

**RIVER BEHAVIOUR,  
CONTROL AND TRAINING**

**(Synopsis)**

**CENTRAL BOARD OF IRRIGATION AND POWER**

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## FOREWORD

Rivers constitute the most valuable natural wealth of a country. They are a boon if properly controlled, but, if left uncontrolled, can be a source of great misery and devastation. River control covers a variety of problems like training of rivers to flow along or away from a structure, through or over a bridge or weir or it may take the form of flood and sand control or again, of control for improving the navigability of rivers. The solution of a problem can be as varied as the number of situations to be tackled.

River training has, for a long time been a matter of mere speculation. Though the designs were usually based on past experience, the results had not always proved satisfactory due to diversity of causes affecting a problem. Hydraulic model tests have, in recent times, come to the help of engineers in tackling such problems successfully. Almost every construction on a river or a creek is now subject to hydraulic model studies before being put into execution. These model tests have proved very reliable and faithful in solving some of the intricate and baffling problems of the engineering profession and demonstrating the advantages and disadvantages of a design to a very high degree of accuracy.

A considerable amount of work on river training has been done in India, and descriptions of these have been published in the Annual Technical Reports of various Research Institutes and of the Central Board of Irrigation and Power. However, the need of a comprehensive manual covering all aspects of river behaviour, control and training has long been felt and the work of compiling such a comprehensive manual has now been entrusted by the Board to the Director, Central Water and Power Research Station, Poona. This manual is under preparation with him and, for the time being, the Board has decided to issue this pamphlet which gives in nutshell, a general idea of the subject and the problems involved.

The Board takes this opportunity of thanking the officers of the Central Water and Power Research Station especially its Director, Shri D. V. Joglekar for working on this compilation and producing this pamphlet which gives in brief the general outline of the subject.

New Delhi :  
1st July, 1954.

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# RIVER BEHAVIOUR, CONTROL AND TRAINING

## INTRODUCTION

For a long time, river training measures have been a matter of speculation. Sometimes the designs are based on previous experience but often the results have proved unsatisfactory due to the diversity of causes affecting the problem. Hydraulic model tests, have, in recent times, helped the engineer to a very great extent, in tackling the problems successfully. A considerable amount of work on river training has been done in India, and descriptions of these have been published in the Annual Technical Reports of various Research Institutes. However, there is a long felt need of a comprehensive manual on "River Behaviour, Control and Training." The Central Board of Irrigation and Power has directed the Central Water and Power Research Station, Poona to take up the work of preparing the manual. For the present, this pamphlet is intended to give in a nutshell a general idea of the subject.

Rivers constitute one of the most natural resources of a nation. They occupy a prominent place in every stage of human development. They are the prime causes of the development of industry and agriculture in a country. India has an immense resource of water which at present is flowing mainly to waste. Still, this enormous quantity of water which is made use of is only a small fraction of the total resources of the country.

For greater utilisation of the river waters, River Valley Schemes on the lines of Tennessee-Valley Project are being undertaken. The Damodar Valley Project is conceived on the same lines and when completed will provide flood control and navigation, electricity and irrigation water, bringing prosperity to millions of people. Krishna-Pennar Project and the Narmada-Mahanadi Project are inter-basin schemes designed for water supply and navigation respectively. These multi-purpose schemes will necessarily make the country prosperous through rapid industrialisation.

Rivers in alluvium are mostly unstable. They change their courses often and create a lot of havoc. Meandering is one of the most pronounced tendencies of these rivers. It gives rise to cut-offs and they in turn throw the river out of regime. The whole process is a sort of vicious circle with one ultimate result—destruction of property and life. The uncontrolled behaviour of the River Kosi has caused devastation and brought misery to the people of Bihar. A number of such instances can be cited. The unstable nature of these rivers causes disruption of the lines of communication, threatens irrigation works, etc. River control and training therefore are very essential if people are to live in peace and safety.

As elsewhere, so in India too, expansion programmes of roads and railways during the last century led to rapid developments in bridge engineering. The excessive cost of construction of unusually long bridges over wide alluvial rivers and the difficulty of subsequently controlling the rivers at the bridges are also major problems which have to be successfully overcome. Indian engineers proved equal to the task and evolved an economical and appropriate remedy in the shape of the guide banks extending above and below the bridge over a constricted river. This was first introduced in 1888 by Mr. Bell while constructing the bridge over the Chenab at *Shershaha*. Later on, the guide bank system was freely adopted and is now in vogue as a standard practice.

In recent years, engineers have realised the importance of hydraulic models in the design and testing of their problems. Almost every construction in a river or creek is subject to hydraulic model study before it is put into execution. Hydraulic models have proved very reliable and faithful in solving some of the intricate and baffling problems of the engineering profession and demonstrating the advantages and disadvantages of a design to a very high degree of accuracy. The technique of hydraulic model study is a specialised subject requiring intimate theoretical knowledge and considerable experience in their design and operation.

## RIVERS

Rivers can be classified under two major heads: (1) incised rivers, and (2) rivers in flood plains or alluvial rivers.

These can however, be also classified into following categories, namely: (a) boulder rivers, (b) flashy rivers and rivers with sustained floods, (c) virgin rivers, (d) delta rivers, and (e) tidal rivers.

**Incised rivers.**—An incised river is one which has formed its channel by the process of degradation and the sediment which it transports is generally dissimilar in character to that in the bed.

**Boulder rivers.**—When the river leaves the hills, it flows through sub-mountainous tracts. The bed consists of boulders of varying sizes. The slopes are steep and consequently the velocity of flow is high. The boulders are carried down by the strong current and by the time the river reaches the plains, the boulders are broken up and their sizes get considerably reduced due to abrasion and impact.

**Rivers in flood plains.**—These rivers are so classified as alluvial rivers. They form their channels by the process of aggradation and the sediment which they carry is similar to that in the bed. Material gets constantly eroded from the concave banks, and is deposited to form shoal along the convex side below. Alluvial streams have a very strong and a free tendency to meander unlike those of incised rivers. The present day knowledge on the subject of meandering is mostly based on field observations backed by laboratory experiments. Development of cut-offs is also a feature of rivers in flood plains.

**Virgin rivers.**—Rivers have been seen to disappear after flowing a certain distance from the source. This is due to the heat and dry soil conditions. Rivers which flow into deserts and arid regions and which do not flow into the sea are called virgin rivers. All the waters are lost in percolation and evaporation.

**Flashy rivers.**—The flood hydrographs of these rivers are steep indicating thereby that the flood flow comes in all of a sudden. During the major part of the year, the flow in the river is practically nothing. During summer, there is absolutely no water in some rivers while in some others, the little flow is confined to a channel, a few feet wide. When the floods come, the river runs full and even bursts its banks at times. The flood lasts for a short period but a fairly good flow persists till the end of the monsoon season. There are several rivers of this type in Ajmer, Merwara, Rajasthan etc.

**Delta rivers.**—The river in this stage is near its outfall into the sea. The river fans out into many branches and is subject to spills. The characteristics of a delta river may be stated as follows: (i) In high floods, it generally spills over its banks. (ii) The bed and surface slopes tend to become flatter and flatter as it proceeds. (iii) Generally its bed is above the surrounding country in a direction perpendicular to its course.

**Tidal rivers**—The rivers in which the effect of tides of the sea is felt are called tidal rivers. Almost all the rivers in India are tidal where they join the sea.

The duration of ebb in upper tidal rivers is generally longer than the flood due to what is known as shallow water effect.

### FACTORS AFFECTING FLOW

Majority of cases confronting an engineer, entrusted with the design, maintenance and operation of irrigation works, are of a nature in which the complex relations governing the flow of water and sediment load are involved directly or indirectly. In India the growth of knowledge in this field has been closely associated with the advance of irrigation.

In 1895, Kennedy, on the basis of canal reaches which are neither silting nor scouring derived a relation correlating the mean velocity of flow in the canal to the average depth of flow. It was:—

$$V_0 = 0.84 L^{0.64} \dots\dots\dots(1)$$

Other stable canal systems gave similar relations in which the coefficients and indices were different. The difference was explained by the variation of the grade of bed material in these systems as compared to Kennedy's canal system.

It was for Lindley and Lacey to put forward the conception of a regime canal. It can be said that in a canal with a given discharge and flowing in its own alluvium, the shape and slope of the canal are uniquely determined for a given grade of bed material consistent with active movement of it. Lacey's contribution was the most

outstanding. After analysis of data of stable canal sites available in India and outside, he evolved a number of relations connecting discharge, bed material, velocity and slope *etc.* He introduced the parameter  $R$ , hydraulic mean depth which is equal to the ratio of area of cross-section of flow and the wetted parameter  $P$ , of the canal boundary, and the silt factor ' $f$ ' representing the bed material in the canal.

Some of his important relations are :

$$V = 1.15\sqrt{fR} \dots\dots\dots(2)$$

$$Af^3 = 4.0 V^{5.0} \dots\dots\dots(3)$$

$$S = 0.000383 f^{3/2} R^{1/2} \dots\dots\dots(4)$$

$$P = 2.668\sqrt{Q} \dots\dots\dots(5)$$

$$V = \frac{1.3458 R^{2/3} S^{1/2}}{Na} \dots\dots\dots(6)$$

$$R = 0.473 Q^{1/3} / f^{1/3} \dots\dots\dots(7)$$

Where,

- $V$ —velocity in ft/sec.
- $A$ —area of cross-section in sq. ft.
- $S$ —slope.
- $P$ —wetter parameter, in ft.
- $Q$ —discharge in cusecs
- $f$ —silt factor
- $R$ —hydraulic mean depth in ft.
- $Na$ —Lacey's roughness coefficient

The last but one relation in the above list was derived by algebraically combining Chezy's equation  $V = C\sqrt{RS}$  with his relations.

It is similar to Manning's relation *viz.*,  $V = \frac{1.486}{N} R^{2/3} S^{1/2}$

These relations though empirical, held the ground for considerable period and were used in designing canals. But as further data regarding stable canals accumulated and was analysed, it came to light that dimensions of these canals, though stable, were considerably different from those obtained on the basis of Lacey theory.

It was for Inglis, White and Hydraulic Research Laboratories in India to explain the divergence from regime dimensions obtained from Lacey's theory. Inglis and the staff of the Central Water and Power Research Station, Poona after a thorough analysis showed that, in addition to grade of material on the bed of the canal, the quantity of sand and silt load which a canal is called upon to carry is equally important in governing the shape and slope of the canal. The Lacey relations were then modified to include this important variable.

The question was tackled from different angles by Rouse, Shield and others. In their analysis the relation between sand load and the

tractive force of the stream was formulated after obtaining the critical tractive force (i. e., the tractive force at which movement of bed material just begins), and allowing for the effect of sidewalls.

A method, based on logarithmic velocity distribution and turbulence functions as affecting the silt in suspension, was applied for assessing the suspended load in a stream. This method has to be however checked in the laboratory.

## BEHAVIOUR OF RIVERS

**Curvature of flow and meandering of rivers.**—A course of a natural stream is never straight for a long distance and it goes on winding from the hills to the sea interspaced by straight reaches. This tendency to develop curvature is stronger in streams in flood plains, where they are mostly flowing in flat regions formed by centuries of deposition of alluvium carried by them.

The main flow in such streams shifts from bank to bank (which are permanent *khadirs*). The process, covering a period of decades, depends to a large extent on the hydrological cycle, the sand load which is carried by the streams and the terrain. This instability of streams has often resulted in attacks on bridges, important towns, marginal embankments, etc. during the downward movement of their meanders.

Local protection is usually done by engineers in charge, but to avoid the recurrence of such conditions or to bring about a reduction in these attacking forces of the river, one must understand the phenomena of meandering of rivers and the causes which govern the meander development.

In a natural stream, a continual readjustment of hydraulic dimensions is constantly occurring. The stream always tries to adjust itself to the prevailing conditions. Small year to year variation in the dominant condition of discharge and sand charge gets adjusted by corresponding changes in the bed and slopes.

It is a common belief among engineers that 'meanders' are caused by existence of a slope exceeding that required to transport the load. The river therefore flattens its slope by lengthening its course, in other words by meandering. This has been shown both by analysis of the meandering channels and studies in laboratories to be an antithesis of what actually happens.

The analysis of data of rivers done at the Central Water and Power Research Station, Poona, showed that  $M_L$  (meander length) varied as  $\sqrt{Q}$  (Figure 1).

The actual relations obtained by analysis were

$$M_L = 30\sqrt{Q} \quad \left\{ \begin{array}{l} \text{for rivers in} \\ \text{flood plains.} \end{array} \right.$$

$$M_L = 25.4\sqrt{Q} \quad \left\{ \begin{array}{l} \text{for incised} \\ \text{rivers.} \end{array} \right.$$



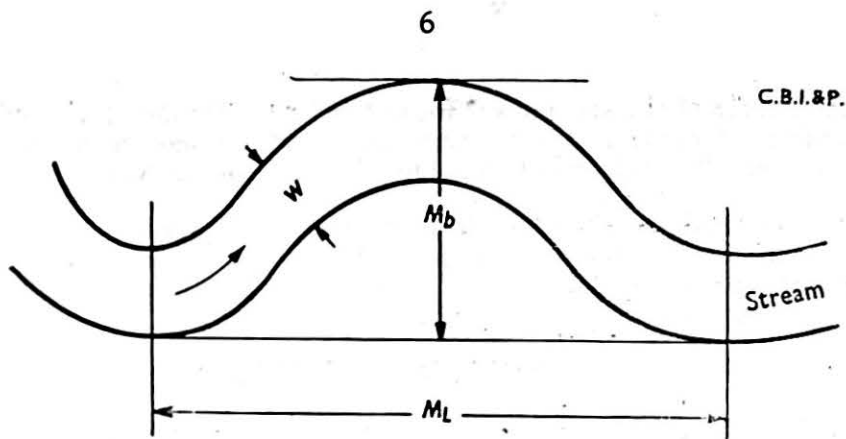


Figure 1

Experiments at the Central Water and Power Research Station, Poona were initiated to study the main factors governing the meander development of streams in incoherent material as shown in Figure 2. The discharge was constant.



Figure 2 : Showing meanders developed in an experimental channel

The results obtained showed that

$$M_L = 36.4\sqrt{Q}$$

The meanders are developed when the bed load in a particular reach in streams exceeds its carrying capacity irrespective of whether

the charge comes from bank erosion or is impressed by a tributary carrying excess charge. Captain Friedkin of the U.S. Corps of Engineers has written a paper "A Laboratory Study of the Meandering of Alluvial Rivers (1942-44)". The general conclusions drawn about the cause of meandering are the same as shown earlier. Mr. Chatley's paper "Theory of Meandering" also gives interesting analysis of the phenomenon.

**Cut-offs.**—A cut-off is essentially a characteristic of alluvial rivers and signifies development of river meandering to acute conditions in the form of hair pin bends. It forms by a break-through at the narrow neck under limiting conditions. Flood spills over concave banks, have an inherent scouring capacity because of lesser relative load and steeper slopes. This results in bed scour and also bank cutting from the downstream end, thus causing the cut-off. A cut-off, artificial or natural, results in violent changes of river regime. As the river tortuosity is decreased, the river slope upstream of the cut-offs steepens and flood levels are lowered. This, however, creates bad conditions downstream of the cut-off.

Cut-off may be developed artificially for improving the navigability of channels. It may also be undertaken as a means to reduce the flood levels locally in certain reaches, though cut-offs by themselves may not be very useful in improving the flood capacity of a channel over a long reach; hence great caution is necessary in affecting artificial cut-offs.

**Delta formation.**—Flood waters of the delta building streams are heavily charged with materials brought down from the catchment, and also picked up on the way. As these streams approach their mouths the water surface slopes become very flat with consequent reduction in velocity which causes the material in suspension to be dropped on the bed and banks, causing rise in the water level. As the water level rises it spills over the banks to flow through low lying areas. Spill flow generally has a low velocity which causes further deposition of the material so as to raise these low lying areas. Under suitable conditions the spill flow develops and establishes branch channels which behave exactly in the same manner as the parent channel. The process of spilling and splitting of the channels, helps to raise the delta already built up, while extension of the delta towards the sea is being carried on by the main volume of the floods carried down the several diverging branches, dropping their silt burden near their mouths. The work of raising the delta is further augmented by the tides which pick up the material deposited near the mouths of the streams and distribute it to the low lands upstream. As a result of this process of extension and raising of the delta, the important channel characteristics namely width, depth and slope are continuously changing.

Type, shape and progress of the delta are affected by the nature and shape of the catchment area, total annual rainfall and its distribution and relative load. Other factors like the tidal range, littoral currents, coastal currents, etc. also affect the delta formation to a considerable extent.

## MEASURES ADOPTED FOR CONTROL OF RIVERS

**Flood control by reservoirs.**—The Control of floods can be accomplished either by the provision of a channel of adequate capacity, to pass the flood without any reduction of its intensity, or by damping its peak intensity by reservoirs so that the moderated floods can be accommodated by the available channel. The comprehensive design of flood control by the latter method with incidental preparation of necessary design data by analysis of hydrological records is an important subject by itself.

The first step in the design of any flood control project is the determination of the probable worst flood conditions. If only rainfall data for the catchment of the river is available, the maximum runoff can be determined either by rational or empirical formula.<sup>6</sup> The rational formulae are of the form

$$Q = CIA$$

where,

$Q$  = runoff,

$C$  = coefficient,

$I$  = intensity of rainfall,

$A$  = area of catchment.

The coefficient  $C$  is fixed after consideration of the characteristics of the catchment such as shape, kind of soil, vegetation, initial stage of wetness, etc. The intensity of rainfall,  $I$ , is determined after a study of the rainfall characteristics viz., incidence, duration and distribution. These formulae give good results for comparatively small areas. Empirical formulae such as Dicken's, Ryve's, Rhind's, Inglis's, Petit's etc, based on one or the other characteristics of catchment or rainfall have also been used. Where an extensive record of floods and rainfall exists, statistical or probability methods have been adopted with better results. There are two methods of estimating flood magnitudes and frequencies viz., (i) the use of flood duration curves and (ii) the use of probability curves. By far the best method which has yet been proposed for determination of maximum flood, is one based upon Sherman's theory of the unit hydrograph. A unit hydrograph is the hydrograph of one inch of rainfall in unit duration and of specific distribution over the catchment. It requires continuous record of rainfall and runoff. The following three general methods are available for developing a unit hydrograph:—

- (a) By analysis of rainfall and runoff records of isolated 'unit storms'.
- (b) By analysis of rainfall and runoff records of major storms.
- (c) By computation of synthetic unit hydrograph from direct or indirect analogy with basins of similar or other characteristics.

The next stage is to determine the 'critical design storm rainfall'. This requires comprehensive study of records of major storms in the region. The design hydrograph is worked out by the

application of the unit hydrograph to the 'critical design storm'. The analysis of hydrologic data as described above would enable one to arrive at a design flood inflow hydrograph. The process of computing the reservoir stage, storage volumes and outflow rates corresponding to a particular hydrograph is known as 'flood routing'. Flood routing through a reservoir can be done by (a) the step method, (b) using inflow-storage-discharge curves for the reservoir and (c) graphical methods. This process provides a means for the determination of the modified flood hydrograph which enters the river from the flood control reservoir.

**Sedimentation of reservoirs.**—Whenever a new dam is contemplated, the first question which has to be satisfactorily answered is, "how quickly the reservoir would silt and what would be its useful life"? Only a couple of decades ago there was neither enough data nor rational approach to this subject to guide the designer and the outcome was left to chance. Some reservoirs served usefully for several generations while others silted rapidly. Such an important question as the life of a reservoir cannot be left to chance and serious thought is being given in recent years, to estimate the 'estimated life' on more systematic observations of silt load in rivers and streams.

The problem of reservoir silting consists of four parts :

- (i) The average yearly rate at which sediment would be brought by the river at the point where a dam is to be constructed.
- (ii) The part of the load which would be retained in the reservoir.
- (iii) Outlet works to pass the largest percentage of the silt load downstream of the reservoir.
- (iv) Methods and works to minimise silt load of the stream.

The most reliable and direct method of assessing silt load is to make long period observations of bed and suspended load. For measuring suspended load various samplers are advocated by different agencies. In India the Punjab type, one litre bottle sampler, for point integration is favoured. No reliable sampler for bed load measurement exists and generally the bed load is taken as about 10 per cent of total silt charge.

Silt charge not only varies widely from stream to stream but also for the same stream, depending on intensity of precipitation, vegetal cover, etc. Estimates of load based on isolated samples can be misleading and averages over long periods should only be considered. In the absence of silt load data in a stream, geological survey of the catchment can give useful indication as to the maximum rates of sediment production from various types of lands, taking into account the vegetal cover, slope, topography etc.

The answer to the question as to how much of the silt load will be retained in the reservoir is not easy. The trap efficiency is

considerably affected by the following factors :—

- (a) Ratio of storage capacity to total runoff. The larger this ratio, the greater is the trap efficiency.
- (b) Grade of silt.
- (c) Location of outlet works and method of operation of reservoir.

Data regarding rates of sedimentation of old reservoirs and their trap efficiencies can be useful as a rough guide for determining the life of a new dam.

**Control measures.**—The silting in a reservoir can be controlled either at the source or at the outlet works. The rate of sediment production in the catchment can be controlled by various measures such as afforestation, gully traps, sediment basins, contour bunding, contour ploughing, crop rotation, *etc.* The results on experimental small basins are only available, and the effectiveness of these measures on large catchments is yet a matter of speculation. The very optimistic results derived from observations of small areas should be taken with reservation.

It is hoped that deep-seated sluices in a dam at bed level would be able to pass a large percentage of fine and medium silt brought down by the river. Much interest has been evoked in density currents. The knowledge in this field is not sufficiently advanced for estimation of usefulness of this method.

**Effects of dams on regime of a river upstream and downstream of a reservoir.**—The river bed upstream of the reservoir is likely to be aggraded due to delta formation at the upstream end of a reservoir and consequent considerable vegetal growth. Though such formation might reduce silting in a reservoir, the upstream flood levels are likely to be adversely affected.

If a large percentage of silt is trapped in a reservoir, the relatively clearer discharge results in retrogression of the river and readjustment of slopes of bed, downstream, affecting foundation of structures, tail-water level in power channels, *etc.*

### **SAND CONTROL IN CHANNELS TAKING OFF FROM ALLUVIAL RIVERS**

Channels taking off from alluvial rivers present baffling problems to the engineer while controlling coarse sand drawn by them. Various methods have been adopted for this purpose. Basically they can be broadly classified as preventive and curative. In the former, sand is prevented from entering an offtake whereas in the latter sand is ejected after being drawn by an offtake.

Among the preventive methods the natural method of locating the offtake either on a straight reach or on a concave curve is the best type to use where conditions permit. In a straight reach the bed charge is mainly confined to the central portion and therefore a

channel taking off from this reach will not generally attract coarse bed material if properly aligned and the relative discharge of the offtake is not very high. But it is very seldom that the river reach is straight. Generally the river reach is curved and sand collects on the convex side.

Canals have to be therefore located on a concave bank for satisfactory sand exclusion as bed flow laden with coarse sand is deflected sufficiently away from the concave side.

When canals take off from both the banks it is very difficult to get a site where favourable curvature exists for the canals taking off from both the banks. In such cases, the canals drawing relatively heavy discharge should be located on the concave side, so that it will be comparatively less difficult to exclude sand from the other canal with suitable training measures. Or the site should be so selected that concave curvature would be available on both the banks or can be created by suitable training measures, as was done in the case of Sukkur Barrage. In nature, however, it is very seldom that a site is found satisfying this condition. It is necessary either to shift the head regulator on the convex side further upstream of the barrage so that it also takes off from a favourable curve or to adopt suitable measures for its satisfactory performance. A classic example of the former is found in Kabo Headworks in the Ye-U canal taking off from the convex side below a sharp bend of the Mu river in Burma as shown in Figure 3.

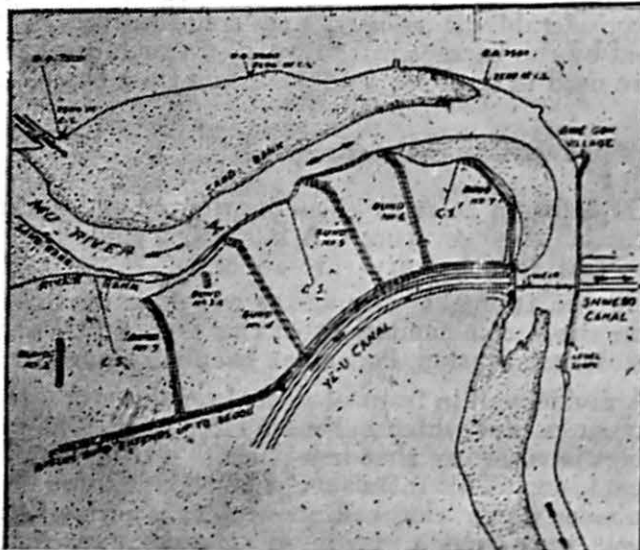


Figure 3: Showing existing conditions of the Barrage (Kabo Headworks, Burma) located just below a bend, Mu River. The Ye-U canal of 1,800 cusecs takes off from the convex side and hence draws bed load.

One of the recommendations made to rectify this defect, consisted in shifting the head regulator upstream at the point of optimum concave curvature (Figure 4).

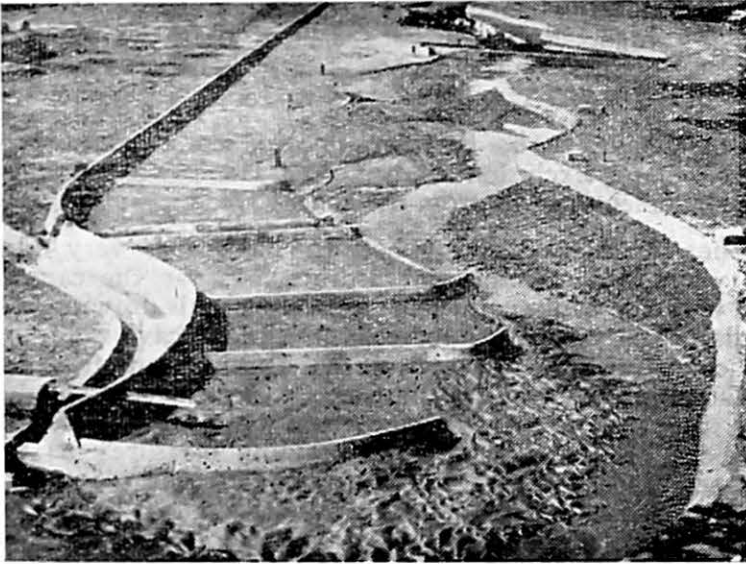


Figure 4 : *Showing new approach channel taking off from the concave curve. It draws sand-free top water only.*

Many times even if the favourable curvature is available initially, it is considerably neutralised and counteracted by the ponding effect caused by the barrage or the weir. In such cases the following methods are used to improve sand exclusion from the canals :

#### **Other preventive methods—**

- (a) Guide banks suitably aligned, oriented and located help to correct the curvature. A fairly long guide bank is required to establish the curvature effect.
- (b) Curved approach channel, as was done in Sukkur Barrage on the recommendations of the Central Water & Power Research Station, Poona has been very successful.
- (c) A divide wall in front of a canal regulator creates a relatively quiet pocket which helps sand exclusion. The ratio of velocity in river to that in a pocket is the factor controlling exclusion. This ratio should be about 1.5 for flood discharge above which the bed movement is active. A long pocket was once much favoured. Later experience however indicates that a divide wall, longer than the length of head regulator is seldom necessary for sand exclusion. This is also more advantageous from the point of view of scouring operations of the pocket and regulation of the barrage.
- (d) Undersluices outside and inside the pocket sometimes improve sand exclusion. They help to establish a deep water channel close to the pocket, which is beneficial to sand exclusion.
- (e) Tunnel excluders in pockets, open and closed type have been evolved by the Punjab Irrigation Research Institute and

constructed on some of the barrages in Punjab. Their principle is to provide tunnels on the bed, with their openings facing the direction of flow through which a percentage of the pocket discharge is passed down into the river carrying with it heavy sand charge. Gates control the discharge thus let out. They require a minimum head of 2.5 to 3 ft. for their satisfactory operation.

- (f) Raised sills of head regulators were once considered to be a complete solution for prevention of coarse sand entry in a canal; but it is not so. It is useful only within limits and in no case should be relied upon to correct the adverse effects of an unfavourable location. It takes very little time to fill up the reserve and thus the very purpose of providing raised sills is defeated.
- (g) Two methods of operating barrages are followed. One is called 'still pond' regulation and other is called 'semi-open flow'. 'Semi-open flow' is possible without detrimental effect to exclusion when the river discharge is very high and the ratio of velocity in the river to velocity in the pocket, that is  $V_R/V_P$ , is not likely to be affected. It is beneficial as it keeps the pond level little lower. But it neutralises the beneficial effect of the deflection of bed flow at the nose of the divide wall. 'Still pond' regulation however maintains the curvature and is more beneficial for control of sand. At low stages of discharge, in addition, wedged shape regulation is also beneficial.
- (h) Training by groynes, pitched islands, vanes, etc. to deflect coarse sand away from the canals is also adopted. The training should be done very cautiously so that it does not create more adverse conditions than before.
- (i) Cantilever platforms in front of the head regulator in the canal pocket are constructed to prevent sand from entering a canal. Such platforms are constructed in front of Western Yamuna Canal head regulators at Tajewala.

#### Curative methods—

- (a) If coarse material finds entry into a canal in spite of corrective measures an ejector is used to eject the sand. These ejectors were developed in the Punjab Irrigation Research Institute, and they have been constructed in some canals in Punjab.
- (b) Slits in the bed of a canal have also been adopted for getting rid of sand after it has entered the canal. These have been provided on Nangal Hydel Channel. This slit system is known to work very efficiently where high head is available.
- (c) Silting tanks or basins consist of a low lying area on the bank of a canal enclosed by high bund. The water after dropping a major sediment load flows back to the canal at the downstream end of the basins where an outlet is provided for this purpose. This method is used on the Western Yamuna



Canal and Upper Bari Doab Canal. Such silting tanks are also used in all the American canals in U.S.A.

- (d) Another method which is gaining increasing use in the U.S.A., Mexico and South America is the vortex-tube, used either alone or in combination with riffle deflectors. The vortex-tube consists of an open top tube placed across the bottom of the canal. The tube is placed in a transverse direction to the flow either normal to it or at some other angle down to  $30^\circ$ . Sand is sucked out by vortex action through the tubes.
- (e) Occasionally, dredging of silt from the canal is also done, especially in navigation-cum-irrigation canal. But such instances are rare.

In conclusion, it may be stated that it is preferable to adopt preventive methods. Only as a last resort, corrective methods should be tried.

### RIVER CONTROL FOR BRIDGES AND THEIR PROTECTION WORKS

A problem often arises when a bridge is to be constructed across an alluvial river which has its surface width varying from 1 to 16 miles during floods. It becomes extremely uneconomical to span the entire width of the river and also unengineering to expose the structures to the vagaries of attack due to deep scour. In such cases the waterway has to be constricted at the site and the wandering river has to be trained so that it may not outflank the structure. Such considerations of economy and protection to the hydraulic structures gave rise to river training by the guide bank system as enunciated by Bell and subsequently developed by Spring.

In essence the training works consist of two heavily built embankments in the river in the form of a bellmouth. The guide banks constrict the waterway by closing the remaining river portion by approach *bunds*. The basic idea of this system is that the river floods should approach the river within the guide banks in a manner which would ensure it a safe and expeditious passage. The different aspects of the bridge design in accordance with the guide bank system to be considered are—

- (1) Selection of site.
- (2) Determination of waterway,
- (3) Design of guide banks, approach banks, *etc.*
- (4) Bridge piers.

**Selection of bridge sites.**—On purely engineering considerations an ideal site would be a straight, narrow and stable reach of the river. It should not be near a confluence. The river bed at the bridge site should be erodible to allow the river to regain the necessary waterway by deepening after constriction is caused by a bridge, the rest of the river being crossed over by approach banks. Advantage of the main deep channel flowing along one of the banks should be

taken whenever possible in locating the bridge on that end of the *khadir*. The natural bank can then be used as one of the guide banks provided the bank is stiff. When indispensable, additional training measures may be provided.

**Waterway.**—Spring, from his experience, arbitrarily proposed to limit the bed scour, after narrowing the river, to different specific depths depending on the grade of bed material and the river slope and thus worked out the minimum waterway, while Gale's method consists in making use of river section, at the bend, in flood, to assess the extent to which the section of the bridge can advantageously be allowed to develop. The present day practice, however, is to use the Lacey formula ; width (in feet) =  $2.67 \sqrt{\text{Discharge}}$  as a guide and after providing for suitable divergence from the coefficient of 2.67 to fix the optimum waterway. The obstruction caused by the piers and by the side slopes of the guide banks in the end spans have to be adequately provided for. The bridge waterway so determined may need further modification from the point of view of anticipated afflux or difficulties in the way of construction of the guide banks. It must be emphasized that the waterway howsoever fixed should not be adopted in practice unless exhaustive tests on scale models have proved its accuracy. Utility of scale models in this respect is now universally accepted, and since their cost is negligible and facilities for conducting them are within easy reach, one can ill-afford to fail to benefit thereby.

**Guide banks and approach banks.**—In designing the guide and approach banks, all the components *viz.*, form in plan, upstream and downstream lengths, radius of the head, cross-section of the shanks and heads, stone protection on the slopes, the apron, *etc.* have to be most carefully designed ; abundant literature is available in this respect, Model experiments are invaluable here also and should be invariably availed of. Figure 5 shows the guide *bund* designed in the model for the Mokameh Bridge on the Ganga.

**Bridge piers.**—Available data shows that the maximum probable scour round bridge piers will be about twice the Lacey depth =  $0.47 (Q/f)^{1/3}$ . To provide adequate foundation grip, additional depth equal to Lacey depth is found to be sufficient. Thus if pier foundations are taken down to 3 times Lacey depth below H.F.L., no extra protection by way of stone pitching round piers is necessary and hence this practice is recommended. In case of existing shallow piers, however, stone protection may be found indispensable for safety of the piers. In such cases only the approved practice evolved from accumulated field experience and knowledge gained from model tests should be followed.

## TRAINING OF RIVERS BY GUIDE BANKS, GROYNES, EMBANKMENTS AND OTHER METHODS

River training, in its broad meaning, covers all the engineering works constructed on a river to guide and confine the flow to the river channel and to control and regulate the river bed configuration

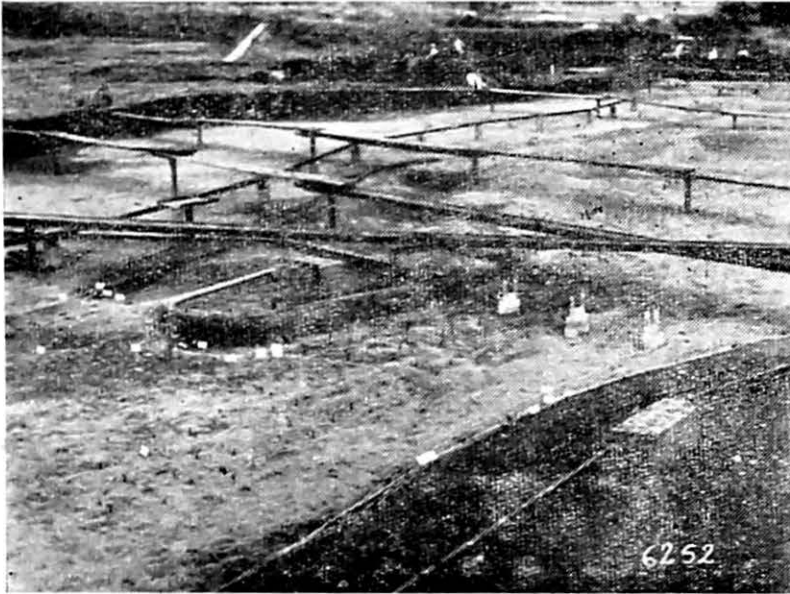


Figure 5

for effective and safe movement of floods and river sediment. River training by embankments for flood protection has a long historical record and must be one of the earliest engineering achievements of mankind.

River training aims at controlling and stabilising a river along a desired course with a suitable waterway for one or more of the following purposes :—

- (i) *Flood protection*: River training for flood protection aims at providing sufficient cross-sectional area for expeditious and safe passage of the maximum flood. It concerns essentially the alignment and height of embankments for a given maximum flood discharge without any attempt at changing the river bed conditions.
- (ii) *Maintaining a safe and good navigable channel*: The aim is to make provision for sufficient depth in the channel during low water period for navigation and is sometimes done by concentrating the flow in the desired channel and closing other bye-channels by the well-known method of "bandalling".
- (iii) *Sediment control*: River training for this purpose aims at the rectification of river bed configuration and efficient movement of suspended and bed load for keeping the channel in good shape. Another aspect of this problem is river training for efficient sand exclusion from canals by correcting adverse river curvature.
- (iv) *Bank protection*: Bank caving is the main cause of river deterioration and, therefore, bank protection, especially

of the pitching type forms an important part of training works. However, the aim of bank protection is generally limited and involves only a local training problem.

- (v) *To direct the flow through a certain defined stretch of the river* : Such a problem usually occurs in protecting hydraulic structures such as weirs, barrages and bridges which would otherwise be damaged or by-passed. It involves overall training which has to be exercised over a considerable distance of the river. An outstanding example of this method is Bell's river training by the guide bank system extensively used for protection of bridges and headworks as already described.

**Types of training works.**—The following list enumerates the various types of training works in vogue :—

1. Guide banks or guide *bunds*
2. Levees or embankments or dykes
3. Pitched banks or bank revetment
4. Artificial and natural cut-offs
5. Groynes or spurs
6. Pitched islands
7. Miscellaneous methods—
  - (a) River training without embankments.
  - (b) Bandalling.

**The guide bank system for weirs and barrages.**—This system is the same as that described earlier but unlike the considerations which determine the waterway through a bridge, the criteria in case of a diversion weir are the permissible intensity of discharge, safe afflux, the pond level and anticipated maximum depth of scour; other aspects of design being common to both. Sometimes auxiliary works such as afflux *bunds* and groynes have to be constructed which complete the general scheme.

**Embankments or levees.**—These are usually earthen banks running along the river banks designed to protect the areas behind them from overflow of flood waters. The embankment system for flood protection is probably as old as recorded history. The top of embankments must be sufficiently higher than the maximum flood level and they must be secure against destruction by seepage or piping. Sometimes where river banks are subject to heavy erosion, embankments are laid in a retired position or methods of bank protection are used for protecting them. Embankments affect river regime depending upon the river being aggrading or stable type. In case of stable rivers flood levels rise but there is no appreciable change in river bed conditions. In an aggrading river, whether it is embanked or not, the inherent instability on account of the heavy sand load continues. This tendency is, however, augmented by embankments.

**Pitched banks or bank revetment.**—Bank protection becomes necessary for two purposes *viz*, protecting persons and property

on the bank threatened by river attack and preventing bank caving which is the main cause of river deterioration downstream. Bank protection works, especially of the pitching type, therefore, form an important part of training works. Pitching may be of boulders or concrete blocks with its toe protected usually by a flexible boulder apron which launches in continuity with the pitched slope as the scour progresses. Another aspect of a pitched bank is that it exerts an attracting influence by drawing the river towards it on account of the deep scour formed at its toe. The river channel is in this way permanently held at the pitched bank.

**Cut-offs.**—The beneficial effects *viz.*, reduction of flood heights and flood periods as also shortening of distance for navigation indicates its usefulness as a river training measure. Because of the violence with which a full-scale cut-off alters the river regime, artificial cut-offs are made by making a pilot cut which is allowed to develop subsequently.

**Groynes or spurs.**—These are structures built transverse to the river flow extending from the bank towards the main river. Depending upon the purpose they serve, they are classified as attracting or repelling. Attracting groyne is usually built facing downstream, with its upstream face bearing the full brunt of the attack and hence armoured heavily. Repelling spurs point upstream. They are permeable or impermeable depending upon the mode of construction. Impermeable groynes may be built with its earth core armoured by boulder pitching and its toe provided with a boulder apron. Materials such as trees, bamboos and bullies, piles and mattresses may be used for making a permeable groyne. They may also be submerged or non-submerged. They are sometimes used in series as the purpose is to deflect the river away and reclaim the bank by silting up the region between them. When used singly a groyne has to be protected and armoured heavily.

**Pitched islands.**—The idea of using a pitched island for river training is still in a formative stage as a few attempts made recently have not yielded the desired success. The construction of a pitched island in the river bed affects velocity distribution and tractive force. Tractive force in the vicinity of the island increases and causes scour. It gradually draws the river channel on to itself and holds it there. This idea tends to make it a training measure.

#### **Miscellaneous methods.**—

- (a) *River training without embankments*: This method is adopted in Burma for building up river banks by driving stake fences on the banks which induce silting. It is used only on hill streams carrying heavy sediment which is essential for its success.
- (b) *Bandalling*: This is practised on rivers during low water period for scouring away shoals to maintain the depths for navigation of country craft.

## TRAINING MEASURES FOR IMPROVING THE NAVIGABILITY OF RIVERS

Navigation facilities available in a country, as history shows, constitute a factor closely associated with its economic development. This is due to the inherent cheapness of water transport. Consequently, it should be realised that a country having a network of navigable rivers or canals stands to gain much in its trade and industry. India has a certain amount of facilities for deep sea navigation, but inland navigation is comparatively a neglected branch. There is, therefore, vast scope for developing inland navigation. The facilities available for deep sea navigation also have to be reconsidered in the light of modern trends in ship building industry.

The training and development of water courses for navigation in India are comparatively new subjects, which the Indian engineers are called upon to tackle. It would be worth while to study what has been done in other countries in this respect.

The principles underlying the development of navigation in one-way rivers are different from those applied to the tidal rivers. These are, therefore, discussed separately.

**Inland navigation in one-way rivers.**—For planning the inland navigation projects, a complete topographic and hydrographic survey of the river has to be first made showing by contours surface and submerged topography, river bed and water surface slopes, hydrograph, minimum flow in the river, etc. This data gives an idea about the width and the depth which would be available for navigation during the critical period.

As regards fixing depth and width of navigation channel, three basic criteria namely, sectional area ratio, draft to depth ratio and manoeuvrability formula are applied. It has been observed that a sectional area ratio *i. e.*, the ratio of the cross-sectional area of the channel to the area of submerged mid-section of the vessel, should be about 6 to 7. If this ratio is less than 6, the resistance offered to the vessel by the restricted channel increases considerably. The resistance to a vessel also unduly increases if its draft is greater than 75 per cent. of the available water depth. Narrow channels also add to the difficulties in manoeuvring the vessels and cause traffic jams. The width also depends upon the length of the vessel using the waterway. With a view to have ease in navigation under all conditions, it is necessary to provide widening of channels at bends.

If the natural depths and widths available are much too less than the projected depths and widths, the following methods are resorted to singly or in combination for the improvement of the channel: (a) Canalisation by locks and dams, (b) Dredging to deepen critical sections, (c) Regulation by training works such as realignment of channels, bank revetment, spurs, dikes etc., (d) Lateral canals by-passing rapids and other major obstructions if any, (e) Reservoir storage to supplement the minimum flow in the river

so as to increase the depths. Dredging is employed principally in maintaining minimum channel depths as an auxiliary method of regulation. By canalisation a stream is converted into a succession of pools of desired minimum depth by constructing weirs across it. This method is adopted when the slope of the river is too steep or the flow too small to permit provision of the desired channel. The method 'e' mentioned above helps to reduce the maintenance cost on dredging and thus there will be less interference to traffic. When the bed of the river is rocky, generally, a lateral canal by-passing this reach is constructed. Various training structures, which are used for maintaining channel in selected alignments can be grouped into the following two categories:—

- (1) *Spurs*: These can be either permeable, impermeable, submerged or non-submerged, of rock, pile or sand.
- (2) *Revetment*: These can be either—
  - (a) Articulated mattresses,
  - (b) Woven lumber or willow mattresses,
  - (c) Mass asphalt,
  - (d) Concrete block and riprap revetments, and
  - (e) Retards.

These are structures causing obstructions on the river bed. They are sunk to the river bed normal to the direction of flow and are maintained by wires tied to anchors placed upstream.

## TIDAL RIVERS AND THEIR IMPROVEMENT FOR NAVIGATION

**Tides and their advantages.**—The solar and lunar differential attractive forces cause tides which are of oscillatory type out in the sea. Their rising and falling periods are equal and the high and low waters coincide with the slacks. When, however, such tidal waves approach the river mouths the troughs of the waves suffer retardation compared to the crests and as a result the ebbing period becomes longer than the flooding one, and as the same amount of water which fills up the tidal compartment has to ebb out, the flood velocities are stronger than the ebb ones. The slacks do not coincide with high and low waters.

As the tidal phenomenon manifests itself, it affords a constant source of energy which can be utilised to further the cause of navigation. A channel or creek in which the flood and the ebb follow the same thread may be expected to maintain itself sufficiently deep and if in addition, the range available is substantial, it is an immense advantage.

Upland discharges of rivers form an additional source of energy to strengthen the ebb flow and as such are an asset to navigation. During the freshets, however, a considerable amount of coarse material may flow down into the tidal compartment and as such freshets contain both the evil and the remedy. It is for the engineers to

induce these natural forces to their advantage. Apart from the freshets, a substantial constant supply of upland waters during the non-freshet season is of immense value because it is naturally relatively clear and helps neutralising salinity and pushing the salt water wedge causing accelerated deposition of suspended silt further downstream.

**Principles of tidal river training.**—The physical characteristics of rivers vary from river to river; and hence it is impossible to lay down a standardised code of river training. However, there are certain fundamental guiding principles which apply to all rivers irrespective of their characteristics :

- (1) The most essential point in a tidal river improvement is to cater to a possible maximum influx. Training measures should always be evolved bearing this aspect in mind. This calls for free propagation of the tidal wave to the furthest limit possible. Unnatural constrictions, bends, hard shoals *etc.* obstruct free propagation of the wave and as such should be removed.
- (2) In a tidal stream, where the flow conditions are ever changing, local training works may be expected to affect reaches both upstream and downstream. Hence, whenever such a training measure is proposed, its effect in the upper and lower reaches should be critically studied.
- (3) Navigational requirements need certain minimum channel width depending on the vessels using it. If the channel maintained is much too wide than required by the discharge characteristics, bar formations and shifting of channels are sure to follow. Hence such a channel should be just wide enough taking into account the navigation requirements and discharge characteristics.
- (4) Divergence of axes of flood and ebb flow is a cause of bar formation and should be avoided. To correct the divergence of axes, training measures should be evolved after model tests.
- (5) A trumpet shaped tidal creek gives a maximum range which is one of the important factors beneficial to navigation. As such, an estuary with its creek should be made to conform to this shape wherever possible.

**Outer bars.**—Outer bars, when they occur well out, are a great handicap to navigation particularly in the monsoon season, when drafts have to be considerably limited due to swells. Training by means of moles and dredging help to get over the difficulty; and where there is a strong littoral drift it is best to extend the moles so that the load can be carried away by the drift. Sometimes dredging the bars deep may serve the purpose, because it then being the way of least resistance, the ebb naturally concentrates in it thus helping to maintain the channel of substantial depth.

It may be finally mentioned that the everchanging flow characteristics, the diversity of currents, eddies *etc.* introduce



complexities so that it is almost impossible to visualise the possible effects of training measures one may contemplate. Experience, though of considerable help, cannot be infallible and hence it is always beneficial to resort to the modern technique of hydraulic model testing which, in the end, proves economical.

## HYDRAULIC MODELS AND MODEL TECHNIQUE

In olden days the design of hydraulic structures used to be based on empirical formulae or past experience of the engineers or sometimes on the intuition of the designer. The engineers then did not have sufficient confidence in hydraulic models. But today, hydraulic models have been accepted as very useful aid to the design of hydraulic structures. Model tests, besides saving *crores* of rupees to the nation, help in clearing the designers' doubts and indecisions.

**Nature of hydraulic problems and principles of design and operation.**—An outline of the principles governing hydraulic problems and their solution by models is furnished in brief below. Various phenomena which are involved in model studies are: (1) irrotational motion as flow over weirs and through sluices, (2) viscous and turbulent flow in pipes and open channels, (3) surface tension, (4) water hammer, (5) cavitation, (6) non-uniform flow and backwater curves, (7) sediment transportation, (8) wave motion, (9) tidal flow, (10) density currents, (11) air entrainment, (12) flow through granular media, (13) hydraulic jump *etc.* Newton's second law of motion, namely  $\text{Force} = \text{mass} \times \text{acceleration}$  is the single fundamental law governing all the phenomena mentioned above. This law is expressed in the form of a dimensionless number called the Newton's number. The primary forces causing the phenomena are gravitational, friction, capillary and elastic. Corresponding to every one of the forces mentioned above there is a dimensionless number called Froude's number, Reynolds' number, Weber's number and Cauchy's or Mach's number respectively. When a specific problem has to be studied by a model, it is first essential to determine what is the primary force operating in that particular case. The problem may generally involve one or at the most two primary forces. The solution to a hydraulic problem, then essentially consists of controlling only three fundamental quantities namely: (1) pressure, (2) velocity, (3) potential *i.e.*, water surface elevations. These fundamental quantities are the same as those which enter the Bernoulli's equation. Various artifices generally employed in solving specific problems are streamlining, aeration, hydraulic jump, direct impact on a hard surface, mutual impact of jets, deflection of bed and surface filaments, *etc.*

**Design and operation of hydraulic models.**—For the proper design of a model, basic knowledge of the phenomena involved and the principles of similitudes are essential. There are three types of similitudes *viz.*, (i) geometric, (ii) kinematic, and (iii) dynamic. Geometric similarity postulates similarity of form, kinematic similarity, similarity of form and motion while dynamic similarity, similarity of forces besides geometric and kinematic similarity. Complete similitude is an ideal, scarcely attainable in

hydraulic model testing. But the practical application of similitude in hydraulic model testing is based on the fact absolute similitude but rather several imperfect similitudes which can be exploited as required. The requirements of similitude are generally studied in terms of dimensionless numbers, which are built up of three variables—length, velocity and operating force.

When more than one type of force plays a significant role, the techniques in use are employing a fluid in the model different from the prototype, adjustment of model rugosity by smoothing or roughening by trial and error, tilting, vertical distortion, linear distortion, that is employing a shorter length than is required by the scale ratio for adjusting friction as in conduit models, extrapolation by constructing three or four models, *etc.*

**Hydraulic models.**—There are mainly two types of models, *viz.*, geometrically similar and distorted models. In the former all dimensions are reduced to the same scale whereas in the latter the scales for vertical dimensions are different from those used for the horizontal dimensions.

Models of spillways, outlet works, canal structures such as head regulators, falls, siphons, harbours in which wave action has to be studied, models of ships, pumps, turbines, propellers *etc.* are made geometrically similar. One-way river problems such as river training, measures for arresting bank erosion, protection to towns, safeguarding of railway bridges, sand exclusion from canals taking off from barrages or weirs *etc.* and also problems of tidal rivers, improvement of the navigability *etc.* are dealt with by vertically exaggerated models. These models can be either rigid bed models or semi-rigid models or mobile bed models.

**Selection of scale ratios for vertically exaggerated movable bed models.**—Longitudinal scale is determined from the considerations of discharge, available space and funds. Generally models having a discharge varying between 6 to 10 cusecs are suitable and are very handy to tackle. There are three methods for fixing the discharge scale; either it is made proportional to  $L^3$  or  $LD^{1.5}$  or adjusted by trial and error. Among these the last is quick and simple, but it is not advisable from the point of view of obtaining long term results. Analysis of data carried out by the Central Water & Power Research Station, Poona has shown that discharge varies as the square of the meander length. Where therefore, meandering predominates, discharge scale is fixed according to  $L^2$ . When water levels and discharge distribution are to be studied over a weir, it is desirable to use discharge relationship  $Q = LD^{1.5}$ . When models are made of mobile bed material, it is very important to select the proper bed material, so that movement of the bed can be properly simulated. Depth is not an independent variable and so cannot be enforced directly. The depth scale has to be fixed in such a way that sufficient tractive force is obtainable for the bed sand used in the model. Depth scale may probably be so chosen that the model depths vary between 6" to about 15". If the depth is too small ripples form on the model bed and upset the results. If the depth is more than 15" it is difficult to observe flow conditions near the bed.

Slope scale ratio depends on the discharge, grade and charge of material in movement on the bed. Although the model operation is simplified when vertical exaggeration is equal to slope exaggeration it is rarely attained because of limited scope of controlling friction.

In mobile bed models the main object is to simulate bed conditions. Depth and slope determine the tractive force available for the particular type of material selected for the model. To simulate proper bed movement it may be necessary to tilt the model, that is, to make the slope exaggeration different from vertical exaggeration. Time scale ratio of the model has to be determined by trial and error. It is found from experience that lower discharges have to be generally run for a relatively much longer time and higher discharges less time so that scouring effect is not exaggerated. Rate of injection of silt has also to be adjusted by trial and error such that the material which is collected at the tail end of the model is equal to the material injected from the upper end of the model i.e. when the model is said to have reached stability and equilibrium conditions.

**Scale ratios for tidal models.**—Length scale is fixed according to the same consideration as for one-way river models. Discharge scale is fixed according to  $LD\sqrt{D}$ . Depth scale is so chosen that sufficiently turbulent flow is obtained as also optimum bed movement. To fix the depth scale Reynolds' criterion, Jack Allen's approach to the question of ensuring bed movement of the selected sand in models, Shield's criterion of sand entrainment have been found very useful. Jack Allen's approach leads to a satisfactory answer to the problem of fixing depth scale. Rate of injection is based on the total reduction in capacity by way of silting in dry weather and freshets. Bed material is so chosen that uniform bed movement is obtained all over the model.

**Verification of model.**—First stage in model operation is to prove it. It has to be seen whether all the prototype conditions are being faithfully reproduced in the model as far as practicable. The main points of comparison are : (i) the discharge, (ii) water levels, (iii) velocities, (iv) flow lines, (v) bed changes, and (vi) other peculiarity which may be observed in the prototype like 'bores' etc. The prototype conditions have to be reproduced to a high degree of accuracy; otherwise it will not be safe to predict the prototype behaviour from the model results.

**Model limitations and difficulties experienced in hydraulic model study.**—There are different time scales for scour and silting; while it has been observed that over 2/3 of the maximum scour takes place in 5 per cent. of the time, silting in the model is relatively slow and has to be artificially exaggerated to simulate natural conditions. The distribution of silt charge in nature cannot be reproduced in the model. While, frequently, more than 90 per cent. of the charge in nature moves in suspension the very reverse is generally the case in models. The model also shows exaggerated scour holes at the rigid structures such as groynes, divide walls, etc. In such cases the scour holes has to be reduced in size according to the model scale and made semi-rigid so that proper flow and scour conditions are obtained in the model. In vertically exaggerated models, the banks also become much

steeper as a result of which the flow conditions are likely to be affected since steeper slopes attract the flow towards them. An allowance has therefore to be properly made for these steeper slopes. The number of piers in case of models for bridges, weirs, barrages, etc. has also to be reduced to maintain approximately the same width to depth relation of waterway through each span as in the river. If this is not done the flow conditions in the model are not reproduced properly. In some models it is observed that the vertices are too much exaggerated. This distorts the flow conditions in the model. Proper precaution should be taken to minimise this effect. It is also sometimes necessary to tilt the masonry structures across the rivers. An interesting example of this necessity is illustrated in the Mahanadi River Model in which Katjuri takes off from the Mahanadi River at a sharp angle to flow over Maraj Weir which is parallel to the axis of flow in the Mahanadi. In the prototype the top of Maraj Weir is at the same level all along. As the model is given slope exaggeration the surface slope in the model is much more than in the prototype. The sill of the weir had therefore to be made sloping from right bank to the left bank.

**Conformity between model and prototype.**—Although great progress has been made in the use of hydraulic models to aid the design of hydraulic structures, very little detailed data is available for comparison of the performance of model and prototype. Such comparisons are very useful and necessary as they alone can instil confidence in the minds of the designer. There have been innumerable difficulties in observing prototype data due to non-availability of proper equipment for making measurements in the prototype. There is also lack of interest in taking prototype observations particularly after the prototype has been operating satisfactorily. The science of hydraulics is still in empirical stages. If this is to advance further it is very essential that prototype and model conformity should be considered at every stage.

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