3]. Study has shown that the common particle size of sediment that reaches to the turbine is in the of range 0.1 to 0.3 mm. Quartz, Feldspar, Muscovite, Biotite, Tourmaline and Garnet...
are the major sediment minerals found in Nepalese rivers. Out of these minerals, quartz has the highest erosion potential as it is harder than turbine materials [2]. Sediment erosion is one of the challenging issues from operational and maintenance of Nepalese hydropower. In Marsyandi Hydropower, Francis turbines of 3 x 23 MW need frequent maintenance of components as this hydropower receives 1.83 million tons average sediment load per year. Francis turbines of 3 x 4 MW in Jhimruk Hydropower need maintenance after almost every monsoon as this hydropower receives 29,700 tons of sediment load per year [4]. Studies and reports shows that turbines in most of the power plants in Nepal have severe erosion problem. Due to these reasons, sediment analysis of each and every hydropower is crucial for hydropower development within Nepal.

Depending on sediment velocity, sediment can be divided into wash load, suspended load and bed load. Wash load has upward velocity greater than settling velocity while suspended load and bed load have upward velocity equal to and less than settling velocity respectively. This paper presents the general overview of sampling method, particle size distribution (PSD) analysis and mineral content (MC) analysis.

2. Sampling Methods
A sample for sediment analysis can be taken from any sediment type using an appropriate sampler. The sampler and the sampling device should be designed to obtain specific volume and surface area up to specific depth of stream and should shield the sample from outside contamination. There are different sampling methods that can be chosen depending on the purpose of sampling, location and characteristics of sediment.

2.1 Point Integration Method
In this method, a sampler is lowered to stream at a specific point where the sediment should be collected. Nozzle of the sampler is opened and closed from the surface electrically. Relative depth of sampling is 0, 0.2, 0.6, 0.8 and 1 which is the ratio of the depth of sampler to the depth of stream flow [5]. The time between opening and closing of a nozzle of the sampler is called sampling time and can be calculated using equation 1.

\[
\text{Sampling time} = \frac{\text{Sample volume} \times 0.1841}{\text{Stream Velocity}}
\]  
(1)

The Federal Interagency Sedimentation Project (FISP) have standardized the sampler as US P-61-A1, US P-72 and US P-63 for this Method.

2.2 Depth Integration method
In this method, suspended sediment is iso-kinetically collected by lowering and raising a sampler in a constant transit rate in a stream. Depth integration is done either by Equal Discharge Integration (EDI) method or by Equal Width Increment (EWI) method [5].

2.2.1 Equal Discharge Increment (EDI) Method
In this method, a cross-section of a river is divided into 3 to 10 equal segments having nearly equal discharge. Averaging of the sediment collected from each segment is done to find the concentration of the sediment in the river.

2.2.2 Equal Width Increment (EWI) Method
In this method, cross-section of a river is divided into 6 to 10 equal segments keeping constant transit rate in each segment. Averaging of the sediment collected from each segment is done to find the concentration of the sediment in the river. FISP developed different depth-integrating samplers which can be used at different sampling sites depending on stream velocity and depth. Some of them are described in Table 1.
Table 1: Velocity range and maximum depth for the sampler [6].

| Sampler   | Velocity range (ft./sec) | Maximum depth (ft.) | Remarks               |
|-----------|--------------------------|---------------------|-----------------------|
| US DH-48  | 1.5 to 8.9               | 12                  |                       |
| US DH-81  | 2 to 6.2                 |                     |                       |
| US DH-59  | 1.5 to 5                 | 15                  |                       |
| US DH-76  | 1.5 to 6.6               | 15                  | Uses pint bottle      |
| US D-74 Al| 1.5 to 5.9               | 15                  |                       |
| US D-95 TM| 1.5 to 7.5               | 15                  | Uses quart bottle     |
| US DH-2   | 2 to 6                   | 37                  |                       |
| US D-96   | 2 to 12.5                | 39                  |                       |
| US DH-96-Al| 2 to 6                 |                     |                       |
| US D-99   | 3 to 15                  | 78                  |                       |

2.3 Bed Load Sampling

Sediment that move along the bed of a stream by rolling or sliding are bed load sediment. In this sampling method, sediment that move along the bed of a stream by rolling or sliding, called bedload sediment is taken for analysis. This method is normally used where the sediment movement and velocity of water is close to the bed [7]. Bed load sampling is carried out using different types of sampler as discussed below.

2.3.1 Box and Basket type Sampler

This sampler consists of a container for the accumulation of sediment, frame to support and a cable, as shown in Figure 1. Firstly, the sampler is lowered to the bed, then the gate is opened to allow sediment and water through it. The sediment passing through the sampler settle on the container and after a certain time the gate is closed. The time of opening and closing the gate is noted [8].

Figure 1: Box Sampler [9].
2.3.2 Pan-type Sampler
This sampler is wedge-shaped in which sample is collected in a container after sediment ascends in the inclined surface as shown in Figure 2. The limitation of this sampler is that, it should be used in a stream of smooth bed and moderate velocity [7].

![Figure 2. Pan-type Sampler](image)

2.3.3 Pit-type Sampler
In this type of sampler, a concrete structure having different slots is built on the bed of the stream. The sediment collected on the slot is used as a sample for sediment analysis.

2.4 Bed Material Sampling
Samples can also be collected from the bed material for the sediment analysis. However, there is no limitation to selection of sampling site. The general rules can avoid anomalies, morphologically stable site, tributary inflow, etc. There are different statistical methods relating to selection of the sites for collection of bottom-material samples. Some of them includes Stochastic Random Method, Stratified Random Method, Systematic Regular Method and Fixed Transed Method [10].

Most commonly used methods for bed material sampling are grab sampling, derge sampling and core sampling. Grab samplers are recommended to use in low-velocity stream for collecting surficial bottom material [11]. An ideal grab sampler can be used in shallow, sandy or clay bottoms creating a pressure wave without any leakage. Van Veen, ponar, orange peel bucket and shipek are most commonly used grab samplers. Similarly, core sampler is a vertical tubular sampler to collect thick sediment deposit for physio-chemical evaluation.

According to Wren [12], selection of the method should be based on budget constraints, manpower and quality of data. In-situ measurement of the sediment is more reliable than ex-situ measurement as particle’s volume may increase by about 24% when allowed to store and settle down for 1 hour. Wren [12] discussed the method, operating principle, advantages and disadvantages of various measurement techniques which are tabulated in Table 2. Further, he mentioned that multi scatter acoustic backscatter shows merit over other techniques for measuring suspended-sediment. However, further refinements and researches are necessary.
| Technology      | Operating Principle                                                                 | Advantages                                                                                                                                  | Disadvantages                                                                                     |
|-----------------|--------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Acoustic        | Sound backscattered from sediment is used to determine size distribution and concentration | Good spatial and temporal resolution, wide vertical range measurement, nonintrusive                                                         | Backscattered acoustic signal is difficult to translate, signal attenuation at high particle concentration |
| Bottle sampling | Water-sediment sample is taken isokinetically by submerging container in stream flow and is analysed later | Accepted, time-tested technique, allows determination of concentration and size distribution, most other techniques are calibrated against bottle samplers | Poor temporal resolution, flow intrusive, requires laboratory analysis to extract data, requires on-site personnel |
| Pump sampling   | Water-sediment sample is pumped from stream and later analysed                       | Accepted, time-tested technique, allows determination of concentration and size distribution                                                  | Poor temporal resolution, intrusive, requires laboratory analysis, does not usually sample isokinetically |
| Focused beam reflectance | Time of reflection of laser incident on sediment particles is measured | No particle size dependency, wide particle size and concentration measuring range                                                             | Expensive, flow intrusive, point measurement only                                                  |
| Laser diffraction | Refraction angle of laser incident on sediment particles is measured              | No particle-size dependency                                                                                                                   | Unreliable, expensive, flow intrusive, point measurement only, limited particle-size range           |
| Nuclear         | Backscatter or transmission of gamma or X-rays through water-sediment samples is measured | Low power consumption, wide particle size and concentration measuring range                                                                   | Low sensitivity, radioactive source decay, regulations, flow intrusive, point measurement only      |
| Optical         | Backscatter or transmission of visible or infrared light through water-sediment sample is measured | Simple, good temporal resolution allows remote deployment and data logging, relatively inexpensive                                           | Exhibits strong particle-size dependency, flow intrusive, point measurement only, instrument fouling |
| Remote spectral reflectance | Light reflected and scattered from body of water is remotely measured | Able to measure over broad areas                                                                                                             | Poor resolution, poor applicability in fluvial environment, particle-size dependency                |
3. Analysis of Particle Size Distribution
Size of particles in sediment reveals many information about geomorphic settling, fluid dynamics of the natural environment, minerals, etc. In case of hydropower, the particle size is another important aspect of sediment analysis as different particle sizes have different erosion potential. Important particle size analysis methods are discussed below:

3.1 Sedigraph Method
This method is an x-ray sedimentation process for analysing the particle size. According to this theory, a particle falling under its own weight in a liquid will reach a terminal velocity when gravitational force balances the buoyancy and drag force acting on the particle. It implies different sizes of particles have different terminal velocities [13]. The size of the particle can be found by equation 2.

$$D^2 = \frac{18v \eta}{(P-P_0)g}$$  \hspace{1cm} (2)

Where $D$ = diameter of particle, $v$ = settling velocity, $\eta$ = viscosity, $P$ = density of particle, $P_0$ = density of liquid.

3.2 Pipette Method
This method is used to find the particle size distribution of fine sediment that is difficult to analyse through dry sediment analysis (example discussed in Section 3.2). It is based on the principle of Stokes’ law. In this method, sediments are allowed to settle freely in an aqueous solution of sodium hydroxide then, using a pipette, sample at different depth at different time interval is drawn out from the solution. The solution is dried out to find particle size distribution [14] [15]. The relation between size and rate of fall of a solid spherical particle in any liquid is given by,

$$t = \frac{18Hv}{(P_1-P_2)gd^2} 10^8$$  \hspace{1cm} (3)

Where, $T$ = time of settling in second, $H$ =depth of settling in centimeters, $r$ = viscosity of the liquid medium, $P_1$ = density of particle, $P_2$ =density of medium, $g$ = acceleration due to gravity, $d$ = diameter of a particle.

3.3 Sieve Analysis Method
This method is one of the simplest and ancient methods for analysis of particle size distribution in which sieves of different sizes are arranged in descending order. The weighted sample is poured on the topmost sieve and vibrated for about five minutes. Total weight of sediment and weight of the sediment in each sieve is noted to find the particle size distribution. Though it is the easiest and simplest method, it does not have an ability to provide high resolution of particle size distribution and the shape of a particle. Neopane [2] carried out analysis of particle size distribution (PSD) of sediment from two different location of Jhimruk Hydropower using sieve analysis method. The result is shown in Figure 3, in which the sieve size is plotted against percentage finer. This is a general plot in sieve analysis, which is used to characterize the size of the sediments and their respective contents in the sample collected. In this figure, the sediments corresponding to 0.1 mm to 0.2 mm were found to be maximum.
Konert [16] compares laser analysis with pipette analysis and sieve analysis. The clay of size less than 2 µm-16 µm are classically analysed with standard pipette procedure while the sand fractions of 63-2000 µm are classified with a set of sieves. The results from these procedures are compared with the laser analysis method.

Firstly, laser analysis was compared with certified BCR sampler consisting of ground powder and quartz. Then, the method was certified for pipette and sieve analysis. The certified sampler selected was BCR 60, BCR 70, BCR 68 and BCR 130. Figure 4 shows the comparison of results obtained from laser analysis with the certified sampler. It is observed that the results obtained from laser analysis and certified sampler are in a good agreement.

It is concluded that laser particle size determination will always differ from sieve and pipette analysis and the deviation is due to the shape of the particle and density of the particle [16].
4. Mineral analysis of sediment

Mineral content analysis is another important part of sediment analysis. Different minerals have different potentials to erode the hydropower component depending on their hardness level. Those minerals, which have greater hardness than hydropower components, have higher potential to erode.

Table 3: Physical Properties of some minerals [17].

| Mineral   | Color                        | Mohr's Hardness | Structure                   | Crystal system       | Specific gravity |
|-----------|------------------------------|-----------------|-----------------------------|----------------------|-----------------|
| Quartz    | clear, white, gray, purple, yellow | 7               | Crystalline, sharp and absence of cleavage | Hexagonal           | 2.65            |
| Feldspar  | Milky white, brown, gray     | 6-6.5           | Cleavage of 2 to 3          | Triclinic or monoclinic | 2.5 - 2.7       |
| Mica      | colorless, yellow, brown, green, red | 2.5-3           | Perfect cleavage            | Monoclinic           | 2.8 - 3         |
| Muscovite | black, dark green, dark brown | 2.5-3           | Basal, perfect cleavage    | Monoclinic           | 2.76 - 3.3      |
| Biotite   | bluish black, black, yellow, pink, blue, green | 7-7.5           | Poor cleavage               | Hexagonal            | 3 - 3.3         |
| Tourmaline| wine red to reddish brown, yellow, green, black | 6.5-8           | Non cleavage                | Isometric            | 3.5 - 4.3       |
| Garnet    | Blue, white, gray, green     | 4.5-5           | Perfect cleavage in two direction | Triclinic in two direction | 3.5 - 3.7       |

Minerals contents in sediment are analysed mainly using three different method i.e. acid wash, optical and physical method. Neopane [2] presented a physical method of mineral analysis using a trinocular microscope. In this method, a strong magnifying microscope as shown in figure 5 is used to observe, identify and count the minerals. A dried sample is prepared and sieve analysis is performed to find the particle size distribution so that all sediment is of the same size range. Then after, the sediment is placed on a slide or watch glass containing grid lines. Based on distinct set of physical properties exhibited by each mineral, one can identify and count the minerals in sediment.

Figure 5: Trinocular Microscope used for mineral content analysis [2]
5. Conclusion and Further Work
Sediment erosion in hydropower components are mainly due to the suspended sediment in rivers which cannot be settled in desilting basin, usually in size range of 100 to 200 micron. Sediment analysis, characterization and its effect on these components must be studied to reduce such erosion, as well as modification of the design and selection of material of those components. Sediment analysis includes sequential process of sample collection and analysis of shape, size, concentration and minerals contents. The efficiency of sediment sampling depends on the method of sampling, sampler used, methods of particle size distribution analysis, mineral analysis methods, stream velocity and depth.

Depending on the nature of sediment, it can be divided into wash load, suspended load, bed load and bed material. Generally, suspended sediment is collected by point integration method and depth integration method. Box sampler, pit-type sampler, pan-type sampler are used for bed load sampling while grab sampling method is widely used for the bed material sampling.

Particle size analysis can be done by sedigraph method, pipette method or sieve analysis method. For the same sample, the size of the sediment can vary according to the method of size analysis used due to sphericity of the particle. In addition to shape size and concentration, the sediment erosion in turbines also depends on the hardness of the sediment particles. Quartz, garnet, tourmaline and feldspar are some of the common hard minerals found in sediment. Percentage content of these minerals is crucial and generally done by physical method using Trinocular Microscope.

Based on the available information, it can be concluded that further analysis should be done on determining the efficiency and selection technique of sediment sampling method. Most of the bed load sampling methods are based on the assumption that sediment settle on the sampler. These methods need be studied and validated. Also, focus must be given to acid wash and optical method of mineral content analysis as physical method can be sometime hectic and cumbersome.

References
[1] Anon Sedimentation and Erosion — Caribbean Environment Programme.
[2] Neopane H, Sujakhun S, 2013, Distribution and Mineral Analysis of Sediments in Nepalese Hydropower Plant: a Case Study of Jhimruk Hydropower Plant, Kucc.Ku.Edu.Np 9, 9.29–36.
[3] Neopane H P, 2010, Sediment erosion in hydro turbines, Doctorial Thesis at NTNU.
[4] Thapa B, 2004, Sand erosion in hydraulic machinery, Doctorial Thesis at NTNU.
[5] Flood C B, Lake G, 2015, Sediment Monitoring Protocols for Churia Originating River Systems.
[6] Davis B E, 2005, A Guide to the Proper Selection and Use of Federally Approved Sediment and Water-Quality Samplers.
[7] M. Travaglio, Orstom, 1980, Bed load measurement and sampling.
[8] FISP - Federal Interagency Sedimentation Project, 1940, Equipment used for sampling bed-load and bed material, vol 2.
[9] Hubbell D W, 1964, Apparatus and Techniques for Measuring Bedload, vol 1748
[10] USDA, 2007, Technical Supplement 13A: Guidelines for Sampling Bed Material.
[11] Radtke D B, 2005, Bottom-material samples, Techniques of Water-Resources Investigation, Handbooks 60.
[12] Wren B D G, Barkdoll B D, Kuhnle R A, Derrow R W, 2000, Field Techniques for Suspended Sediment Measurement, 97–104.
[13] UCL, SediGraph particle size analysis, lab Manual.
[14] Haywick D W, 2004, Pipette and Sieve Grain Size Analysis: Procedures Guide Pipette and Sieve Grain Size Analysis, Third Ed.
[15] Jackson C E, Saeger C M, 2012, Use of the pipette method in the fineness test of molding sand, 14-59
[16] Konert M, Vandenberghe J, 1997, Comparison of laser grain size analysis with pipette and sieve analysis: A solution for the underestimation of the clay fraction, Sedimentology 44, 523–535.

[17] Turbine Testing Lab Technical Survey Report Feasibility Study for Turbine Manufacturing and Testing Facility in Nepal

Acknowledgments

This study was part of Francis turbine for sediment laden waters FranSed Project, work package 1. Authors would like to thank TTL, Aatmaram Kayastha, Amul Ghimire, Dadi Ram Dahal, Ram Lama, Aman Kapali and Nischal Pokherel for their continuous help and support.