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EXCLUSION AND EJECTION OF EXCESS SEDIMENT FROM CANALS, DISTRIBUTARIES, AND RESERVOIRS

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Apparently Masters' Thesis
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I. Introduction

This report is a review of methods utilized to control, exclude, and eject excess sediment from canals, distributaries and reservoirs.

Sand, silt, gravel and other insoluble materials transported by streams either as suspended material or bed load presents problems of vital importance in:

1. Flood Control Projects
2. Soil Conservation Work
3. Irrigation Projects
4. Navigation
5. Water Power developments
6. Municipal Engineering

In many cases complete destruction of important engineering works has resulted from unsolved sedimentation problems. Wherever irrigation has developed, man has been confronted with the problem of the deposit of sediment in the ditches and the cutting of the canal banks by the flowing water. Later reservoirs came into use and with them came the problem arising from the filling of them by the load of solid particles carried by the flowing water. In the nineteenth century navigation became of sufficient importance to justify the improvements of natural streams to facilitate it, and the channel forming processes of these streams began to be considered. In recent years the problem of sedimentation control has become even more important. Several new problems have forced themselves upon us as a result of the construction of major engineering projects.

The science of sediment transport and deposition, so far as is known, began with works attributed to Hippocrates around 400 B.C. A search of the literature of Egypt, Babylonia and China indicates the acquaintance of very ancient people with the problem of sedimentation. Early European contributions were made by two Italians:

1. Dominique Guglielmini, a physician and hydraulician, born in 1655. His greatest works were the building of the levees on the River Po in Italy and his book Della Natura di Fiumi Trattato Fisico Matematico, dealing with river control.

2. Paul Frizi was born in 1727 and was a professor of mathematics at Milan. He published a book titled Treatise on Rivers and Torrents with the Method of Regulating Their Courses and Channels. This text was translated into English by Major General John Gaistin, and was published in London in 1818.

Additional knowledge was contributed in this field by five Frenchmen, all of whom, with the possible exception of the first, were connected with improvements of rivers for navigation. The names of these men and their major contributions are listed:

1. Dubat - Best known for his laboratory work. In 1786 he published Principles d'Hydraulique in which he recorded the results of various experiments on the velocities necessary to move particles of various sizes.

2. Baumgarten (1848) - Published a book, Navigation Fluviale Garonne. This works recorded the results of an extensive hydrologic study of the river Garonne for a distance of 45 miles below the junction with the River Lot, and covered a period of seven years. It is here that we

find the first record of sediment load measurement.

3. Dupeut (1848) seems to have been the first person to give serious consideration to the transportation of sediment in suspension. In 1848 he published a book containing his theory of silt transportation.

4. Partiot - Published an article, apparently the first on this subject, dealing with the role of turbulent eddies and vortices in the transportation of sediment.

5. DuPoys, M.P. - Presented in 1879 his theory of tractive force which has been widely accepted, and has been extensively used in studying bed-load movements.

The first to work on the problem of sedimentation in this country were Sidell and Meade (1838). They measured sediment load in the mouth of the Mississippi River. Results of their investigation were reported by Humphreys & Abbott, (1). Later (1843) to 1846 Ridell made additional measurements on the Mississippi. Measurements were also made by Brown, July 1846 - June 1848; Marr, April - July of 1849 & March 1850 to March 1851. The experiments of Ridell, Brown, and Marr are also reported by Humphreys and Abbott(1). The first comprehensive study of sediment in the U.S.A. seems to have been made by Froshey in connection with Humphrey's & Abbott's study on the Mississippi (1851-1852). An additional study which resulted in another extensive series of measurements was made by Webster & Fillbrown during the period March 1858 to November 1858. Humphreys and Abbot found little relation between load of sediment carried by the Mississippi and either its discharge or velocity; they concluded that this resulted due to nonsaturation of stream with load. Other American contributors were Mr. James B. Eads who improved navigation channels at the mouth of the Mississippi by construction of jetties (1874-1879), and Dr. Eldon H. Hooker who presented one of the outstanding papers in the field of sediment movement, "The Suspension of Solids Flowing in Water."

In this he gave an excellent summary of practically all the literature in the field up to date of publication (1896).

The successive steps in the development of the science of sediment transportation and deposition in the engineering field has been the result of some pressing engineering problem. In the United States the primary initial problems were problems of flood control and navigation. In India the big problem was sediment deposition in irrigation canals: It is noteworthy that irrigation development in India is more extensive than anywhere else in the world. The problems of India were first attacked in a scientific way by R. G. Kennedy, who in 1895 reported his conclusions in a paper entitled "The Prevention of Silting in Irrigation Canals", (9).

II. Stable Channel Theory

Kennedy's general procedure was based on the assumption that mean speed of flow, when a channel became stable, was a function of the depth, D. To test his theory, Kennedy plotted the data of 22 channels of the Upper Bari Doab Canal (India) that had become steady without, or in spite of, interference from engineers. The resultant equation was of the form:

$$V = CD^{m} \qquad (1)$$

D = regime depth.
C = 0.84 , m = 0.64
V = minimum velocity to avoid silting

His approach to the problem was very sensible but his selection of canals was poor. A proper choice of canals would have shown "m" to be equal to ($\frac{1}{2}$). In essence he said that we had neglected sediment transport and that velocity was the answer; actually it was only half of the answer. It was soon apparent that C & m were different from those established for equation 1.

Considering alluvial channels it is obvious that they are free to adjust in depth, width, and slope. These three unknowns imply that 3 equations are needed for a solution. Kennedy had two equations, his own and Kutter's, the third required equation did not exist and a solution was obtained by guessing at the slope. This theory or method was in general use until 1930 and is unfortunately still used by some engineers. About 1919 advanced engineering opinion accepted the basic fact that regime channels have three degrees of freedom to require three equations for complete design. At this time Lindley presented his ideas which were primarily those of Kennedy except that he established a different value of (m) for the Kennedy equation and he provided a third equation. His equations are:

$$V = 0.95\, D^{0.57} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$V = 0.57\, W^{0.355} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Lindley probably realized that the coefficients in his equations were really functions of the properties of bed and side material but was not in a position to carry on the required investigation necessary to prove this. He did, however, establish the basic foundation for all future work.

In 1920 the United Provinces Government placed Mr. Gerald Lacey of their Irrigation Service on special duty so that he could collect and analyze canal data from anywhere in the world. Lacey's outlook was essentially that of the physicist. He believed that there must be relatively simple laws connecting relations shown by emperical plottings and proceeded to prove it. His three practical equations for stable channels are as follows:

$$V = 1.151 \sqrt{f R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$P = 2.67\, Q^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$S = f^{5/3} / 1788\, Q^{1/6} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

V = mean velocity of flow
P = Wetted perimeter
S = channel slope
$f \times \frac{V^2}{gR}$ = sediment factor Lacey's f

The development of the above theory is presented in reference (9). Further work has been done in this field by T. Blench (3). His three practical design equations are:

$$W = \sqrt{b/s}\quad Q^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

$$D = \sqrt[3]{s/b^2}\quad Q^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

$$S = \frac{b^{5/6}\, s^{1/12}\, Q^{-1/6}}{2080} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

The units in these equations are feet and seconds and:

Q = discharge

W = width that multiplied by D gives the x- sectional area of flow

D = mean depth from supply level (corresponding to Q) down to the bed, in that portion of the x- section that contains no point vertically above a cohesive side.

S = water surface slope

b = bed factor = V^2/D, depends on the nature of the bed sediment load.

s = side factor = V^3/W and depends on the nature of the cohesive sides.

$$r = \left(\frac{10^{-5}}{\nu}\right)^{\frac{1}{4}}$$

ν = working mean taken for kinematic viscosity.

Considerable progress in advancing the theory of the design of stable alluvial channels has also been made by E. W. Lane, (8), based on a limiting tractive force. Additional research relative to this method of design is in progress at present.

Proper application of the Lacey (9), Blench (3), or Lane (8) theory should allow canals to be designed that are essentially stable channels.

Degradation and aggregation would be insignificant in this case and hence for the given sediment load for which the channels were designed, silt problems in the channels would be a minimum. In order to be able to control the amount of sediment in a canal within limits so that it can be designed to function efficiently, it may be necessary to design diversions or canal heads so that the sediment charge they allow to pass is reduced to regime charge for the channel. (Regime charge is defined as that sediment load for which a channel is essentially stable or in regime.) The reason charge in the river or feeder canal is different from regime charge in the canals is threefold:

1. The regime charge is a function of the dominant discharge; so it is greater in the river than in the canal.

2. The charge in the river at dominant discharge exceeds the regime charge.

3. Super-dominant discharges in the river carry super-dominant charges.

(Dominant-discharge is defined as the steady discharge which would produce the same results in the channel as the actual varying discharge.) The combined effect of these causes necessitates a large portion of the coarser fractions of the river charge being excluded. This is especially important during floods. It is known that charge decreases from midstream towards the banks. From this it follows that where flow in a parent channel is axial, a small channel taking off over a raised sill does not draw an excess charge; but where the off-taking channels draw a considerable portion of the parent channel discharge, unfavorable curvature of flow develops toward the off-take and a considerable portion of bed material is drawn into the canal. To illustrate this consider a two dimensional resolution of the velocities in the river and toward the canal, Fig. (1).

Effect of Canal Draw - Considered Two-Dimensionally
See Reference (9)

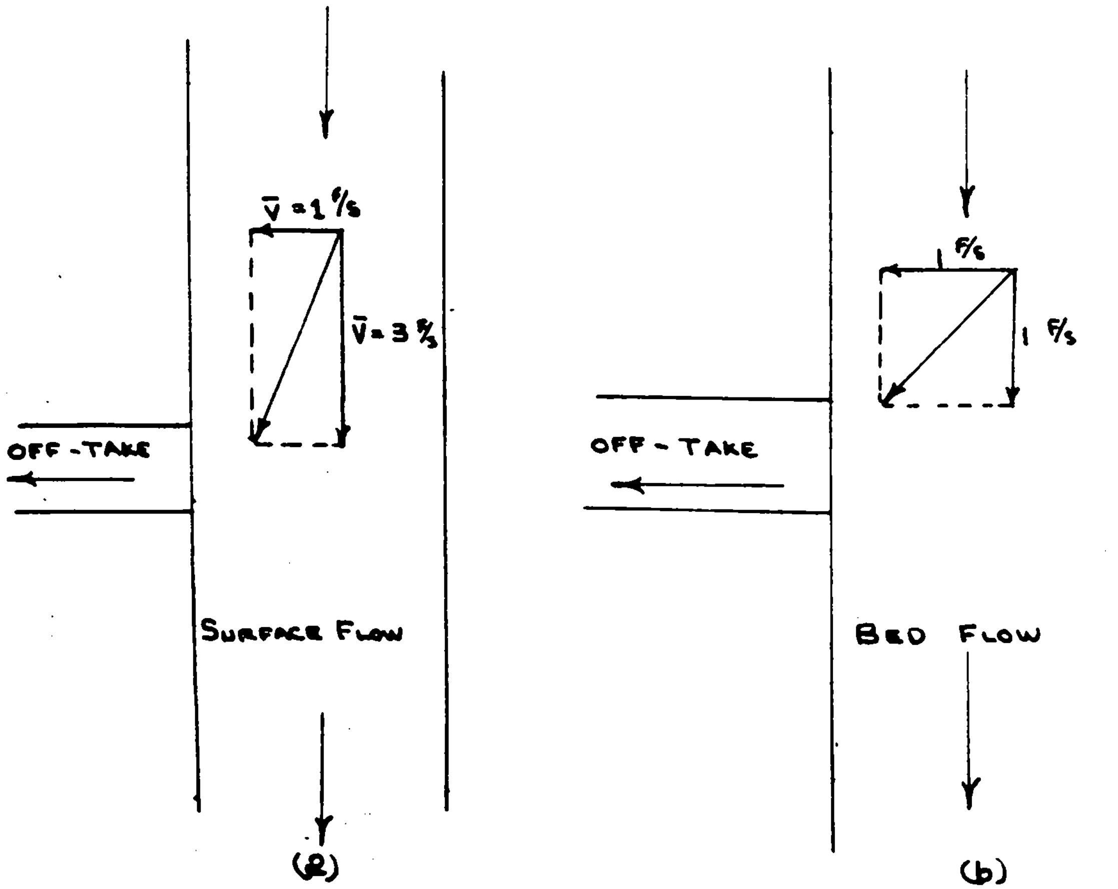


Fig. (1)

The figure shows that high velocity surface water is not greatly influenced by the draw of the canal, but the bed filaments containing the coarser particles are considerably deflected. It is clear that the portion of bed material drawn by a canal increases as the proportion of discharge draw-off increases.

When the problem is analyzed as a three dimensional problem, as it actually is, and water is drawn into a canal through a head regulator, the canal induces curved flow which tends to sweep the bed material towards and into the canal.

Three methods can be employed to prevent excess bed material passing down a canal:

(1) Sand can be ejected at the head, i.e. not allowed to enter.

(2) Sand can be ejected after it has entered the canal.

(3) The excess can be trapped near the head of the canal and later removed by hand or machinery.

When the material in movement consists of a very heavy charge of fine material little of the excess can be excluded; so settling tanks must be provided if the excess silt is to be trapped. In some instances silt deposited in inundation canals during flood season has been removed from the beds before the ensuing flood season. Removal was practiced in the belief that larger floods could be passed down the channels in the early part of the high runoff season and that more capacity would be available for irrigation water during the peak demand period. When this practice was discontinued it was found that there was little reduction in discharge and better conditions could be obtained at much less cost by remodeling instead of removing.

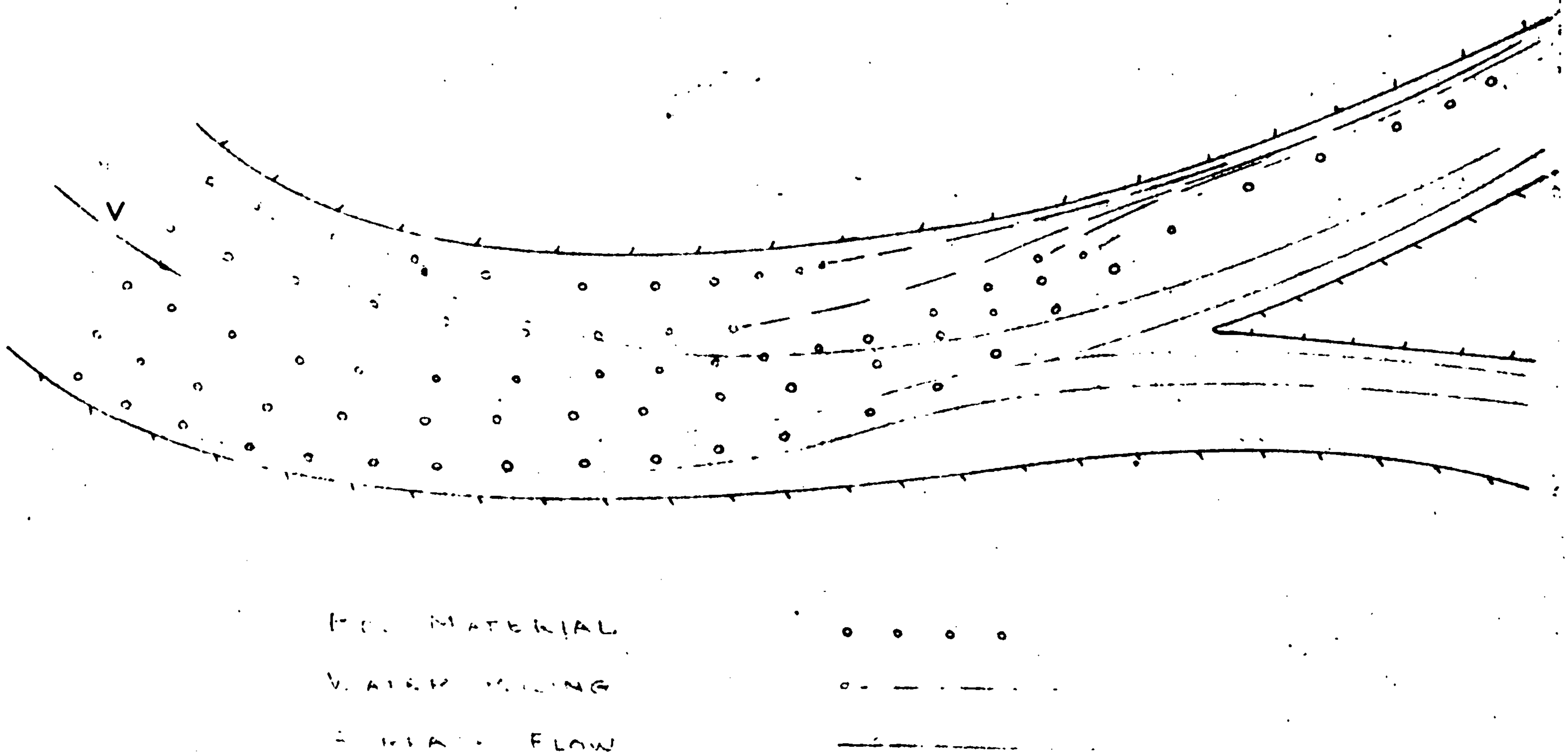
III. Sediment Excluders and Ejectors

Sand excluders prevent the coarser head materials from entering the head of a canal, and ejectors are used to remove coarser particles after they have entered the canal. Excluders are used as a preventative, ejectors are used as a cure, and where practical prevention is better than cure.

A. Excluders

(a) Natures Way

This method of sand exclusion simply takes advantage of flow conditions that are favorable to exclusion. The offtaking channel is located toward the downstream end of the outer bank of a concave bend, a little downstream of where diving flow, after reaching the bed near



PLAN SHOWING LINES OF FLOW IN AN APPROACH CHANNEL

FIG 2

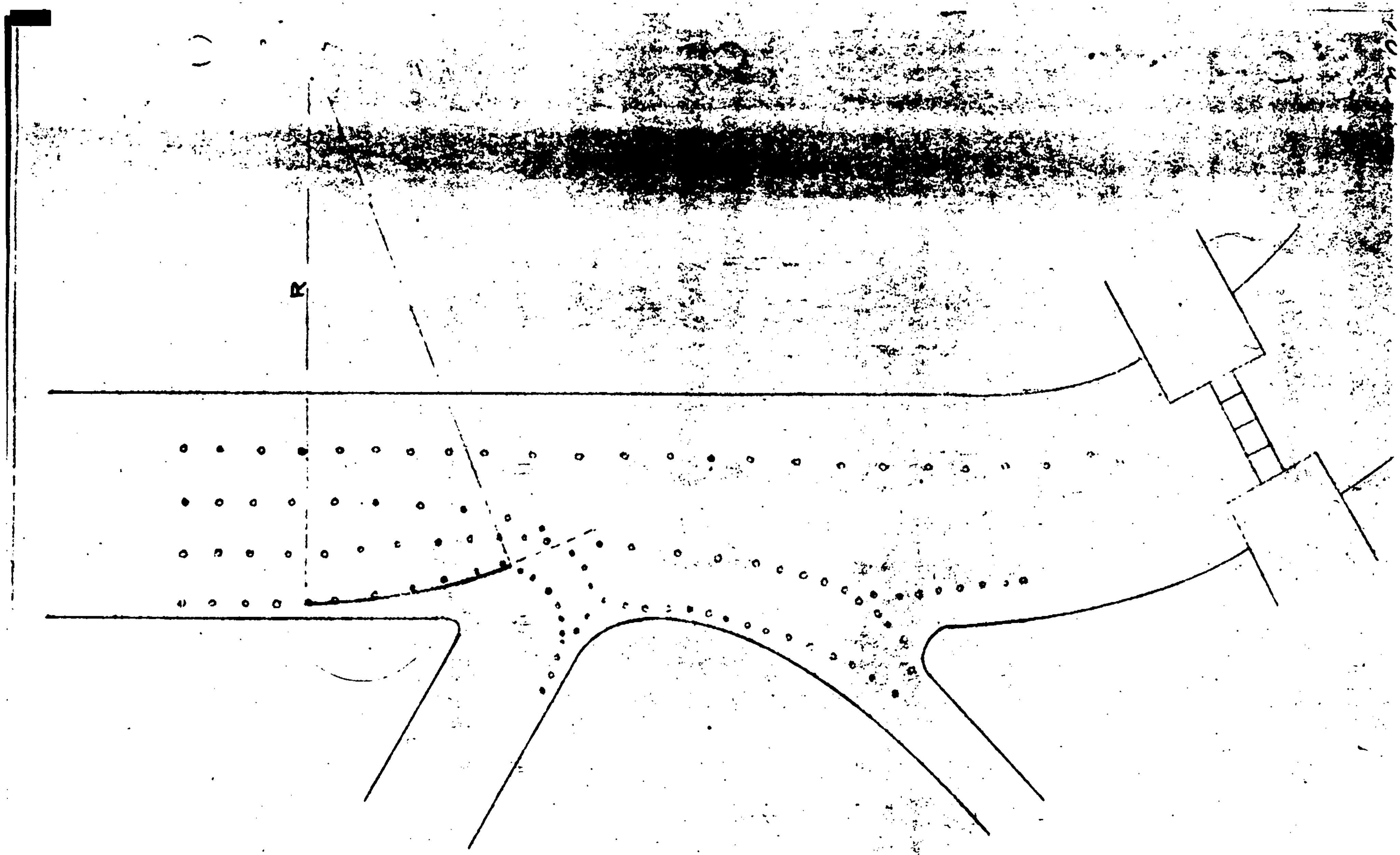
the bank, is diverted towards the opposite convex bank, thus sweeping the bed load away. See fig. (2). This method of excluding sand from canals has been practiced since the dawn of irrigation. It is practical and used extensively for excluding sand from inundation canals in Sind. A disadvantage is that there is a tendency for the meander pattern on rivers to shift so that what initially was a favorable condition becomes unfavorable and the canal begins to draw bed sand. This condition can be overcome by opening a new head if a right of way for the new location is available.

b. Increase in Quantity of Sediment Entering canals Resulting from Construction of Diversion Wiers & Head Regulators.

Diversion Wiers are built to bring higher lands under command, and head regulators are used to maintain water at any desired level. When these devices are improperly located as a result of a desire to cut construction costs or through sheer ignorance, the sand exclusion is unsatisfactory. A model study will assist materially in finding a suitable location. It is worth noting that these hydraulic structures may not give rise to unfavorable conditions when canals take off from only one bank but when diversions take off from both banks unfavorable conditions exist on one side or the other and special steps must be taken.

C. Reduction of Sand Entry by Means of a Submerged Concave Vane.

Model studies have proven that a submerged concave vane built upstream of off-takes in the proper location will help induce favorable curvature of flow. Size, shape and location of the vane are best determined by a model study. In some cases a second vane located on the opposite side of the river to the first one further improves conditions from the point of view of sand exclusion. See fig. (3), this illustrates the use of a single submerged, concave vane and gives data regarding its size and effectiveness.



BED LINE OF FLOW WITH SUBMERGED CURVED VANE

FIG. 3

d. Reduction of Sand Entry by Means of an Approach Channel.

This method consists of constructing an approach channel in which favorable curvature of flow is induced in order to prevent excess sand from being drawn into canal off-takes. It can be used jointly with raised sills, submerged vanes and etc. It is possible to create other adverse flow conditions by constructing approach channels as follows:

1. The change of channel may tend to alter the course of the river.
2. May require relocation of roads, railways, and takeoffs both before alteration and after.
3. May cause deep erosion along one of the banks depending on the approach channel.

It is necessary to conduct detailed model experiments if the answers to various aspects of the problem indicated above are to be accurately determined.

e. High Level Sill at Canal Head

High level sills are constructed at the canal head. Water is drawn over the sill and into the canal. Where upstream flow is axial and only a small part of the total flow is drawn off, this method is successful. If a considerable part of total flow is drawn by a takeoff, unfavorable curvature of flow will develop in the river and the method is no longer effective for sand exclusion.

f. Divide Wall

The first man to understand this method of controlling silt was Mr. A. S. Gibb who worked in India some 35 years ago. He realized that sand was drawn by offtakes because side eddies with vertical axes were bent toward the offtake which caused the lower end of the eddy to rise abruptly throwing bed material into suspension. Working on this theory, Gibb held

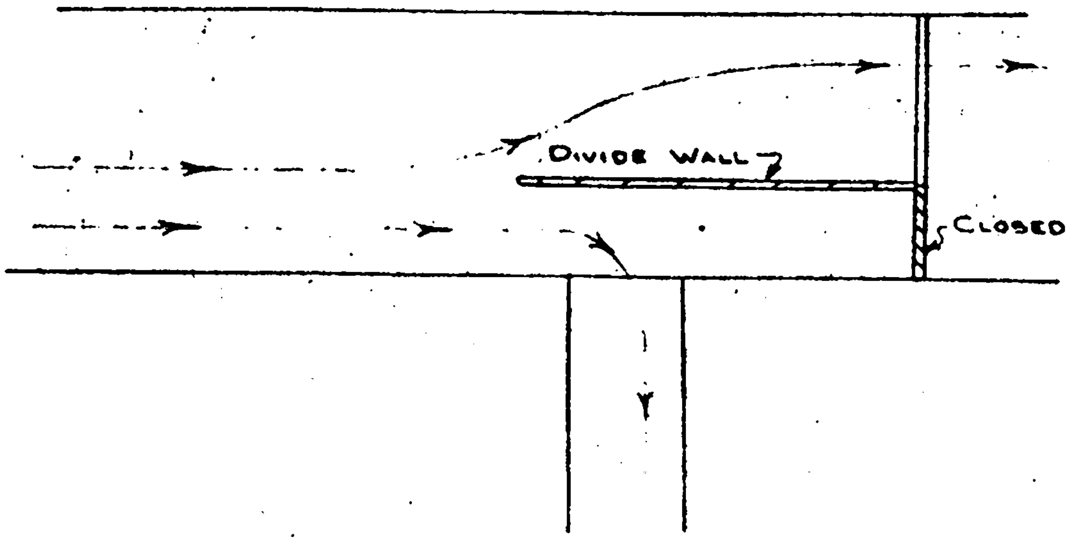


FIG. 4A

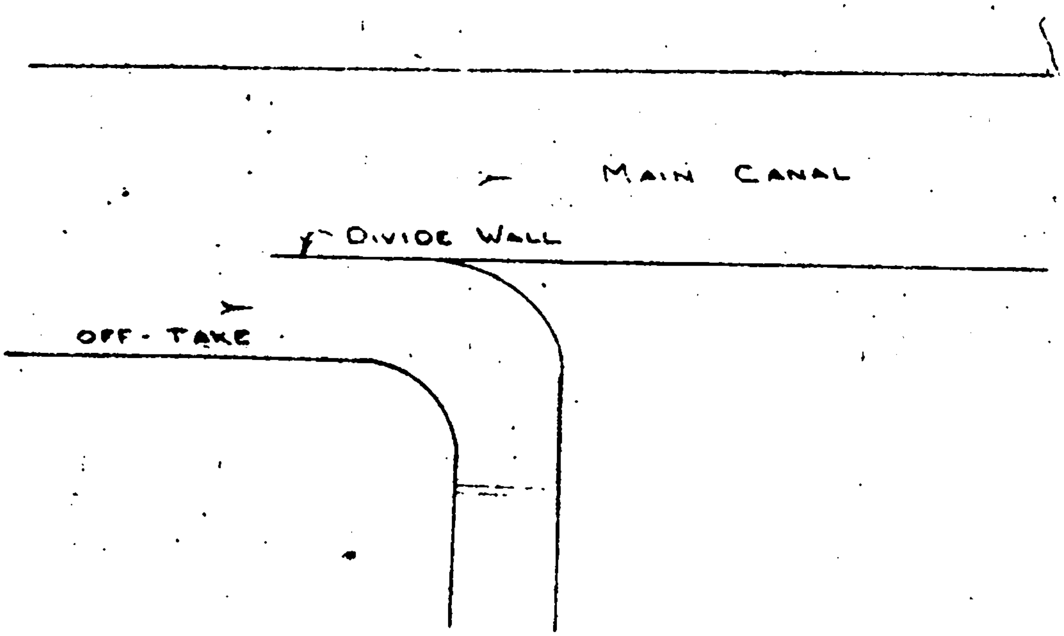


FIG 4B

DIVIDE WALLS USED TO EXCLUDE EXCESS SEDIMENT FROM OFF-TAKES that the right way to overcome excessive sand being drawn was to divide water before it was affected by the draw of the takeoff by building a divide wall. See fig. (4a) and(4b). The divide wall produces a still pond pocket, if constructed as in fig. (4a), in which the silt can deposit to be subsequently scoured through undersluices at the down stream end of the pocket. This type of undersluicing is temporarily helpful, but the effect lasts for only a few days and the head of the canal has to be closed while the pockets are being scoured if curvature of flow is not favorable. The closures interfere seriously with canal irrigation and hence this method under this condition of operation is not too desirable. The divide wall, when used where favorable curvature of flow exists, excludes the excess sand even if the pocket is run semi open flow. Favorable curvature will exist where:

(1) the approach flow is axial & the portion of the flow drawn into the pocket is small, or

(2) the approach flow has sufficient favorable curvature to neutralize the draw of a larger off-take.

Favorable curvature of flow can often be created artificially as discussed above. Many variations are possible when using the divide wall.

9. Open Type Excluders at Heads of Canals

Exclusion of excess sand from distributaries taking off from canals is a relatively simple problem because:

1. The charge in the parent canal is much less than that in the river.

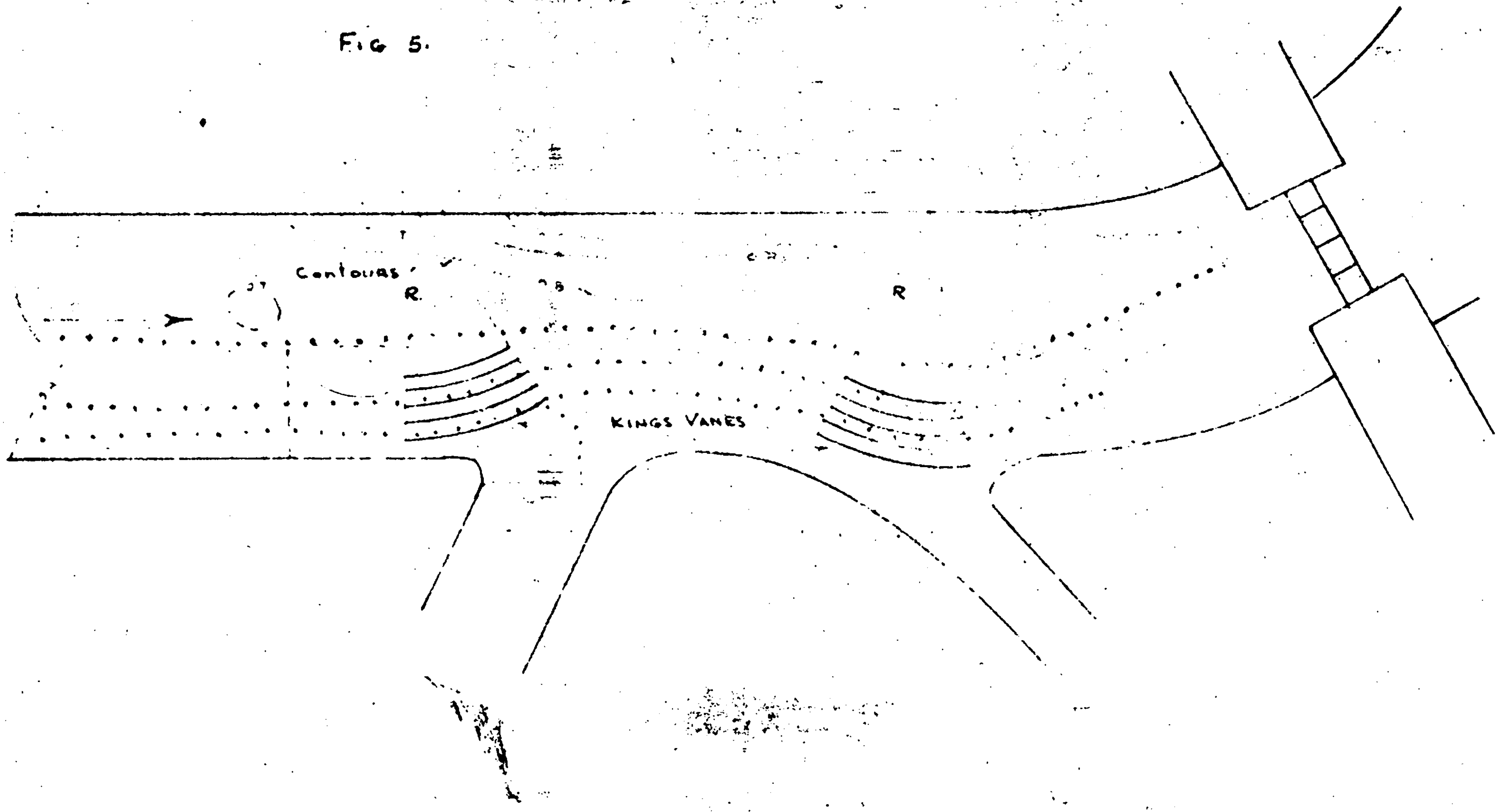
2. The parent channel is generally straight, and unfavorable curvature is not apt to develop.

3. Small channels drawing water from a large channel tend to draw surface water and hence finer material than that moving along the bed of the main canal, especially where they are set back or have a raised sill.

BED LINE OF FLOW • • • •

KINGS VANES

FIG 5.



4. Branches and distributaries generally take off from above regulators so that the draw can be controlled to a considerable degree by gate regulation.

The only time that canals of the above type draw an excess charge is when the head of the off-take is located at an unfavorable angle, or at an unsuitable point inside of a bend. It is at times desirable to give these canals a very flat grade to make it possible to serve higher land; this being the case it is practical to utilize some means of sand exclusion.

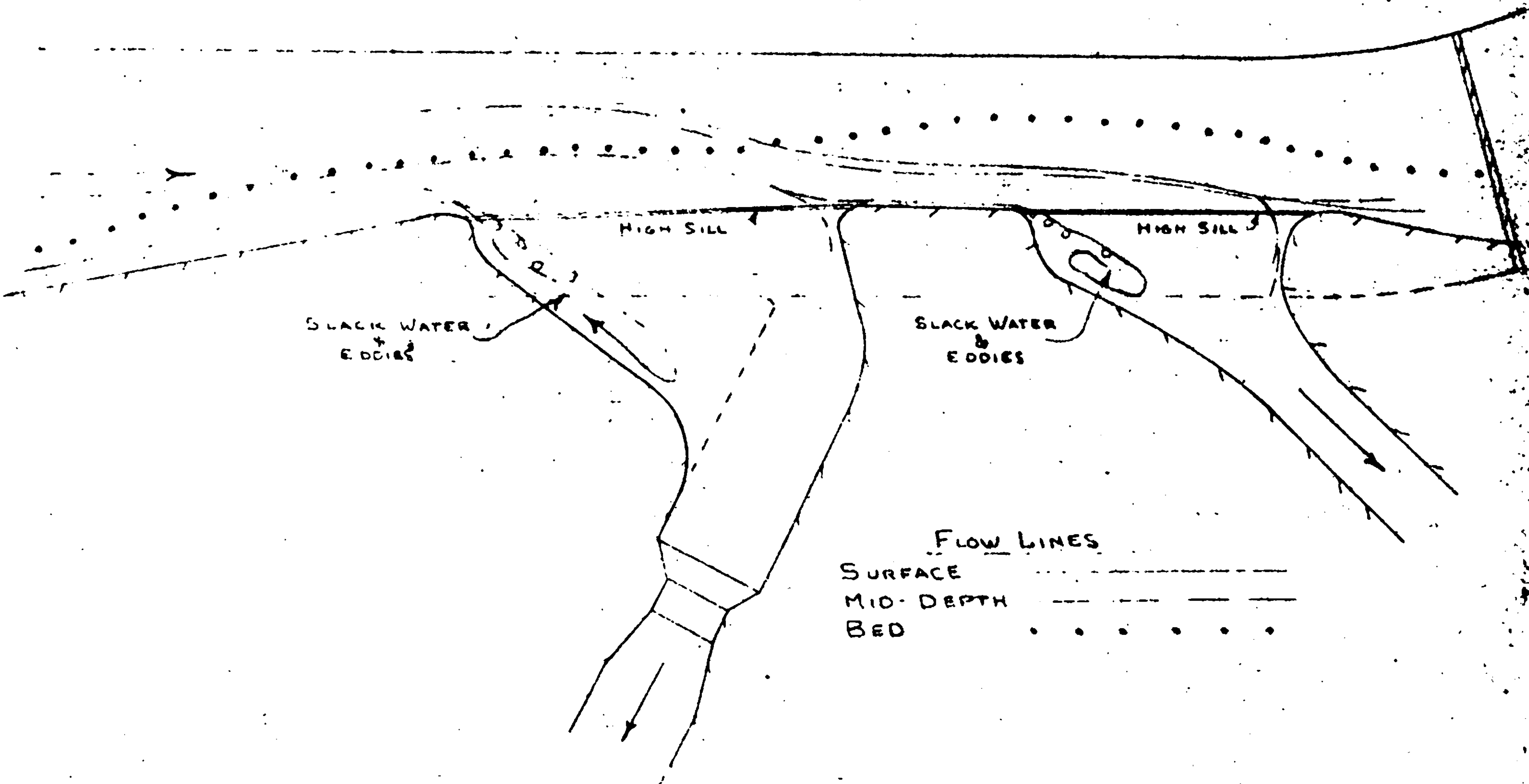
h. Kings Vanes

They consist of a series of curved vanes extending from the bed up to about one third of the water depth and are spaced about one and one-half their height apart. Actual spacing, height, and location are best determined by model analysis. The vanes are usually mounted in a smooth, rigid floor opposite the canal take-off. See fig. (5).

Kings Vanes will exclude practically the total bed charge where discharge is constant providing the vanes are in line with the on-coming current. If rate of discharge varies in the canal or if discharge varies in the off-take, the vanes will not be in line with the oncoming current and their efficiency will be considerably less than that obtained for the ideal case. The unsatisfactory results are caused by the formation of a sand bank down stream of the vanes; and where flow is not completely controlled turbulence tends to throw coarse material into suspension. In general, it may be stated that Kings Vanes have a place if complete exclusion is required, but under varying flow conditions other methods of exclusion should be considered.

i. Exclusion by Means of Raised Sills Projecting into the Parent Channel with a Warped Convergence Upstream.

In this type of design favorable curvature of flow is created by



EXPERIMENT WITH CONVERGENCE UP-STREAM OF OFF-TAKE

FIG 6

utilizing a warped convergence with a long high sill.. (See fig. (6). It is necessary to make the left bank scour proof if successful results are to be obtained. Best results can be expected where the design is based on a model analysis study.

j. Exclusion by Means of a Projection Downstream of a Canal.

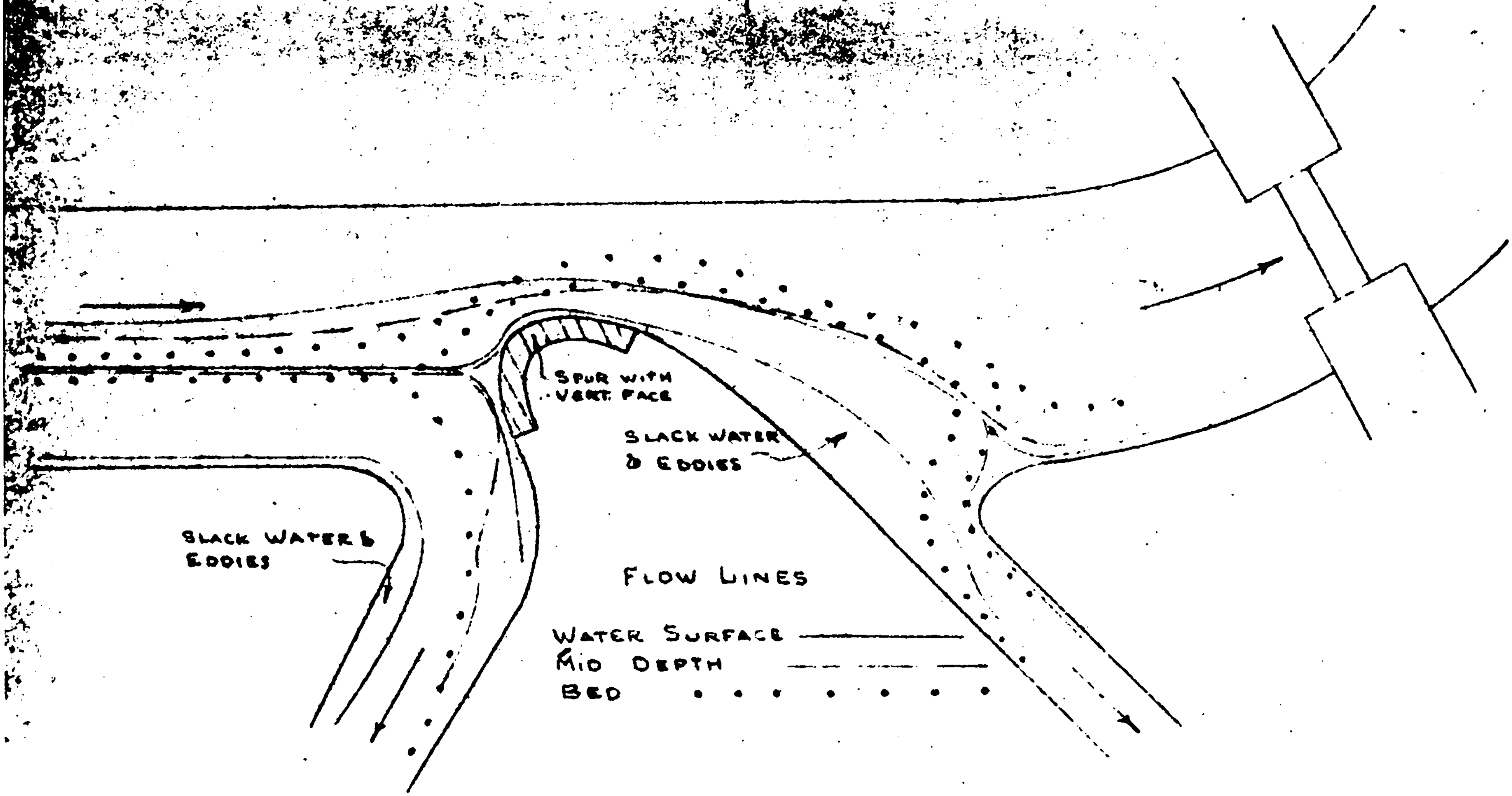
Curved flow is created by building a nose out into the river or feeder canal extending to a point determined as best by model analysis. See Fig. (7). This type of design will reduce entry of coarse sand into the canal upstream of the nose by about one half, but creates violent eddy action and the left bank must be protected from scour. The canal below the nose tends to draw an excess charge.

k. Tunnel Type Excluders

The idea of tunnel type excluders was originated by F. V. Elsden in 1922, "Irrigation Canal HeadWorks," Punjab Irrigation Branch Paper No. 25, 1922. The first excluder of this t pe was built in 1934 and is now known as the Kanki type excluder. Several others have been constructed since. The principle in every case is to pass the slow moving bed water, containing a heavy charge of the coarser grades of material through tunnels whose tops act as platforms at about canal sill level. These tunnels lead to under sluice gates in the diversion weir and should be so regulated that:

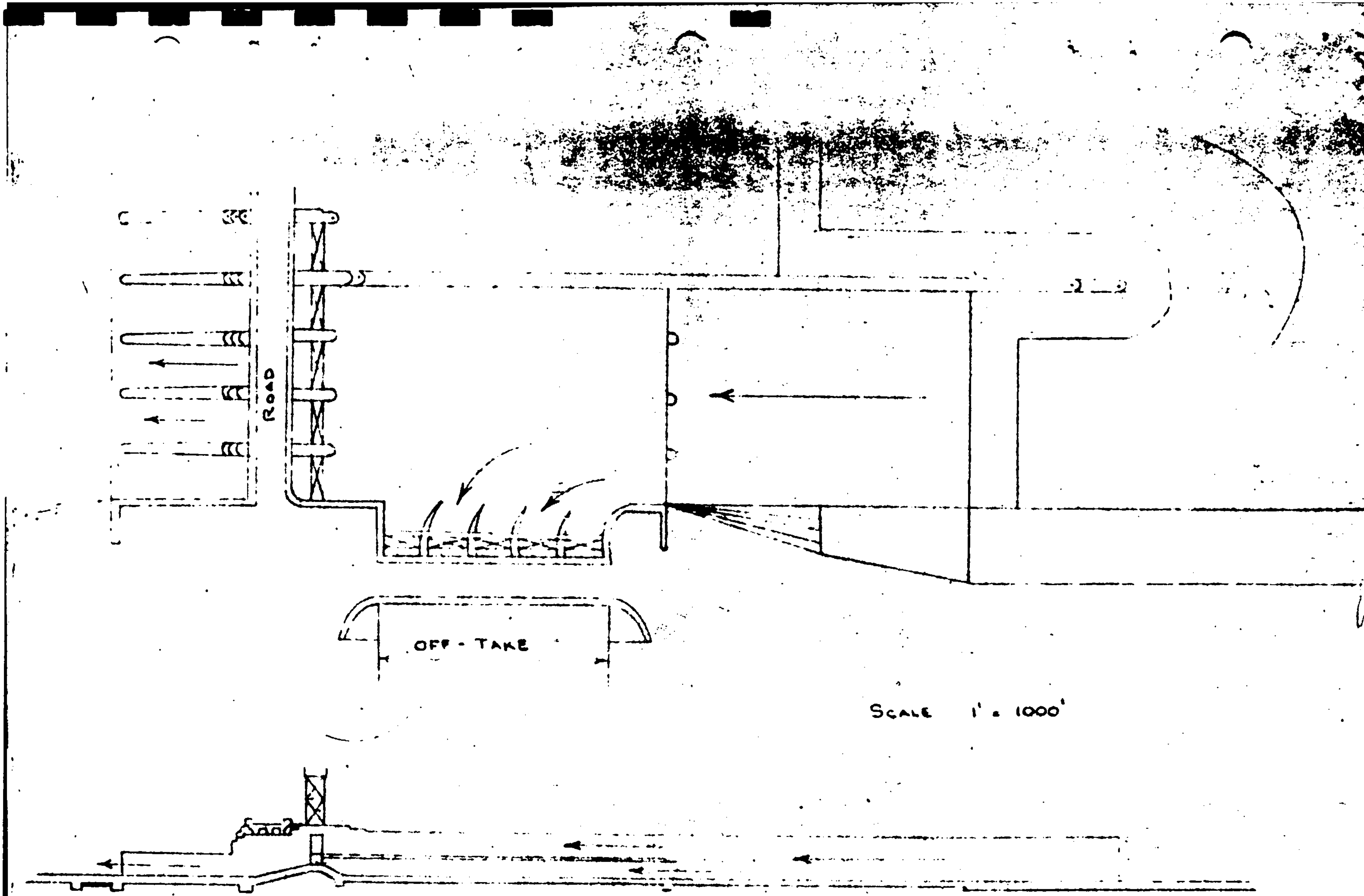
1. The tunnel does not get clogged with sand.
2. The bed water and top water are divided without developing eddies which would throw the coarser grades into suspension.

A second type of tunnel excluder developed more recently (9) depends on inducing optimum curvature of flow in the successful exclusion of coarse material. This type of excluder was used at Tajewala in the Punjab and was extraordinarily successful - so successfulthat the design was judged



EXCLUSION BY MEANS OF A PROJECTION DOWNSTREAM OF A CANAL

FIG 7



TRIMMU POCKET EXCLUDER

FIG 8

to be a failure because it excluded such a heavy charge of boulders and pebbles that the water could not carry them down the river under existing conditions of flow at the time.

The following advantages are common to all tunnel type excluders:

1. The head across the diversion weir is always available for operating them.
2. Economy is secured by using diversion weir gates and cisterns.
3. Large orifices, unlikely to be choked by rolling or submerged floating debris are easily provided.

The disadvantages of this type are:

1. The difficulty of securing good approach conditions.
2. The undersluice bays covered by the excluder cannot be used simultaneously for exclusion and their proper purpose of passing high river discharges.
3. The work being subject to the river action has to be of very strong construction.

There are two types of tunnel type or pocket excluders being used in the Punjab. The Trimmu type is illustrated in fig. (8).

B. EJECTORS

Ejectors are designed to get rid of excess sediment after it has entered a canal. It usually consists of slots or apertures in the bed of a canal through which a large part of the coarser particles are ejected by passing a relatively small quantity of canal water from near the bed of the canal. In many cases it is expedient to install ejectors in series. There are six ejectors installed in series near the head of the Thal Canal (9). The advantage of multiple ejectors is that more sediment can be ejected with a minimum amount of water. The coarser particles are removed by the first ejector and then finer and finer grades are taken care of by the following ejectors.

The main principle to be followed is that the bed upstream of an ejector should be smooth and have such a slope that with a suitably adjusted velocity the grade of material which it is desired to eject will be just moving along the bed, while finer grades will remain, so far as practicable, in suspension or soltation.

Where there is a single ejector with a cross regulator downstream the water level can be regulated so as to attain any desired velocity; but where there are several ejectors in series and only one cross regulater, there can only be one regulation of velocity for all the ejectors and a reduced efficiency must, therefore, be expected.

Advantages and disadvantages of ejectors as listed by Haigh (9):

Advantages

1. The ease with which good approach conditions are secured.
2. The relative lightness of the work.
3. The possibility of multiple extraction.

Disadvantages

1. The difficulty of securing a working head with a high river and low canal supplies.
2. The necessity of increasing the size of head regulator to accomodate the escapage.
3. The increase in size of the canal section above the ejectors necessary to accomodate the escapage.
4. The necessity of providing separate outfall works.
5. The comparatively small orifices are liable to be blocked by sunken debris and may necessitate the provision of a trash rock.

If disadvantage (1) can be overcome, the others are a matter of cost only and in comparison with other alternate methods the use of ejectors appears favorable.

The problem of water-borne gravel, sand and silt incident to operation of irrigation and power canals of the west has been investigated, primarily, at the Bellvue Hydraulic Laboratory at Fort Collins, Colorado by the Division of Irrigation and Water Conservation, S. C. S., U.S.D.A., in cooperation with the Colorado Agricultural Experiment Station (12). Two practical methods have been developed to protect channels from bed load deposits - the vortex tube and riffle deflector, vortex tube sand traps. They catch the bed load as it is moved along by the flowing water.

a. Vortex Tube

The vortex tube sand trap is a tube with an opening along the top side laid in the bottom of the channel at an angle of about 45° to the axis of flow. The elevation of the top edge or lip is the same as the bottom or grade of the channel. As the water flows over the opening, a pronounced whirling or spiraled vortical motion is established within the tube. This motion extends throughout the full lenth of the tube and it catches the bed load as it passes over the lip of the opening and carries the sediment to the outlet at the downstream end of the tube; where it is discharged into a suitable sluiceway for disposal. The vortex tube is illustrated in fig. (9).

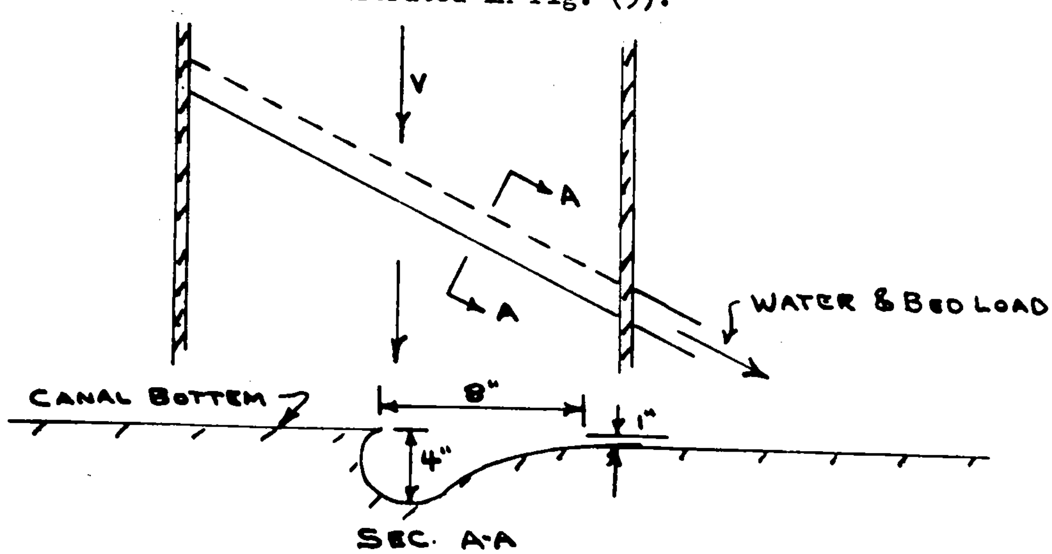


Fig. (9)

Model and field tests prove that efficiency is highest when the velocity passing over the lip of the tube is at or near critical velocity. Various shapes and sizes have been tested. In one case a 4" tube with a 10% - 15% waste was tested, V = 2.5 ft./sec. over the lip. It was found that the rate of rotation near the outlet was about 200 rpm. Under these conditions the tube ejected heavy gravel and stones, some having diameters in the vicinity of two inches, very readily.

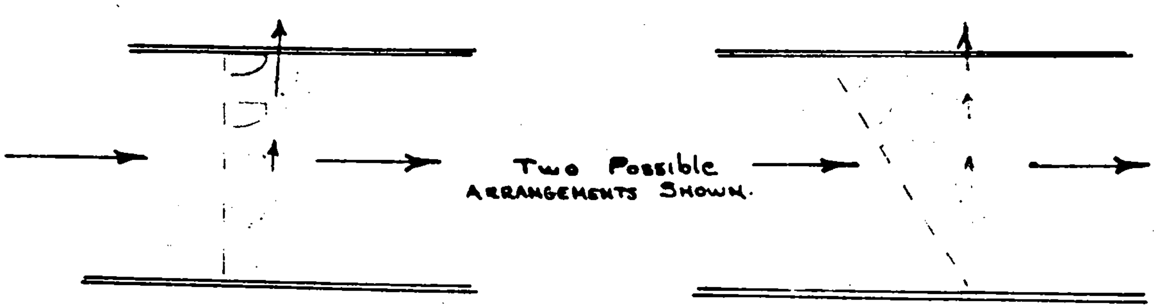
In another similar test utilizing a 4 inch tube and a mean velocity of flow of 6.6 ft.per sec., axis of the tube placed at a 30° angle to the direction of flow, and having a slope toward the outlet of 2 inches in 4 feet, very large boulders were moved. One weighing 7½ pounds was moved at a uniform rate of 1/2 ft. per second along the tube. The maximum speed of rotation was 300 rpm. With the above tube placed at an angle of 45° with axis of flow and utilizing a velocity of 6.9 ft. per second. The maximum rate of rotation measured was 500 rpm. Tests run indicate an efficiency in diverting bed load of about 90%. Most tests were run on large scale working models in which diameters of tubes ranged from 4 inches to 12 inches.

The vortex tube sand trap has been tried in the field. In some cases it has performed in an efficient fashion and in other cases its usefulness has been of doubtful value.

b. <u>The Riffle Vane Deflector</u> (12)

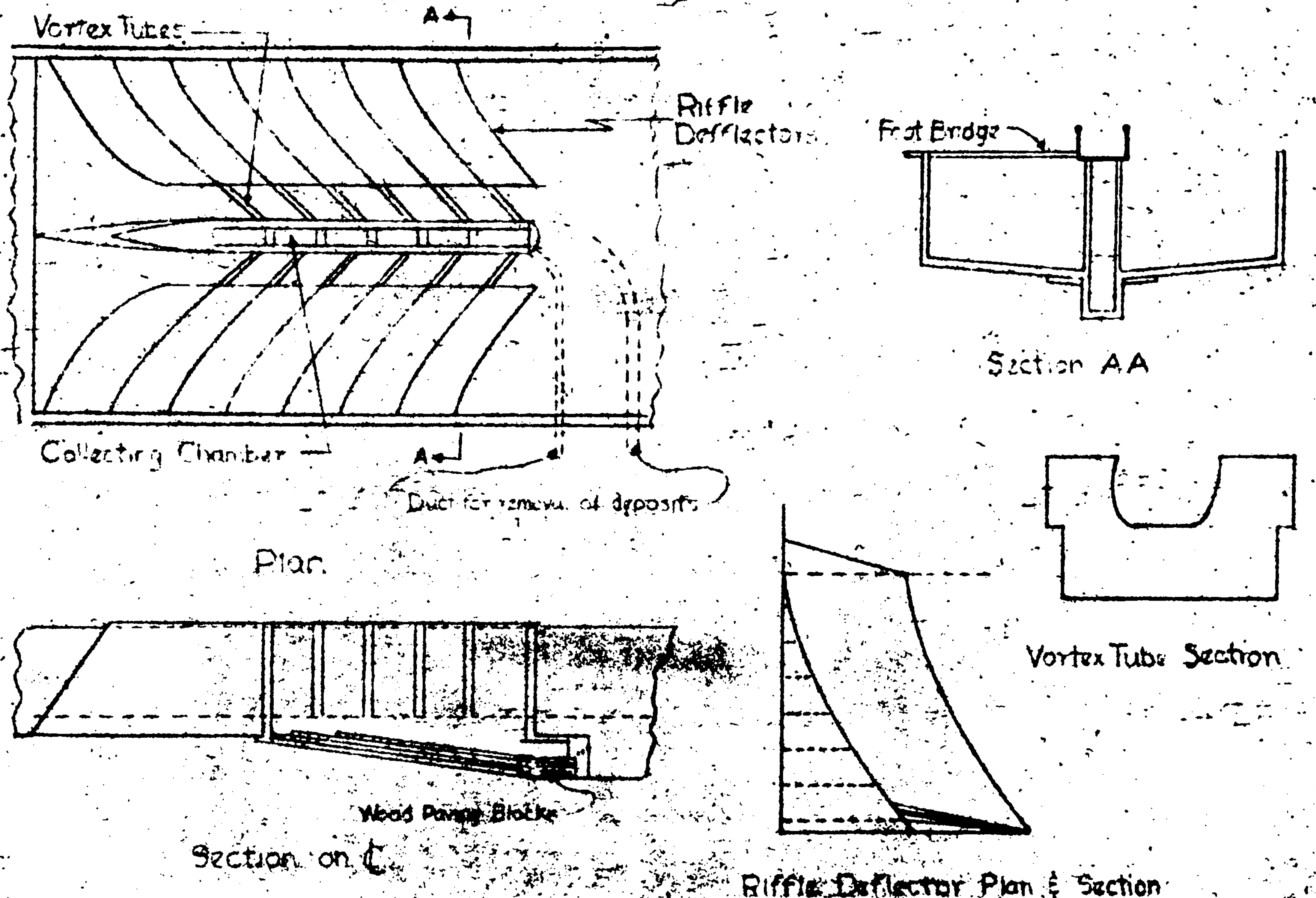
The riffle vane deflector sand trap consists of a series of curved sheet metal vanes. The plan view approximates the quadrant of a circle, the side view is triangular in shape and the top line is curved toward the downstream side. The vanes used in the study were of various shapes, sizes and spacing, and were attached in a vertical position to the smooth level floor of the channel. In some installations the floor has been sloped laterally. For some settings the functioning was very good. When the riffles are set in a line normal to the axis of the canal the bed load is moved laterally at 90° toward the outlet in a well defined limited area immediately downstream from the line of riffles. The action of flowing water over the riffles is to maintain the bed load in a ridge downstream from the riffles. The action of the riffle deflector seems to be independent of depth of flow.

The tests ran showed that for a channel velocity of 4 ft. per sec., the energy developed was sufficient to move large cobblestones, exceeding the dimensions of the outlet, laterally. Field tests made using this type of sand trap have not been too successful. The paramount disadvantage of this type trap is that debris lodges on the riffles, destroying the efficiency. An installation of this type was made in the Wannamaker Ditch near Golden, Colorado. A series of six sets of riffles were placed in a channel 6 ft. wide. The riffles were 6 inches high. Sand removal under optimum conditions is about 15 lbs. per second. If vanes can be kept free of debris, sand traps of this type are very efficient. This method of ejection works best when channel velocities are around 2 to 3 ft. per second. It is not intended for wide channels . See fig. (10).



Riffle Vane Deflector

Fig 10



Vortex Tubes
A
Riffle Deflectors
Collecting Chamber
A
Duct for removal of deposits
Plan
Foot Bridge
Section AA
Vortex Tube Section
Wood Paving Blocks
Section on ℄
Riffle Deflector Plan & Section

FIG. 21

c. The Riffle Deflector Vortex Tube

According to Parshall (12), the most promising and practical sand trap developed is the riffle-deflector, vortex tube type. This device consists of a series of curved vanes or riffle deflectors on the bed of the channel which move the bed load laterally to the end of the riffles where it is taken off through small vortex tubes discharging into a common compartment as shown in fig. (11). The Common compartment is provided with an outlet that sluices the controlled bed load out of the channel where it can be disposed of. The riffles are parabolic in plan, have a vertical upstream face height of about 1½ ft., and a top surface sloping downward to a feather edge in a distance of about 5 ft. downstream, as measured parallel to the axis of the channel. A cross section of a single riffle is a right triangle. The riffles are all the same shape and are fitted progressively, one against the other, in a down stream direction. The number of riffles used depends on the nature of the bed load. Fewer riffles are needed for coarse sand and gravel than for fine sand. In every case 10 or 12 riffles should be adequate.

This type of trap is adaptable to wide or narrow channels and to flow ranging from 10 cfs to more than 200 cfs. For channels 20 ft. to 50 ft. wide it is suggested that two series of riffles be provided to crowd the bed load to the middle or axis of the channel. Short vortex tubes at the ends of the riffles carry the load into a narrow compartment built along the center line of the channel, where an outlet pipe conducts the trapped sand and water to the point of disposal. For channels 50 to 100 ft. wide a double installation with four series of riffles is recommended. The outlets from the twin installation join in a common pipe placed below the bed of the canal, leading under the canal bank. Laboratory tests on models indicate that traps of this type are

Upstream view of riffle-deflector vortex-tube sand trap installation in supply canal for Colorado Fuel and Iron Co. (Pueblo, Colorado). Capacity equals 250 ft^3/s.

Downstream view of riffle-deflector vortex-tube sand trap installation in supply canal for Colorado Fuel and Iron Co. (Pueblo, Colorado). Capacity equals 250 ft^3/s.

Figure 7

capable of ejecting 90% or more of the weighed bed load sample introduced in the approach channel upstream from the riffles.

Field installations have been successful in catching bed loads, not only of relatively coarse material but also of fine sand. Installations of this type trap have been made at Sheep Creek Ditch, Torrington, Wyo. (Timber Structure); and Colorado Fuel and Iron Co., Pueblo, Colorado (reinforced concrete structure). Based on the success of the installation at Pueblo, Colo., the Consolidated Irrigation District that diverts from the King's River near Fresno, California arranged for the building of a model at the Bellvue Hydraulics Laboratory to check the feasibility of using this type of trap on one of their canals. Model tests indicated the trap would be successful and the prototype was constructed and put in operation in 1947. Detailed observations of the canal at various points below the installation indicate that its efficiency exceeds 75%. It was estimated that previous annual cleaning operations cost $4,000.00 peryear. Need for cleaning was eliminated by the installed sand trap which cost $15,000.00.

d. Punjab Irrigation Service Practice

The first bed sediment ejector in Pakistan (previously India) was devised in the early 1930's for a flow of nearly 7000 cfs by E. S. Crump of the Punjab Irrigation Service. The Upper Jelm Canal, a feeder canal about 100 miles long, had its upstream 50 miles excavated in erodible material along the base of foothills. Torrents came down from the hills and were passed through the Upper Jelm Canal by level crossings Fig. (12).

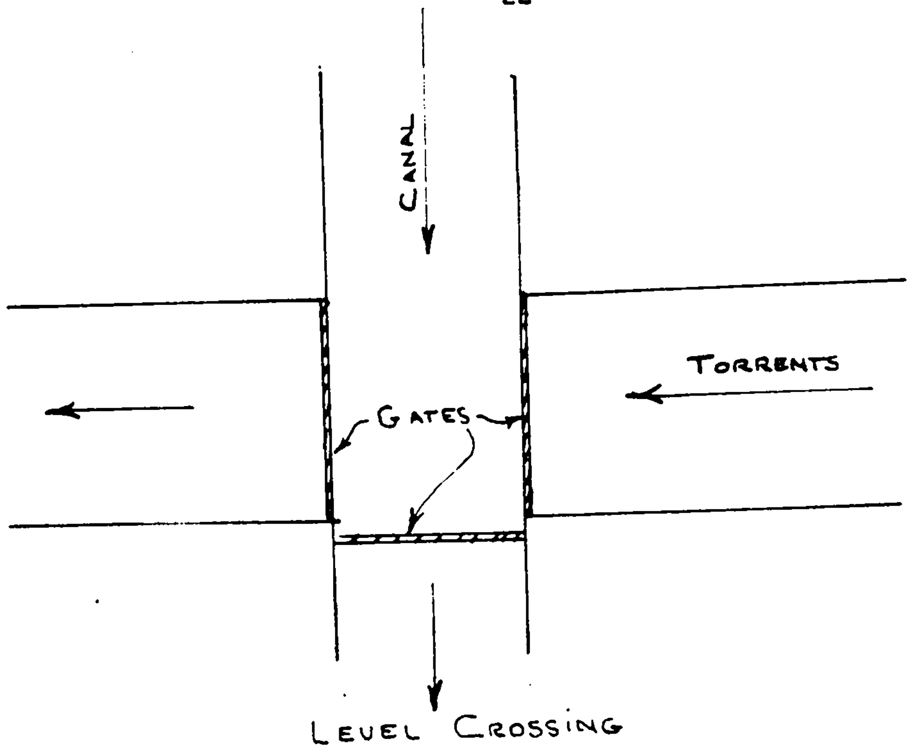


Fig. (12)

Some of the coarse sediment injected by torrents was carried on into the lower reaches of the canal, the lower 50 miles, and regime was upset. Luckily the tail end of the upper 50 miles possessed several siphons well below canal bed level to take care of moderate-sized cross-drainages. Mr. Crump selected a location on the canal over one of the siphons and built a tunnel under the canal with its roof at canal bed level. Holes were provided in the roof for bed sand to drop into. One end of the tunnel was blocked, the other end was provided with a gate which, when opened caused the tunnel to function as an ejector discharging its sludge into the cross-drainage syphon beneath. The gate was operated whenever a heavy bed load arrived provided water could be spared. The results were so good that several syphons were adapted in the same way. Within a few months the canal was back to normal. Since that time practically every new system has been provided with ejectors near headworks. Ejectors for flows of even 10,000 cfs can now be considered as established practice.

Such ejectors can be 100% efficient for coarse material such as gravel. For fine sand their efficiency is poor, and two or three have to be built in series to have much effect. The inefficiency for fine materials arises from the ease with which these materials go into suspension. Little model work is needed in the case of ejectors as the work of the prototypes is understood.

Where the ratio of discharge of off-take to that of the parent channel is high, ejectors may be the only solution. When nearly the whole discharge of a river is drawn off by an off-taking canal the best method of controlling sediment is the one requiring the least waste of water in the elimination of excess sand. This means ejectors which in turn means a considerable loss of head in some cases and in addition there is the problem of getting rid of the ejected materials. Dumping the waste back into the river or parent channel may not always be the solution since the river with its reduced rate of flow may not be capable of handling it.

e. Distribution of Bed-Load Between Off-Takes

In the case of distributaries and branches taking off from a canal the object may not be mere exclusion of sand, but the suitable division of sand between the parent channel and the off-taking channels; so, correct quantitative distribution is required (9). Distributaries or laterals usually take off above a regulator so that flow can be controlled to a considerable extent. Where, however, a lateral draws off a large portion of the discharge of the parent channel, the off-take should not be at right angles but should face somewhat upstream, Fig. (13).

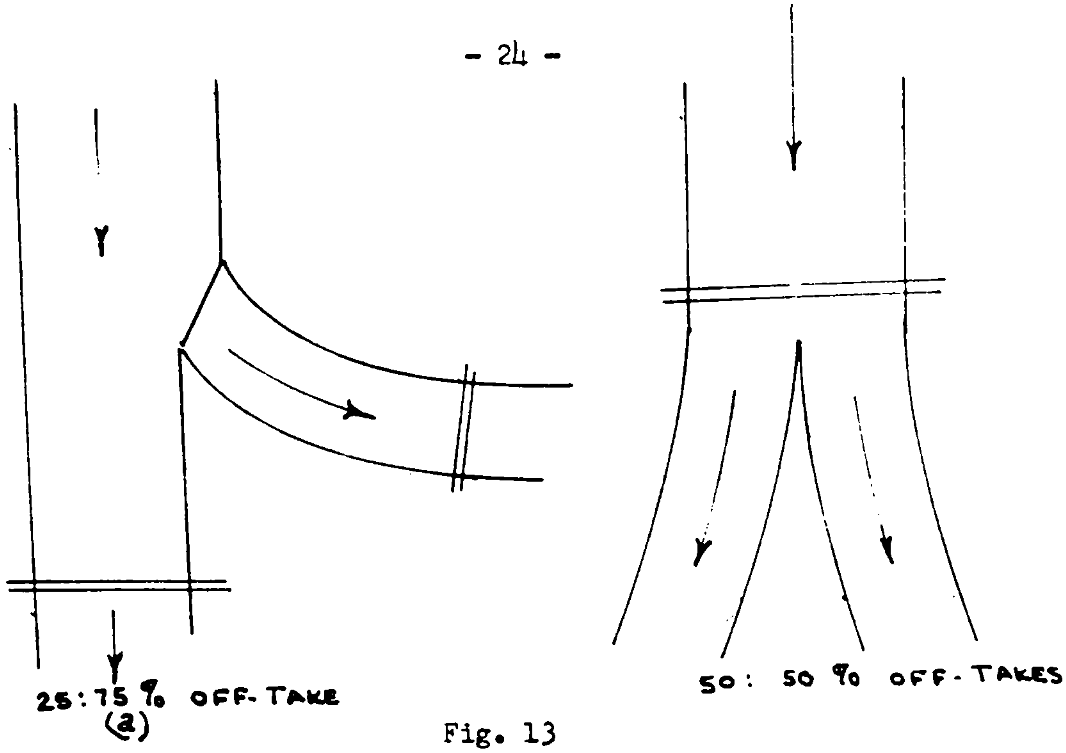


Fig. 13

When 50% is drawn it should take off at the same angle as the tail channel, (Fig. 13_b), where equal distribution of bed sand is desired.

In some cases it may be necessary to run an off-take with a very flat gradient in order to feed high land near the tail of the channel. It is then necessary to design the off-take to draw a sub-normal charge. This can be achieved by super normal exclusion by methods already described.

IV. Design of Settling Basins

In many cases when canals are subjected to sediment loads that are of a larger size than the canal is capable of transporting, such material must b e removed by desilting. Sediment of even smaller sizes may also have to be eliminated because of its damaging effects to irrigated crops or its abrasive action on such hydraulic machinery as turbines and pumps. Desilting is in general accomplished by reducing velocity of flow to the point where settling occurs. Effective design of a desilting basin depends upon an analysis of the effect of turbulence on rate of deposition. Camp (5) has evaluated the turbulent transport function for two dimensional flow by using the following simplifying assumptions:

1. The fluid velocity is the same at every point in the channel.
2. The mixing coefficient is the same at every point.

The functional relationship developed by Camp (5) is:

$$\frac{(q_s)_e}{(q_s)_i} = \phi\left(\frac{W}{\sqrt{\tau/\rho}}, \frac{W\,L}{V y}\right) \qquad 10$$

$(q_s)_e$ = quantity of sediment of a given particle size in effluent.

$(q_s)_i$ = quantity of sediment of a given particle size in influent.

W = fall velocity of the given particle size.

$\sqrt{\tau/\rho}$ = Shear velocity = $\frac{Vn\ \sqrt{g}}{1.49\ (y)^{1/6}}$

y = basin depth

L = basin length

V = Mean velocity of flow in the basin

The function has been evaluated analytically, see fig. (14), and verified experimentally by Dobbins (13). It provides a practical and relatively easy way of estimating the effectiveness of a settling basin in removing suspended sediment, and, conversely, of designing a basin to remove sediment of a size which can't be transported in the canal which the basin will serve.

The following steps are necessary when designing settling basins in accordance with the foregoing function:

1. Determination of the maximum size of sediment which the canal will transport. This will be the minimum size which the settling basin will be designed to remove, unless smaller material is to be taken out because of its detrimental effect. Maximum size of sediment which the canal will transport can be calculated from the following equation, Reference (13).

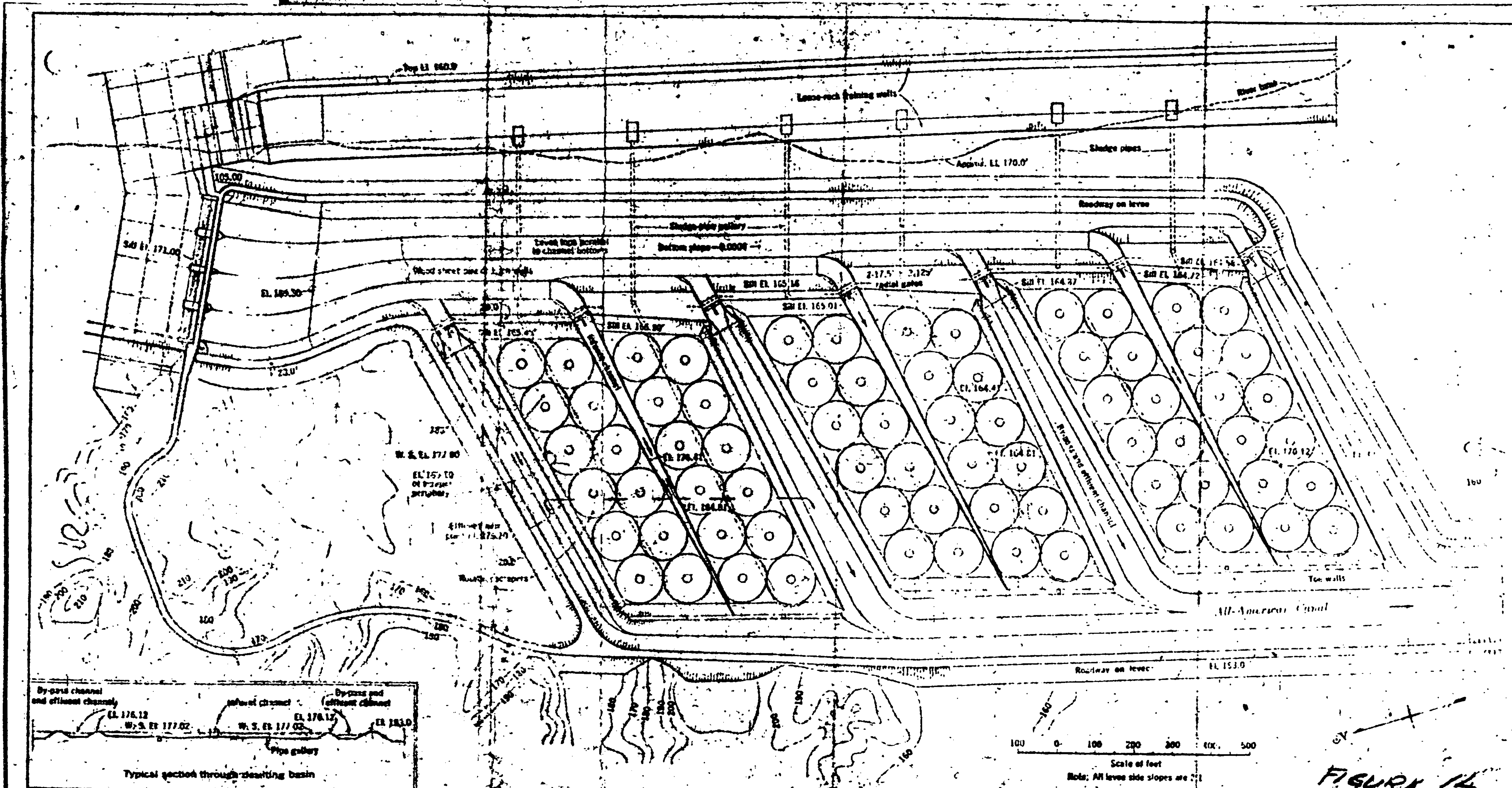


FIGURE 14

Fig. 7 · Desilting works for the All-American Canal at Imperial Dam. (U. S. Bureau of Reclamation.)

$$V = 0.2 \left(\frac{q_s}{q}\right)^{1/3} \frac{dm^{\frac{1}{4}}}{n^{4/3} (1 - \frac{Sc}{s})^{1/3}} y^{5/9} \qquad 11$$

q_s = rate of transport in volume of material per unit time per unit width of section.

q = rate of flow per unit width.

= Mannings roughness factor

S_c = critical slope = 0.00025 $(\frac{dm + 0.8}{y})$

where d is in millimeters.

S = slope

V = average velocity of flow

y = depth of flow

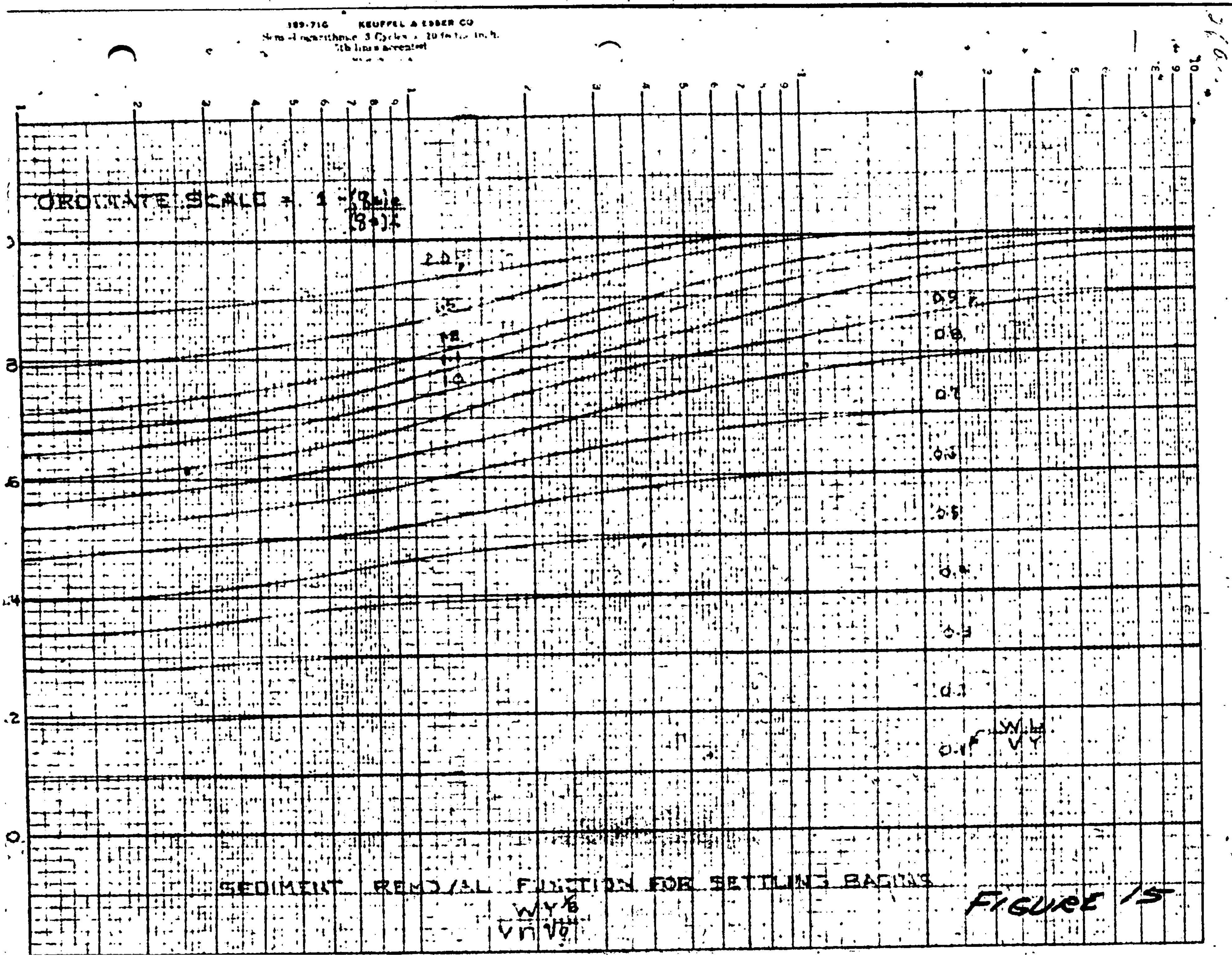
2. Preparation from the sediment size distribution curve of a table of size ranges, mean sizes, and quantities of sediment in each size range.
3. Determination of fall velocity, W, for each mean sediment size.
4. Preparation of a systematic series of combinations of settling basin dimensions, Y_o, L, and B., and computation therefrom of the mean velocity, V, for the design discharge.
5. Selection of the Manning and evaluation of the term

$$\frac{1}{1.49} \frac{W}{\sqrt{\tau_o/\rho}} = \frac{Wy^{1/6}}{V n \sqrt{g}} \qquad 12$$

6. Determination of the ratio $(q_s)_e/(q_s)_i$ for the various combinations of dimensions by solution of the functional relation and use of figure (14).
7. Selection of the basin dimensions on the basis of cost of construction weighted against sediment removed.

A. Desilting Works for All American Canal.

The most outstanding example of a desilting works in America is that provided for the All-American Canal. The sediment load is reduced from an estimated 60,000 tons per day to 12,000 tons per day in a flow of 15,000 cubic feet per second. A series of 6 settling basins are used, each basin is 769 feet long,



SEDIMENT REMOVAL FUNCTION FOR SETTLING BASINS

FIGURE 15

269 ft. wide and [illegible] ft. deep. The mean velocity of flow through each basin is 0.21 feet per second. The time of retention is approximately 21 minutes. There is one influent channel for each pair of settling basins; these channels have diminishing cross-sections and specially designed vertical slots in the channel walls to give an even distribution of the velocity through the basins. The water flows across each basin and over a weir, where it is collected in an effluent channel and led into the canal. Each effluent channel is designed to operate as a by pass channel if it should be necessary to take a settling basin out of service

Dorr rotary scrapers, 125 ft. in diameter, scrape the deposited silt into collecting trenches at the pedestals. With a 6 ft. hydrostatic head, the sludge, a solution of 10% silt concentration, is sluiced from the pedestals to the main collector pipes. Each basin has its own concrete sludge pipe gallery or tunnel which carries a main collector pipe and directs the flow of sludge into the river below the dam. See fig. (15).

V. Dams of Debris Barriers

Dams are in general constructed for the purpose of storage, regulation, or diversion of flow of water. Debris barriers,on the contrary,are installed for the specific purpose of inhibiting the movement of sediment, the effect on the stream flow being incidental. Any man-made barrier across a stream course causes the transport capacity of the stream, up stream of the barrier to be reduced below the actual sediment load; downstream from the obstruction the actual load will be reduced well below the transport capacity. In each zone the existing conditions of sediment transport are destroyed and the stream reacts accordingly.

The construction of a barrier causes the flow to establish a backwater curve varying from zero slope at the barrier to normal slope some distance upstream of the barrier. This alteration of slope will bring about sediment deposition, the rate varying from section to section along the reach being considered. It may eventually be possible to predict this rate of deposition from the characteristics of the sediment, the discharge, and the backwater profile. So far as is known, this has not been carried out successfully in this country.

The condition downstream of a dam is usually the reverse of the above. If relatively clear water is released before the dam the channel is not stable initially. The stream has an ability to carry a certain sediment load which it has been deprived of and consequently it entrains material from the bed and banks. The net result is degradation until stability is reestablished. The equation

$$Q_s\, d \sim Qu\, S \qquad (13).$$

Q_s = quantity of sediment (bed material load)

d = particle diameter or size of sediment

Q = water discharge

S = slope of the stream

is an equation of equilibrium and if anyone of the four variables is altered, it indicates the changes which are necessary in one or more of the other variables to restore equilibrium. This equation can then be used to indicate qualitatively the changes which will take place in a stream when a variable is altered by the construction of a barrier, the diversion of water without dividing sediment load propotionately to rate of flow and etc.

Debris barriers are constructed across channels, often at the mouth of steep canyon streams for the purpose of entrapping debris and preventing damage by its movement. Storing or regulation discharge is not an essential part of the design. These barriers act like a storage dam in that they set up conditions favorable to agradation upstream and degradation downstream. As debris fills the provided storage space upstream agradation establishes a flatter slope and there is a tendency for transport capacity and actual load to approach a common limit. It may be necessary to construct a series of barriers on the same stream to bring about the above balance, and channel stability, (14).

A. Rates of Silting

The rate of silting of an impounding reservoir may be expressed by the equation

$$C_1 = \frac{EQ_s}{C} \qquad 14$$

C_1 = annual silting rate or capacity loss in percent per year

E = trap efficiency or incoming sediment trapped per year

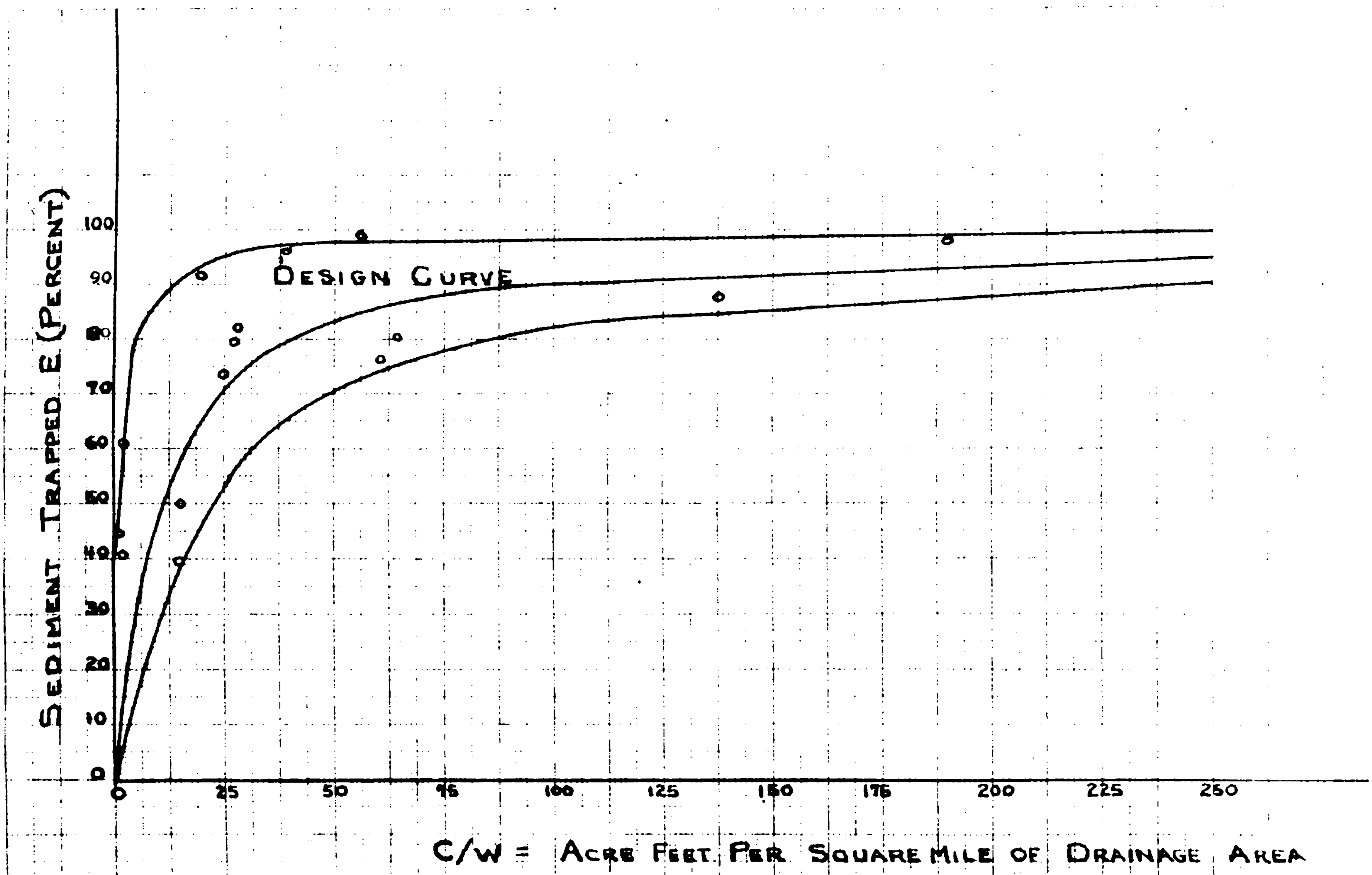
Q_s = annual net sediment production from the drainage area (sediment discharge into the reservoir in [redacted]-ft. per yr.

C = original reservoir storage capacity in acre feet.

The trap efficiency depends primarily on the sediment load characteristics and the detention time of flow. The important sediment characteristics are the grade size distribution and behavior of the finer fractions under the influence of varying concentration, dissolved load, temperature, etc. in aggregating and in forming density currents. The detention time depends primarily upon:

1. The ratio between storage capacity and inflow.
2. Shape of reservoir and basin.
3. Type of outlets and operation schedule.

Relatively few data have been obtained on actual trap efficiency of existing reservoirs. Several of the existing records are plotted in fig. (16). It is apparent from general considerations that any curve defining trap efficiency must pass through the origin and approach E = 100% asymptotically.



Trap Efficiency of Typical Reservoirs

Fig. 16

Envelope curves enclosing the data in fig.(16) may be defined by an equation of the form

$$E = 100\left(1 - \frac{1}{1+K\frac{C}{W}}\right) \qquad (15)$$

The spread of the curves is due to the effects of the variables other than $\frac{C}{W}$ upon which E depends. The sum of the effects of these other variables is expressed in the range of the value of (K) from 0.046 for the lower curve to 1.00 for the upper curve. The value of (K) for the middle curve is 0.1. Values of K tend toward that of the upper curve for reservoirs,

1. in regions of smaller and more variable run off.
2. whose shape and length tend to increase detention time of inflow.
3. where sediment load is mainly coarse or highly coagulated.
4. where outlets and operation practice are such as to release little water from the bottom of the dam and to hold back and store most of the flood flows.

VI. Control of Reservoir Silting

Water storage is a vital cog in the economy of war production in the U.S. We have 9,000 large dams and impounding reservoirs.

1. 1/3 nation's electrical power is developed
2. Reservoirs furnish water to areas where 1/5 the nation's population and 1/2 the nation's war industry is located.
3. Irrigated areas under these reservoirs account for 5% of our agricultural crops.

Silting is cutting our reservoir capacities at rates equal to 1%, 2%, 3% and even 5% per year. Some small dams have filled with silt and debris in 1-5 years of operation. The cost of reservoir silting (1943) - 50 million dollars/year. During a 3 month investigation in certain southern states, power storage reservoirs were silted in to the extent that electrical production was reduced by 90 million killowatt-hours.

Water supply for many communities is endangered because reservoirs are 1/3 - 1/2 full of silt at a time of industrial increase and population boost that requires 2-3 times the amount of water normally used.

Methods of Silting Control

A. Selection of reservoir site

B. Design of reservoir

C. Control of sediment inflow

D. Control of sediment deposition

E. Removal of sediment deposits

F. Watershed erosion control

Brief note on each:

A. Selection of Reservoir Site

Choose site by considering type of sediment loads expected to be developed.

Amount of sediment will vary with: Soil types, stream gradients, land use, erosion of land slopes, and stream channel.

Silting is a critical factor in choosing between alternate sites.

In estimated sediment production of a drainage area, 3 types of data should be considered:

1. Results of reservoir sedimentation surveys.
2. Records of the suspended loads of streams and by new methods of estimating bed load.
3. Conservation, Reclamation, Corp of Engineers, and T.V.A. surveys.

70% - 100% of the sediment delivered by a stream to a reservoir is trapped there.

Nearly 1,000 suspended load records of American streams are now in existence.

Methods and techniques of sampling and methods of analysis to determine sediment load has been prepared by Iowa Institute of Hydraulic Research.

In order for measurements of stream load to be of value, data must be collected over a period of at least 5-10 years.

In case of large reservoirs sedimentation considerations must be secondary to available head for power and volume of water impounded.

Silting can be a primary consideration on all smaller reservoirs - power, recreation and stream regulation.

B. Design of the Reservoir

Two elements affecting rate of silting are:

a. Total capacity to be provided

b. Design of water and sediment release works in the dam.

Capacity of reservoir is governed by:

a. Physical characteristics of the dam site.

b. Estimated available runoff

c. Service requirements of the reservoir.

d. Funds available for construction.

Only a few of the larger reservoirs have been designed so as to take silting into consideration; these are in the southwest.

If a reservoir is being designed - over design it so that a surplus volume is provided for silt storage - a design period of at least 100 years should be adopted.

Many reservoirs have been built since 1930 that have completely filled with sediment at this time.

Lake Mead capacity - 32, 359, 274 A.F., 5 - 8 million of this is for silt storage.

Raising the dam may be thought of as a way of off-setting the silting in. This may or may not be good depending on physical characteristics of the reservoir site. Poor site gives large surface area and a shallow depth contributing to very high evaporation losses.

Adequate outlet works will help vent the density currents and move more silt on through the reservoir - very few designs have considered this aspect of reducing silting.

C. Control of Sediment Inflow

Four principle methods used:

a. Construction of silting basins
b. Propagation of vegetative screens
c. Location of reservoir off the main channel.
d. Construction of by-passing channels or conduits.

a. Silting basins:

1. May be formed by dike or dam construction across inflow channels.
2. Usually constructed a short distance above head or back water of reservoir.
3. Fundamental principle is to check velocity so silting can occur.
4. Small velocity reduction takes care of sand to all coarser particles. May take several hours for silt and clay unless water can be passed in a thin sheet over broad flats, particularly a densely vegetated one.
5. Settling basins must have spillway - large enough to handle floods.
6. Settling basins must be designed to take care of largest amount of sediment at lowest possible cost.

b. Vegetative screens:

1. Means dense growth of vegetation through which the sediment laden water must flow to enter the reservoir.
2. Vegetation must cover original channel entrance and flood plain.
3. Vegetation must be deep rooted, small stemmed, grow in dense stands, be tough and fibrous, large growing, resistant to drouth and inundation, and non-palatable to stock.
4. Tamarisk or salt cedar - good. Grows so dense almost impenetrable. 1 - 20 ft. high. Diameter - size of pencil to 6" - 8". Originally a native of Mediterranean area. Very showy - pink and white flowers. May cause trouble if it gets in canals.

c. Off channel reservoirs:

1. Means any reservoir developed in any location other than on the main feeder stream.
2. Filled with water through canals or conduits leading from diversion dam or main stream.
3. Good only when entire stream flow is not to be stored.
4. Idea is to by-pass flood flows laden with silt and debris - store higher quality water when possible.
5. Can install desilting works at diversion point if necessary.

d. By-pass canals and conduits:

1. Build canals or conduits by-passing the reservoir.
2. Bypass as much water as necessary to meet immediate irrigation needs down-stream.
   a. Reservoir not used as silting basin for by-passed water.
3. Spillways dumping water into the reservoir should skim off top cleaner water and allow the heavily contaminated water to pass around to meet immediate irrigation needs.

D. <u>Control of Sediment Deposition</u>

a. Deposition of sediment in reservoirs can be controlled to certain extent by designing and operating gates or other outlets in the dam in such a number as to permit selective withdrawal of water having a higher than average sediment content.

b. By-pass heavily laden flood water when possible.

c. After flood water enters reservoir, different levels will contain radically different concentrations of suspended sediment.

d. Pictures show the stratification of layers of water - some very heavy with silt load. Makes above mentioned selective drawing off possible.

E. <u>Removal of Sediment Deposits</u>

Removal may be accomplished in many ways: excavation, dredging, siphoning, draining, and flushing, flood sluicing, and sluicing aided by such measures as hydraulic or mechanical agitation.

Deposits become sufficiently compact so that they are unable to flow under their own weight.

Cost:

Few places exist where excavation by power shovel and dump truck could be accomplished for less than $400.00/A.F.

Drag line excavation cost = $150 - $200.00/A.F.

Dredging costs = $80.00/A.F.

Cost is high enough so as to limit excavation to small flood control reservoirs, pondage or regulating pools, small water supply, irrigation, and special purpose reservoirs.

F. <u>Water Shed Erosion Control</u>

The method is aimed at handling the problem at its source, a preventative measure. The methods involved are as broad as the fields of soil conservation, forestry, and land utilization.

a. First trace sediments to their source so preventative measures can be taken.

Principal types of erosion are:

1. Sheet erosion (no gully formation)
2. Gullying or cutting of channels by concentrated runoff
3. Road and R.R. erosion
4. Stream channel erosion
5. Flood erosion on flood plains
6. Erosion incident to construction of buildings, bridges, and airports.
7. Mining and industrial wastes.

b. The more important types of land treatment that cause an accelerated erosion rate are:

1. Burning of vegetative cover (man and lightning).
2. Logging and deforestation
3. Overgrazing
4. Cultivation
5. Construction (roads, bridges, powerline, etc.)
6. Mining operations (hydraulic)

c. Methods of erosion control

1. Afforestation and forest management
2. Regrassing and grassland management
3. Cultivation practices (crop rotation, seasonal cover crops, contour farming, terracing).
4. Gully control
5. Highway erosion control
6. Stream bank erosion control
7. Flood plain protection
8. Beaver propagation

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