REPORT No. R-11

DEVELOPMENT OF SEDIMENT TRANSPORT TECHNOLOGY IN PAKISTAN

AN ANNOTATED BIBLIOGRAPHY

MUHAMMAD HASNAIN KHAN

OCTOBER 1996
PAKISTAN NATIONAL PROGRAM
INTERNATIONAL IRRIGATION MANAGEMENT INSTITUTE
LAHORE

TABLE OF CONTENTS

LIST OF FIGURES

PREFACE

The idea of a literature survey on sediment transport in the canals of Pakistan has come into reality by the author as a joint venture between IIMI Pakistan and the Government Engineering Academy Punjab, Lahore. The literature survey work was initiated to bridge the gap of understanding in the empirical nature of research work done in Pakistan on sediment transport and the efforts of various research organizations around the world to introduce Sediment Transport Computer Simulation Models of canal flows. The purpose of this work is to familiarize the researchers working on Sediment Transport with the research work done in this field in Pakistan and the experience of engineers while dealing with the vast irrigation network of the Indus Basin Irrigation System.

The articles in this literature survey cover a wide variety of subjects, like basic concepts developed in the region on sediment transport, techniques of sediment sampling applied in this area, and maintenance methods in relation to sedimentation of canals for desilting of channels. There is no relationship developed in quantitative terms between suspended sediment load, channel roughness and channel parameters. The author has tried to describe the work done in Pakistan on this subject in qualitative terms. To control the sediment entry into the canals the operational devices, such as silt selective head regulators, silt excluders/silt ejectors, have been presented and the experience gained by the engineers/scientists in this respect have been given in the literature survey.

There has been difficulty in reproducing some of the photographs. Not only thgre were some of the photographs quite old, but a few had been damaged by moisture. As a consequence, certain photographs were eliminated from the text, but those with historical significance were retained.

The research work done by scientists of the Irrigation Research Institute of Pakistan in developing sediment transport equations based on observed sediment and hydraulic data, which has been empirical in nature, has been given due consideration to evolve a strategy for validation of sediment transport relations to the Indus Basin Irrigation System by the researchers. The researchers have paid less attention to the role of silt drawing by outlets/turnouts through the canal irrigation network. The author has tried to introduce the work done by researchers/engineers related with the silt drawing capacity of outlets. It is hoped that articles of this literature survey would be helpful in opening new avenues for research opportunities in the field of sediment transport in the canals of Pakistan.

ACKNOWLEDGEMENTS

I would like to express gratitude to Mr. Munir Ahmad Zafar, Principal, Government Engineering Academy Punjab (Pakistan) for his cooperation to initiate this work on a Literature Survey on Sediment Transport in the Canats of Pakistan's Indus Basin Irrigation System.

I would like to express my gratitude to IIMI Pakistan for its technical support and guidance by the research experts and for the provision of manpower for word processing. In this regard, I am grateful to Mr. Marcel Kuper for his support and encouragement. Also I am thankful to Mr. Muhammad Manshah for typing and formatting the text. I would like to thank Prof. Gaylord V. Skogerboe for reviewing the document.

I would like to offer special thanks to Dr. Siddique and Mr. Mujeeb of the International Sedimentation Research Institute, Pakistan (ISRIP) for their technical support on reviewing these articles.

Mr. Hasnain Khan
Assistant Professor
Government Engineering Academy
Punjab, Lahore

1. SPECIFIC TERMS USED IN SEDIMENT STUDIES OF CANALS IN PAKISTAN

Introduction:

There are a number of specific terms used by the irrigation/hydraulic engineers while dealing with the sediment transport/sedimentation of canals. In each region of the world, the engineers use some specific terms which have their own characteristic meaning in that field of study. For example, in the sub-continent, Irrigation Engineers use the term silt for all sediment material carried by the canals or deposited on the bed. Similar is the case with particle size classification of coarse silt, medium silt and fine silt which is different from the grade scale proposed by the Sub-committee on Sediment Terminology of the American Geophysical Union. In this paper, some of the specific terms used for sediment studies in Pakistan have been given for the interest of the readers to familiarize them with their basic definition as available in the literature.

Accretion:- A process of sediment accumulation by flowing water due to any cause, including alluviation.

Aggradation:- The raising of the surface of stream beds, flood plains, and the bottoms of other water bodies by the accretion or deposition of material eroded and transported from other areas. This is the opposite of degradation.

Alluvial:- Pertains to alluvium deposited by stream or flowing water.

Alluvial stream:- A stream whose channel boundary is composed of appreciable quantities of the sediments transported by the flow, and which generally changes its bed forms as the rate of flow changes.

Alluvium:- A general term for all detrital deposits resulting from the sediment transport of (modern) streams, thus including the sediments laid down in riverbeds, flood plains, and stream-created fans at the foot of mountain slopes.

Antidunes:- Bed forms which occur at a velocity higher than that which forms dunes and plane beds. Antidunes commonly move upstream, and are accompanied by, and in phase with waves, on the water surface.

Armouring:- The formation of a resistant layer of relatively large particles resulting from removal of fine particles by erosion.

Barrage:- Barrier provided with a series of gates or other control mechanisms, across a stream to control the water surface level upstream, in order to regulate the flow or to divert water supplies into a canal. **Also,** a structure which prevents the intrusion of saltwater in a tidal river.

Bedload Sampler:- **A** device for measuring sediment moving on or along the bottom of the river bed, or channel bed.

Bed-material sampler:- **A** device for taking a sample of the sediment of which the stream bed is composed.

Bed-material load or bed sediment load:- Consists of particles that are generally found in the bed material. Bed material load is the summation of the bed load and the suspended load excluding the wash load. Bed material load is also referred to as the total load.

Boil sample:- Sediment sample obtained immediately downstream **of** a regulator or fall structure coupled with energy resistance blocks is known as a boil **sample.** The characteristics of this sample are that it contains all sizes of sediment, including those which form bed material due to the churning action of water caused by energy dissipation, where all sediments get into suspension. A boil sample is collected to estimate the total sediment load in the channel.

Channel:- A natural or artificial waterway which periodically or continuously contains moving water.

Channel-fill deposits:- Deposits of sediment within a channel, partly or completely filling the channel. Such materials accumulate where the transporting capacity has been insufficient to remove other sediment as rapidly as it has been delivered.

Channel, regime:- Channel which is in average equilibrium in its cross-section and longitudinal slope. Channel in which accretion balances scour on the average.

Cohesive sediments:- Sediments whose resistance to initial movement or erosion is influenced by the existence of cohesive bonds between particles, in addition to the physical properties of the particles.

Coarse **silt:**- The particles *of* sediment above 0.2 mm diameter

Critical tractive force:- The minimum force necessary to initiate movement *of* sediment particles from the stream bed.

Degradation:- The lowering of the surface of streambeds, flood plains, and the bottoms of other water bodies by the removal of material from the boundary. This **is** the opposite of aggradation.

Depth-Integrating sedlment sampler:- An instrument that is moved vertically at an approximately constant rate between the water surface and a point a few inches above the streambed, which collects a representative discharge-weighted water-sediment mixture at all points along the sampling vertical.

Depth integration:- A method of sampling to obtain a representative, discharge-weighted water-sediment sample of stream verticals, except an unmeasured zone near the streambed, by continuously compositing a portion of the water-sediment mixture as the sampler traverses the vertical at approximately a constant transit rate.

Dunes:- Bed form with a triangular profile having a gentle upstream slope, which advances downstream by the movement of sediment up the upstream slope and by the deposition of the sediment on the steep downstream slope. Dunes move downstream at velocities that are small compared to the stream flow velocity.

Echo sounder:- Instrument by means of which the depth of water is determined by measuring the time required for a sound signal to travel to the bed and return.

Equal-discharge-increments (EDI):- A procedure for obtaining the discharge-weighted suspended sediment concentration of flow at a cross section, whereby; (1) the depth integration is performed at the centers of three or more equal flow segments of the cross section; and (2) a vertical transit rate is used at each sampling vertical that will provide equal volumes from all flow segments.

Erosion:- (1) The natural processes by which earth or rock material is comminuted in a broad sense and moved, or (2) the wearing away of the land surface by detachment and transport of soil and rock materials through the action of moving water or other geological agents.

Fall Diameter:- This is the diameter of a sphere having a specific gravity of 2.65 and having the same terminal velocity as the particle when each is allowed to settle alone in a quiescent distilled water of infinite extent at 24°C.

Fine:-[1] Small particles of sediment below 0.07 mm diameter.

Gauging station:- A selected section of stream channel at which one or more variables are measured continuously or periodically as an index to discharge and other parameters.

---

[1] According to the grade scale proposed by the Sub-committee on Sediment Terminology of the American Geophysical Union (Lane 1947). sand particles are 0.062 mm to 2 mm in size, silt sizes are from 4 microns to 62 microns, while particles finer than 4 microns are classified as clays.

Instantaneous sample:- A suspended-sediment sampler which essentially instantaneously traps and removes a representative specimen of the water-sediment mixture in a stream at a desired depth and time.

Mean particle size or diameter:- The weighted average of different sediment size classes by weight.

Median size or diameter:- Particles size of sediment for which 50 percent by weight is finer, obtained graphically by locating the diameter associated with the midpoint of the particle size distribution.

Medium silt:- The particles of sediment below 0.07 mm diameter.

Nominal diameter:- This is the diameter of a sphere having the same volume as the particle.

Noncohesive sediments:- Sediments consisting of discrete particles, the movement of which for given erosive forces depends only upon the physical properties of shape, size, and density, and upon the relative position of the particle with respect to surrounding particles.

Particle Size:- The diameter of a particle measured by settling, sieving, micrometric, or direct measurement methods.

Particle size, average:. The average size of particles from a sediment sample may be computed from the averages of D_{10}, D_{50}, and D_{90}.

Particle size distribution:- The relative amount of a sediment sample having a specific size, usually in terms of percentage by weight finer than a given size, **D,.**

Plane **bed:-** A sedimentary bed without elevations or depressions larger than the maximum size of the bed material, which is characteristic of the lower part of the upper flow regime.

Point-integrating sediment **sampler:**- An instrument designed to collect a representative sample of the water-sediment mixture at a selected depth in a stream vertical over a specific time period.

Point-integrated sample (point sample):- A water sediment mixture that is accumulated continuously at about the prevailing stream velocity, over a specific time period, in a sampler that is suspended at a relatively fixed point in the stream vertical.

Point integration:- Method of sampling to obtain the mean concentration of sediment at a point in the stream.

Point sample:- Sample of water-sediment mixture taken at a single point, either with an instantaneous or a point-integrating sampler.

Pumping sampler:- A suspended-sediment load sampler in which the water sediment mixture is drawn through a pipe or hose, the intake of which is placed at the desired sampling point.

Ratlng curve, sedlment:- The relationship at some stream cross section between stream discharge and sediment discharge.

Ripple:- Small triangular-shaped bed forms that are similar to dunes but have much smaller amplitudes and lengths.

Scour:- The enlargement of a flow section by the removal of material composing the boundary through the action of the fluid motion.

Sediment:- Solid particles derived from rocks or biological material, which are or have been transported by water.

Sedimentation:- A term applied to the five fundamental processes responsible for the formation of sediment: (1) weathering. (2) detachment, (3) transportation, (4) deposition and (5) digenesis.

Sedimentation Diameter:- This is the diameter of a sphere having the same specific weight and the same terminal velocity as the given particle in the same fluid under the same condition.

Sediment concentration in ppm:- Concentration of each sample fraction in parts per million is determined on the basis of one million times the ratio of the net weight of the sediment to the net weight of water-sediment mixture by the formula:.

$$\textit{Sediment Concentration} = \frac{\textit{Net weight of sediment} * 10^6}{\textit{Net weight of water sediment mixture}}$$

Sieve diameter:- The size of sieve opening through which a given particle of sediment will just pass.

Silt:- **All** sediment material upto 3.6 mm diameter, whether in suspension, or moving on the bed, or deposited on the bed.

Silt load:-

Suspended load:	By definition, refers to the sediment moving in suspension.
- Bed load:	Silt moving on the bed of the channel **is** known as the bedload. This silt slides, rolls or jumps along the bed depending upon the velocity near the bed. Certain grades of silt are, however, capable of moving either in suspension, or on the bed, depending upon the turbulence of flow.
Wash load:	This refers to the finest portion of sediment generally silt and clay; that is washed through the channel, with an insignificant amount of it being found in the bed. The demarcation line for wash load is particle sizes finer than 62 microns.

Silt grade:- Refers to sediment size

Silt charge:- This refers to sediment load carried by the flowing channel.

Sieve Diameter:- This is the diameter of a sphere equal to the length of the side of a square sieve opening through which the given particle will just pass.

Silt **Draw of Outlet:-** This is the share of silt drawn by an outlet from the channel. The silt draw of an outlet depends on the type of outlet and its crest setting relative to the bed of the channel, which is expressed as a percentage ratio of sediment concentration in the water drawn by an outlet into a watercourse to the sediment concentration in the channel.

Silt ejector:. This is a device to remove excessive sediment load after it has entered the canal downstream of the head regulator. The extraction of sediment is affected by causing the sediment concentration to occur in the bottom layers and separating them in such a way that there is the least disturbance in sediment distribution ***of*** the approaching flow.

Silt excluder:. This is a device constructed in the river bed in front of a canal head regulator to prevent, as far as possible, sediment entering into the offtaking canal. The bottom layer sediment load is intercepted by this device and excluded before water enters the canal.

Silt intensity:- Silt intensity can be calculated from the mean value of all the coarse and medium silt observations taken at one particular site as:

Silt intensity in cubic feet (cft) per% cft = grams per litre * 5/8

Silt intensity in cft per cusec-day = grams per litre * 54

Total silt which passes a canal section per day is given as

Total silt in cft = silt intensity in cft per cusec day * discharge in cft per sec

Stream discharge:- The quantity of flow passing through a cross section of a stream in a unit of time. (The natural water contains both dissolved solids and sediment).

Tractive force:- Force exerted by flowing water on the sediment particle at a standstill on the river bed, to induce movement.

Trap efficiency:- The proportion of the incoming sediment load deposited in a lake or reservoir, in percent.

2. EXPLANATION OF PHENOMENON OF SEDIMENTATION OR SCOURING IN ALLUVIAL CANALS AND THE CORRELATION OF SUSPENDED SEDIMENT CONCENTRATION WITH THE CHANNEL ROUGHNESS AND CHANNEL GEOMETRY PARAMETERS

Introduction:

The phenomenon of sedimentation has been observed in alluvial and lined canals when heavily silt-laden water flows through them. A large amount of expenditure is incurred on maintenance of canals in either desilting of channels or raising of banks for provision of adequate freeboard on a continuous basis to sustain the irrigation of farm lands. In some of the channels, due to silt-free water, there is a scouring of the bed which impedes the capacity of the channel. This paper explains the phenomenon of sedimentation and scouring of channels on the basis of sediment transport concepts and in the light of channel instability criteria introduced by E.W. Lane in 1953. Also, the work of Dr. N.K. Bose at the Irrigation Research Institute (IRI) on the use of silt size distribution curves as an indicator of the stage of equilibrium of the bed has been given in this paper to signify the study of channel bed material for explanation of phenomenon of sedimentation in a channel.

In Pakistan, the channel data of some of the major canals of Punjab was observed and analyzed under the Channel Observation Program (CHOP) in 1962. In that study, S.S. Kirmani correlated silt charge, channel roughness and channel geometry in qualitative terms. However, there was no explicit relationship between these variables defining the channel flow carrying sediment-laden water. Flume studies by Simons and Richardson show a correlation between bed forms and channel roughness as given by Manning's roughness coefficient. An extensive research study has been made by Khalid Mahmood in the recent past to measure and analyze bed forms and to correlate them with the bed load of the channel carrying sediment. This paper is based on a literature survey of the work of eminent scientists and engineers as mentioned above in order to briefly describe their research efforts in their respective fields. The purpose of this paper is to briefly introduce their work, which is based on an analysis of irrigation canal data of Pakistan and the recent advances made in extending this research work on measurement and analysis of bed forms to estimate the bed load of canals. These efforts have been made by the researchers to explain the natural phenomenon of sedimentation and scouring in the alluvial channels. Still, there is much to be done in order to determine an explicit relationship for the variables defining the channel flow carrying sediment.

Phenomenon of Sedimentation and Scouring:

A major problem in the canal commands of Pakistan is either sedimentation (silting) or scouring, which reduces the capacity of the channel to carry its design discharge. Silting of the channel is due to higher flow resistance and low sediment carrying capacity of the channel for a given set of geometric boundary conditions, as well as fluid and sediment characteristics. Scour refers to the removal of material by running water. According to Lindley " when an artificial channel is used to convey silty water, both bed and banks scour or fill, changing depth, gradient and width". Sedimentation or scouring is due to an imbalance of sediment entering the channel and its sediment carrying capacity. The channel condition during this transitional state becomes unstable.

Channel Instability Criteria by Lane (1953):

There are three classes of unstable channels:

a) Channels in which the banks or bed are scoured without objectionable deposits being formed;

a) Channels where objectionable sediment deposits occur without scour being produced; and

c) Channels in which scour and objectionable deposits are both present.

When sediment-free water is present in a channel, only the first class of instability can occur. The first class of instability can also be caused by water which carries sediment, especially when the amount of sediment carried by the water is small.

The second class of instability (deposit without scour) can only be caused by the sediment brought into the canal with the flowing water, or that scoured from the banks and bed of an upstream (reach of the) channel. An example of this case is a lined channel or a canal cut through a scour resistant material into which large quantities of coarse sediment enter with the inflowing water.

The third class of instability (scour and deposit) usually occurs when water containing large quantities of coarse sediment enters a canal, the bank and bed of which are composed of material which has little resistance to scour.

Silt Size Distribution Curves As Indicators:

This relates to work of Dr. N.K. Bose at the Irrigation Research Institute. The silt size distribution curves (see next page) can be classified as of three types:

a) the left hand type, where the apex of the curves (and hence the major part of the sample by weight) consists of silt finer than the average diameter;

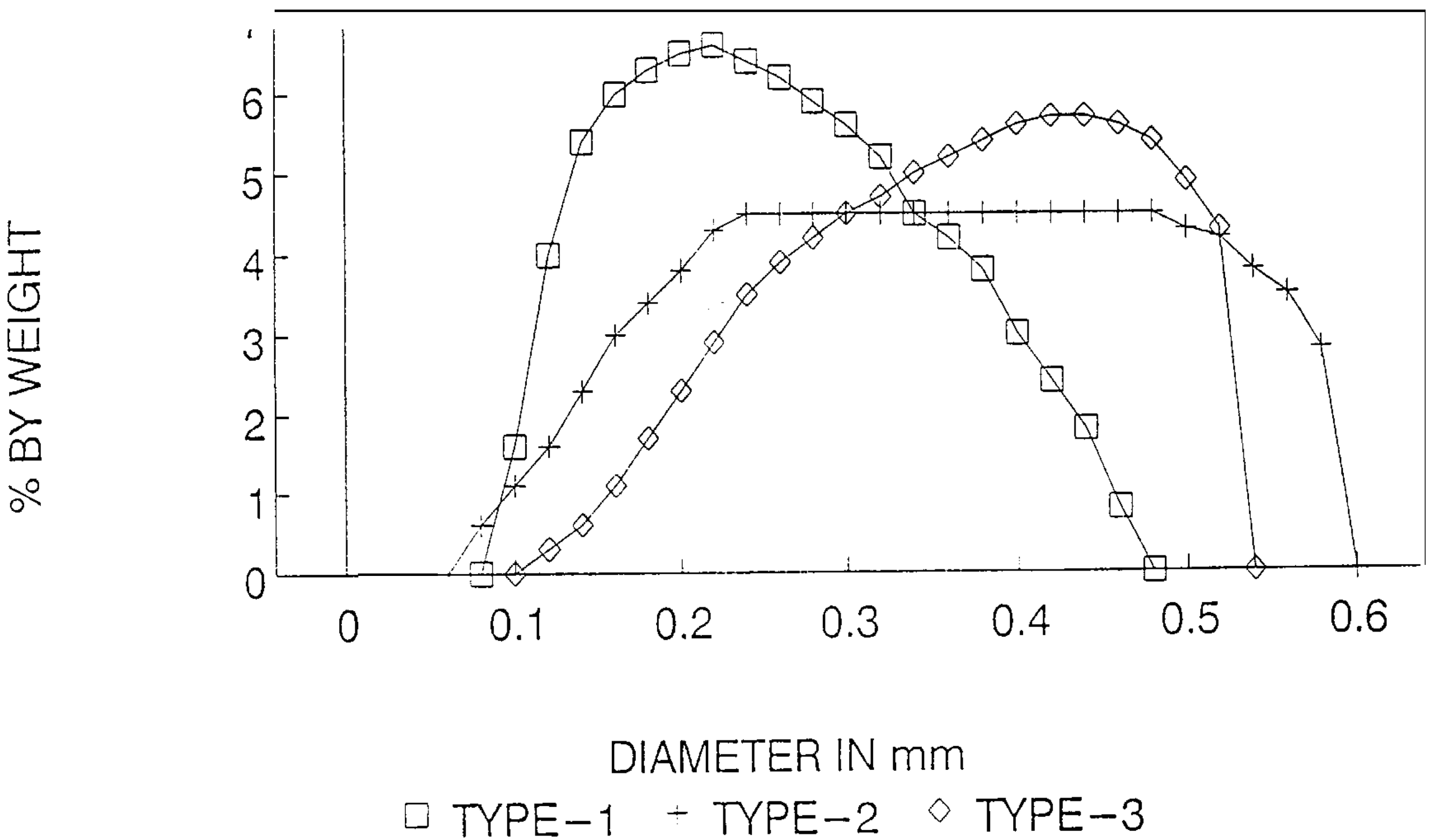


Figure 2.1. Size distribution curves.

b) the middle type, where the distribution of various silt diameters by weight was constant; and

c) the right hand type, where the major part of the sample by weight consisted of particles coarser than the average diameter.

These three types, which were observed even at the same site at different times, were believed to signify the stage of equilibrium of the bed. It was stated: "The left hand type indicate that the predominant components of the bed silt consist mostly of silts that are relatively fine, and either the coarse component has already settled in the upper reaches or are absent at the head."

The right hand type curve indicates that either the coarse components have not churned up from the bed, or have come down to the section from some upstream point where scouring is taking place, or from the head. In either of the latter alternatives, if the middle curves are absent, then the channel will have a strong tendency for silting. It also appears that canals in which all the three types occur frequently, with no bias for any particular type, will be the most stable type.

Experience of Punjab Canals (Common Observations):

Relating sediment charge and geometry of the channels, some of the common observations made by the Irrigation Engineers are:

a) According to LIndley "while it is known that greater or lesser silt charges demand greater or lesser velocities for equal depth, the case of width is not necessarily similar. Berms forming the sides of the channel are composed of such fine muddy silt, so easily suspended in flowing water, that it flows equally all through a canal system. Berms formed of the same silt, at the same velocity, should be similar in character."

b) The two channels carrying the same discharge, that which gets the greater silt charge, must be wider, shallower and steeper.

c) Considering the discharge of the channel, small discharge channels attain steeper slopes than those attained by large discharges under the same condition of sediment flow and type of soil composing the wetted perimeter.

Correlating Silt Charge, Channel Roughness and Channel Geometry (Qualitative Approach)

Analysis of CHOP Data **(1962):**

The channel data of some of the major canals of Punjab were observed and analyzed under the channel observation program (CHOP) in **1962.** The study of the discharge and geometric parameters of the canals show that the canal sections, in certain cases, have characteristic features different from those at other sections. When the width is small, the depth is generally large, and vice versa. That there should be such variations in a canal within a short distance is rather surprising, but knowing that measurements were made with great care, it seems that in spite of identical condition of discharge and sediment, the canal sections have individual characteristics of their own. This is due to the fact that as the irrigation demand increased with the passage of time, more water was forced into the canal, and the channel sections increased but erosion of the bed and sides was not uniform throughout the length of the canal. At some places the bed was easily eroded, while the sides armored with grass berms resisted erosion. At other places, the erosion pattern was quite reversed.

Manning's Roughness Factor 'n':

One of the early empirical equations based on Sticklers work regarding alluvial canals which is widely used for describing uniform steady flow in open channels is Manning' equation expressed as:

$$V = 1.486\, R^{2/3}\, S^{1/2}/n$$

In this equation n is a Manning's roughness factor which varies with the frictional resistance to flow offered by the channel bed and side material.

In most sediment-laden channels, Manning's roughness factor "n" is not a permanent characteristic, but changes with configuration of the bed. The form of bed roughness depends primarily on the slope, depth, fall velocity, or effective fall diameter of the bed material, and shape of the channel.

Leopold and Maddock have demonstrated that at constant discharge, the suspended sediment load is related to the channel parameters, that is width, velocity and depth. At constant width and discharge, increased sediment load would be associated with increased velocity, which requires a decrease in depth and that must be achieved by an increase in channel slope, or a decrease of roughness, or both. A decrease in sediment load causes scour or degradation in the channel bed and is accompanied by an important increase in bed roughness, while the slope remains essentiallv constant.

Einstein and Babarossa divided the bed resistance into two parts. The first part of resistance is transmitted to the bottom by shear on the roughness of the grainy sand surface. The second part is transmitted to the boundary in the form of normal water pressure at the different sides of each sand dune or ripple. From river measurements, they found that the second part, which is the form resistance of the bed irregularities, is a function of the sediment transport rate alone.

Vanoni and Brooks observed that two depths of flow were possible for a given combination of slope and discharge. When the sediment discharge was small, the depth was large, the velocity was small and the bed was rough. When the sediment discharge was large, the depth was small and the bed was smooth.

From the experiments performed by the USBR on the San Luis Valley Canals, Lane showed that the roughness factor n increases as the size of the material becomes larger. A study was also made which showed that the roughness is a function of the ratio of the size of the particle to the hydraulic radius.

There are three major factors effecting bed roughness:

a) particle size of bed material;
b) bed configuration; and
c) suspended sediment load.

The analysis of CHOP data in relation to channel roughness, and its geometric parameters and suspended sediment load, leads to the following conclusions:

a) For the same discharge and bed width, a decrease in velocity is associated with an increase in depth. If the slope remains substantially unaltered, an important increase in bed roughness is caused. Conversely, an increase in velocity is associated with a decrease in depth, and if the slope remained substantially unaltered, an important decrease in roughness is caused.

b) The roughness factor decreased with increase in the suspended sediment load as long as the slope remained substantially the same.

c) The roughness factor is not a constant in all seasons. It is high during the period October to June when the suspended sediment load is small and the bed material size is relatively large due to washing of the fine material from between the larger particles. During the period July to September, when the suspended sediment load is relatively large, the roughness factor, for the same discharge and bed width, is small.

d) The roughness factor is minimum in the month of maximum sediment load.

Flume Studies by Simons and Richardson **(1960):**

Simons and Richardson carried out flume studies in fluvial channels and made a detailed classification of the regime flows, the form of bed roughness, and the basic concepts pertaining to resistance to flow. In the "tranquil flow regime", which is the normal condition of flow in a canal, the following results were obtained:

a) With a plane bed and no movement of bed material, the bed was soft and easily disturbed. The value of Manning' n for no bed material movement was approximately 0.015.

b) With the movement of the bed materials, ripples started. As ripples formed in the bed, slope and depth increased and Manning's n increased from 0.015 to 0.022. **As** the ratio of the depth of flow to ripple height increased, Manning's n increased from 0.019 to 0.027.

c) When the slope or depth were increased beyond a certain limit, ripples were modified to dunes and Manning's n varied from 0.018 to 0.035.

Simons and Albertson Study of Canal Data **(1960):**

Simons and Albertson analyzed the data of stable canal reaches in which no objectionable scour or deposition on the bed was observed. The canals from which **some** 113 reaches were studied, belong to Punjab, Sindh and USA. The range of discharge studied is 5 to more than 9000 cusecs, with an average sediment discharge of **156** to 8000 ppm. The following observations were made with regard to the relationship between the Froude Number, channel regime, bed roughness, sediment transportation and channel stability:

i) **It** is reported that with regard to the field and laboratory observations, the following relationship exist between these factors.

Fr.No.	Flow Regime	Form of bed roughness	Sediment load
		Ripples	
Fr < 1	Tranquil Flow Regime	Dunes	
		Transition of Dunes to rapid flow	1000 - *3000*
		Plane bed with movement of bed material	*2000 - 5000*

ii) If the channel is to be stable, the Froude number, Fr, should be less than 0.3 for the alluvial material in the sand range and finer, and when $Fr > 0.3$, the banks scour.

iii) To meet the requirement of stability, the form of bed roughness is restricted to ripple or dune form, while the magnitude of the sand - silt sediment load that can be transported is limited to less than 500 ppm.

iv) If a larger sediment load is to be transported, it will be necessary to provide bank stabilization in view of the higher Froude number of the flow required.

Correlation of Bedforms with Bed Load:

Bed forms are undulating features which develop on alluvial beds after the commencement of sediment transport. The minor bed forms in sand bed channels, such as ripples, primarily determine the resistance to flow, whereas the major bed forms (such as dunes and bars) manifest incipient or established instability of alluvial channels in the lateral or vertical direction. The quantitative analyses are needed for defining the length, height, width and other pertinent geometric features of bed forms. This information is then used in the calculation of bed load and its spatial - temporal variations. For analysis purposes both manual and computer methods are used. The latter includes the zero-crossing, the maxima - minima, the auto correlation and the spectral methods. Bed load calculations are made through sequential profiles of bed forms.

The following conclusions were made after analysis of Alluvial Channels Observation Project (ACOP) data observed in Pakistan Canals in respect to the method of measurement and analysis of bed forms.

a) For the analysis of a single profile , the method of zero-crossing is the most suitable method. This method is applicable to non-stationary profiles and does not require detrending or filtering. The method is computationally efficient, compared to autocorrelation or spectral analysis. Also, it provides the length and height of individual bedforms, which is not done in the other methods.

b) Bedform width can be measured by cross-spectral analysis. This method has been verified by extensive graphical analysis of multiple profiles measured on the Missouri River and in ACOP canals. This method is less subjective than the graphical analysis.

c) The method of maxima-minima is useful in isolating individual bedforms for detailed analysis of their shape. The success of this method depends parameters along the entire channel reach. Computer simulation of this phenomenon through mathematical modelling is in its stage of infancy and it requires a lot of research effort to simulate this natural phenomenon.

There is a correlation between channel roughness (i.e. Manning roughness factor, n) and suspended sediment load and the bed configuration. During high sediment concentration periods of July and August, the channel roughness reduces with the changing of ripple bed configuration to plane bed, whereas during low sediment concentrations, the roughness factor n increases. There is a need to extend this. research study further to determine the mathematical relationships for bed configuration geometry and channel roughness either in terms of the Manning roughness factor n or the Darcy-Weisbach friction factor f. ACOP data obtained for Punjab and Sindh canals, by recording bed configuration using various sounding techniques, will be of great value for this purpose.

The research work correlating bed configuration with the bed sediment load shows that there is a scope for further research in this field using modern techniques to analyze bed configuration and to obtain bed load concentrations which are at present calculated by indirect methods, such as the Einstein bed load functions.

3. EVOLUTION OF BASIC CONCEPTS IN CANAL SEDIMENTATION/SEDIMENT TRANSPORT RELATED TO DESIGN OF CHANNELS IN PAKISTAN

Introduction:

Maintenance of canals has traditionally been a concern associated with canal irrigation caused by silt. Canal banks were built with sediments cleared out of the bed. A stage, therefore, came when it was easier to abandon the existing banks and construct new canals. With experience, the personnel responsible for the construction and maintenance of various canal systems have realized that a canal has to be *so* designed in such a way that it is able to transport the requisite quantity of water and the sediment carried by it in such a manner that water could be applied to the fields, preferably by gravity, and the channel should not experience objectionable scour or sediment deposition over long periods of use. In this paper as part of a literature survey, the evolution of basic concepts in canal sedimentation and sediment transport has been described considering the theories behind the design equations developed by the Irrigation Engineers of the sub-continent. These concepts of design and theories were modified from time to time as a result of analyzing observed canal data, as well as their experience while dealing with operation and maintenance of this vast canal irrigation network in Pakistan.

Design approaches:

The latest developments in the design criteria for stable channels in alluvium can be broadly divided into two main classes. The "Regime Theory" which represents the empirical approach basically developed in the plains of the Indus and Ganges and the "Rational Approach" which was developed in Europe and America. The difference between the two approaches is that while the Regime Theory considers the channel, including its fluid, sediment and alluvial periphery as a single whole, the "Rational Approach" considers these three components as independent factors.

The first definition of "Regime Channel" was given by E.S. Lindley " When an artificial channel is used to convey silty water, both bed and banks scour or fill, changing depth, gradient and width, until a state of balance is attained at which the channel is said to be in regime". For regime to be established, the fundamental requirements are that the discharge should be constant, the channel flowing in unlimited incoherent alluvium of the same character as that transported, and the silt grade and silt charge a constant. According to Lacey, this results in a unique channel section for a given discharge and silt grade.

Kennedy's Silt Theory - 1895:

Kennedy was the first to formulate the basic law that shallower canal sections are capable of transporting greater silt loads, which is now almost recognized as an empirical, but well established, design concept. His basic assumptions were that the vertical components of eddies supported silt particles; the silt transporting power of a channel was also dependent upon the depth which limits the effect of eddies, and the silt transporting power of a channel was not influenced by its bed width. On the basis of these assumptions, and using the observed data of UBDC (Upper Bari Doab Canal), Kennedy developed his famous equation:

$$V_o = 0.84\, D^{0.64}$$

where V_o is the critical velocity and D is the flow depth of the channel. Kennedy recognized that the grade of sand played a part in his relationship and assigned values of critical velocity in the ratio of 1.1 and 1.2 for sands coarser than standard and 0.9 - 0.80 for finer sands. During that period, the Lower Chenab, Lower Jehlum, Upper Chenab, Lower Bari Doab and Upper Jehlum canals were designed and built using Kennedy's theory. The application of Kennedy's approach for the design of channels saved millions and millions of rupees in the maintenance cost of canals but the correlation had its critics from the very beginning. The differences of opinion was on the following points:

1) Variability of both the coefficient and index (0.84and 0.64 respectively) in his equation;

2) Effect of bed width-depth ratio on the silt transporting capacity of the channel; and

3) Empirical nature of his equation.

Lindley's Approach **(1919)**:

Lindley carried out an extensive survey of the Lower Chenab Canal System. On the basis of this data, he developed the following equations.

$$V = 0.95\, D^{.57}$$

$$V = 0.59\, B^{0.355}$$

$$B = 3.80\, D^{1.61}$$

Lindley's main hypothesis was that the sediment load carried in a channel controlled the bed width in the same way as it unquestionably defined tho depth. This study demonstrated the important effect of the canal section geometry on its sediment transport capacity.

In examining data collected at different points of a canal system that has run long enough to attain regime, great variations are observable; these are sometimes due to regime having been disturbed and sometimes to regime at different points being naturally different. The main causes of these variations are:

1) Silt clearance, berm cutting, the use of bushing and the working of silting tanks;

2) Use of cross-regulators in heading up more or less at different times;

3) Running of feeder channels with varying discharges;

4) Breaches which scour the bed locally;

5) Difference between the silt drawing power of an offtake, not at present measurable, but causing regime changes in the parent channel as well as in the distributary; and

6) Effect of different rugosities in allowing regime velocities to be attained with lesser or steeper gradients.

About the difference between non-Silting and non-scouring velocities, Lindley states that:

"Under any set of conditions, there is some latitude in the difference between the velocity that just fails to cause scour and that which just suffices to prevent deposits". Again on the velocity-width relation " a certain velocity is required along the sides of the channel to strike a balance between berming and eroding, the wider the channel, the greater a central and therefore also a mean velocity will this permit of, while the depth can adjust to this velocity". This means that of the two channels carrying the same discharge, that which gets the grater silt charge must be wider, shallower and steeper.

Lacey's Regime Theory (1919-1928):-

Using the regime concept given by Lindley, while analyzing the data observed by Kennedy and Lindley, Lacey derived his regime equations in terms of channel geometry parameters given by hydraulic radius "R" and wetted perimeter "P" as follows:

$$V = 1.155\sqrt{fR}$$

$$V = 16(R^2 S)^{1/3}$$

$$P=2.667Q^{1/2}$$

where f is the silt factor which is related with the mean bed silt diameter in mm as

$$f=1.76m^{1/2}$$

where 'm' is the weighted mean diameter of the bed material

According to Lacey "On artificial channels there is a marked difference between 'injtial' and 'final' regime .... channels of this type (clayey berm providing side restraint) achieve a working stability but are not in 'final' regime". Final regime represents the channel conditions when discharge and silt grade are constant. Lacey correlated the rugosity coefficient N_a with the silt factor f as

$$N_a = .0225\ f^{1/4}$$

to arrive at the channel geometry and slope relation which is given as

$$f=193.10(R^{1/2}S)^{2/3}$$

The above Lacey's silt factor relating slope and hydraulic radius is known as f_{sr} whereas Lacey's silt factor correlating velocity and hydraulic radius is known as f_{vr} and is given by;

$$f_{vr}=0.75\ \frac{V^2}{R}$$

Lacey proposed that the regime channels have an elliptical shape, but maintained the side slopes of 1/2:1 for normal channel design. Lacey's method was accepted officially by the Central Board of Irrigation in **1934** as standard design criteria for regime canals. The design of some of the major canals based on Lacey's formulae were the Haveli, Thal, BRBD Link, B.S. Link and Marala Ravi Link Canals.

Irrigation Research Institute Formula - (1933):-

In order to determine a relationship between the silt factor and the bed silt , the IRI made observations of bed silt samples and hydraulic data in the corresponding sections of the Lower Chenab Canal, Lower Jehlum Canal, Upper Chenab Canal and Upper Bari Doab Canal systems. Observations showed that Lacey's silt factor "f" is not a unique entity for the given set of hydraulic data of the channel because the two silt factors f_{sR} and f_{vR} were found to be different. Also, the coefficient in Laceys' f and mean bed silt diameter equation varied from **1.54** to **2.13.**

The first enunciation of the results of IRI work was given by Dr. N.K. Bose. He undertook to describe the silt transportation in alluvial canals and also to analyze the type of size distribution curves for the bed silt, their annual frequency, and their interpretation as an indication of the equilibrium stage of the canal. In his words "Silts in channels have been broadly divided into two components - one is known as the rolling silt, a silt that hops and rolls and moves slowly as sand dunes on the bed of the canal. This silt is mainly confined to the bottom 3 to 6 inches of the canal. The other component is known as the floating silt - a silt that is always kept in suspension and once in suspension remains almost always in suspension and the line of demarcation can be roughly drawn near about 0.05 mm diameter". Dr. Bose (1936) derived the following formula after statistical analysis of the field data

$$S10^3 = 2.09 m^{0.86} / Q^{.21}$$

Both the silt factor 'f" of Lacey and the weighted mean diameter 'm' of Bose define the size of the sediment but not the sediment charge, or the rate at which sediment is transported. Sir Claude Inglis **(1948)** recognized this limitation and after analyzing the data of the Lower Chenab Canal System produced a set of dimensionless equations to take care of the sediment charge. He showed that the rate of sedimentation was proportional to CW, where

C = Sediment concentration
W = Terminal fall velocity of particle in still water.

He concluded that the sediment charge had a small effect on the area of a channel, a relatively large effect on the slope and shape, and considerable effect on the width of the channel.

After the work of IRI and that of Inglis, which showed the divergence of a channel from Regime Theory, Mr. Lacey **(1940)** postulated his shock theory. Recognizing the difference between an ideal regime channel, which flowed in an unlimited alluvium of perfect incoherence, and the real canal, with its curves and irregular banks, Lacey stated that "the slope may also include 'shock' due to bends or irregularities in the channel and 'shock' due to channel conditions as opposed to channel material. In such circumstances, it is preferable to assign to **'N'** a value which the bed material warrants and to account separately for the energy destroyed in shock by making an appropriate deduction from the gross slope as measured". According to Lacey "perfect incoherence would suggest that bed material particles could be picked up as readily as they were deposited. Before particles can be picked up friction must be overcome: thus, in practice, incoherent silt devoid of colloids must have some measure of coherence". In the Punjab Irrigation Department, Laceys' Regime equations still form the basis for designing of alluvial channels. Yet, some channels designed on Laceys' regime equation or the Bose formula of S-Q have also silted, or scoured, depending on whether these channels were called upon to carry a silt charge greater or less than their normal silt carrying capacity.

Blench Regime Theory - **(1951):**

The difference in the roles played by the bed and side in the stability of alluvial channels was recognized by Lindley. Blench determined two factors with the objective of separating the effects of sides and bed, and introducing the effect of sides in the slope equation. The factors were the bed sediment factor

$$F_b = \frac{V^2}{d}$$

and the side factor

$$F_s = \frac{V^3}{d}$$

For small bed loads, the channel geometry (i.e. bed width b, depth d and bed slope S) can be obtained by the following equations:

$$b = \sqrt{\frac{F_b}{F_s} Q}$$

$$d = \left(\frac{F_s}{F_b^2} Q\right)^{1/3}$$

$$S = \frac{F_b^{5/6} F_s^{1/2} V^{1/4}}{3.63 g Q^{1/6}}$$

For channels with a bed load concentration greater than 20 ppm, the equation for slope becomes

$$S = \frac{F_b^{5/6} F_s^{1/2} V^{1/4}}{3.63 Q^{1/6} g (1 + C/233)}$$

where C is bed load concentration in ppm and

$$F_b = F_b\ (1 \div 0.0126)$$

and

$$F_{b_o} = 1.9\sqrt{d}$$

where d is the mean diameter of the bed material.

Simons and Albertson Regime Method (1957):

Simons and Albertson analyzed river and canal data in a wider context that contained details regarding the bed and bank materials, as well as the rate of sediment transport. The canals from which some 113 reaches were studied belong to Pakistan and USA. The range of discharges studied was 5 to more than 9000 cusecs, with an average sediment discharge of 156 to 8000 ppm. The mean size of the bed material varied from 0.1 mm to 7.5 mm.

The types of canal bed and banks used by Simons and Albertson are:

1. Sand bed and banks;
2. Sand bed and cohesive banks;
3. Cohesive bed and banks;
4. Coarse non-cohesive material; and
5. Same as for 2, but with heavy sediment loads (2000 to 8000 ppm).

The proposed equations defining the geometry of the alluvial channel are:

$$P = K_1 Q^{1/2}$$

$$b = 0.9\ P$$

$$b = 0.92\ \mathbf{0} - 2.0$$

$$R = K_2 Q^{.36}$$

$$y = 1.21\ R \text{ for } R <= 7 \text{ ft.}$$

$$y = 2 + 0.93\ R \text{ for } R >= 7 \text{ ft.}$$

$$V = K_3 (R^2 S)^m$$

$$\frac{C_2}{g} = \frac{V^2}{gys} = K_4 (\frac{vb}{\nu})^{0.37}$$

where C is Chezy's constant, b and B are mean and surface widths, respectively, and y is the depth of the channel.

Coefficients and exponents for the above equations are:

	Channel Type				
Coefficients	1	2	3	4	5
K_1	3.5	2.6	2.2	1.75	1.7
K_2	0.52	0.44	0.37	0.23	0.34
K_3	13.90	16.00	-	17.90	16.00
K_4	0.33	0.54	0.87	-	-
m	0.33	0.33	-	0.29	0.29

Mushtaq and Rehman **(1961):**

The first attempt to determine the silt carrying capacity of channels designed by Regime equations was made by Mushtaq and Rehman of the Irrigation Research Institute (IRI) Punjab. E.M. Laursen's relationships giving the quantity of the total suspended and bed loads as functions of the stream and sediment characteristics were used by the authors. The field data of Upper Chenab Canal, Marala Ravi Link Canal and Lower Bari Doab Canal were used to test the following two parameters:

$$\frac{q_s}{q} = \phi (\frac{V}{R})^3$$

$$\frac{q_s}{q} = \phi (\frac{fV^4}{R})$$

where

q_s/q	=	Suspended silt charge;
V	=	Mean velocity;
R	=	Hydraulic mean radius;
f	=	Darcy - Weisbach friction factor; and
ϕ	–	means function of.

They found functional relationships for the above parameters, which was linear for the first function in the range V^3/R = **3·6** and consisted of a band represented by two lines for the second.

Modifying the parameters V^3/R to f^2 V (where f = Lacey's silt factor and utilizing the field data of the Punjab Canals: (L.C.C., U.C.C, L.B.D.C. and M.R. Link Canal), they found the approximate relationship for the silt charge as

$$C=0.1(f^2V)\sqrt{\frac{\tau/\rho}{W}}$$

where C = Suspended sediment charge of coarse and medium sand > 0.05 mm dia in gms per litre.

Also,

$$\sqrt{\frac{\tau/\rho}{W}}$$

where the above relation is a ratio of shear velocity and fall velocity of the sediment.

The above relationship was used to determine the permissible silt intensity of Lacey's Channel for various values of velocity and silt factor. It was found that Lacey's channels are capable of carrying about 500 ppm of silt intensity.

Study to Establish Hydraulic Design Criteria for Pakistan Irrigation System (1986):

Hydraulic design criteria developed by the PRC/CHECCHI for redesign of alluvial channels under the Irrigation System Rehabilitation Project (ISRP) was based on the rational approach. The proposed design method, called the design cycle, had three computation steps:

i) Width computation:
ii) Depth-Velocity computation; and
iii) Sediment transport capacity computation.

Selection of the correct slope would achieve a sediment transport capacity equal to the sediment input.

a) Depth-Velocity Relations Study

A number of velocity predictors including Lacey, Engelund (1966), White (1979), Karim (1981), Van Ryn (1985) were tested on ACOP (Alluvial Channel Observation Project) observed hydraulic data of Punjab and Sindh canals and all of thkm gave reasonable results. The best results were obtained from the approach based on Van Ryn's formula using an iterative method of computation. The method presented by Van Ryn was based on the prediction of bed form dimensions and, hence, the effective bed roughness which formed the basis for the prediction of flow depth. However, it was observed that inclusion of the ripple roughness is a necessary expansion for an accurate depth-velocity predictor in the canals of Pakistan.

b) Width Predictor Study

The relation between the equilibrium width of an alluvial canal and its hydraulic and sediment characteristics is not fully understood. The relations presented in the literature are therefore mostly empirical. They relate the width to discharge, slope with grain size, and occasionally to the soil characteristics. In this study, a number of width predictorsas given by Lacey (1929). Chang (1985), Yalin and Lai (1985), and Blench (1957) were tested.

All the formula show the same relationship between discharge and width:

$$B = XQ^{.5}$$

where X varies from 2.2 to 2.6 for Sindh and Punjab canals.

Observations based on an analysis of ACOP data sets disclosed there exists no relationship between the canal width and respectively depth, slope, sediment concentration and particle size D_{50} and D_{90}.

c) Sediment Transport Relations

A number of sediment transport relations as given by Ackers and White, Engelund and Hansen, Karim and Kennedy, Van Ryn and Yang were tested on ACOP sediment data observed for the Sindh and Punjab canals. The following were the observations of the consultants.

The available data sets seem to be inconsistent. Under the same hydraulic and sediment conditions, a wide range of concentrations have been measured. This is in contradiction to current theories for sediment transport. The results for the application of the selected transport formula are disappointing.

The consultants recommended the use of the Engelund-Hansen sediment transport relation for HDC under ISRP to determine the sediment transport capacity of the alluvial channels. They suggested that apparent inconsistencies in measured sediment concentrations require further explanation. A detailed measuring campaign by ACOP under supervision by an experienced "Sediment Transport Engineer" would be required.

Alluvial Channel Redesign Procedure (Naimatullah Cheema, et **al** 1992):

Cheema et al compared the sediment transport concept and the tractive force method with the Regime Theory as alternative design approaches for Punjab canals. The conclusion was that the sediment transport relations predict widely varying transport capacities of canals and show a poor correlation with sediment data observed in Punjab. Also, huge variations in sediment inflows over the year, and the lack of research work to account for the operating conditions of Punjab canals, make the sediment transport concept an inadequate choice as a design approach given that present stage of research. Practical considerations involve sediment distribution at offtake points, which has a vital influence on the design output. The sediment transport approach must take into account the silt induction of the outlets and the offtakes in accordance with carefully established criterion.

A relatively flatter slope of the downstream reach will not transport the sediment load conveyed by a steeper slope of the upstream reach. This poses a conceptual problem as the design approach is sensitive to the sediment charge. Practically, the channel dimensions get adjusted by distributing the effect over an extended length of the channel. Topography and channel command conditions impose a rather inflexible constraint on changing the bed slopes for most channels of Punjab canals. Heading up, as so frequently done at regulation points, generates a backwater which affects water surface slopes along a considerable length of the channel. When the channels are run in rotation, the effect of heading up becomes even more significant. A realistic computation of the sediment carrying capacity is not possible without considering the backwater effects of heading up.

The tractive force method does not effectively deal with the more common problem of sedimentation in Punjab canals. It does not as such qualify for a reliable design alternative.

Regime Theory is a dependable design tool for Punjab canals. There is a need for improvement of design equations used by the Punjab Irrigation and Power

Department. The Alluvial Channel Redesign Procedure (ACRP), developed by the authors based on data sets observed by ACOP and applicable for channels upto 1000 cfs discharge, uses accepted relations of Regime Theory. without the disputed estimation of Lacey's 'f'.

The controlling relations in ACRP are:

$$P=2.8Q^{1/2}$$

$$V=16R^{2/3}S^{1/3}$$

$$LF_r=0.195Q^{-0.025}$$

where LF, is a limiting Froude number.

Shahld and Watts **(1994):**

The authors proposed a new approach for the design of alluvial canal systems in Pakistan which was based on the analysis of ACOP data observed for Punjab canals. They suggested a modification in Lacey's regime equation to include the sediment concentration and sediment size in the slope equation. In the proposed procedure, the hydraulic geometry of the alluvial canal is expressed as simple exponential functions of discharge only. The values of the exponent vary from region to region and with the size of the canal.

The silt factor "f" in the regime equation was quantified by the following expression in relation to the total concentration of bed material load in ppm.

(a) For the Indus River,

$$f_c=\frac{(0.46+0.0046C_t)^{2/3}}{1+\frac{C_t}{465}}$$

(b) For the Jehlum River,

$$f_c=\frac{(0.50+0.005C_t)^{3/4}}{1+\frac{C_t}{470}}$$

(c) For the Chenab River,

$$f_c = \frac{(0.33 + 0.0033 C_t)^{7/8}}{1 + \frac{C_t}{395}}$$

where the channel slope is given by

$$S = \frac{(f_c)^{5/3}}{1840 (Q)^{1/6}}$$

The results showed that about 98% of the measured slopes are within ± 10% of the computed slopes.

The suggested design approach assumes that the sediment concentration in the channel is in the vicinity of 500 ppm (excluding wash load) and use of devices such as silt excluders or silt ejectors is recommended to control the excessive sediment entry into the canal.

Concluding Remarks:

In Pakistan, the earthen channels are still being designed using the Lacey's regime equations, as well as using empirical relations based on statistical correlations of bbserved channel geometry parameters and discharge flowing through the existing canals. The recently constructed canals (like Chashma Right Bank Canal (CRBC) earthen section) and the ongoing projects in N.W.F.P. (like Pehur High Level Canal Project) have been designed using regime concepts without considering the effect of sediment transport. In lined canal sections, the Manning's equations have been used for design purpose based on non-silting non-scouring velocity criteria. The results from monitoring of the CRBC indicate that sediment transport in alluvial and lined canal systems is an important concern for the efficient operation of the canal system and subsequent maintenance of the canals as well as sustainability of the irrigation system.

The sediment transport concepts have developed to such a level that they should now form a part of design strategy for alluvial and lined canal systems along with empirical approaches. There are a number of sediment transport equations available in the literature to predict the sediment transport capacity of the channel but they need validation to our canal system by properly monitoring the channels through sediment and discharge observations. The channel geometry parameters obtained from empirical relations need to be checked for sediment carrying capacity to have an adequate decision-making mechanism *so* as to address the problems of sedimentation and scouring in our canal system and to predict the behavior of channels due to variation of sediment concentration from the parent canal.

4. SEDIMENT TRANSPORT EQUATIONS DEVELOPED IN PAKISTAN

Introduction:

In Pakistan, the Irrigation Research Institute (IRI), Punjab has been involved in the study of sedimentation/sediment transport in canals of the Indus Basin Irrigation System, Sediment transport relations were evolved from the basic concept of tractive force using a sediment transport model given by E.M Laursen. The coefficient of these relations were obtained from the observed data of suspended sediment of canals in the Indus Basin system. In this context, the research work done by Dr. Mushtaq and Ch. Muhammad Ali of the Irrigation Research Institute is of great value and the sediment transport relations developed by them were considered by the Technical Sub-Committee for Evaluation of Alternative Hydraulic Design Procedure in 1987, along with the Engelund and Hansen sediment transport relation. This paper, based on a literature survey, gives a brief description of the sediment transport relations developed from time-to-time using CHOP (Channel Observation Programme) and ACOP (Alluvial Channel Observation Programme) observed hydraulic and sediment data.

Sediment Transport Relation by Dr. Mushtaq:

a) Incorporating Lacey's Silt Factor "f"

Dr. Mushtaq used E.M Laursen published the results of observations obtained on the total and suspended load transportation of two sands of median diameters (.04 and .11 mm) from experiments conducted on a recirculating flume at the Iowa Institute of Hydraulic Research (U.S.A). This data was used to test the following two parameters:

$$\frac{q_s}{q} = \phi\left(\frac{V}{R}\right)^3$$

$$\frac{q_s}{q} = \phi\left(\frac{fV^4}{R}\right)$$

where

q_s/q = the suspended silt charge
V = mean velocity
R = Hydraulic mean radius
f = Darcy-Weisbach friction factor given by $8\,g/c^2$
c = Chezy's coefficient

Modifying the parameters V^3/R to $f^2 V$, where f is Lacey's silt factor, which is given as:

$$f=0.75\frac{V^2}{R}$$

Utilizing the field data from the Lower Chenab, Upper Chenab, Lower Bari Ooab canals and Marala Ravi Link Canal, Dr. Mushtaq found the approximate relationship for the silt charge as:

$$C=0.1(f^2V)\sqrt{\frac{\tau/\rho}{W}}$$

where

C = Suspended sediment charge of coarse and medium sands (i.e greater than 0.05 mm dia) in gm/litre

$$\sqrt{\frac{\tau/\rho}{W}}$$

The above expression is the ratio of shear velocity and the fall velocity of the sediment.

The above relation for suspended sediment charge was used to determine the permissible average silt intensity of Lacey's channels for various values of velocity and silt factor.

b) Based on CHOP Data (1962)

Dr.Mushtaq proposed the following sediment transport equation for the Indus Basin System based on observed suspended sediment data during the Channel Observation Programme (CHOP) in 1962.

$$C=1000((1.13q^{1/3}-1)/7)^{1.5}$$

Let $q=Q/B_t$, then ;

$$C=1000(0.16(Q/B_t)^{1/3}-0.14)^{1.5}$$

where

C = Bed material transport capacity in ppm
Q = Channel discharge in cusecs
B_t = Top width in feet

c) Eased on ACOP Data tor Establishing Simplified Hydraulic Design Criteria

The simplified equation for predicting sediment transport capacity was developed by Dr.Mushtaq as a member of an expert committee for evaluation of alternative hydraulic design procedures. At first, the decision was made regarding the selection of channel flow variables which could be used as independent variables in a simplified sediment transport equation. The ACOP data base for hydraulic equilibrium of channels and the observed sediment concentrations were used in this analysis. The selected independent variables were discharge Q, top width B_t ,water surface slope in ft/1000 ft S_* and mean sediment size of bed material d_{50} in mm. The required coefficients for a best fit curve were obtained by least squares regression technique. The resulting equation predicting sediment transport capacity of a channel as proposed by Dr. Mushtaq is as under:

$$C=54((Q/B_t)^{2/3}\frac{S_*}{(d_{50})^{.86}}-1)^{1.5}$$

where

C = Sediment transport capacity in ppm
Q = Discharge in cusecs
B_t = Top width in feet
S_* = Water surface slope in ft/1000 ft
d_{50} = Mean size of channel bed material in mms

Sediment Transport Relation by Ch. Muhammad Ali (1987):

Ch.Muhammad Ali, a research scientist with the Irrigation Research Institute, proposed his own sediment transport equation while working as a member of the expert committee for evaluation of alternative hydraulic design procedures in 1987. The function S. V/W was plotted against sediment concentration *C* from international literature which resulted in the following equation:

$$0.2C^{3/4}=\frac{VS_*}{W} \quad for\ C >= 100\ ppm$$

where

C = Bed material load concentration (ppm)
V = Average velocity (ft/s)
S. = Water surface slope in ft/1000 ft
W = Particle fall velocity in still water (ft/s)

The values of particle fall velocity W in the above sediment transport relation were taken from Ruby's curve or Ruby's equation, which is given below:

$$W = 1.57 * 10^{-3} d_{50}^{1.54} T^{.35}$$

where

d_{50} = Grain size diameter of bed material load in ($ft * 10^4$)
T = Water temperature in °C

The resulting sediment transport equation as proposed by *C.* Muhammad Ali is given below:

$$C = 3.41 \times 10^{4} Q^{.19} \frac{S_*^{1.5}}{d_{50}^{1.88}} T^{.47}$$

Comparison of Sediment Transport Relations:

There have been two sediment transport relations developed in Europe (i.e Engelund-Hansen and Ackers and White equations) which has been proposed by the Consultants for prediction of sediment carrying capacity of channels in the Indus Basin System. Both of these formulae are based on the stream power concept given by Bagnold. Bed material load (i.e bed load plus the suspended load excluding the wash load) in terms of sediment concentration is determined by these equations.

Engelund-Hansen obtained the following sediment transport relation using laboratory flume and field data, which was analyzed using the dimensionless shear stress parameter given by Shields.

$$C_s = 0.05\left(\frac{s}{s-1}\right)\frac{US}{((s-1)gd)^{1/2}}\frac{RS}{(s-1)d}10^6$$

where

C_s = Sediment concentration in ppm
s = Specific gravity of sediment particle
U = Average velocity of flow in channel
S = Bed slope or water surface slope
R = Hydraulic radius of channel
d = Median fall diameter of bed material In mm

Based on Bagnold's stream power concept, Ackers and White (1973) related the concentration of bed material load as a function of the mobility number F_g:

$$C_s = cs\frac{d}{R}\left(\frac{U}{U_*}\right)^n\left(\frac{F_g}{A}-1\right)^m 10^6$$

where

C_s	=	Sediment concentration in ppm
d	=	Average particle diameter in mm
s	=	Specific gravity of sediment particles
U	=	Average velocity of flow
U.	=	Shear velocity which is expressed'as

$$U_* = \sqrt{gRS}$$

and

n,c,m and A are coefficients.

The mobility number F_g is given by;

$$F_g = \frac{U_*^n}{[gd(s-1)]^{1/2}}\left[\frac{U}{\sqrt{32}\log(\frac{10R}{d})}\right]^{1-n}$$

They also expressed the sediment size by a dimensionless grain diameter d_g;

$$d_g = d\left[\frac{g(s-1)}{\nu^2}\right]^{1/3}$$

where v is the kinematic viscosity of water.

The coefficients c,m,n and A have been determined by laboratory flume data with sediment sizes greater than 0.04 mm and Froude Numbers **less** than 0.8. Values of thekoefficients, as modified by Ackers and White in 1990, are given below:

$$m = \frac{6.83}{d_g} + 1.67 \quad for \quad 1 \le d_g \le 60$$

$m = 1.78$ for $d_g > 60$

$$\log c = 2.79 \log d_g - 0.98 (\log d_g)^2 - 3.46$$

for $1 <= d_g <= 60$
$c = 0.025$ for $d_g >= 60$
$n = 1 - 0.56 \log d_g$ for $60 >= d_g >= 1$
$n = 0$ for $d_g > 60$

$$A = \frac{0.23}{(d_g)^{1/2}} + 0.14 \quad for \quad 60 \ge d_g > 1$$

$A = 0.17$ for $d_g > 60$

The sediment carrying capacity of Lacey's channel section from 30 cfs to 3000 cfs has been calculated for 0.2mm average particle diameter by the following sediment transport predictors:

a) Engelund Hansen Formula
b) Ackers and White Formula
c) Mushtaq's Formula
d) Mushtaq's Formula based on Lacey's f

The Lacey's channel section geometric parameters for varying discharges are based on average sediment particle size of 0.20 rnm and a corresponding silt factor of 0.79, which are tabulated below:

Table 4.1.

Q (cfs)	f	B (ft)	D (ft)	Z	S
30	0.79	9.88	2.12	0.50	0.000206
100	0.79	20.15	2.93	0.50	0.000168
300	0.79	37.23	4.03	0.50	0.000140
500	0.79	49.20	4.70	0.50	0.000129
800	0.79	63.40	5.42	0.50	0.000119
1000	0.79	71.46	5.80	0.50	0.000115
1500	0.79	88.70	6.58	0.50	0.000107
2000	0.79	103.33	7.19	0.50	0.000102
3000	0.79	127.99	8.16	0.50	0.000095

The sediment transport capacity *of* Lacey's channel section for varying discharges has been computed using the following parameters;

a) average sediment particle size = 0.20 mm
b) specific gravity of sediment particles = 2.65
c) kinematic viscosity = 0.0000159 ft^2/sec
d) sediment particle fall velocity = 0.08 ft/sec

The **results** of the analysis are indicated in the graph given in Figure 4.1.

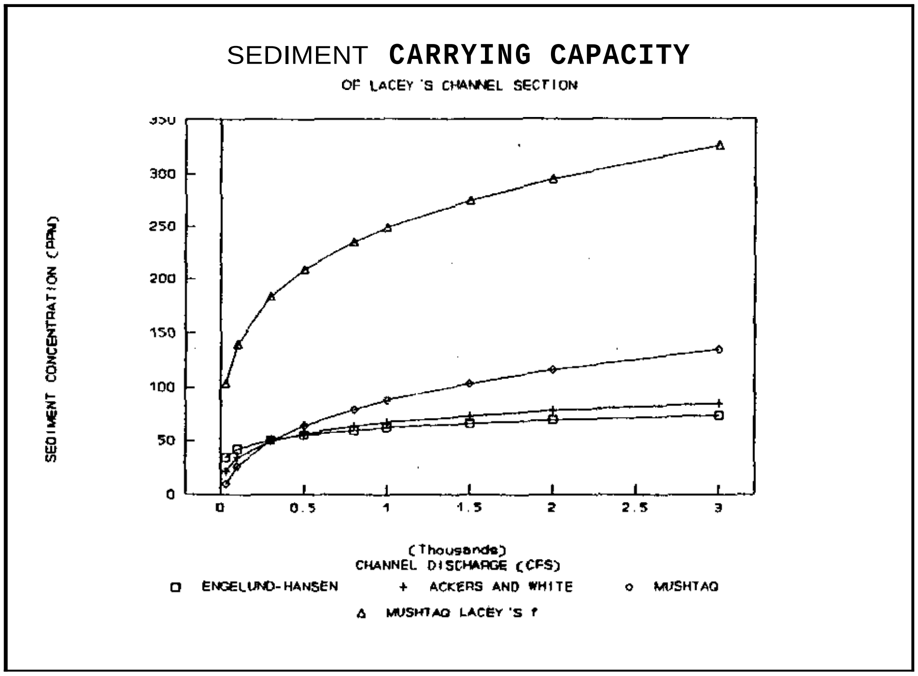


Figure **4.1.** Comparison of sediment transport predictions for Lacey's Channel Sections.

Formulas for predicting sediment concentration can be found in abundance. Such relations have been developed for noncohesive sediment in steady uniform flow. All existing sediment formulas have been established relying on calibrations using flume and field data supposedly under steady uniform flow conditions. Sediment transport formulas are based on the following three approaches (Chang, **1988):**

1) Shear Stress Approach: The shear stress approach is based on tractive force per unit area applied to the channel boundary on which the bed load moves by rolling, sliding and sometimes saltating (Duboys, Shield formula, Einstein bed load functions, Meyer-Peter-Muller formula, Einstein Brown and Parker et al formula).

2) Power Approach: The stream power approach is based on the rate of energy expenditure per unit bed area that is a product of bed shear stress and mean flow velocity (Engelund-Hansen formula, Ackers and White formula, and Yang formula).

3) Parametric Approach: (Colby relations) The parametric approach is based on channel and sediment parameters.

The phenomenon of sediment particle suspension in an alluvial channel has been explained by Khalid Mahmood (1990) as follows:

> After the critical shear stress has been exceeded, sediment particles are entrained by the flow at the bed itself. Initially, the movement of entrained particles is by rolling, sliding or hopping, that essentially remains a bed load transport. As the boundary shear stress becomes more intense, the entrained particles are thrown into suspension by turbulent eddies emanating from the bed. Physically, the suspension of sediment is a turbulent diffusion process from a high concentration of particles in the bed to zero concentration at the water surface. This process cannot be completely simulated by sediment transport equations based on either the shear stress approach, power approach or parametric approach. Because of the complexity of the sediment transport processes, prediction of the transport rate has not been accomplished following a theoretical pursuit.

Concluding Remarks:

The sediment transport equations developed by the scientists of the Irrigation Research Institute are empirical in nature based on the statistical correlations. They represent the narrow range of the data base for hydraulic as well as sediment data observed by CHOP and ACOP. These formulae need validation to a larger data base in the Indus Basin system and other systems of the world. In Pakistan, flume studies on sediment transport have been done in a very limited way. Flume studies were carried out at the Nandipur Research Station of the Irrigation Research Institute of Punjab, but no efforts were made to develop sediment transport relations from the observed data base.

Cheema et al (1992) while comparing the different sediment transport relations (such as Engelund-Hansen, Acker's and White, Karim & Kennedy, etc.) and the sediment transport relation given by Dr. Mushtaq for simplified hydraulic design criteria (1987), showed an entirely different trend as compared with other formulae. Also, each sediment transport relation for a given set of hydraulic parameters and sediment concentrations gave widely varying sediment transport capacities for a channel. This fact indicates, that in Pakistan, there is a large scope for research in determining a sediment transport relation which can be used in a sediment transport model for canals of the Indus Basin Irrigation System based on physical principles of fluid mechanics and sediment transport dynamics in alluvial channel flow. The sediment transport model should have the ability to simulate the channels in silting as well as scouring conditions, that is, it should be able to explain the phenomenon of sedimentation as well as scouring in a channel system.

5. SEDIMENT SAMPLING TECHNIQUES AND THEIR IMPROVEMENT/ IMPROVISATION IN PAKISTAN

Introduction:

Sediment transported by streams/Irrigation canals presents problems like silting and scouring of irrigation channels, silting of reservoirs, meandering of rivers, accretion of levels causing increased frequency of flooding, with which Irrigation Engineers are directly concerned. A knowledge of the nature and amount of silt transported is useful and to attain this objective, silt samples are taken from channels and analyzed.

In the Punjab, silt observations have been carried out extending over a number of years on certain selected channels to study Lacey's silt factor and other problems connected with silt. Observations are also made at canal headworks to determine the amount of silt passing through the head regulator in order to supply information regarding the concentration of silt, to the officer in- charge of regulation at the headworks. At certain headworks. observations are made to determine the silt concentration in the river pocket for use in the design and working of the silt excluder within the river pocket. Similar observations in the canal are also made in connection with the design and working of silt ejectors. At specified regulators and offtakes, silt observations are carried out to investigate the distribution of silt between the parent channel and the offtake.

Suspended Sediment Samplers **(1941-42-IRI)0:**

Samples of silt-water mixture are taken from the channel at any specified site and depth by means of one of the following suspended silt samplers:

i) The Bottle Sampler
ii) The Tait Binckley Sampler
iii) The Uppal Sampler

Bottle Sampler

The silt sampler mostly used in the Punjab is a bottle sampler. It consists of a brass frame holding a one liter bottle fitted with a rubber stopper. The stopper is operated by a lever at the top of the suspension pipe. When the lever is pressed down, the bottle is opened. The length of the suspension pipe of the sampler is varied to suit the depth of water in the channel at the sampling site. The two essentials regarding the working of the sampler are:

a) The mouth of the bottle should be opened only when it reaches the required depth; and

b) The mouth of the bottle should be kept open for the minimum time required to fill the bottle.

Tait-Binckley Sampler

The Tait-Binckley sampler consists of a control pipe with rubber extensions on both sides. The extensions are twisted by an arrangement fitted at the top of a suspension pipe to enclose a sample of water. The sampler is shown in Figure-5.1.

Uppal Sampler

This sampler consists of a brass barrel with guides fitted at each end. Brass diaphragms move in the guides vertically like the shutters of a camera. Both the diaphragms and guides are given a slight taper to secure a leak tight contact. The top ends of the diaphragms are connected together by an iron rod, which is worked by a lever at the end of the suspension pipe. The sampler is shown in Figure-5.2.

The sediment sample analysis from these samples give information regarding coarse, medium and fine silt. For detailed analysis regarding the size of the particles, a large quantity of suspended silt has to be collected. About 30 to 50 one-liter samples are taken from each point and collected in a bucket. The top clear liquid is syphoned off and the residue is collected after removing the fine particles by decantation. The residue is graded by means of standard sieves.

Silt Sampling of Bed Material:

Samples of bed silt have been taken and analyzed for determining the nature of material forming the bed and also any periodical variation of the grading of the bed silt. Bed silt samples are taken with the help of a special apparatus - the bed silt sampler. This sampler consists of an eccentrally mounted scoop and a corol. At the top end of the suspension pipe, a handle is fitted which is connected to the scoop by means of a wire and pully arrangement. For taking a sample, the apparatus is lowered to the bed and the handle at the top rotated which in turn rotates the scoop. The sampler collects about 2 lbs of bed material which is air dried and about 1 lb of material is packed in an empty tin.

There are three types of siltometers which are used to analyze the bed silt samples:

i) Vaidhinathan's optical siltometer;
ii) Puri's siltometer; and
iii) Uppal's air sittometer.

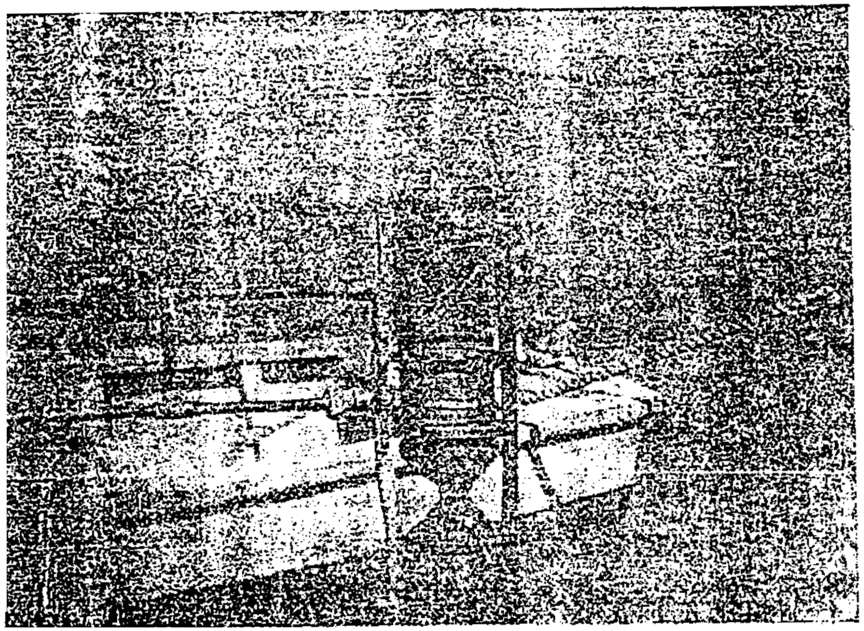


Figure 5.1. Tait-Binckley Sampler.

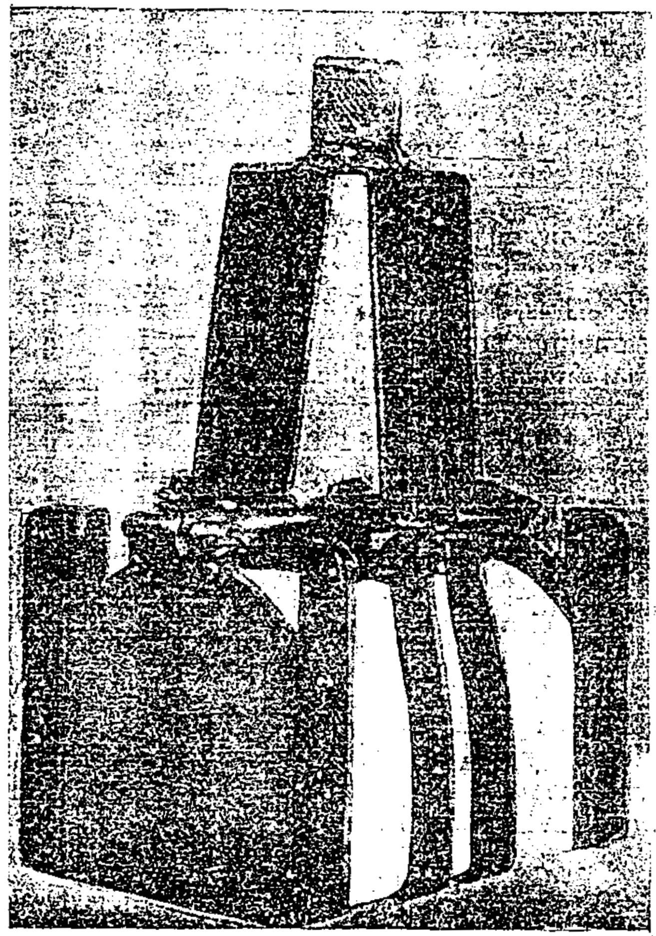


Figure 5.2. Uppal Sampler.

With the help of these siltometers, it is possible to determine the quantities and proportions of different sizes of particles in a representative sample.

Sediment Samplers used **by ACOP/ISRIP:**

In this section, various types *of* instrumentation and measurement procedures, including equipment and methodology used by ACOP/ISRIP for sediment research on Pakistan canals, have been described. The procedures of sediment sampling are similar to those used by the **USGS** but, however, these have been modified/amended to suit the local conditions. In addition, some new instrumentation/improvisations have been successfully developed to improve the existing procedures for suspended sediment sampling. Following are the different samplers used for collection of suspended sediment samples.

1. DH - 48 and DH - **59** (Hand-held Samplers)

   Where streams can be waded, or where a low bridge is accessible, a choice of two lightweight hand samplers can be used to obtain suspended sediment samples.

   The smallest of the two is designated 'DH-48' (Figure-5.3). It consists of a streamlined aluminum casting, 13 inches (33 cm) long, which partly encloses the sample container. The container, usually a round pint glass milk bottle, is sealed against a gasket in the head cavity of the sampler by a hand operated spring tensioned pull-rod assembly at the tail of the sampler. The sample is collected through the intake nozzle and is discharged into the bottle. The displaced air from the bottle is ejected downstream through the air exhaust alongside the head of the sampler. The sampler, including the container, weighs 4.5 pounds (2 kgs). **A** standard stream gauging wading rod, or other suitable handle, is threaded into the top of the sampler body for its suspension. The instrument can sample to within $3^{1}/_{2}$ inches (9 cms) *of* the stream bed. It is calibrated with a nozzle that has an inside diameter of **1/4** inch (6.3 mms). However, a 3/16 inch (4.8 mms) nozzle may also be used.

   The other lightweight sampler, designated 'DH-59' (Figure-5.4) is designed to be suspended by a hand held rope in stream too deep to be waded. It too, only partly encloses the sample container. The sampler body is 15 inches (3.8 cms) long, is made of bronze in the form of a streamlined casting, and weighs about 24 pounds (1 1 kg). Because of its light weight, it is limited in use to streams with velocities less than about 5 feet per second (1.5 meters per second). The tail vane of the sampler extends below the body of the sampler and the bottle. This extension forces the sampler nozzle to orient itself into the flow before submergence. The sampler will not traverse closer than about **4**

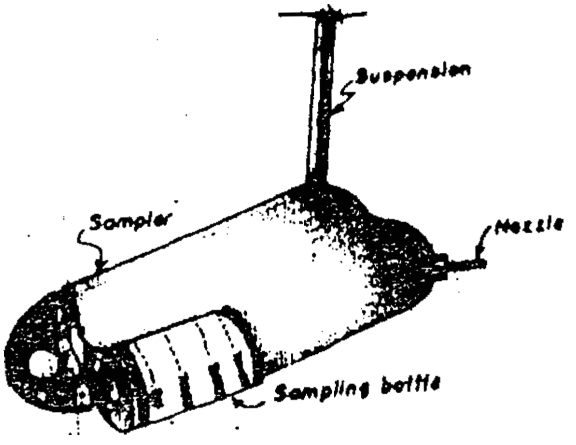
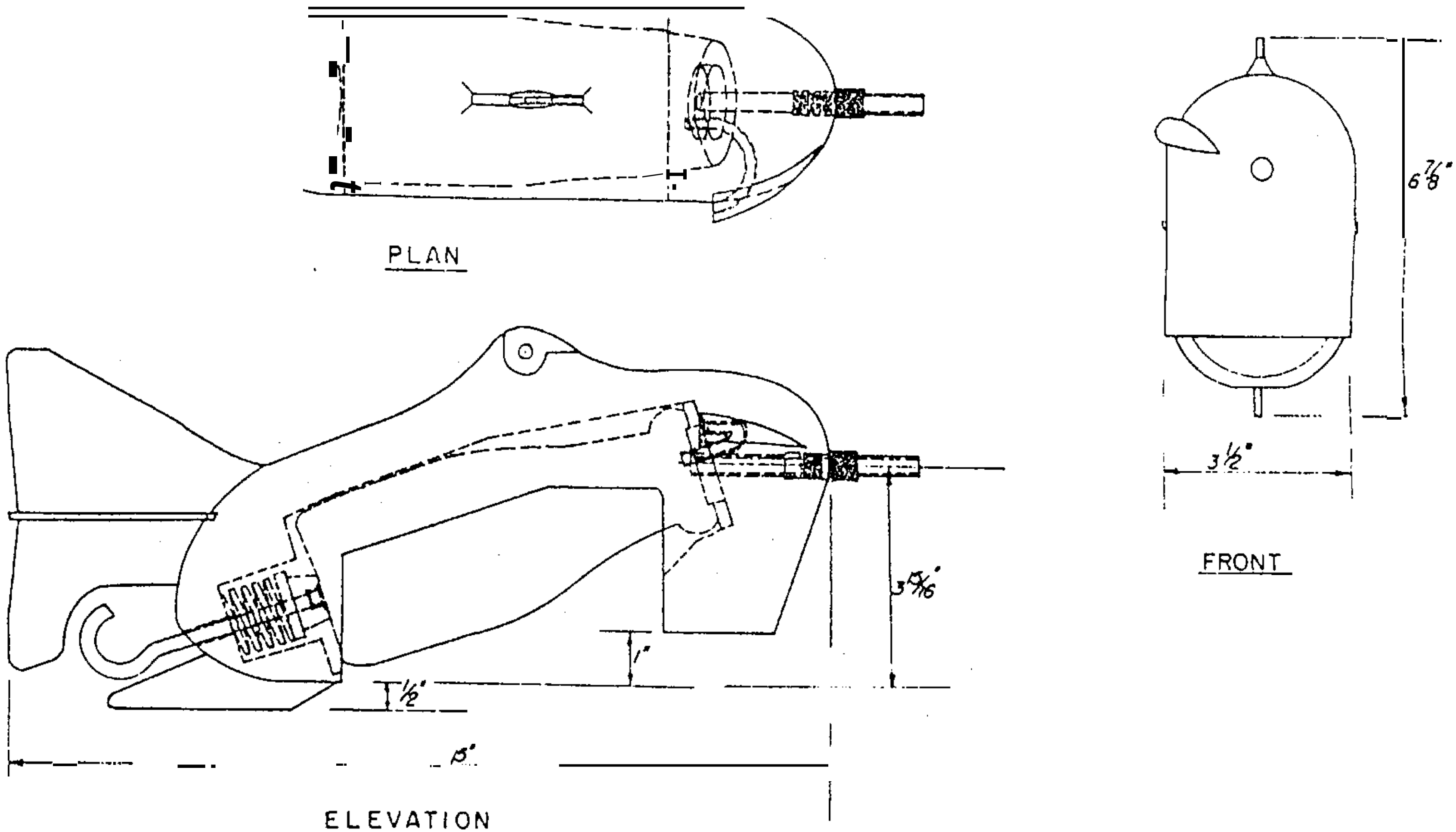


Figure 5.3. Suspended - Sediment Sampler US OH-48 Hand Line Suspension,



IV - 35

Figure 5 4. Suspended Sediment Sampler US DH-33 Hand Line Suspension inches (10cm) of the stream bed. The instrument is calibrated and supplied with 1/4 inch (6.3 mm) 3/16 inch (4.8 mm) and 1/8 inch (3.2 mm) nozzles.

2. D-49 (Cable and Reel Sampler)

The D-49 suspended sediment sampler (Figure-5.5) is a depth integrating instrument designed for use in streams not more than about 15 feet (4.5 meters) in depth. The sampler has a streamlined body weighing about 62 pounds (28 kg) which is recessed to accommodate a round 1 - pint milk bottle sample container. Tail vanes to orient the instrument into the direction of flow and an air escape passage are cast integrally. The head of the sampler is drilled and tapped to receive the intake nozzles, and hinged to permit access to the sample bottle cavity by releasing the catch and swinging the head downward, away from the hanger bar support. Nine brass nozzles, three each with 1/4 inch (6.3 mm), 3/16 inch (4.8 mm) and 1/8 inch (3.2 mm) diameter bore, threaded to permit hand assembly to the head, are supplied with the instrument. In the sampling operation, the head should be oriented upstream with the nozzle pointed directly into the current, and the sampler lowered from the water surface to the stream bed and then raised to a position above the water surface.. A stream filament, continuous during the period of submersion, is intercepted by the nozzle and discharged into the sample container. During the collection of a water-sediment sample, the air displaced from the bottle is ejected through the air escape passage which points downstream. The instrument provides a fixed static head differential of 1/2 inch (12.5 mm) to facilitate sampling in low stream velocities and slack waters.

The D-49 integrating suspended sediment sampler continues to accumulate a sample in a flowing stream throughout the period of submergence, even after the sample bottle has been filled. If the sample bottle becomes completely filled during a sampling operation, a representative sample will not be obtained and the sample must be discarded. Samples must be collected in clean bottles and covered with suitable bottle caps to prevent contamination or loss of the sample. Capacity of the bottle is about 470 cc., however, the bottle is inclined to the vertical to such a degree that any sample containing more than 440 cc. of a water-sediment mixture may be in error. The period of submergence should be sufficient to produce sample volumes less than 440 cc., but greater than 375 cc., in order to obtain a sample large enough for a laboratory analysis. (In ACOP the normal practice is to obtain at least three samples at each vertical and then composited to obtain a sufficient quantity of sample for laboratory analysis).

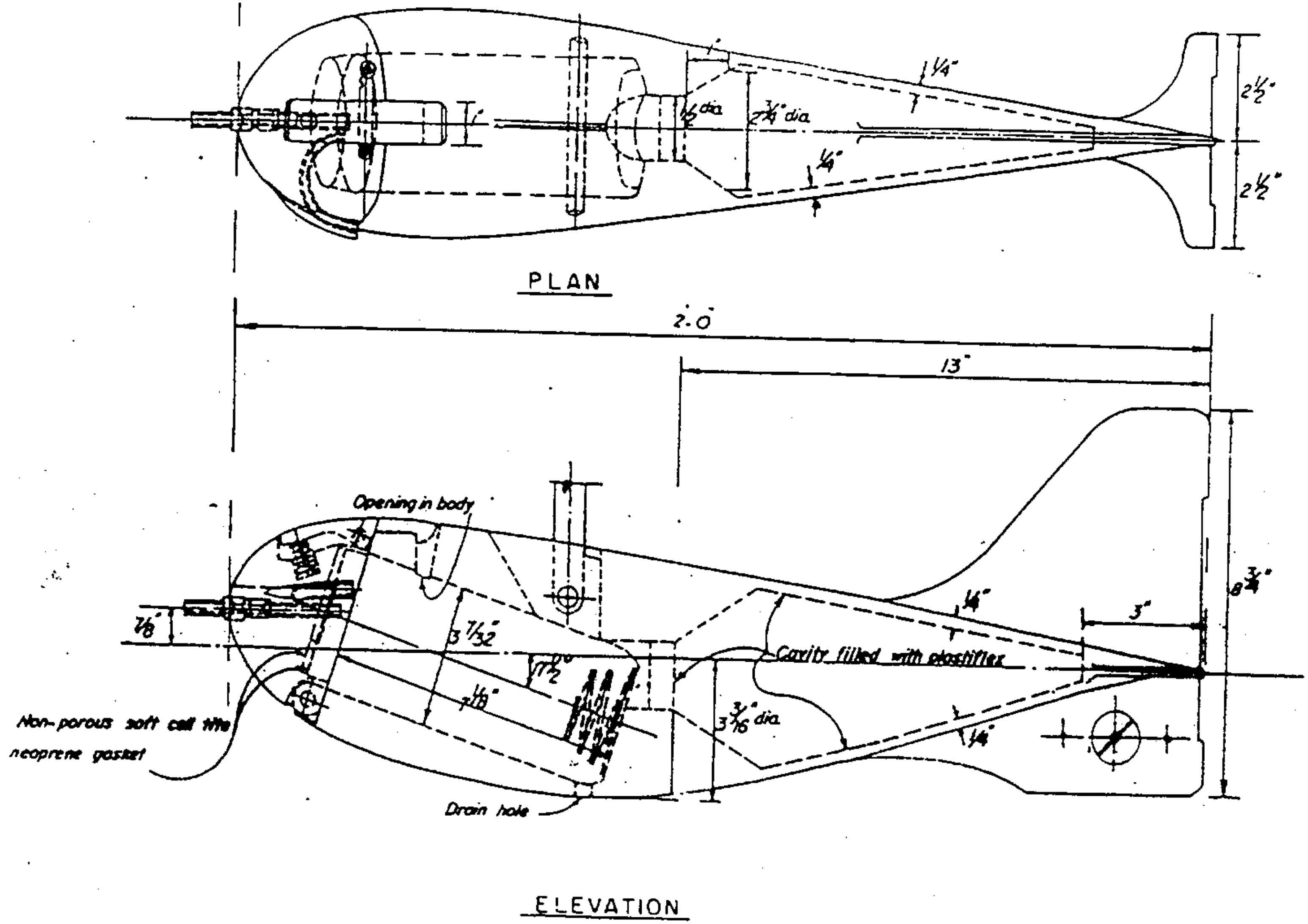


Figure 5.5. Suspended - Sediment Sampler US DH-49 Hand Line Suspension.

3. P-46, P-61 and P-50 (Point Integrating Samplers)

Point integrating samplers are more versatile than the simple depth integrating types. They can be used to collect a sample that represents the mean sediment concentration at any selected point beneath the surface of a stream except within a few inches of the bed, and also to sample continuously over a range of depths. They are used for depth integration in streams too deep (or too swift) to sample in a round trip integration. In depth integration, sampling can start at any depth and continue in either an upward or downward direction for a maximum vertical distance of about 30 feet (9 meters).

A point integrating sampler has a 3/16 inch (4.8 mm) nozzle that points directly into the stream flow, and an air exhaust that permits air to leave the samplelsamplerlcontainer as the sample enters. The intake of the exhaust passages are controlled by a valve. When the valve is in the sampling position, the sampling action is the same as in a depth integrating sampler. A pressure equalizing chamber (diving bell principle) is enclosed in the sampler body to equalize the air pressure in the container with the external hydrostatic head at the intake nozzle at all depths. The inrush, which would otherwise occur when the intake and air exhaust are opened below the surface of the stream, is thereby eliminated.

The sampler P-46 (Figure-5.6) consists of a 100 pound (46 kg) streamlined cast bronze shell, and inner recess to hold a round pint milk bottle, a pressure equalizing chamber, and a tapered three position rotary valve operated by a solenoid which controls the sample intake and air exhaust passages. The three positions for the valve are: (i) intake and air exhaust closed, pressure equalizing passage open; (ii) intake and air exhaust open, equilizing passages closed; and (iii) all passages closed. As the sampler is submerged, water enters the pressure equalization chamber through a permanent opening in the bottom of the shell, and this compresses the air in the chamber and sample container.

The 105 pound (48 kgs) P-61 sampler (Figure-5.7) is similar to P-46, but is simpler and somewhat less expensive. It can be used for depth integration as well as for point integration for stream depths of at least 180 feet (55 meters), whereas P-46 is limited to 75-100 feet (22-30 meters) depending on the arrangement of the air exhaust in the sampler head. The sampler valve for P-61 has two positions instead of three in P-46. When the solenoid is not energized, the valve is in the non-sampling position whereby the intake and air exhaust passages are closed. The air chamber in the body is connected to the cavity in the sampler head, and the head cavity is connected through the valve to the sample container. When the solenoid is energized, the valve is in the sampling position, whereby the intake and air exhaust are open and the

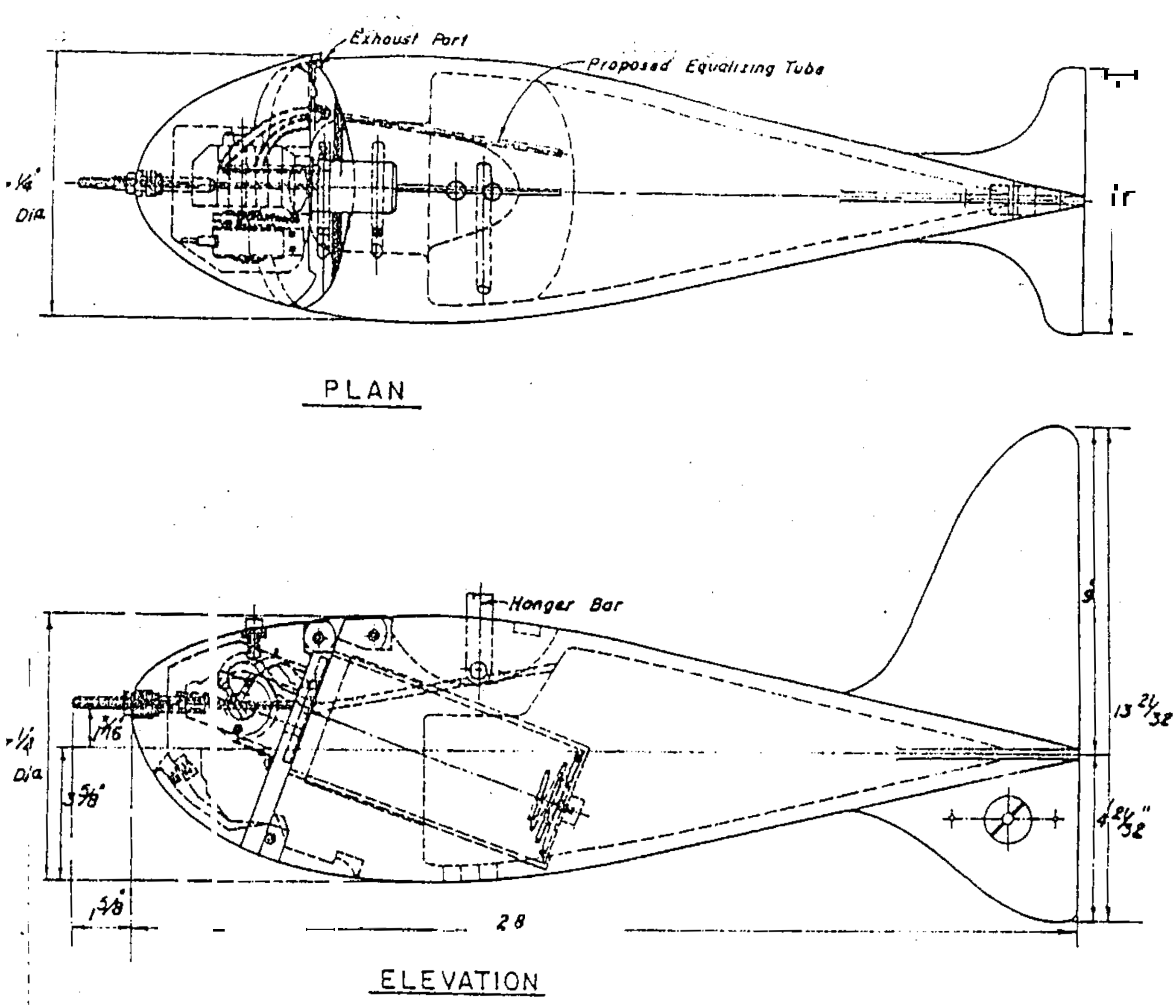
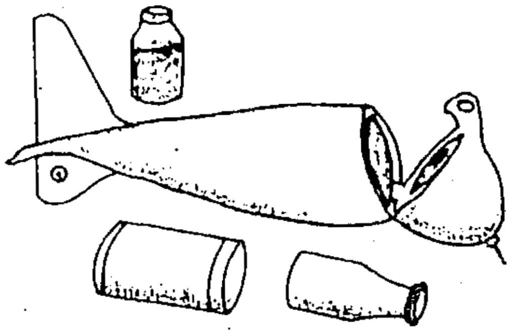


Figure 5 6. Point Integrating Suspended - Sediment Sampler, USP-46



{105 lb (48 kg) for depths upto 180 ft. (55 m)}

Figure 5.7. Point - Integrating Suspended-Sediment Cable-And-Reel Sampler US **P-61.**

connection from the sample container to the head cavity is closed. **P-61** can also be modified to accommodate a quart sized mayonnaise bottle. When the ordinary pint bottle is used, the cylindrical adapter must be inserted into the bottle cavity. The maximum sampling depth should be limited to about 120 feet (36 meters) when the quart sized container is used.

US P-63, A 200 pound (91 kg) electrically operated suspended sediment sampler, is better adapted to very great depths and high velocities. P-63 differs from the P-61 mainly in size, weight, and in the capacity of the sample container that can be used. P-63 (Figure-5.8) is cast bronze, 34 inches (86 cms) long, and has the capacity for a quart sized round milk bottle. An adapter is furnished *so* that a round pint sized milk bottle can also be used. The maximum sampling depth is about 180 feet (55 meters) with a pint sample container and 120 feet (36 meters) with a quart container.

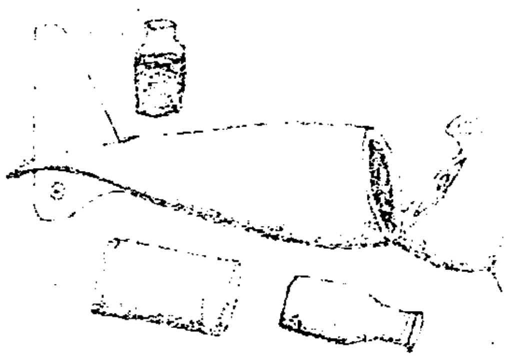
The 300 pound (136 kg) P-50 sampler (Figure-5.9) is designed for use in extremely deep streams and high velocities. This sampler has some obvious handling difficulties due to excessive weight and is normally used for hydrographic surveys in large reservoirs.

All the point samplers are designed for suspension with a steel cable having an insulated inner conductor core. By pressing a switch located at the operator's station, the operating current may be supplied through the cable to the solenoid in the sampler head by storage batteries connected in series to produce 24 to 48 volts. If the suspension cable is longer than 100 feet (30 meters) a higher voltage may be desirable.

4 ACOP Pumping Sampler an Improvisation

Presently, ACOP has improvised their own P-type samplers for Obtaining point integrated samples. They have developed a sophisticated point integrating pump sampler of its own which is more convenient and a very precise instrument.

ACOP, with the help and assistance of the US collaborating agency (Colorado State University), has developed a Pumping Sampler (Figure-5.10) designed for collecting point integrated suspended sediment samples from sand bed channels. The sampler is designed to be a robust device that requires a minimum of field maintenance over long operational periods. It is also designed to obtain a large volume of samples by directly filtering out the sediment from the pumped supply besides obtaining the periodic pint bottle samples.



{34" long, 200 lb (91 kg) for depths above 180 ft (55 m)}

Figure 5.8. Point - Integrating Suspended-Sediment Cable-And-Reel Sampler **US** P-63.

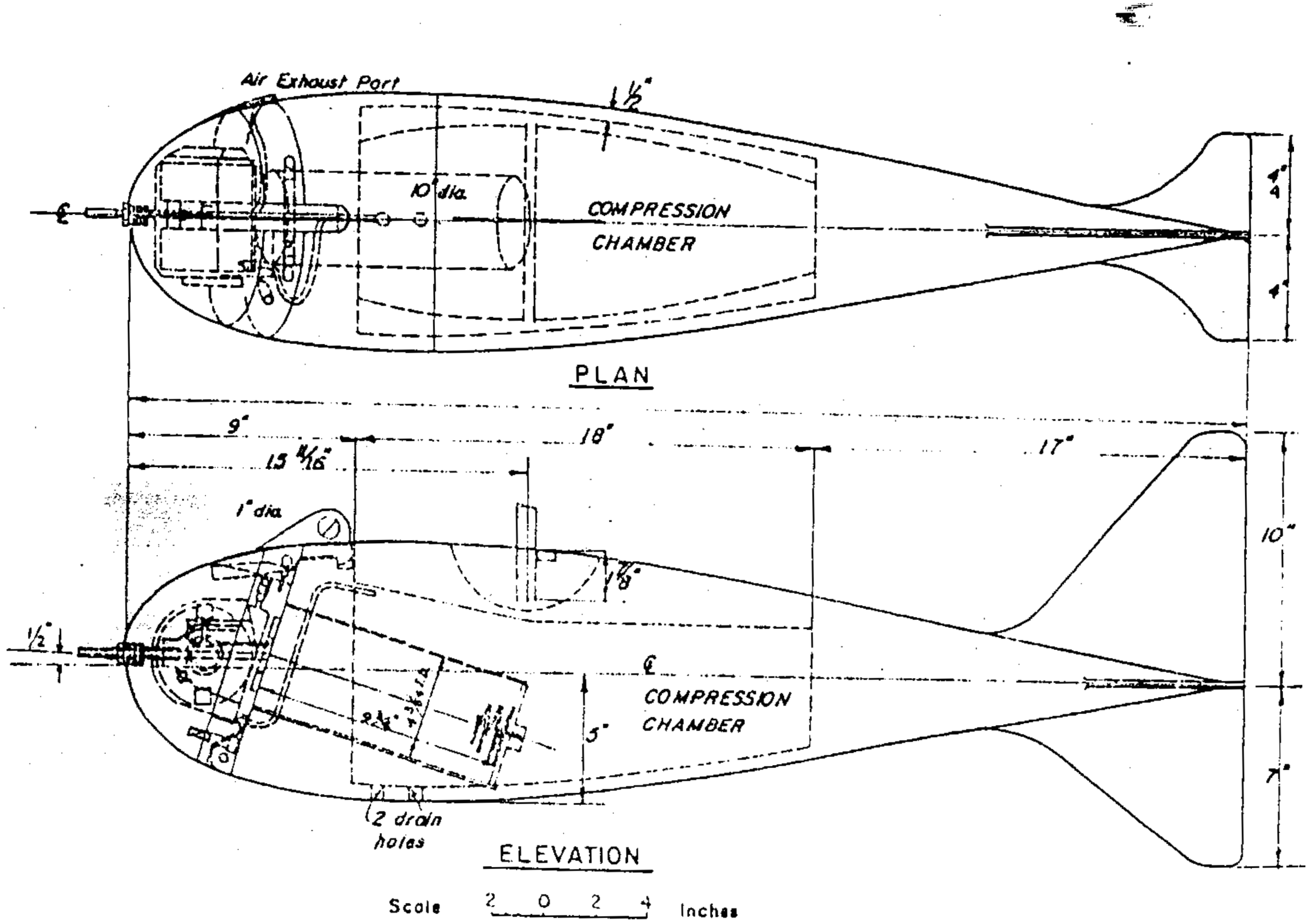


Figure 5 3 Point - Integrating Suspended-Sediment Sampler USP-50

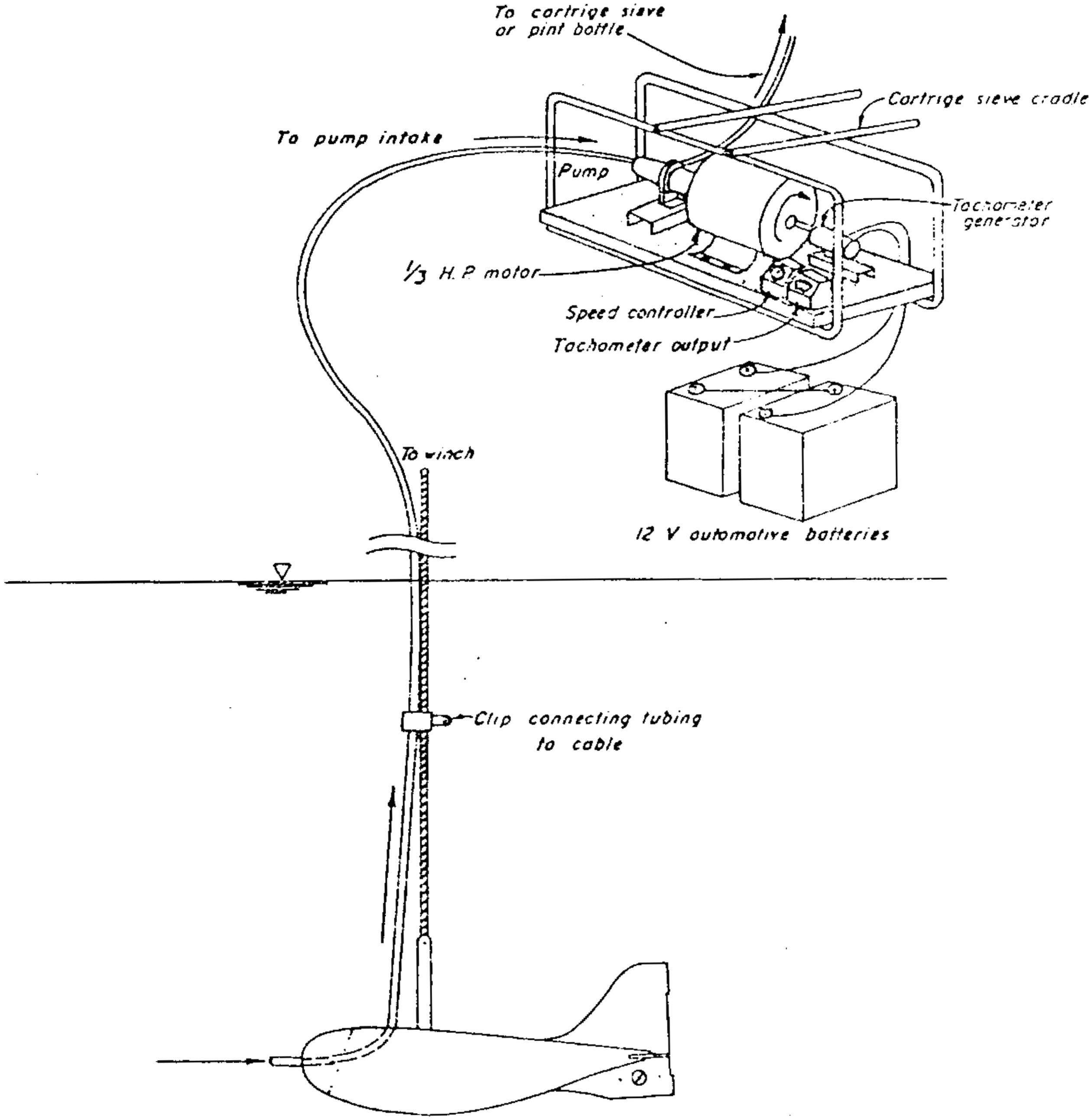


Figure 5.10. Layout **of** ACOP Pumping Sampler.

The Pumping Sampler is a point integrating device. It draws a water-sediment sample through a nozzle directed into the flow which is connected to a positive displacement pump. The pump is powered by a 12 volt lead battery. The velocity of water through the nozzle is manually controlled by using different size nozzles and varying the discharge of the pump. This type of operation avoids the use of an automatic velocity and feed-back electronic control in the sampler. A necessary operation for using the pumping sampler, therefore, is the prior determination of velocity at each point of sampling.

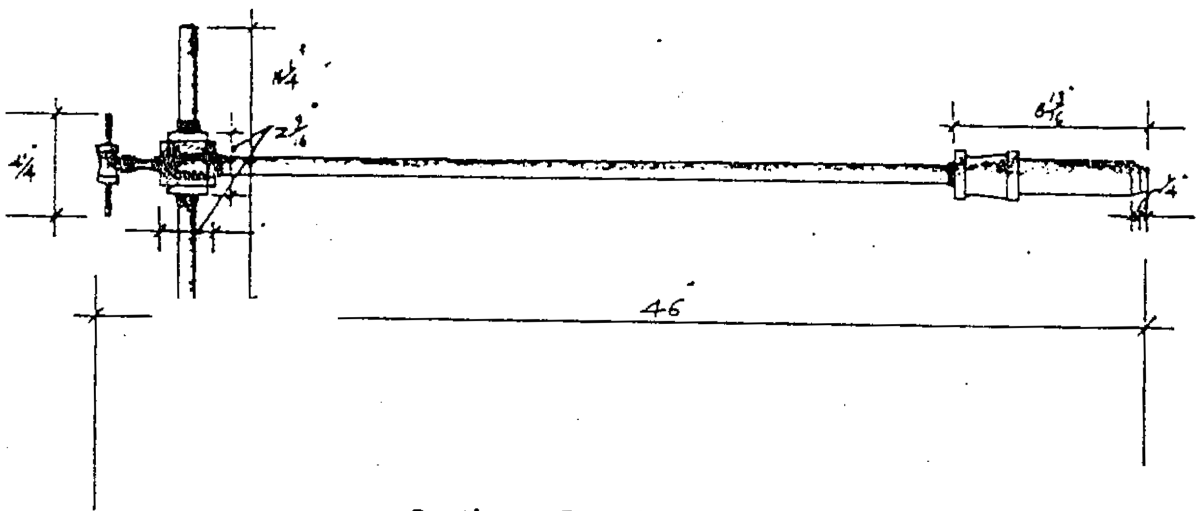
Bed Material Sampling:

Bed material samples are collected by different samplers as described hereunder. These samplers are physically limited to those capable of collecting bed material samples consisting of particles coarser than about 30 or 40 microns in diameter.

1. BMH-53 and BMH-60 (Hand-held Samplers)

The Federal Inter-Agency Sedimentation Project (F.I.A.S.P) of USA developed three types of instruments for sampling the bed material of streams where most of the material is finer than medium gravel. The smallest of the three, designated as the BMH-53 sampler (Figure-5.11) is designed to collect core samples from the bed of wadeable streams. The instrument is 46 inches (1.5 m) in total length and usually is made of corrosion resistant materials. The collecting end of the sampler is a stainless steel thin-walled cylinder 2 inches (5 cm) in diameter and 8 inches (20 cm) long with a tight fitting brass piston. The piston is held in position by a rod which passes through the handle to the opposite end. The piston creates a partial vacuum above the material being sampled, thereby compensating in a reverse direction for some of the frictional resistance required to push the sampler into the bed. This particle vacuum also retains the sample in the cylinder while the sampler is being removed from the bed. The piston also serves to force the sample from the cylinder in a manner that results in a sample column with a minimum of distortion from which material at different depths from the surface may be visualized and sub-samples obtained.

Bed material of deeper streams or lakes can be sampled with the BMH-60 sampler (Figure-5.12). This is a hand-line sampler about 22 inches (56 cm) long, made of cast aluminum, has tail vanes, and is available in weights of 30, 35 or 40 pounds (13.6, 15.9 or 18.2 kg). Because of its light weight, its use is restricted to streams of moderate depths and velocities and whose bed material is also moderately firm and yet does not contain much gravel.



Sectional Elevation

Figure 5 11 Hand-Held Piston-Type Bed material Sampler US - I

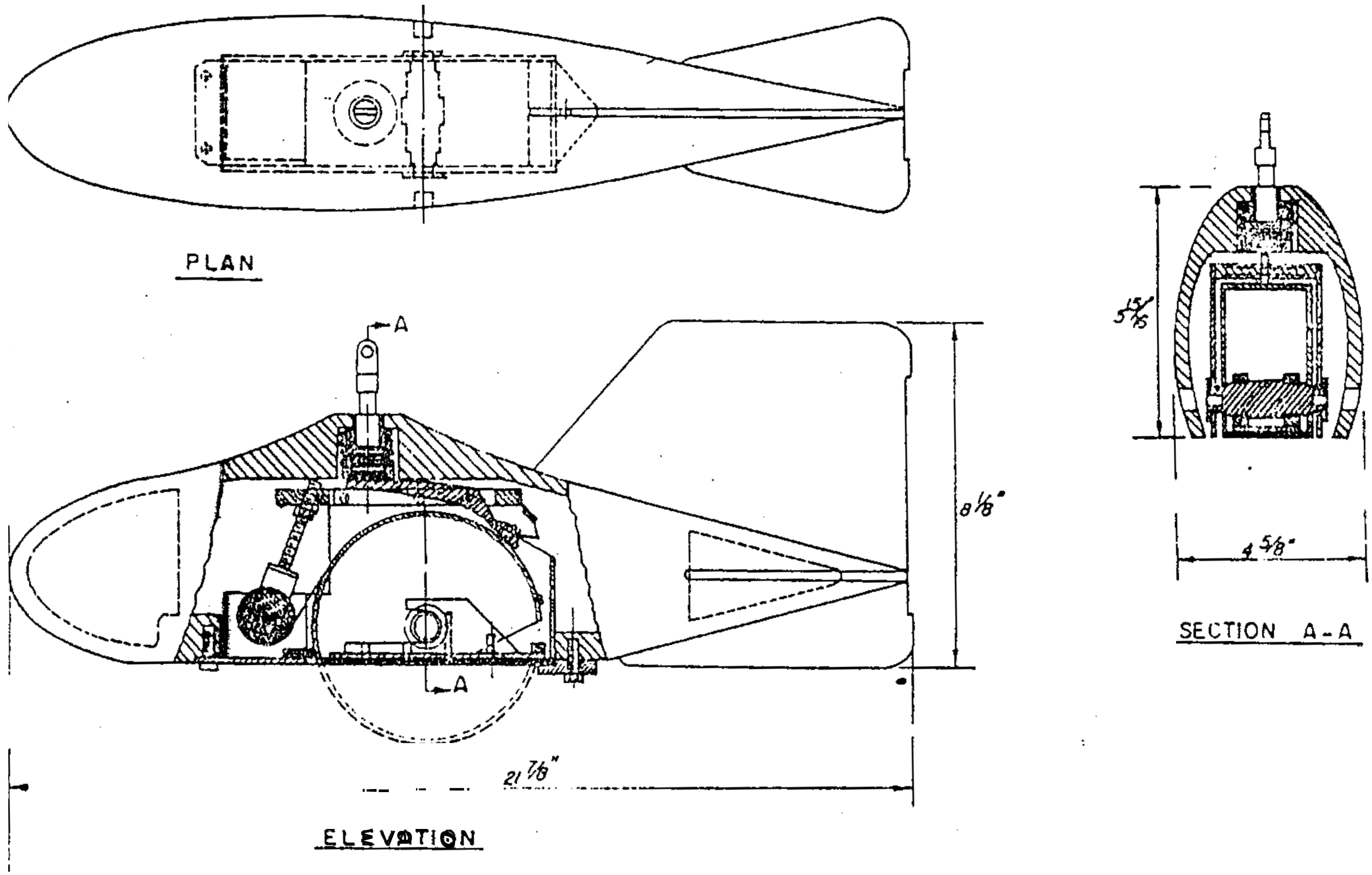


Figure 5.12 Hand Held Piston-Type Bed material Sampler US - BMH-60.

The sampler mechanism of the BMH-60 consists of a scoop or bucket driven by a cross curved constant torque motor type spring that rotates the bucket from front to back. The scoop, when activated by release of tension on the hanger rod, can penetrate into the bed about 1.7 inches (4.3cm) and can hold approximately 175 cc of material. The scoop is aided in penetration of the bed by extra weight in the sampler nose. To cock the bucket into an open position for sampling (that is, retracted into the body) the sampler must first be supported by the hand line; then, the bucket can be rotated (back to front) with an allen wrench to an open position, The hanger rod, to which the hand line is attached, is grooved *so* that a safety yoke can be placed in position to maintain tension on the hanger rod assembly. (Caution: At no time should the hand or fingers be placed in the bucket opening, as the bucket may accidentally close with sufficient force to cause permanent injury.) A piece of wood or a brush can be used to remove any material adhering to the inside of the sample bucket.

The bucket closes when the safety yoke is removed and tension on the hand line is released, as will occur when the sampler comes to rest on the stream bed. A gasket on the closure plate prevents trapped material from contamination or being washed from the bucket.

2. EM-54 (Cable and Reel Sampler)

The 100 pound (45 kg) cable and reel suspended EM-54 is of cast steel (Figure 5.13). Its physical configuration is nearly identical with the cast aluminum BMH-60, 22 inches (56 cm) long and with tail vanes. Its operation is also similar to the BMH-60 in that it takes a sample when tension on the cable is released as the sampler touches the bed. The sampling mechanism externally looks similar to that of the BMH-60, but its operation is somewhat different.

The driving force of the bucket comes not from a constant torque spring, but rather from a conventional coil type spring. The tension on the spring is adjusted by the nut and bolt assembly protruding from the front of the sampler to obtain a bite powerful enough to obtain a sample from the bed of very compacted sand. It is suggested that the tension on the spring be released during extended periods of idleness even though the bucket is closed. Maximum tension should be used only when the stream bed is very firm. Unlike the BMH-60, the spring and cable assembly rotates the bucket from the back to the front of the sampler. Again, the trapped sample is kept from washing out by a rubber gasket.

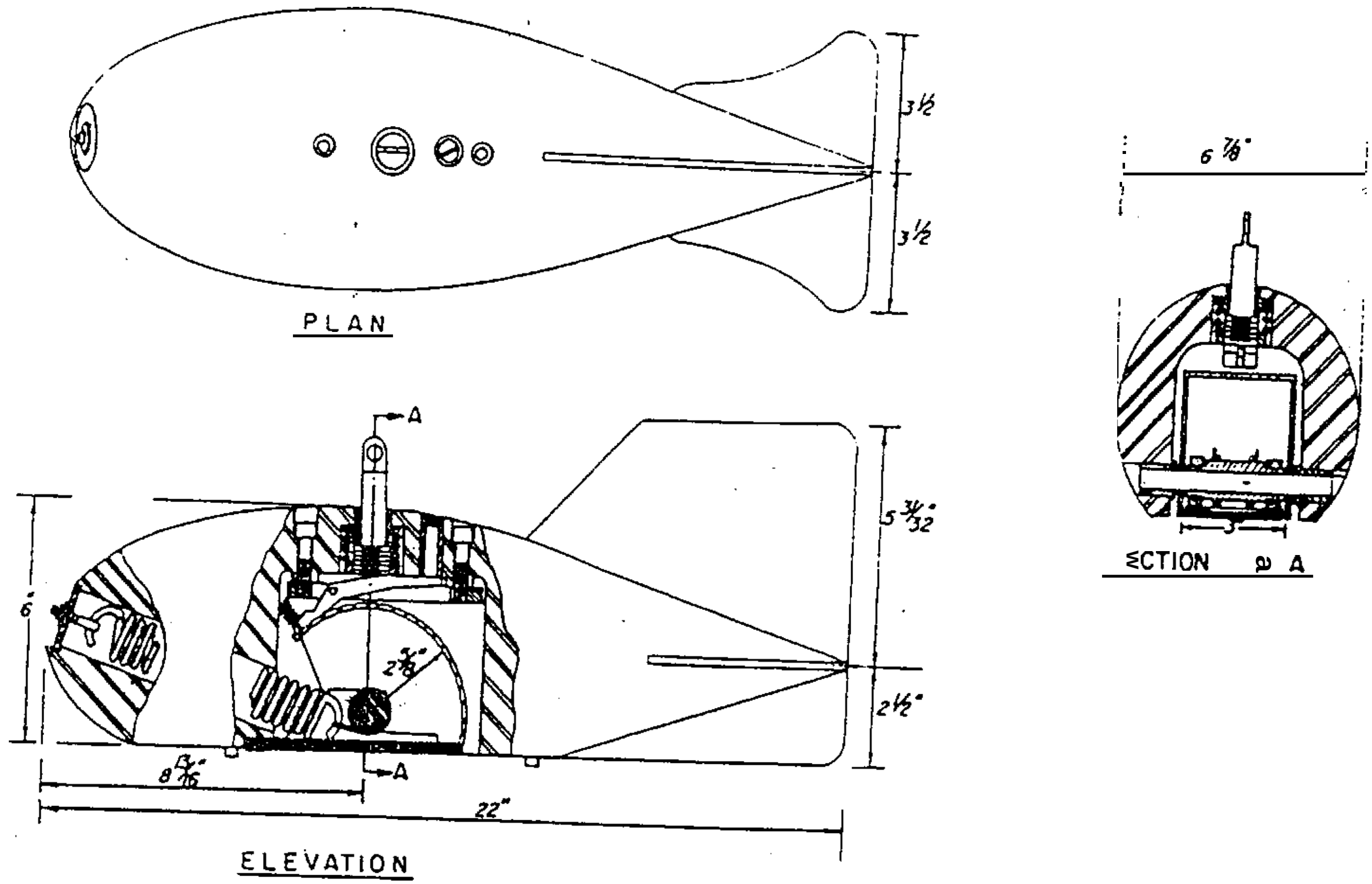


Figure 5.13. Bed Material Sampler WS BM 54

Determination of Sediment Size Distribution by ACOPIISRIP:

The particle size distribution is determined for the sample bed material and for the measured suspended load. It is based on the behavioral particle size given by the fall diameter and is obtained by VA (visual accumulation) tube analysis for bed material samples and VA tube-pipette analysis for the measured suspended load. The particle sizes, such as D or D are based on log normal interpolation of the particle size distribution curve and represent the fall diameter of which the specified percent of the bed material is finer than by weight. The particle size distribution for the measured load is given for a lower cutoff size of 2 microns. The concentration of particles finer than this size limit is assumed constant throughout the flow, and their load is computed as such.

Determination of Sediment **Load** Concentration **(ppm)** by ACOPIISRIP:

The sediment load is computed by the Modified Einstein procedure. The computed results are listed in three parts: for particles smaller than 2 microns; particles between 2 and 62 microns; and particles larger than 62 microns. The ratio of sampled suspended to suspended sediment concentration represents the fraction of sediment load (for different particles size dimensions) that is measured by the field procedures, adopted in ACOP.

Experience of ACOPIISRIP with Sediment Samplers:

ACOP has applied the ETR (Equal Transit Rate) method for taking suspended sediment samples in channels using the depth integrating sampling technique. A cross-sectional suspended sediment sample obtained by the ETR method requires a sample volume proportional to the amount of flow at each of several equi-spaced verticals in the cross-section. This equal spacing between verticals across the stream and equal transit rate, both up and down in each vertical, yields a gross sample proportional to the total stream flow. Therefore, it becomes necessary to keep the same size nozzle in the sampler for a given measurement. This method is most often used in shallow or sand bed streams where the distribution of water discharge in the cross-section is not stable. As channels under study by ACOP are sand beds, the ETR method has been used for all suspended sampling.

There are two common varieties of hand-held samplers known as DH-48 and DH-59. Out of these, the DH-59 has been mostly used by ACOP for taking boil samples. Because of its light weight, it is limited in use to velocities of about 5 feet per second.

The Cable-and-Reel Sampler D-49 is a depth integrating instrument which has been used by ACOP for sediment sampling of streams of upto about 15 feet depth. This sampler continues to accumulate a sample in a flowing stream throughout the period of submergence, even after the sample bottle becomes completely filled during a sampling operation; thus, a representative sample will not be obtained and the sample must be discarded. Generally, in ACOP, it has been a normal practice to obtain at least three samples at each vertical and then composite them to obtain a sufficient quantity of sample for laboratory analysis. ACOP has developed its own sophisticated point integrating pump sampler, which is more convenient to use and is a precise instrument. This is a robust device that requires a minimum of field maintenance over long operational periods. This instrument can obtain a large volume of point samples by directly filtering out the sediment from the pumped supply, besides obtaining the periodic pint bottle samples. However, a necessary operation for using the pumping sampler is the prior determination of velocity at each point of sampling.

Concluding Remarks:

The purpose of sediment sampling is to determine the sediment load or its concentration, bed load, and the particle size distribution of the sediment load. What is required in most investigations is the size distribution of the load, as well as its fractions located between different elevations above the bed. When representing the size distribution of load, the use of lognormal distribution provides the conciseness required when dealing with large data sets. The techniques of routine measurement often yield substantial errors in the measured quantities, while for some quantities, such as the bed load. methods of direct measurement are not available.

In the current measurement practices, depth integrated suspended sediment samples are obtained on a number of verticals, concurrent with a discharge measurement. Of necessity, the samples are obtained from the water surface down to about 10 cm above the local bed. They provide the average suspended sediment concentrations and its particle size distribution for the measured zone of channel cross-section. The extrapolation of measured concentration to the total cross-section, including the bed load, is carried out through a procedure which is based on a simplified version of the Einstein bed load function. This method of extrapolation of measured to total load is called the Modified Einstein Procedure (MEP).

Most of the bed material load data raported in the field are based on part measurement and part extrapolation by MEP. Experience with the application of MEP to the Missouri River, as well as ACOP canals, shows that (on the average) the ratio of measured to computed bed material load in these channels varies from 40 to 80% (Khalid Mehmood. 1990). Comparison of predicted with measured values of bed material load are always based on computed MEP values. As a result, any errors in the MEP extrapolation are reflected in errors of prediction.

ISRIP/ACOP uses sediment sampling techniques and procedures standardized by the United States Geological Survey (USGS). However, some specialized sediment

Next >>