THE DESIGN OF HEAD REGULATORS OF IRRIGATING DISTRIBUTARIES.

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The Functions of a Head Regulator.

The subject of this paper is the design of the masonry work through which water flows from a main or branch canal into a distributary, or from a major or branch distributary into a minor distributary. The same general principles of design apply also to the masonry work through which water flows from a river into an irrigating canal, or from a main canal into a branch canal ; but this paper is concerned chiefly with the special case of the head regulators of distributaries ; *i.e.*, of irrigating channels whose discharge as a rule does not greatly exceed one hundred cusecs.

The principal functions of a head regulator of a distributary may be said to be :—

(*a*) To regulate the flow of water from a trunk, or parent channel, into a branch, or off-taking channel.

(*b*) To regulate the flow of silt, or detritus, from the trunk to the branch channel.

(*c*) To measure with reasonable accuracy, and by some simple means, the quantity of water passing through it, whether that quantity be constant, or periodically variable.

The Natural Laws governing Silt Flow.

It is reasonable to suppose that the transportation of silt by a current of water is governed by certain natural laws which hold good whether the flow be through an open channel, or through a pipe, tunnel, or orifice of any kind. Before proceeding, therefore, to design a regulator, intended to control the flow of silt-laden water from one open channel to another, we ought to have some definite conception of these laws.

Dupuit's theories.

About the year 1860 the hydraulician, Dupuit, enunciated the following theories on this subject :—

(1) That running water can hold in suspension solids much heavier than itself.

(2) That the power of suspension depends on the relative velocity of the threads of the current, and is so much the greater as the relative velocity increases, the upper layers conveying only the slightest matters, because the threads there have their velocities nearly equal, whilst those of the lower, possessing less *absolute*, but more *relative*, velocity, can carry solids of greater size, or in greater quantities.

(3) That the power of suspension of a layer is limited ; *viz.*, a square foot can contain only a certain number of particles of a fixed volume ; so that for each layer there is a different degree of saturation. The effects of this power increase with the breadth, depth and slope of the channel ; as these increase, so does the power of suspension, until certain limits are reached. The lowest layer will contain stones ; those above, gravel, sand, silt, in their order.

When the liquid is saturated with these different materials and the section and slope remain constant, no deposition takes place ; but, supposing the section to be altered, the velocities at every point are changed, and, consequently, the power of suspension of the current. If this power is diminished, a deposit forms ; if increased, a scour. All causes which alter velocities at any point, affect the power of saturation, such as ascending, descending, or transverse movements, the action of the winds, &c., &c.

Humphreys and Abbott.

Humphreys and Abbott, the Mississippi hydraulicians, adopted Dupuit's theories in their report, which was published in the year 1861.

Login.

In November 1867 Mr. Login, the engineer who built some of the most important works of the Ganges Canal, and afterwards controlled its maintenance for many years, read a paper before the Institution of Civil Engineers, from which the following is an extract :—

" The author believes that the power of water to hold matter in suspension is directly as the velocity and inversely as the depth. It is also suggested that water in motion rolls, rather than slides, and that it is owing to this rotary motion that water has the power to hold matter in suspension. Further, that with given velocities, and defined depths, only a certain quantity of matter can be held in suspension, whatever may be the characteristics of the bed and banks of the river or canal. If the velocity be increased, and the depth remain constant, scour will take place If the velocity be decreased, and the depth is the same, there will be deposit."

Mr. Login was evidently reciting Dupuit's theory, and a perusal of this extract from his paper tempts one to the reflection that the science of silt transportation by currents of water has not, up to date, advanced greatly beyond the point reached by engineers fifty years ago.

The Ganges Canal.

Mr. Login's opinions are valuable because he was the Executive Engineer in charge of the Ganges Canal, near Roorkee, in the early days of its flow history, when it suffered seriously from bed-scour. This portion of the canal was designed as follows :—

Bed width, 140 feet ; water depth, 10 feet ; gradient 1 in 3520 (1·5 feet per mile) ; mean velocity 4·5 feet per second ; discharge 6,700 cusecs.

This was by Dupuit's formula. By the later formula of Kutter, putting $N. = 0{\cdot}0225$, the mean velocity would be 4·75 feet per second, and the discharge 7,125 cusecs. By Kennedy's silt formula, the mean velocity would be $1{\cdot}3\ V_0$ or thirty per cent in excess of the critical velocity required for silt regime.

In practice the water surface gradient became steeper than 1 in 3520, because the falls at Asufnagar, in the twenty-third mile, were built with their lip, or sill, flush with canal bed ; so that there was acceleration of velocity in the approach to the fall, and probably a water depth, at the sill, not exceeding 4·25 feet. The water surface gradient was probably about 1 in 3000, and the mean velocity anything up to eight feet per second in the approach to the fall, or anything up to four times the critical velocity desirable for stability of silt regime.

Under such conditions the bed of the canal was violently eroded, and the stability of its masonry works endangered. In 1861 it was sought to arrest this erosion by raising a cribwork on the sill of the fall, as shown in Plate 1, which has been copied from the paper read by Mr. Login before the Institution of Civil Engineers. This reduced the water surface gradient to

1 in 3750, or 1·41 feet per mile, and the mean velocity to 4·4 feet per second, which was still, however, excessive for a seven foot depth of water (1·5 V.). In 1863 the cribwork on the sill of the fall was raised still higher, so as to give eight feet of water over the sill. This gave the canal upstream a mean velocity of 3·7 feet per second in a ten foot depth of water, which represented Kennedy's critical velocity for that depth, and silt began to be deposited in the scours. In 1867 a masonry crest wall was substituted for the cribwork on the sill of the fall.

This experience qualified Mr. Login to speak with authority on the silt-carrying capacity of streams of water ; and it is interesting to note that his opinion, quoted above, to the effect that this capacity varies directly as the velocity and inversely with the depth, was exactly in accordance with Dupuit's theory, and also with the essential theory underlying Kennedy's subsequent discoveries. In his paper, Login suggested the adjustment of mean velocity to water depth, as indicated below :—

TABLE I.

Water-depth (Feet).	Mean Velocity (Login).	Critical Velocity. (Kennedy).
4	2	2·04
5	2·5	2·50
6	3·0	2·64
8	3·5	3·18

Kennedy's data have been added for the sake of comparison.

Kennedy's Experiments, 1883.

About the years 1883-84 Kennedy made his brilliant investigations into the cause of silt-transportation by currents in the lower reaches of the Bari Doab Canal. His method of procedure was to observe the hydraulic data of this canal and its distributaries at some twenty-two places where these channels appeared to be in a settled regime, neither scouring, nor suffering from silt deposits ; and where the discharge varied between 20 and 1,700 cusecs. Plotting his data diagrammatically, he found that, in channels of settled silt regime, the mean velocity varied with a function of the depth of water ; and, drawing a curve that reconciled the depths and mean velocities of such channels, he evolved a formula which he conceived would satisfy non-silting conditions in any channel so designed.

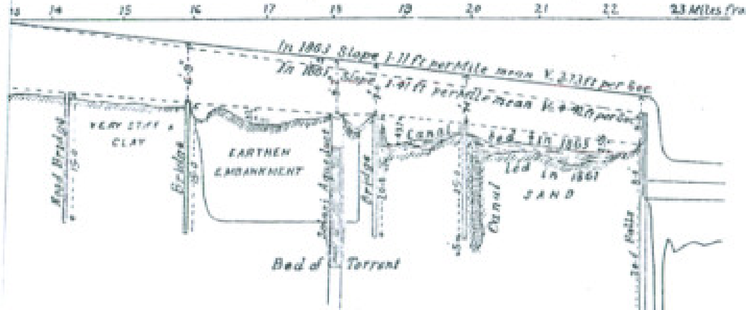
PLATE I

Diagrams Illustrating the Erosion of the Bed of the Ganges Canal near Roorkee

From 1854 to 1863

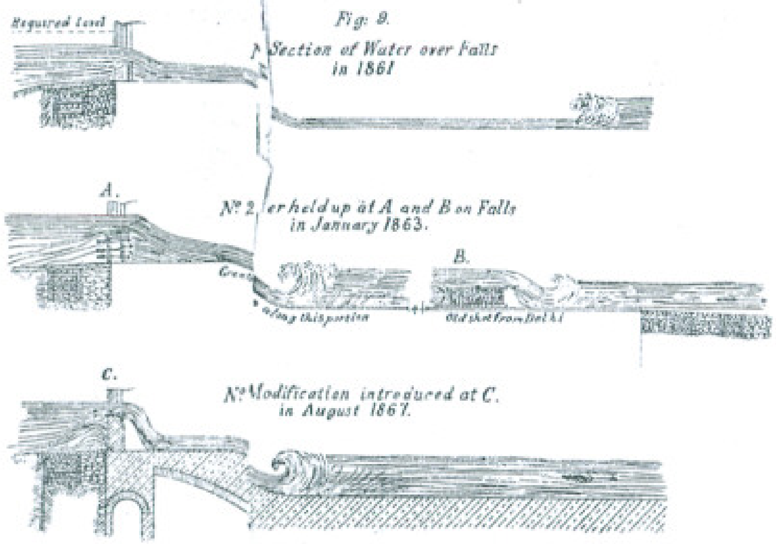
Reproduced from Vol XXVII Min: Proceedings of the Institution of Ci Engineers

Fig: 2.



SECTION OF THE GANGES CANAL AT ROORKEE
in 1861 and 1863

Fig: 9.



Section of Water over Falls
in 1861

Nº 2 er held up at A and B on Falls
in January 1863.

Nº Modification introduced at C.
in August 1867.

IONS OF THE GANGES CANAL FALLS

Scale.

Feet 10 5 10 20 30 40 50 60 Feet

2/6-12-15

Kennedy's methods of investigation were almost purely empirical, which is regrettable, as, although they led to useful practical results for the moment, they rather tended to obscure, than to clarify, the scientific aspects of the silt problem. With his mathematical talent and acute powers of observation, there can be small doubt but that the science of the subject would have advanced far more rapidly than it has done, if he had not been diverted, by the rule-of-thumb simplicity of his formula, from the more strictly scientific foundation, in theory, of the natural laws governing the silt problem. So far as his formula went, it was reconcileable with Dupuit's theory, though Kennedy did not point this out. He expressed no clear theory, but it was stated succinctly for him by Mr. (afterwards Sir) Thomas Higham, in the words:—

"This theory (Kennedy's) may be briefly stated to the effect that the silt-carrying capacity of a channel varies directly with some function of the mean velocity, and inversely with some function of the depth."

These are almost exactly the words used by Login in 1867, and express also Dupuit's theory of the effect of velocity relatively to depth of water.

Kennedy's mathematical treatment of his problem was excellent; but his speculations in the region of theory, so far as he stated them at all, were not sufficiently explicit.

Thus, he wrote:—

"Sediment in a flowing canal is kept in suspension solely by the vertical components of the constant eddies, which can always be observed in any stream, boiling up gently to the surface over the whole breadth. From the sides also some such eddies may occur to a much smaller degree, but such eddies must be for the greater part horizontal, and of no silt supporting power."

If we stir up silt in a tumbler of water we see that even horizontal eddies have silt supporting power; whilst, even apart from the question of silt suspension, there is the *erosive* capacity of horizontal eddies to consider. If Kennedy had pursued his experiments on the Bari Doab Canal a little further upstream, he would have found the upper main branch of the canal eroding its banks, by reason of the channel being too narrow relatively to the high velocities prevailing in it. Unfortunately his thoughts were fixed too rigidly on the problem of *preventing deposits* of silt, and when he came across channels that were scouring, or not silting, he ignored their evidence, on the ground that they had not arrived at a settled silt regime.

Higham on Kennedy.

The results of Kennedy's investigations were published in 1894-95 in the Proceedings of the Institution of Civil Engineers; and in 1896 they were tentatively accepted by, and received the official imprimatur of, Mr. Higham, Chief Engineer, Irrigation Works, Punjab.

Harris.

Kennedy's views had been criticized, and in some measure disputed, in 1892 and 1895 by an anonymous contributor (subsequently identified as Mr. Frank Harris, who had succeeded Kennedy in charge of the lower reaches of the Bari Doab Canal in 1885) to the journal "Indian Engineering." In particular, Harris disputed Kennedy's conclusion that the width of a channel had no effect on its silt transporting capacity, as well as his assumption or belief that the silt charge of the Bari Doab Canal, throughout its tail reaches, was uniform or constant. Examining Kennedy's experimental data, Harris thought that they hardly proved the former's conclusions, and wrote :—

"The results show that it is neither the surface fall nor the mean longitudinal velocity that determines the silt carrying capacity, but rather the ratio of breadth to depth. Those channels are best compared which take off from the canal under nearly similar conditions."

Gudha Minor Experiments.

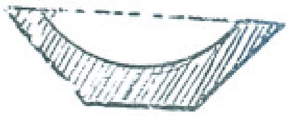
The present writer found some difficulty in accepting the theory thus expressed; and in the year 1897 he made some elementary experiments in order to ascertain the essential differences of hydraulic conditions between a silting channel and a non-silting one.

The Gudha Minor of the Bazida Distributary of the Western Jumna Canal had been constructed to the following design :—

Bed width 3 feet; water depth 3 feet; slope 1 in 5000; discharge 16 cusecs; mean velocity 0·91.

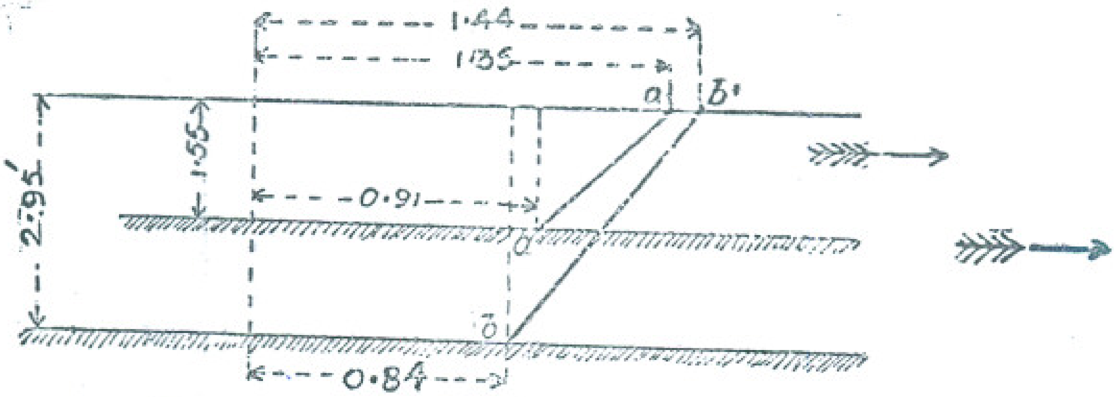
According to Kennedy's diagrams its mean velocity was only about half of the "critical" velocity for that depth of water; and as a matter of fact, the channel used to silt up rapidly, till its depth was reduced by half. If cleared of silt to its original section and gradient, it used to silt up again very rapidly; at any rate during the season when the water was well charged with silt. The following hydraulic conditions were observed by means of twin floats:—

TABLE II.

Case.	Gauge reading.	Greatest depth.	Slope.	Mean velocity.	Discharge.	Surface velocity.	Bottom velocity.	Kutter's N.	Critical velocity Ratio.	Cross Section.
A	3·3	1·55	$\frac{1}{2777}$	0·96	7·8	1·35	0·91	0·025	0·87	
B	3·2	2·95	$\frac{1}{4444}$	1·06	16·27	1·44	0·84	0·026	0·63	

The question arose as to what was the essential difference between the conditions of case A on the one hand, and of case B on the other, which led to silt deposit in the latter and to cessation of silt deposit in the former? To the writer the solution appeared to be given by Dupuit's theory, when the velocities were plotted graphically, in the vertical longitudinal plane of flow:—

FIG 1.



The surface and bottom velocities, respectively, were nearly the same in both cases, but the water depth in case A was only about half that of case B; so that the *difference* of velocity between any two filaments of the current, a unit distance apart, in the vertical plane, was much greater in case A than in case B; being, in fact, proportionate to $\frac{1{\cdot}35-0{\cdot}91}{1{\cdot}55}=0{\cdot}28$ in the former case, and to $\frac{1{\cdot}44-0{\cdot}84}{2{\cdot}95}=0{\cdot}20$ in the latter—a difference of forty per cent.

The forward force of water flowing along a channel, and the retarding frictional resistance of the bed and sides of the channel, form a couple which sets up in the current the eddies which cause suspension and transportation of silt.

FIG. 2.

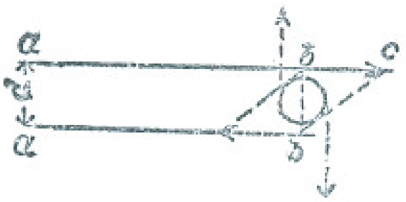
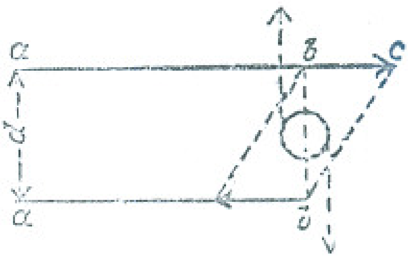
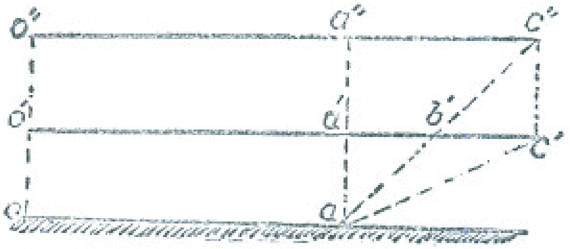


FIG. 3.



If the arm d (Fig 2), of the couple, formed by two filaments of a current, of magnitude, respectively abc, and ab, a certain distance, d, apart in the vertical plane be constant, the force of the eddy will be proportionate to the *relative* velocity bc; but with a fixed relative velocity, bc (Fig 3), the force of the eddy will be inversely proportional to the arm of the couple, or to the distance between the filaments of velocity.

FIG. 4.



In Fig. 4 if $o' a' b'$ and $o\ a$ be two filaments of velocity of a current, distant oo' from each other in the vertical plane, the eddy set up by their difference ($a' b'$) of velocity will be proportionate to the ratio $a' b' : oa'$. If the velocity $o' a' b'$ be increased to $o' a' b' c'$, the force of the eddy will increase to the ratio

$a'b'c' : aa'$. But if the distance between the two filaments in the vertical plane be increased to, say, oo'', then the velocity $o''a''c''$, though equal to, $o'a'c'$, will set up no greater eddy than is expressed by the ratio $a''c'' : aa''$, which is the same as $a'b' : aa'$.

The silt index of a current ; that is, the index of its power of erosion or transportation of silt, may be said to be proportionate to the difference of velocity of two filaments of a current a unit distance apart in the vertical plane ; or to the ratio borne by some function of any given filament of velocity to its distance from the retarding surface. It will vary with the inclination from the vertical, at any point of the curve of velocities in the vertical plane ; and will be greatest in those portions of a current which are nearest to the retarding surfaces.

Higham's Suggestion.

These considerations were presented to Messrs. Higham and Kennedy, sometime between the years 1898—1900, and generally accepted by them as being probably correct. Mr. Higham put the matter in writing thus :—

" I think it is highly probable that the difference between the surface and bottom velocity is a very important factor, but it may be doubted whether the value of T (the transporting power of the current) is independent of the absolute value of the mean velocity, $V = \frac{V_o + V_d}{2}$

The following might be suggested as a rational formula for the variation of T :—

T varies as some function of $\frac{(V_o - V_d)(V_o + V_d)}{d}$;

or as $\frac{Q(V_o^2 - V_d^2)}{d}$ (where Q is the discharge).

I readily admit that this, or something like it, may be a more rational formula than T varies as $\frac{QV}{fd}$."

Applying this formula to the case of the Gudha Minor we get :—

$$\textit{Case A.} \quad T = \frac{V_o^2 - V_d^2}{d} = \frac{1{\cdot}35^2 - 0{\cdot}91^2}{1{\cdot}55} = 0{\cdot}67$$

$$\textit{Case B.} \quad T = \frac{1{\cdot}44^2 - 0{\cdot}84^2}{2{\cdot}95} = 0{\cdot}46$$

indicating a silt carrying power forty-five per cent. greater in the former case than in the latter.

What has been called the "bottom" velocity, in the preceding remarks, is, of course, only the velocity within a few inches of the bed of the channel. The absolute bottom velocity may be considered as zero, in which case the above formula resolves itself into:—

$$\text{Case } A. \quad T = \frac{V_o^2}{d} = \frac{1{\cdot}35^2}{1{\cdot}55} = 1{\cdot}17$$

$$\text{Case } B. \quad T = \frac{1{\cdot}44^2}{2{\cdot}95} = 0{\cdot}70$$

indicating a silt carrying power sixty-seven per cent. greater in the former case than in the latter.

It may conceivably be convenient and useful to be able to judge of the silt carrying power of a current by measuring only its maximum surface velocity and maximum water depth. It is noteworthy that Cunningham, in his Roorkee experiments, inferred that, for a given part of a stream where the bed was regular and of permanent section, a simple formula might be found for the variation of the central surface velocity with the depth. Thus $V_s^2 = c\,d$, where Vs is the surface velocity, and d the depth, both measured at the centre of the stream; and c, a constant, whose value, on the Solani aqueduct, was 1·9 to 2·0, in depths 6 to 10 feet, and with velocities of 3·5 to 4·5 feet per second. In the Gudha Minor, in Case *A*, the value of $C = \frac{V_s^2}{d}$ was 1·17; but the mean velocity in this case was only eighty-seven per cent. of Kennedy's critical velocity. As the channel approached finality in silt regime the ratio $\frac{V_s^2}{d}$ would increase, and might possibly rise to Cunningham's value.

Horizontal Eddies.

If it be accepted that the erosive, or silt transporting, power of a current is proportionate to the difference of velocity of two filaments of the current a unit distance apart in the vertical plane, similar reasoning will also apply to the relative velocities in the horizontal plane, or in any plane, inclined at any angle. In the horizontal plane a filament of given velocity in a stream will have greater or less power of erosion, according as its distance from the side of the channel is less or greater ; and at a given distance from the side of a channel the erosive power will be proportionate to some function of the velocity at that distance.

FIG. 5.

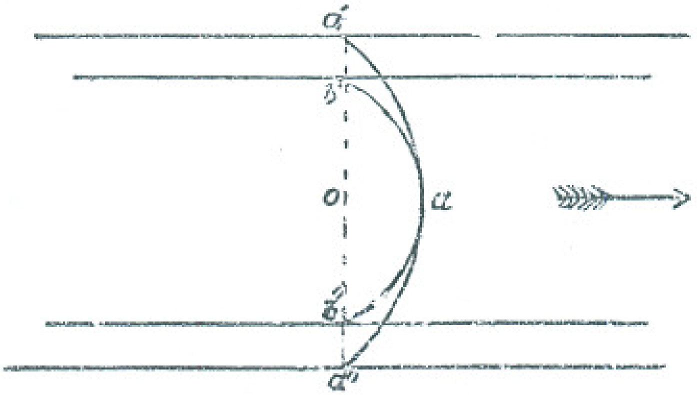
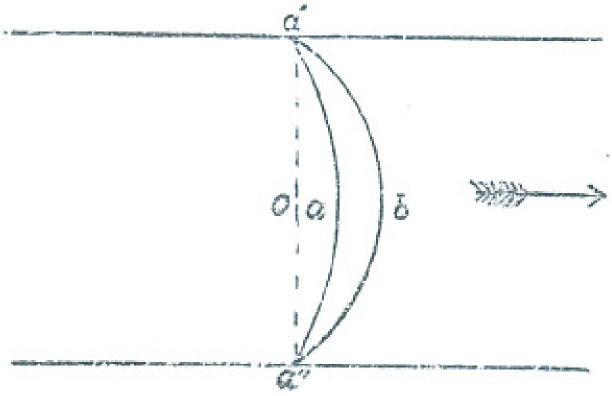


FIG. 6.



In Fig. 5, a channel with a given midstream velocity, *o a*, would exert a greater erosive action on the banks of a channel of width *b' b''* than in one of width *a' a''* ; and in Fig. 6, a channel of given width *a' a''* would have its banks eroded more by a current of midstream velocity equal to *o b*, than by one of midstream velocity equal to *o a*.

Bed Scour at Amipur, Lower Chenab Canal.

The following is an illustration, taken from actual experience, of the application in practice of the ideas just discussed.

The Jhang Branch Upper of the Lower Chenab Canal terminates at Amipur, where it bifurcates into the Jhang Branch Lower and the Bhowana Branch. There is a fall from the upper canal into the branches, and the flow is controlled at the bifurcation by the Amipur Regulator.

Plate II shows the longitudinal section of the tail reaches of the Jhang Branch, from R. D. 250,000 to R. D. 308,500. At R. D. 260,000 and 277,500 there are vertical falls, over which the water drops through trapezoidal notches. The sill of the Amipur regulator, at R. D. 308,500, was flush with the canal bed upstream, and the flow over it was controlled by gates sliding in vertical grooves—the water passing through the orifices formed by the sill, the gates, and the piers of the regulator, under a head of pressure. In practice the head of pressure there was four feet into the Jhang Branch Lower and five feet into the Bhowana Branch.

The canal upstream of the regulator was designed thus :—

Bed width 67 feet ; water depth 8 feet ; gradient 1 in 7147 ; discharge 1610 cusecs ; mean velocity 2·8 feet per second.

According to Kennedy's formula 3·18 is the critical velocity for an eight foot depth of water, and if that formula were correctly applicable to the case, the canal, with a velocity of 2·8 only, *should have deposited silt.* On the contrary, however, it scoured its bed ; not only near the regulator, but right away back to R. D. 285,000, nearly five miles upstream of the regulator.

With the idea of checking this erosion, a telephone connection was set up between the regulator and the fall at R. D. 277,500, and the water depth above the regulator was maintained constantly equal to that below the fall, so as to keep the water surface gradient parallel to the designed bed gradient. Yet the erosion continued, from the time the canal first flowed, in 1896, till the spring of the year 1900 ; getting worse and worse.

In April 1900 a masonry crest wall, four feet high, was built along the entire sill of the regulator, and forthwith silt deposits took place ; and three years later all the scours had been filled with silt, as shown by the undulating dotted line in Plate II.

The regulator had five spans of 8·75 feet for the Jhang Branch Lower, discharging 26·5 cusecs per foot-run of sill, and two spans of 8·75 feet for the Bhowana Branch, discharging 24·8 cusecs per foot-run of sill. The mean velocity through the orifices was 12·8 feet per second for the Jhang Branch Lower and 14·1 feet per second for the Bhowana Branch.

LONGITUDINAL SECTION OF JH

LOWER CHENAB CAN

SURVEYED IN 1899,1903,AND 1904 SHOWI
BED BEFORE AND AFTER THE ERECTION OF A C
OF THE FALL AT R.D 308500 IN A

SCALES
HORIZONTAL = 2" : 1 MILE
VERTICAL = 1/100

DATUM LINE

BED LEVELS JANU
BED LEVELS APRI
BED LEVELS MAR
ORIGINAL DESIGNED
REDUCED DISTANCES(T

The heights of the orifices, *i.e.*, the distance between sill and bottom of gates, was 2·07 feet in the case of the Jhang Branch Lower, and 1·76 feet in the case of the Bhowana Branch.

The maximum velocities, at the centres of the orifices were, perhaps, as much as twenty feet per second, at a level about one foot above the canal bed upstream ; and it is not surprising that this had erosive effect upstream.

When the water was passed over a masonry crest wall four feet high, instead of over a flush sill, the mean velocity of discharge was 6·6 feet per second, and the maximum 9·9 feet per second, at a level four feet above canal bed. The conditions before and after the construction of the crest wall may be compared thus :—

FIG 7.

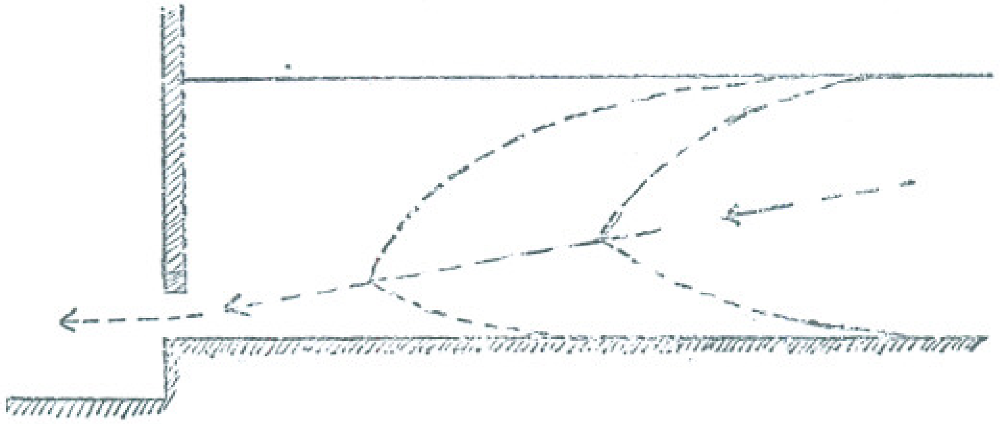
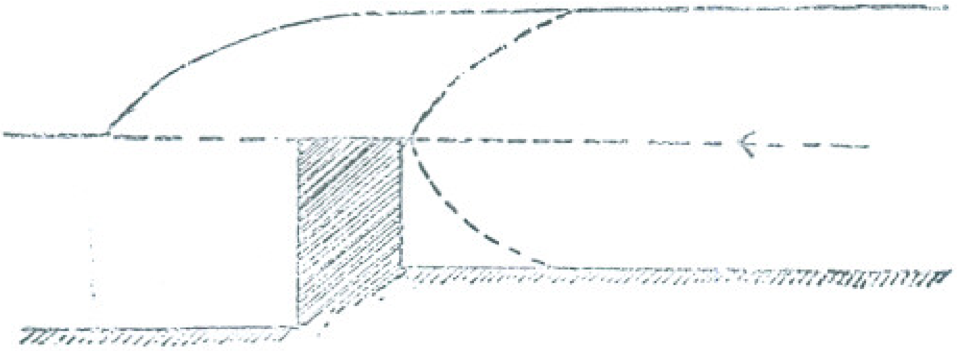


FIG 8.



We may represent the erosive, or silt-carrying, force of the stream, as a ratio between the maximum velocity and the distance of the filament possessing that velocity from the bed of the channel ; and we may call this ratio the silt index of the current. The silt index of Fig. 7 would then be 20, and that of Fig. 8 $\frac{9\cdot9}{4}=2\cdot5$; indicating an erosive potentiality eight times as great in Fig. 7 as in Fig. 8.

The Shortcomings of an Empirical Formula.

Whatever may be thought of the theory outlined above, every one will probably agree that the silt-carrying, or erosive, power of a stream, will be different, according as it is controlled at the tail in the manner depicted in Fig. 7, or as in Fig. 8 above; and yet Kennedy's formula would throw no light on that difference of power; for the mean velocity and depth of the stream in the open channel upstream of the regulator would be the same in either case. This is an illustration of the shortcomings of the empirical method of investigation, and of the necessity for a consistent and rational theory, of universal applicability to silt-carriage problems, and not limited in its application to a particular range of conditions.

Kennedy's formula does not help us to design water channels in their relation to the masonry works built on them; nor to design these masonry works so as to secure and maintain suitable conditions of silt-carriage in the open channel.

A Case of Excessive Gradient.

On the Jhang Branch there were numerous examples of regulators, similar to the Amipur Regulator, passing water over flush sills under a head of pressure; and in every case erosion of the canal bed upstream, similar to the case described above, was found to have occurred. In every case, this erosion was stopped, and a regular bed obtained by silt deposit upstream, by the construction of raised crest walls on the sills of the regulators. There were numerous cases, also, of falls, over which the water flowed through trapezoidal notches, and in every such case (with one exception) the canal bed upstream was found to be in good order, with no sign of erosion. The one exception was the reach of the Jhang Branch Lower, from R. D. 48,500 to R. D. 71,000 (See Plate IV).

In this case the water entered the reach through a trapezoidal notched fall at R. D. 48,500, and left it through a similar fall at R. D. 71,000; yet the canal bed was badly scoured. This reach was designed as follows:—

Bed width 43 feet; water depth 6·5; gradient 1 in 5000; discharge 856 cusecs; mean velocity 2·85 feet per

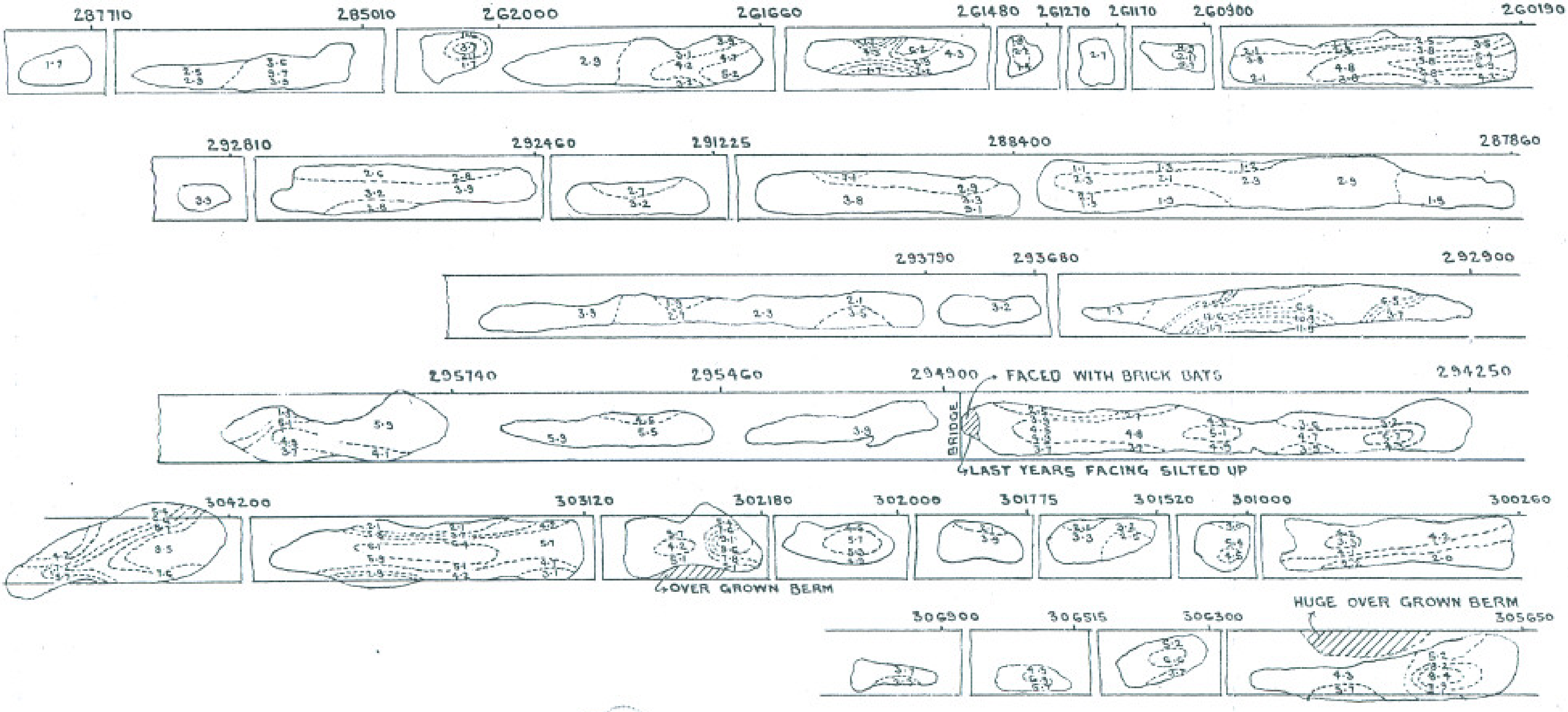
PLAN OF BED OF JHANG BRANCH UPPER

SURVEYED IN JANUARY 1899

SHOWING HOLES SCOURED IN THE BED

SCALE = 1/100

PLATE III



second, which was only slightly greater than Kennedy's critical velocity ($1 \cdot 03\ V_o$).

A careful hydraulic survey showed, however, that by an error of construction the downstream sill of the fall at R. D. 48,500 had been built 0·66 foot too high ; so that the declivity of the reach averaged 1 in 4385, instead of 1 in 5000, and the mean velocity was 3·0 instead of Kennedy's value (2·78). The trapezoidal notches of the fall at R. D. 71,000 were dismantled, and rebuilt at a level 0·66 foot higher than before ; with the result that the scours in the canal bed upstream were smoothed out by deposits of silt.

Causes of Erosion compared.

It is interesting to compare Plates I, II and IV, and to note that precisely the same effect was produced on the canal bed upstream of the Amipur Regulator as was produced by excessive declivity in the R. D. 48,500—71,000 reach of the Jhang Branch Lower ; and by excessive declivity in the Ganges Canal, combined with lack of elevation in the sill of the terminal fall. It is noteworthy also that precisely the same cure was effected at Amipur by substituting overfall for under-scour, and in the Ganges Canal, by building a raised crest on the sill of the terminal fall, as was affected by a reduction of declivity in the 48,500—71,000 reach of the Jhang Branch Lower.

The inference seems reasonable that a depression of the level of the orifice of discharge from a channel has the same erosive effect on the channel upstream, as an increase of the declivity of the channel ; and that the erosive effect is produced in the one case by the maximum velocity being brought closer to the canal bed, and in the other by the maximum velocity being increased at a given distance from that bed.

The non-finality of Kennedy's Designs.

In the Paper which he read to the Institution of Civil Engineers in 1894-95 on the " Prevention of Silting in Irrigation Canals, " Kennedy stated that in the reaches of the Bari Doab Canal, on which he made the observations from which he deduced his critical velocity formula, the amount of silt carried for any given discharge was more or less constant all the year round. This statement was disputed by Harris, who succeeded Kennedy in charge of that same portion of the canal in 1885 ; and the present writer, who made a hydraulic survey of the Thamman Rajbaha in 1888, found silt clearances by manual labour in vogue then.

Kennedy also claimed that, by designing channels as to width, depth, and mean velocity, in accordance with his formula, bed-silting could be prevented. The channels experimented on by him appear, however, to have continued to experience silt troubles long after his time ; as evidenced by the raising of the arches of bridges which had become converted into syphon bridges by the progressive rise of level of the channels from silt deposits. The present writer was for long of opinion that, in cases where channels refused to conform to Kennedy's formula, and continued to suffer from silt deposits in spite of designs indicated by that formula to be non-silting, the cause of the silt trouble was to be found in the syphoning of the flow of these channels through submerged bridge waterways ; but after a long course of experimental observations, he has come round to the opinion that another, and perhaps greater, cause of silt troubles in a channel, otherwise suitably designed, is to be found in the design of its head regulator, through which it is supplied with water.

Kennedy himself seems to have been conscious of something of this sort ; for, in a note written by him as Chief Engineer, in the year 1906, on the design of the head regulator of the Rasulpur Distributary, Upper Bari Doab Canal, we find the following observations :—

" The present difficulty is that though V_o may obtain in a parent channel, yet, owing to peculiarities of some of the off-takes, which we at present do not understand, some of the distributaries carry into themselves more than their proper share of silt, and consequently require more than V_o in their head reaches." Here we find an admission of the failure of the empirical formula for want of a scientific basis of theory ; and if we are to solve the problem we must first establish a rational theory which may be applicable to every manifestation of the silt difficulty.

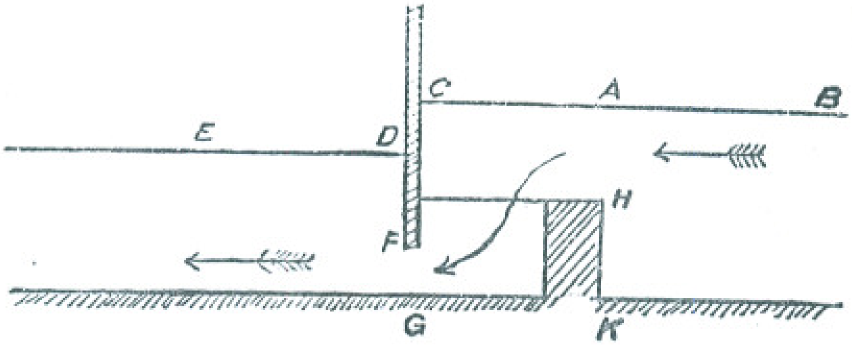
The Mithalak Distributary.

A useful object lesson in the design of the head regulator of a distributary is afforded by the case of the Mithalak Distributary of the Lower Jhelum Canal. This channel off-takes at R. D. 63,875 of the Northern Branch, a few chains upstream of the fall at R. D. 64,200. The canal at this point was designed thus :—Bed width 82 feet ; water depth 6 feet ; gradient 1 in 4444 ; Kutter's $N = 0{\cdot}0225$; discharge 1,550 cusecs ; mean velocity $= 3{\cdot}05 = 1{\cdot}155\ V_o$.

The Mithalak Distributary was designed as follows :—Bed width 20 feet ; water depth 4·2 feet ; gradient 1 in 5000 ; Kutter's $N=0{\cdot}025$; discharge 167 cusecs ; mean velocity $=1{\cdot}8=0{\cdot}86\,V_o$.

The distributary was opened for irrigation in 1903, and forthwith suffered from silt deposits. In three years its bed rose by silt deposit an average of two feet in the first two miles. The influence of the head regulator on the silt deposits must have been felt, for early in 1907 it was sought to prevent silt from entering the distributary by building a crest wall, or advanced sill, three feet high, in front of the regulator in the canal.

FIG. 9.



A Mistaken Device.

This is a device very commonly in use on Punjab canals for the exclusion of silt from a regulator. The writer has seen numerous examples of it, but has not met with a single one that has fulfilled the purpose for which it was devised. If the water surface AB (Fig. 9) of the parent channel, outside the advanced sill, be flush with the water surface AC between the sill and the gateway of the regulator, the sill can hardly be controlling the flow over itself. If the head of water pressure acts at the gate orifice only, the silt-carrying eddies of the inflowing water must be determined by the velocity of flow through the gateway FG, rather than by that over the sill HK.

In order to be the main factor controlling the silt-flow, the sill HK would need to be high enough to cause an overfall, and a substantial drop of water surface, from AB to AC.

The Silting of the Mithalak Distributary.

In spite of the advanced sill the Mithalak Distributary continued to suffer from silt deposits. Plate V shows, in a broken line, the original designed gradient ; in a fine line the state of the silted bed in 1906 ; and in a thick line the silted bed of 1914. The actual water surface levels of 1914 are also shown 2·6 feet higher than those of the original design. Hydraulic observations were made in 1914, in the canal, and in the distributary, respectively, just above, and just below, the off-take. The results were as follows :—

Canal.

Water depth 5·9 feet ; Kutter's N=0·026 ; gradient 1 in 3636 ; discharge 1,503 cusecs ; mean velocity $=1·12\ V_0$ *cf* p. 98

Distributary.

Water depth=2·5 feet ; Kutter's N=0·021 ; gradient 1 in 3077 ; discharge=146 cusecs ; mean velocity $=2·24=1·48\ V_0$.

The critical velocity ratio of the canal has remained much the same as it was designed, *viz.* 1·12 ; but that of the distributary has risen from 0·86 to 1·48. How are we to account for this forty-eight per cent. excess over the critical velocity of Kennedy's formula ? The site is fifty miles from canal head.

The writer's explanation is that the conditions of design of the head regulator were such that it swept vast quantities of silt into the distributary, in excess of the latter's carrying capacity.

According to the Mississippi hydraulicians, and M. Bazin, the mid-depth velocity in the vertical longitudinal plane is not appreciably different from the mean velocity in that plane. Without accepting this as true, we may conveniently, for the moment, assume that a filament at mid-depth of one of the vertical longitudinal planes of each stream is equal to the mean velocity of the whole stream. According to the theory set forth in this paper, the silt carrying power of the stream may be represented by the ratio borne by a function of the velocity of a filament of the current in a vertical plane, to the vertical distance between it and the retarding surface of the channels. And if the bottom velocity of the stream be zero, the silt carrying power of the stream may be represented by the ratio borne by a function of the velocity of any filament, to its elevation above the bed. If we assume, conventionally, that the mid-depth velocity in mid, stream is equal to the mean velocity of the stream, we may say that the silt carrying power of the stream is roughly proportionate to the ratio of the mean velocity to the half depth of the stream, *i.e.* proportionate to $\frac{2\,V_m}{d}$; and this might be called the *silt index* of the stream,

PLATE IV

LONGITUDINAL SECTION OF JHANG BRANCH LOWER

FROM R.D. 45,000 TO R.D. 75,000
(SURVEYED IN JANUARY 1901)

SCALE {HORIZONTAL-2"=1 MILE
VERTICAL = 1/100

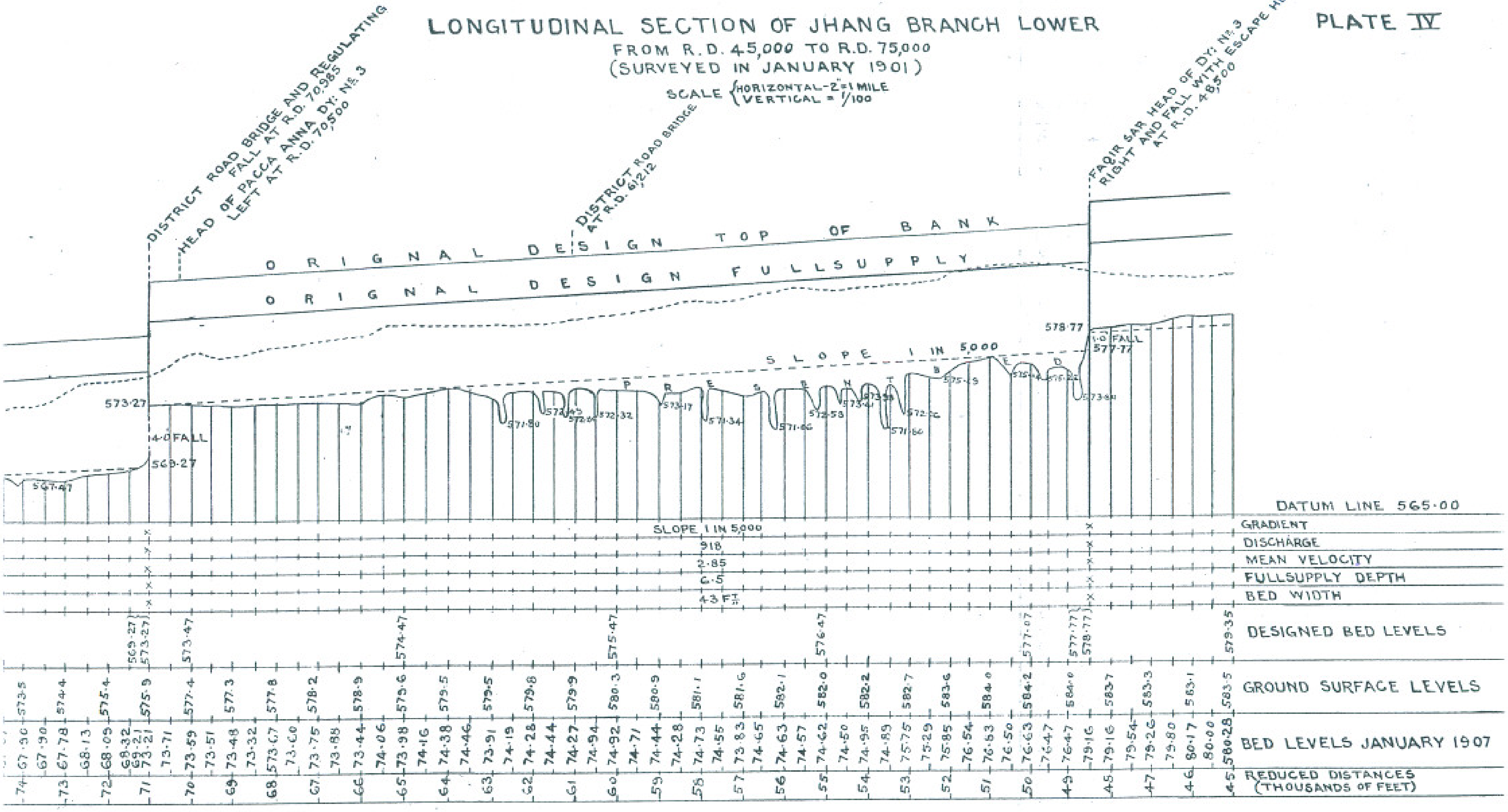
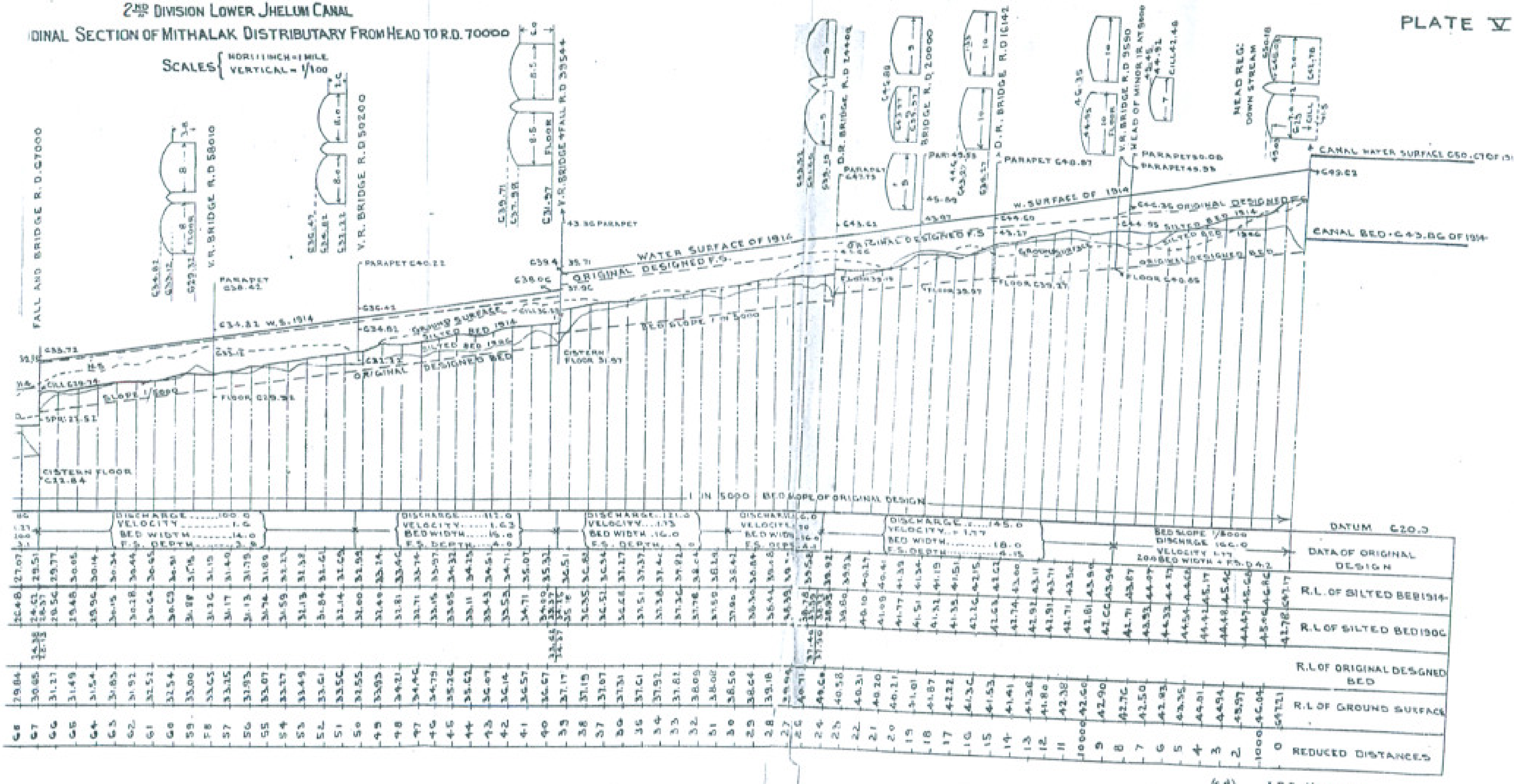


PLATE V

2ND DIVISION LOWER JHELUM CANAL

DINAL SECTION OF MITHALAK DISTRIBUTARY FROM HEAD TO R.D. 70000

SCALES { HORI: 1 INCH = 1 MILE
VERTICAL = 1/100

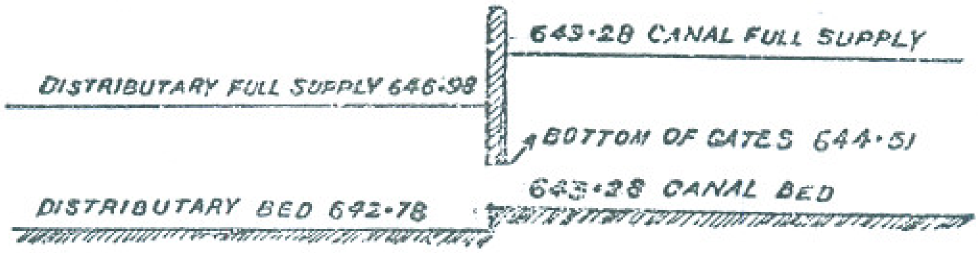


(Sd) I.D.E. HUGHES
EXECUTIVE ENGINEER DATED [illegible]
2ND DIVISION LOWER JHELUM CANAL

The *silt index* of the Northern Branch, Lower Jhelum Canal, at R. D. 63,600, in the year 1914, would then be $\frac{2{\cdot}93 \times 2}{5{\cdot}9} = 1$. And the *silt index* of the distributary at R. D. 200 would be $\frac{2{\cdot}24 \times 2}{2{\cdot}5} = 1{\cdot}8$. The cause of the higher silt index of the distributary, as compared with that of the canal is to be found in the high silt index of the head regulator of the former.

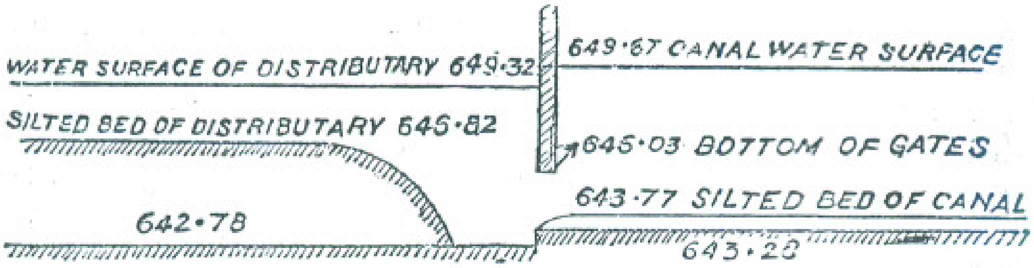
Under its original design the conditions of inflow through the head of the Mithalak Distributary were as sketched below :—

FIG. 10.



The gateway consisted of two openings, each seven feet wide, so that the discharge was $\frac{167}{14} = 12$ cusecs per foot run of sill. The height of the openings was 1·23 feet, and the mean velocity of discharge through them was $12 \div 1{\cdot}23 = 9{\cdot}76$ feet per second, with a maximum of, say, 14·6 feet per second at the centre of orifice, only 0·62 foot above canal bed. This implies a silt index of $\frac{14{\cdot}6}{0{\cdot}62} = 23{\cdot}6$, as compared with only $\frac{1{\cdot}8 \times 2}{4{\cdot}2} = 0{\cdot}86$ in the distributary under its original design. Naturally the open stream of the distributary could not carry on the silt brought through the regulator with an index of 23·6. Consequently the bed of the channel silted up, and its water surface levels rose, until, in July 1914, the conditions of flow through the head were as sketched below :

FIG. 11.



The discharge was $\frac{146}{14} = 10{\cdot}4$ cusecs per foot run of sill, and the mean velocity of entry was $\frac{10{\cdot}4}{2{\cdot}77} = 3{\cdot}79$ feet per second; with a maximum of, say, 5·7 feet per second, at a level 1·38 feet above sill.

The silt index of the current of entry would be $\frac{5{\cdot}7}{1{\cdot}38} = 4$, as compared with 1·1 in the canal and 1·8 in the open channel of the distributary.

These conditions betokened an approach to uniformity as compared with the original silt indices of 23·6 at regulator and 0·86 in the distributary; but there still remained scope for improvement, and a necessity for reducing the silt charge of the distributary, which required a slope so steep as 1 in 3077 to keep it moving on.

Proposed Remedy.

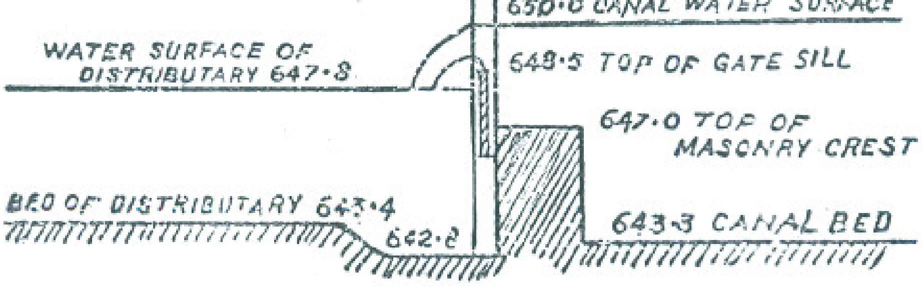
This improvement can be effected by increasing the waterway of the head regulator from two to four spans of seven feet. The discharge per foot run of sill would then be $\frac{166}{28} = 6$ cusecs.

Design a "free" overfall :—

$$\tfrac{2}{3} \times 0{\cdot}625 \sqrt{2gh} \times h = 6$$

whence h = 1·5 feet and the mean velocity of overflow = 6 ÷ 1·5 = 4 feet per second.

FIG. 12.



A masonry crest wall should be built across the waterways up to a level of 647·0, and behind this wall a gate sliding in vertical grooves, to act as a sill with the water discharging *over* it, instead of under it. There would then be a free fall over the sill, and the maximum velocity of overflow would be six feet per second, acting at a level 5·2 feet above canal bed, and implying a silt index of 1·15 only; about the same as the silt index of the canal. It may reasonably be anticipated that, with the water entering the distributary under such conditions, its silt charge will be so low, that the distributary, whose present silt index is 1·8, will be able to scour its bed, and regrade it at a lower level, to a flatter slope, say 1 in 4444. The current might, in fact, remodel its channel to something like the following data :—

Bed width 18 ; water depth 4·4 ; gradient 1 in 4444 ; Kutter's $N = 0·0225$: discharge 166 ; mean velocity $= 2·15 = V_o$; silt index $= \dfrac{2·15 \times 2}{4·4} = 1.$

The silt index of an off-taking channel, based on mean velocity and half water depth, will usually be less than that of its head regulator ; partly because the silt carrying power of a stream is less at mid-depth than in the layers of water which lie closest to the stream-bed ; and partly because the elevated sill of the head regulator permits of a higher index by reason of its lateral obstruction to silt flow.

The Ludewala Distributary.

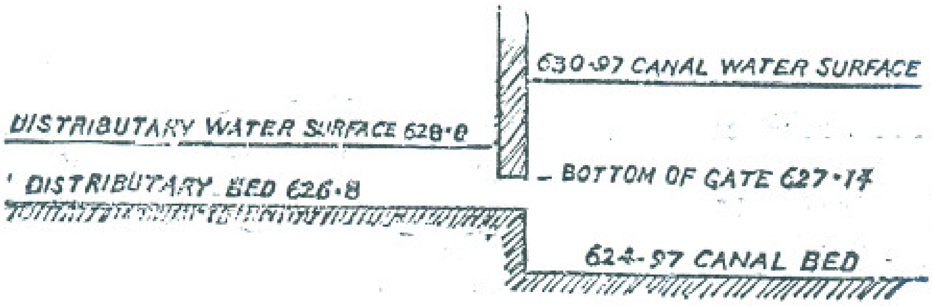
The Ludewala Distributary, which off-takes from the Northern Branch, Lower Jhelum Canal, at R. D. 146,000, just upstream of the fall at R. D. 146,250, is another example. The canal at this point was originally designed with a mean velocity of three feet per second in six feet depth of water. Its critical velocity ratio was $\dfrac{3·0}{2·64} = 1·14\ V_o$, and its silt index (I_t) was $\dfrac{3 \times 2}{6} = 1.$

The distributary was originally designed to—

Water depth $= 2·0$; mean velocity $= 1·3 = V_o$. Its silt index (I_b) was $\dfrac{1·3 \times 2}{2} = 1·3.$

The conditions of flow through the head of the distributary were :—

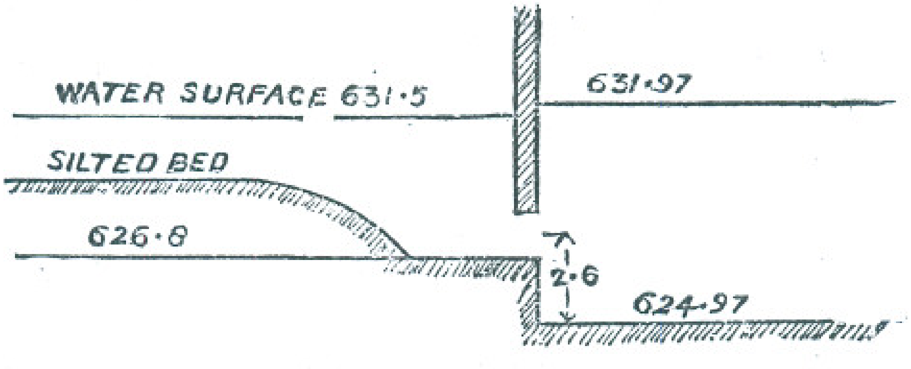
FIG. 13.



Mean velocity $= c\sqrt{2gh} = 9{\cdot}6$; discharge = 25 cusecs ; span = 8 feet ; height of opening = 0·33 foot ; centre of orifice above canal bed 2 feet ; maximum velocity = 14·4 ; silt index $(I_r)\ \frac{14{\cdot}4}{2} = 7{\cdot}2$.

The distributary silted heavily ; and the water surface levels of the canal had to be raised in order to pass sufficient water over the silt ; till in 1914 the conditions were thus :—

FIG 14.



With the following data :—

Discharge = 44 cusecs ; mean velocity = 4 ; height of orifice = 1·4 feet ; elevation of orifice above canal bed = 2·6 feet ; maximum velocity = 6 ; $I_r = \frac{6}{2{\cdot}6} = 2{\cdot}3$.

By silting up to a higher level the distributary reduced the silt index of its head from 7·2 to 2·3.