THE DESIGN OF CANAL HEAD WORKS.

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SYNOPSIS.—The great rivers of North India—Alluvion and Diluvion—The Western Jumna Canal—Permanent Head Works—The hydraulics of Indian rivers—General design—The Head Works at Tajawala—The Bari Doab Canal—Madhopur Weir—Training Works—Shingle troubles and attempted remedies—The Sirhind Canal Head Works—Silt troubles at Rupar—Remedial Devices—The Lower Chenab Canal—Head Works at Khanki—Silt troubles—The Lower Jhelum Canal—Rasul Head Works—Full discussion desirable—Declivities of canals and rivers—The Author's theory illustrated—Inundation canal heads—Sluice power—Afflux at weirs—Calculation of afflux—Weir shutters—Cost of Head Works—Concluding summary.

The Great Rivers of North India.

The great rivers of Northern India, the Ganges, the Jumna, the Indus and its great tributaries, discharge volumes of water varying between *minima* of from 2,000 to 6,000 cubic feet per second in the winter, and *maxima* of a hundred times those volumes in the flood season (June to September) at their points of exit from the Himalaya Mountains, where the declivities of their courses range from 1—200 to 1—500. Their ordinary floods, which may be looked for every year, amount to anything between 100,000 and 3,00,000 cubic feet per second; and it can easily be understood that such volumes of water, flowing down such steep declivities, with velocities up to fifteen or twenty feet per second, have great erosive power, and are capable of moving and transporting boulders of all sizes up to a quarter of a ton in weight. Consequently we find the bed-soil of these rivers, at their exit from the mountains, composed of boulders and shingle, compactly deposited. As the rivers progress down the plains of Hindustan, towards the sea, their declivities gradually flatten, and their power of transporting heavy solid matter by their currents correspondingly diminishes. Boulders and shingle, in their bed-soil, give way to shingle and coarse sand; which again, progressively, give way to fine sand and finer sand, and clayey silt. The declivity of the River Jumna, after it emerges from the Siwalik Hills, 110 miles from its source in the Himalayan glaciers, is about 1—300; 150 miles further downstream, near Delhi, its declivity is about 1—5,000, and its bed-soil sand; downstream of Allahabad, where the Jumna, 860 miles from its source, unites with the Ganges, the declivity of the latter is about 1-10,000; upstream of its delta, in Bengal, 1,300 miles from the source of the Jumna, the declivity of the Ganges is about 1—16,000; and down its delta the declivity diminishes steadily to about 1—60,000 in its approach to the sea.

Alluvion and Diluvion.

In the upper portions of their courses through the plains of Northern India the river currents are steadily degrading and lowering the levels of their beds by erosion; whilst in their lower reaches, approaching the sea, their tendency is to raise their beds by silt-deposit; but everywhere there is an alternation of erosion and silt-deposit, alluvion and diluvion; the silt-scouring power of their mighty, but ephemeral floods, being limited by the silt-transporting power of their normal flow. One of the greatest problems of perennial canal design, in a country relatively flat, is to secure by appropriate designs that permanence of silt-regime, and that absence of erosion or silt deposit, which is not obtainable in natural streams.

Just as the bed-soil of the Himalayan rivers is graduated from boulders to shingle, and from shingle to coarse sand, and thence to fine and finer sand, according as the declivities flatten in the progress from the mountains to the sea, so the silt of Indian perennial canals varies in coarseness from their heads to their tails.

On a reach, twenty-four miles long, of the main branch of the Upper Bari Doab Canal, Messrs. J. M. Roberts and F. V. Elsden found by examination and analysis of samples of sandy silt, taken from the bed of the canal at six points at intervals of four miles from each other, that there was a very marked, easily measurable, gradation in the quality of the silt, from coarse to fine, progressively, in the downstream direction.

This reach of the canal was on the average about forty miles distant from the canal head, or offtake of the canal from the river; whilst Mr. Kennedy's famous silt-investigations were carried out on the same canal, but further downstream, at sites averaging a hundred miles distant from the canal-head.

The Western Jumna Canal.

The earliest perennial canal constructed in India for the purpose of irrigation, was one that took off from the west bank of the River Jumna just below the point where the river emerges from the Siwalik Hills. It was first constructed in the fourteenth century; and, after falling into disuse, was restored during the Mughal Empire in the sixteenth century; and after once more falling into disuse in the eighteenth century, it was again restored by the British Government in the year 1820. Throughout these different periods the water of the river was diverted into the canal by simple dams, consisting of shingle, brushwood, wicker-work gabions filled with stones, and such like devices. The gradient of the river at the

canal head was about seventeen feet per mile; so that it was not difficult to divert the winter flow, of about 3,000 cubic feet per second (or part thereof), on to the adjacent watershed by the means just mentioned, which were both cheap and fairly effective, though they had their drawbacks. The temporary dams, or bunds, were usually constructed in October, at the end of the flood season, when water was needed for completing the irrigation of the summer crop, and for sowing the winter crop. The trouble was that it took some time to construct the bunds, and until they were completed agricultural operations were delayed; whilst there was always the risk of an unusually late flood coming down the river and sweeping away the bunds, whether complete or incomplete. Early construction increased the risk of complete destruction, whilst late construction meant agricultural loss.

Permanent Head Works.

After fifty years' experience of feeding the Western Jumna Canal by the above discussed methods, the Punjab Government about the year 1870 decided to control the river more effectively at the off-take of the canal by means of permanent masonry works. This was done; and since then no irrigation canal of any importance (with a single exception) has been constructed in the Punjab without a masonry weir to control the flow of the river from which it is fed. The Government of the United Provinces of Agra and Oudh has, until lately, adhered to the ancient methods of temporary dams for the supply of its Eastern Jumna Canal and the Upper Ganges Canal; but it is now coming into line with the practice of the Punjab in the matter of Canal Head Works.

The Hydraulics of Indian Rivers.

The channels of the great Indian rivers, at the points where canals have to off-take from them, may be less than a mile wide, or they may be several miles wide; and their maximum discharges in the flood season may be, and generally are, about a hundred times greater than their minimum discharges in the winter. The width and depth of a channel, which is only sufficient for the great floods, is vastly in excess of the requirements of the ordinary cold weather flow, and the latter, in an uncontrolled river, will generally occupy only a portion of the width of the flood channel, and may in different years occupy a different portion of the flood channel, sometimes towards the right bank, and sometimes towards the left, or in any intermediate position. The func-

tion of a properly-designed canal-head river-weir is not to maintain the low-water surface of the river at a ce minimum level, but also to ensure that the minimum w flow of the river will flow along that bank of the river which the canal off-takes, so as to enable the canal to take whole of that minimum flow, if necessary.

General Design.

The general features of the ordinary Canal Head W in the Punjab comprise :—

(*a*) A masonry weir laid across the river with crest approximately at the mean bed level the river on that cross section.

(*b*) A portion of the weir, at the end nearest the bank from which the canal off-takes, is bu at a level several feet lower than the rest of t weir. This end portion of the weir is divide by means of piers, into bays usually twenty fe wide, fitted with gates sliding vertically in groov in the sides or the piers ; and is known as the unde sluices. These gates can be opened so as cause the river to scour for itself a deep chann along that bank from which the canal off-takes or they can be closed so as to force the grea est possible volume of water into the canal.

(*c*) The canal in-take, or head regulator, usuall built in juxtaposition to the under-sluices, wit the main current of the river scouring past its face

(*d*) The river-training works, consisting of embank ments, revetments, spurs, groynes, &c., which aim at protecting riverain lands upstream from inundation due to the afflux caused by the weir; or at guiding the course of the river upstream and downstream of the weir.

Of the above features (*a*), (*b*) and (*c*) first appear to have been copied from the designs of irrigating canals in Spain France, and Italy, which have some hundreds of years of experience behind them, and which have progressed those features mainly by process of trial and error.

The Head Works at Tajawala.

The very first masonry weir built across any river of import ance in India was that built across the River Jumna at Taja-

wala to feed the Western and Eastern Jumna canals. This presented the peculiar difficulty of having to keep the perennial flow of the river always in contact with two canal-heads, situated on opposite banks of the river.

Colonel Crofton, in designing the Tajawala weir, probably had little in the way of precedent to guide him. He met the case by locating the head of the Eastern Jumna Canal higher up the river than the head of the Western Canal, and by building the weir slantwise across the river from the eastern head downstream to the western head; so that the perennial stream might flow first past the eastern head, then along the weir, and thereafter past the western head. (See Plate I.) One set of under-sluices was built with the eastern end of the weir, and another set at the western end; so as to create the necessary draught to each end of the weir. The device was well-conceived but had some defects of detail, and a continuous and costly series of river training works has been undertaken during the past forty years in order to force the perennial stream to keep to the programme planned for it, though a higher weir with lighter, deeper, sluices at each end, might have been successful without the aid of separate river training works.

The Government of the United Provinces did not approve of the permanent head works at Tajawala; preferring to feed the Eastern Canal in the old way, by means of temporary spurs and embankments renewed annually; and so the eastern sluices and regulator have not been practically tested, consequently in practice the Tajawala works have only had to feed the Western Jumna Canal.

The weir was built with the crest approximately at the bed level of the river; and slantwise, so that it offered little or no obstruction to the floods. Having an excess of waterway, it was liable to be masked by shoals and shingle-banks; so that, on the occurrence of a flood, if the main stream of the river happened to set towards the eastern side of the river channel, it might flow over the weir, and prevented from reaching the western head, by intervening shoals.

To cut through these shoals would necessarily involve the stoppage of the water supply to the canals; and the time might mean widespread injury to agriculturists, loss of irrigation revenue. After attempts to solve this difficulty, by process of trial and error, of river training works, a portion of the

downstream wall with a masonry

left flank, was built up so as to reduce the effec
over the rest. Shoaling troubles continued, howeve
device adopted was the erection of hinged shu
high, along the crest of the weir, to permit of the s
water, being ponded up and forced over the top of
if necessary. Amongst the latest remedial project
one proposing to abandon the existing western under-
western canal head, and to rebuild them on a
thousand feet closer to the east bank of the river, and n
middle of the river channel, so as to reduce the length c
between the east and west canal-heads, and thereby c
the river's flow, and facilitate its control. This remed
yet been carried out, but is still under discussion.

The western sluices of the Tajawala weir w
with ten bays, each 20 feet wide, and eight bays e
feet wide, or 385 feet width of waterway in all ; this
excessive. The sluices have attracted an undue sha
river's floods, but, even so, the centrifugal conditions o
shoaled up a great portion, and concentrated the
the rest, and for this reason, in the year 18
portion of the western under sluices was wrecked by

While the western sluices have too wide
the western canal head has rather too narrow
viz., thirty-five bays of six feet each, or a wid
all for its present full supply of 6,700
in-take means too low a sill, too high a
heavy draught of detritus from the river in
difficulty of control of the regulating gates in time
The mean velocity of entry through the canal
eight feet per second ; and the maximum vel
about twelve feet per second ; the sill being four
the river bed in front of it.

The Bari Doab Canal.

The Bari Doab Canal, opened in the ye
h Government, superseded a small cana
f some two to four hundred cusecs dischar
tructed about the year 1633 by the M
n to convey water to the gardens of
off-took from the river at Madhopur
f the last of the Hamalayan foot-hills,
vity of the river was about 1—250, and w
oulders and shingle dropped by floods.

e years the head of the Bari Doab Canal was
t cut in the left bank of the river, into which the
by means of temporary dams of shingle and
lt across the river; but the drawbacks of this
onel Crofton, about the year 1871, to substitute a
asonry weir with sluices and canal head regula-
masonry head works were of the same type as
the same time for the Jumna Canals at Tajawala;
ıe weir was built normal to the general line of the
of askew to it.

iver Ravi at Madhopur flows between high bluffs
housand feet apart, and prior to the construction of the
ir was liable to flow in any part of that width, but
t times it had actually silted up about a thousand
ight bank, and was ordinarily utilizing a width of
housand feet on the left.

onry weir was built transversely to the axis of the
th of 2,750 feet, out of which 300 feet, on the
levoted to the under-sluices.

ing the line of the weir on its right flank an
ıent was made to connect with the high bluff on
the riverain space. Where this embankment
the Kashmir Canal, a petty channel of less
s discharge, flowing through the riverain
ıt, or Kashmir, side of the river, and open
was an error; for it is conceivable that a flood
hrough this gap, and, outflanking the weir,
left side of the riverair, and the off-take
oab Canal (Plate II).

adhopur weir.

11. he Madhopur weir across the River Ravi was
(Plate II) at h a level as to block eighteen per cent. of
flood wate the river; while the sluices were built
their floc ee feet below the cre of the weir. The
lt was th displayed no tendency to keep its main
m past th canal head and through the sluices
he left ba

The Mhopur weir had scarcely been completed in the
ner of the year 1871, when it was considerably damage
ood, which cut right through it in several places. This w
e the one across the Jumna at Tajawala, merely consiste
o parallel walls laid across the river, about forty feet apar
stream with its top four feet higher than tha

downstream wall, and the space between the ...tive water... with a masonry pavement sloped at 1 in 10 (F...r, and the ... workmanship may have been defective, or the mo...utters, four f... when attacked by the flood, or even the tran...eam, at l... sions or the depth of the foundations of the wei...lateral shoa... any how, a legend arose that the weir was "weak,"...s has bee... of strengthening it by increasing the dimensions, at ...sluices an... made to protect it from the direct onslaught of floods ...new site ... training works upstream. ...early in th... ...of the we...

An embankment known as "Jacob's Bund" ...oncentra... 2,300 feet long and rivetted with stone, was constr...ly has n... wise along the right margin of the main stream, w... about 3,500 feet upstream of the weir, with th...ere b... of deflecting the current away from the right flank ...ach 23 weir towards the canal head and sluices on the left. Th...has pr...ever, only served to compass the destruction of the ...are of ... otherwise known as the "outlet," for in the year ...f flow h... undermined and entirely swept away these sluices ...current ... time outflanking the weir at its right flank. ...94, a gre...

The sluices were rebuilt to stronger dimen...a flood. bays each twenty feet wide; but in the follo...a water way... were again seriously damaged, and the training ...a wat... destroyed. The sluices were again however, str...210 ... very substantial masonry floor, 3·5 feet lowe...oo n... one, and a deep curtain wall constructed down ...of ent... less, in the year 1878 the work was foun...canal ... undermined throughout, and had to be still furth...of er... (Plate III). In the year 1880 the floor do...ream. ... sluices was once more undermined, and the weir cut thro... four places.

By this time the engineers had lost faith in t... ... of the weir; but instead of still further stren...eni... it ... to render it impregnabl..., as was their policy in ... to the ...es at its left flank, the...proceeded to build ...ar ...rainin... works upstream similar to Jacob's Bund, but of fa...l, kn...bstan... con- struction, and in the year 1882-0... work known as the Lower Training Works (Plate II) was constructed. Th... was a spur, ...r submerged weir, about 2,500 feet long, projecti... from a point ... the right margin of the main stream, ab... 3,000 feet ...ream of the weir, slantwise downstream ... across the ...el, so as to mask the right half of the w...d to deflect ...ent to its left flank.

This was justified in the following words :—"Though the permanent weir was intact, it afforded no command over the river and was almost useless for the purpose of maintaining the canal supply. This necessitated the construction of temporary crate weirs higher up the river, at Sidhouri, arranged so as to throw the river to the left side of its bed. It was now decided to construct permanent works free from the defects of the old crate weirs in alignment and design."

Since the permanent weir was admittedly intact, it would appear to have been simpler to have raised and strengthened it, so as to render it impregnable and thus ensure command of the river, than to have built other permanent works *de novo* ; but the engineers of 1882 thought otherwise.

Training Works.

The shoulder of the lower training work was located in soft alluvial soil on the right margin of the main stream, instead of being carried on to connect with the impregnable bluff which bounds the river valley on the right. Consequently, when the river threatened to outflank the lower training work on its right flank, or shoulder, it was thought necessary, in the year 1884-85, to construct the upper training work (Plate II) as a protection to the lower training work. This tended to throw the force of the current still more strongly against the sluices, or outlet, on the left flank of the weir ; and is the more remarkable as the Superintending Engineer, in February 1885, stated that in his opinion the state of the "outlet" was "critical in the extreme." It is not surprising therefore that the floods of 1885 damaged the "outlet" very seriously, and necessitated the very substantial additional work that is shown in Plate III. Had the weir been raised and strengthened as the sluices had been improved, the enormous expenditure on the upstream training works might have been saved.

The lower training work was built in the year 1883 at a cost of Rs. 80,000, to protect the Madhopur weir; and when this in turn was threatened with being outflanked, the upper training work was built, in the year 1885, at a cost of Rs. 91,647 for its protection. And, again, when the upper training work was threatened with outflanking (Jacob's Bund having by this time been discredited as "weak") new works were built, in the year 1892, further upstream at Dhanna, at a cost of Rs. 64,000. The Dhanna Training Bund, like the Upper and Lower Training Works, had its shoulder in insecure alluvial soil of recent formation ; and when

the river threatened to outflank it, the Dhanna Bund was extended past and across the gap of the intake of the Kashmir Canal. This led to a dispute with the Kashmir Durbar, with the result that we accepted responsibility for the maintenance of the future supply of the Kashmir Canal. A submerged weir of wooden or wire-work crates was also built across the main stream of the river (for the time being) in connection with the Dhanna Bund, which has frequently been seriously damaged and almost wiped out by floods. The maintenance of the Dhanna works alone, during the five years ending 1910, cost over two lakhs of rupees. They are still liable to be outflanked on the left, and have been entirely deserted by the perennial flow of the river.

From an inspection of the plan of the river shown in Plate II, it will be seen that there is nothing to prevent the river, in some great flood, scouring out for itself a new main channel to the left of the Dhanna Works where it formerly flowed ; and in that case nothing less than a weir right across the whole width of the river would retain for us our means of feeding the Kashmir Canal.

The Dhanna site is four miles upstream of the Madhopur weir, and at an elevation seventy-five feet higher. Between Dhanna and the Madhopur weir the river flows over a series of natural rapids and through a succession of short reaches of varying hydraulic condition ; whilst the *thalweg* of the stream oscillates from right to left, and back again, at the caprice of every flood; and is in any flood season liable to shift its main channel a thousand feet or so to right or left. To tinker with the stream at Dhanna, with the idea of benefitting the canal head at Madhopur, is like tickling a Himalayan glacier in the hope of producing spasms in the Hooghly at Calcutta.

Other river training works at Madhopur are the Escape Weir and the " Sidhowri Crate Bar" ; both of them submerged weirs laid across different channels of the river, upstream of the Madhopur Weir, with the object of deflecting the main stream to its left flank, but these training works only save the Madhopur Weir from the action of petty floods. Floods exceeding 30,000 cusecs in volume pass over both the training works and the main weir ; and the bulk of any high flood, exceeding 1,00,000 cusecs, has always passed over the main weir. Since it is these high floods that do most of the damage that ever is done to our head works, it seems clear that the Madhopur weir is not protected by the upstream

training works, and has to rely mainly on its own strength and stability, and when we find it stated in the completion report of the canal, that :—" The training works have from first to last cost even more than the maintenance and strengthening of the head works," one can only wonder at the policy which led to their original construction, and at the lack of policy that has acquiesced in their subsequent maintenance.

The works mentioned above do not exhaust the list of river-training devices that have been tried from time to time at Madhopur. In 1887 the Supply Weir was built with its crest at the same level as the Madhopur weir, and springing from its left flank at an angle of 30° to it. The Supply Weir was 2,500 feet long, and masked all the Madhopur Weir which had not been masked already by the lower training works. (See Plate II). Its object was to deflect the current towards the undersluices at the left flank of the main weir, but proving to be ineffective for this purpose, the practice was adopted of building along its crest every flood season an embankment of shingle to a considerable height, with the object of preventing the low-water flow of the river from spilling over the Supply and Madhopur Weirs, away from the sluices and canal head.

The result of this expedient has been thus described by Mr. Kanthack, an Executive Engineer who had charge of these works in the year 1905 :—" Every flood that comes down breaches this shingle bund, and it is necessary that it should do so, as the complete closure of the spillway to the right of the undersluices, across the weir, throws an enormous strain on the undersluices, which is a constant source of danger. Again, as the bunds have gradually grown in height, and therefore in strength, their capacity for resisting floods has also increased, so that it now takes sometimes a twenty-foot flood to breach this bund, which is a dangerous state of things for the head works generally, as about three-fourths of the flood must pass through the sluices until relief is obtained by the Supply Weir breaching. "

The writer has reviewed the history of the head works of the Upper Bari Doab Canal, on the River Ravi, at Madhopur, in some detail, as they appear to be a striking illustration of methods of river-control misconceived for the purpose aimed at. During the fifteen years, 1875-90, no less than seventeen lakhs of rupees were spent on the maintenance and repairs of these works ; the original cost of which, debited to capital ac-

count, was only Rs. 4,72,680 in the year 1872 ; a figu- which rose to Rs 7,59,147 by the year 1876-77. In t completion report of the Bari Doab Canal, dated 189 Col., Ottley and Mr Higham estimated that the future ma tenance of these works would cost not less than one *lakh* rupees per annum, and the writer submit that a small fracti of the sum above mentioned, if applied to the strengthening an improvement of the design of the weir, sluices, and can head, *as River-Controls*, would have ensured a more p manent effect than the labyrinth of River Training Works, wh up to the present continues to worry the Ravi near Madhop

Shingle troubles.

The Canal Head Regulator at Madhopur has a waterw 230 feet wide, divided into twenty-three bays, each ten fe wide. Its permanent masonry sill is supplemented by plan resting thereon, and affording a sill five or six feet above th floor level of the sluices. The water entering the canal flow over this sill with a mean velocity of entry of about nin or ten feet per second, and a maximum velocity, at sill level of about fifteen feet per second. This velocity of entry is excessive, and draws into the canal from the river an excess of detritus, which the current of the canal, with its mean velocity of about four feet per second, is unable to carry on.

From its earliest days the head reach of the canal has been troubled with heavy deposits of shingle, which have at times almost sufficed to put it out of action ; but the cause of the trouble does not appear to have been correctly diagnosed. In 1890 Mr. C. Tickell, Executive Engineer, recommended the clearance of the shingle deposits by means of dredgers worked by the force of the current ; but the scheme was dropped as impracticable.

Mr. R. G. Kennedy, C.I.E., Chief Engineer, endeavoured to apply at Madhopur the remedy which he believed had cured a similar silt trouble at the head of the Sirhind Canal. The result has thus been described by Mr. Kanthack, the Executive Engineer who carried out the operation :— " When the new regulation rules (ordered by Mr. Kennedy) were brought into force, an enormous shoal of shingle at once formed in front of the closed gates near the regulator, and was immediately drawn into the right divide of the canal. The ' draw, ' which was supposed to be created away from the regulator by working the right hand undersluice gates, did not exist. The entire draw was into canal, and the water

only flowed mildly and in small quantity through the right hand end of the sluices, and although the movable sill in the regulator was raised to double its usual height, by means of four *karries*, the shingle immediately commenced rolling into the canal over this sill." Mr. Kennedy, on Mr. Kanthack's Report, cancelled his orders as to the means to be adopted for the exclusion of shingle from the canal.

Mr. Kanthack's alternative remedy for the shingle problem was stated by him thus:—"To reduce shingling two conditions are necessary, viz.—

(1) A higher sill to the inlet.

(2) Greater face-scour.

To get 6,600 cusecs into the canal with the water level at 1138·5, and over a sill at least five feet above the sill of the undersluices, is the problem to be solved."

Mr. Kanthack's remedy was tried for several years, but failed to cure the evil; and during the five years, ending 1909-10, an annual expenditure of Rs. 21,400 was incurred on the shingle clearance of the head reach of this canal, apart from the cost of tram-lines, wagons, &c., for conveying the removed shingle to a distance. Additional expenditure of Rs. 20,000 per annum was sanctioned by the Chief Engineer for the work further downstream, which was necessitated by the heavy shingle deposits on the bed of the canal.

24. The sluices or undersluices, or outlet, of the Madhopur Weir, were originally composed of twenty bays, each ten feet wide, formed by masonry piers on a masonry floor at R.L. 1133, or three feet lower than the crest of the weir, but after the flood-damage of 1871 the floor was lowered two feet, to R.L. 1131. When the sluices were entirely destroyed by the of 1875 they were rebuilt with twelve bays, each twenty wide between piers, arched over, and fitted with sliding worked by an overhead winch, or crane. The floor also lowered still further to R. L. 1129·5.

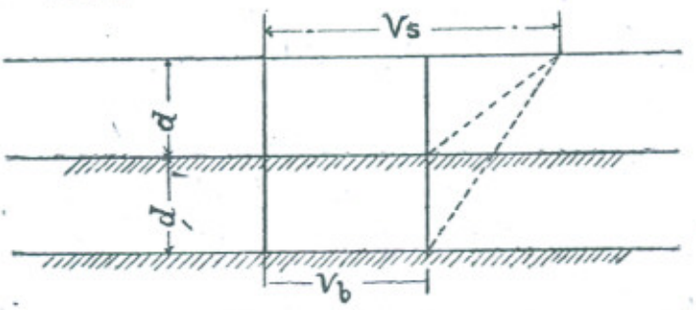
leve
that Ever since then sluices composed of twelve bays, each divnty feet wide, have been furnished to every perennial canal thed works that has been built in the Punjab, without regard the he different conditions governing the different cases.

gre The function of undersluices is to scour the river-bed in As t of the canal-head, to keep the river bed low, and to

prevent shoaling. This function is not best served by great width of waterway, but by afflux, or head of pressure, and the writer thinks it will be convenient if he indicates briefly here his views on the silt problem, and the road by which he has arrived at them.

In the year 1897, soon after Mr. Kennedy's well-known hydraulic diagrams first received the official *imprimatur*, the writer undertook some experiments in order to determine the essential differences, if any, in hydraulic conditions, that existed between a channel of high silt-carrying power, and one of low silt-carrying power. For this purpose a distributary was selected that had been originally constructed with a bed-width of three feet, a water depth of three feet, and a gradient of 1 in 5,000 ; but which used to silt up very quickly till it had a water depth of only 1·5 feet over a similar depth of silt, and a water surface gradient of 1 in 2,700. Whilst in this condition it silted no further ; but if cleared of silt it use to silt up rapidly again within a fortnight. A careful hydraulic survey was made of this channel in its silted condition, and its velocities measured from top to bottom, in the vertical longitudinal plane at midstream. It was then closed, cleared of silt to its original section, and its hydraulic conditions again observed, with the result that the surface and bottom velocities were found to be about the same in both conditions of the channel ; and that the essential difference between the two cases was the ratio of the velocity to the depth of the water. Thus, if we assume, for convenience of illustration, that the vertical curve of velocities is a straight line, the essential difference between the two conditions of channel is as follows :—

FIG. 1



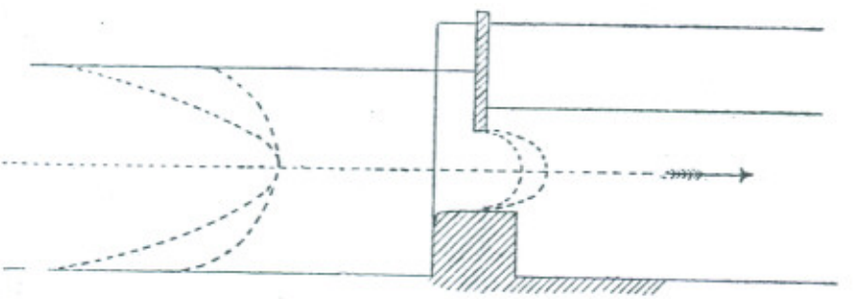
If the surface velocity (Vs.) and the bottom velocity (Vb.) be the same, in a stream of depth *d*, as in a stream of depth 2*d*, the line, or curve of velocities in the vertical plane will have a greater inclination away from the vertical in the case of the shallow channel than in the case of the deeper one.

This is in accord with the theory stated by Dupuit, in his treatise "Etudes Theoriques et Pratiques sur les mouvements des eaux courantes," that the silt-transporting power of a current varies with the *differences* of velocity of adjacent threads of the current. A glance at Fig. I will show that the difference of velocity between two filaments of the stream, a unit distance apart in the vertical plane, is greater in the case of the shallow channel than in the case of the deeper one. This sufficiently accounted for the silting of the deep, narrow, channel in the experiment, and the cessation of silt-deposit in the same stream when it had become shallower by deposit of silt to a certain extent.

It is important that we should start with a sound theory on the subject of the method of silt-transportation and silt deposit by currents of water, if we are to successfully solve problems connected therewith, and the author believes that Dupuit's theory, as illustrated by the experiments above-mentioned, furnishes a simple and rational basis for the comprehension and effective treatment of all such problems.

Consider the ordinary case of water entering a canal-head, under pressure, through a rectangular orifice formed by the sill at the bottom, the piers on the two sides, and the gate descending from above.

FIG. II



The maximum velocity of entry will be horizontal at the level of the centre of the orifice; and it is easy to understand that, the greater the velocity of entry, the greater will be the divergence of the curve of velocities from the vertical plane of the orifice. It is also easy to understand, in the light of the theory stated above, that, the greater the velocity of entry, the greater will be the silt-carrying power of the current of entry. As the velocity of entry diminishes, the vertical velocity curve

will approach the vertical plane of the orifice, and for any particular grade of silt or shingle, there must be some *critical* velocity curve, anything less convex than which will not carry silt or shingle of that particular degree of coarseness; because the differential velocities of the current forming that curve will not set up eddies strong enough to keep that quality of silt or shingle suspended. If, then, we can arrange so that the water enters the orifice under appropriate conditions of velocity, we shall ensure that coarse silt will not be brought into the canal by the current, and it seems simpler to effect our purpose in this way than to persevere in the hit-or-miss expedients of stillponds, divide-walls, weir-shutters, or sluice-gates, which have been so much in vogue hitherto.

Consider, again, the influence of the *level* of the orifice of entry on the problem of silt-import.

FIG. III

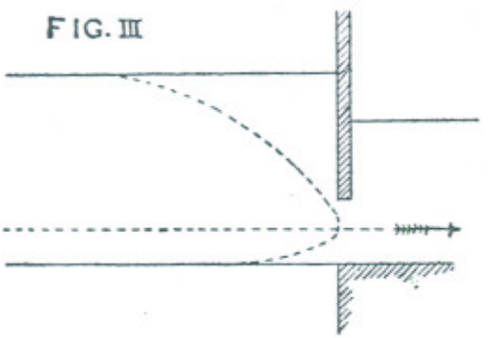
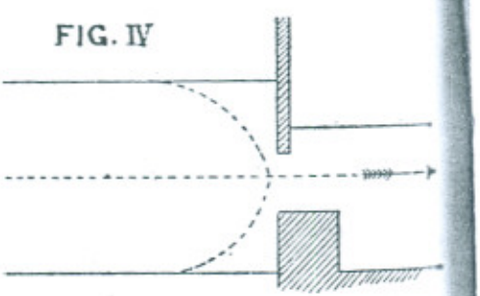


FIG. IV



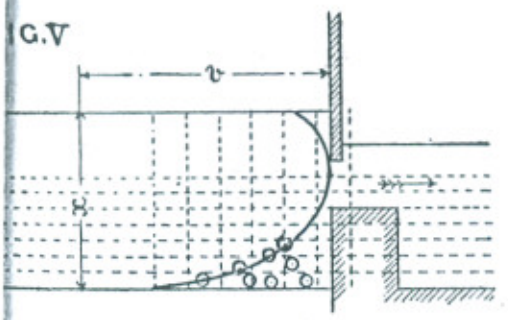
The horizontal filament of maximum velocity being at the level of the centre of the orifice, it is easy to realize that the differences of velocity between adjacent filaments of the current, in the vertical plane, will be greater in the case depicted in Fig. III, where the orifice is at a low level, than in Fig. IV, where the orifice is at a higher level.

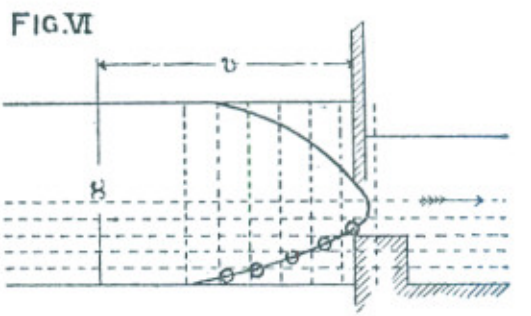
This explains, rationally, how it is that a high sill to a canal-head may exclude heavy silt, which might be swept into the canal if the sill were low. In whatever direction the river may be flowing, in mass, there will always be a current of approach towards the canal-head (when open) in the immediate vicinity of the latter ; and the relative level of the orifice of the canal head will affect the shape of the vertical velocity curve of the current of approach.

"*Rolling*" silt is sometimes referred to as though it were something that followed different hydraulic laws from those actuat-

ing silt carried suspended by a current, and even so distinguished a hydraulic expert as Mr. R. G. Kennedy has written somewhat loosely on this subject. It is easier, however, to believe that rolling silt obeys the same force of differential velocities as suspended silt

Let us suppose that a grain of sand, or a pebble, or a boulder, is being rolled along the river-bed by the current. Its rolling is actuated by an eddy set up by the differences of velocity of those threads of the current which are nearest to the river bed. If those differences of velocity should happen to diminish (from any cause) the solid will stop rolling ; *per contra*, if those differences of velocity increase, the rolling stone, or sand, will be lifted up and suspended in the current, by the more powerful eddies thus set up. If, in any given instance, the raising of the sill, of the orifice of entry of a canal-head excludes rolling silt from the orifice, it will be, not because the silt cannot roll up the sill, but because the raising of the orifice has elevated the filament of maximum velocity of the current, thereby reducing the differences of velocity of adjacent threads of the current of approach to the orifice to less than the minimum difference necessary to cause the silt to roll or to rise.





Figs. V, VI may be understood to represent the conditions of flow into an orifice at a high and at a low level, respectively, the orifice being of the same size and submerged in both cases and working under the same head of pressure and with the same velocity. The curved line represents the vertical velocity curve of the current of approach to the orifice in each case.

The thread of maximum velocity is horizontal, at the level of the centre of the orifice, and the only essential difference between the two cases is that in Fig. V the height above bed of stream of the filament of maximum velocity is greater than in Fig. VI; with the result that the portion of the vertical velocity

curve below this level, which is the portion which generates the eddies that cause scour, or suspension of silt, deviates more from the vertical in Fig. VI than in Fig. V.

The fine dotted horizontal lines in the sketches divide the water depth into conventional units of depth; and the fine dotted vertical lines intercept horizontal spaces representing conventionally the least increment of velocity ($d\,v$), which, occurring in the said unit of depth ($d\,x$), will set up an eddy capable of supporting silt of a given coarseness.

These sketches will help to explain how a class of silt which can be lifted by the current over the low sill depicted in Fig. VI may not be able to reach the level of the high sill in Fig. V. In the latter case it is not that the silt cannot roll up and over the high crest wall; it cannot even be deposited upstream of that wall to a greater height than that to which the velocity, obtaining at that level, bears to the critical ratio for the particular grade of silt in question. In other words, in the case depicted in Fig. V. silt of the given coarseness cannot be lifted higher than the level at which the vertical velocity curve begins to have a less inclination away from the vertical than the diagonals of the minute rectangles whose sides are $d\,v$ and $d\,x$, respectively.

The Sirhind Canal Head Works.

After the Western Jumna Canal, and the Bari Doab Canal, the next great perennial canal constructed in the Punjab was the Sirhind, offtaking from the river Sutlej. The site of the head works at Rupar was somewhat further downstream from tbe Himalayas than those of the Jumna and Bari Doab Canals. There was less shingle and boulders in the bed-soil of the river, while the declivity of the latter was 1-2,500, as compared with 1-250 to1-300 in the case of the older canals.

The design of the Rupar head works (see Plate IV) was, as nearly as possible, the same as those of the earlier canals; comprising, as it did, a low weir stretching right across the river, with undersluices 240 feet wide in waterway; and a canal head with a waterway 195 feet wide, divided by piers and jackpiers into thirty-nine bays, each of five feet.

The weir extended across the whole width of the river, 2,600 feet, between the high banks which formed its ultimate boundaries; and its crest level was fixed at what was believed to be the ordinary water surface level of the river in early summer, viz., R. L. 865·00.

The average minimum winter flow of the river Sutlej was estimated to be 3,000 cusecs ; and the Sirhind Canal, offtaking from it at Rupar, was designed, with a bed-width of 200 feet and a gradient of 1 in 8,000, to discharge 3,000 cusecs with a depth of 6 feet in winter, and 6,000 cusecs with a depth of 9·4 feet in the summer. That design implied a mean velocity of 2·4 feet per second in a 6 foot depth of water, and a mean velocity of 3·2 feet per second in a depth of 9·4 feet of water; conditions which favoured the deposit of silt.

Silt Troubles at Rupar.

The canal was first opened for irrigation in the year 1882, and very soon experienced silt troubles. The crest level of the weir was fixed at 865·00, and the last 240 feet of its length, at the end nearest to the canal-head, was built eight feet lower (857·00) to form the sill of the undersluices.

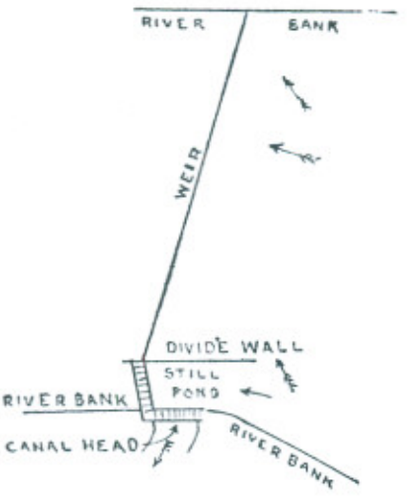
The sill canal bed-level and the sill of the orifice were fixed at 859·00, six feet below the crest of the weir; and the idea (oblivious of silt) obviously was that, with these levels, the winter supply of the canal would be assured. But silt was rapidly deposited in the canal, and higher and higher water-levels were needed to pass a sufficient supply over the deposit. In 1885 the crest of the weir was raised, from 865·0 to 866·5, but the height of the shoal in the canal rose, *pari passu*, with this increased command. In the year 1886, the engineers, fearing to further raise the crest of the permanent masonry weir, affixed four feet high hinged iron shutters on its crest which could be lowered on the approach of floods, and raised again, on their subsidence, so as to hold up water for the canal. The silt trouble, however, continued to increase, and in the year 1891 things had got so bad that it was only with difficulty that the winter supply could be got into the canals.

In 1893, Col. Ottley, Chief Engineer, in desperation ordered the application of seven distinct remedies in the forlorn hope that some of them might do good.

During the summer of that year the canal was kept closed for three months, from 11th May till 7th August, from fear of silt entry, and in November 1893, a fleet of boats with scrapers was employed to stir up the silt on the bed of the canal to enable the current to scour it away through escape channels.

The general disposition of the Canal Head Works was as shown in outline in the sketch below :—

FIG. VII



A wall, called a divide-wall, 700 feet long, was built out from the junction between the weir and its undersluices, nearly at right angles to the axis of the sluices, in an upstream direction, with the object of separating the canal head and undersluices from the flowing river and its rapid currents, by creating a comparative still-pond, or back-water, in front of the canal works. The water entering the canal-head from this back-water (the undersluices gates being closed at the time) was comparatively free of silt, and was incapable of increasing the silt deposits in the canal. To be sure it had deposited its injurious grades of silt in the back-water outside the canal-head, and the silt so deposited formed a shoal, steadily increasing in height, which was liable to choke up the entrance to the canal ; but this difficulty was met by periodically closing the canal-head, and scouring away the shoal by opening the undersluices.

Concurrently with the above mentioned device, hinged shutters, six feet high, were substituted for the existing shutters four feet high, along the entire crest of the weir ; so as to afford greater control of the river. Also, as experiments had shown, that the coarser grades of silt were found more plentifully in the lower depths of the river and canal currents ; with the idea of skimming the "topwater" the masonry sill of the canal-head was raised from its original level of 859·00 to 866·00. The

gates were also remodelled, so as to rise from below upwards, in order to pass the water into the canal over their tops, instead of *vice versa*.

The highest water surface level of the canal had been raised from its original 865·0 to 869·0, and even to 873·0, in order to pass its full supply over the shoals; and in connection with the raising of the sill of the canal head it was found necessary to widen its waterway of entry from 195 feet to 273 feet, by knocking out its jack-piers; in order to pass full supplies into the canal

Remedial Devices.

Of the seven remedies applied to the silt troubles at Rupar, five were mentioned at the Simla Irrigation Conference of 1904. These were as follows :—

(1) An increase of escape power at the twelfth mile of the canal, so as to scour silt out of the canal.

(2) Closing the canal during heavy river floods, so as to exclude the heaviest river silt.

(3) Constructing the divide-wall, mentioned above, so as to create a still-pond, or slack water, outside the canal-head.

(4) Raising the sill of the canal-head seven feet above the river-bed and adding a movable sill above that height.

(5) Increasing the waterway through the canal-head, by adding a new length of sill.

By the year 1901 the silt trouble at Rupar was cured; but there has been much difference of opinion as to the particular remedy which effected the cure. Mr. Kennedy attributed the cure to the still-pond device; but we have seen that the same remedy, when applied by Mr. Kennedy to the case of the Ravi at Madhopur, utterly failed. Mr. Kennedy, at the Simla Irrigation Conference of 1904, claimed to have shown "without doubt" that "raising the sill" of the Sirhind Canal head "did no good." Mr. Benton disagreed with him on that point, but concurred as to the benefit of the still-pond. The late Mr. H. Johnston, C. I. E., alone, of the engineers at the Irrigation Conference recognized the influence of the *velocity of entry* into a canal-head, as a factor in the problem of silt-entry into the canal, when he stated:—"Raising the sill itself never is good; *i. e.*, taking fast running water over a raised sill is better than that that just as much silt is taken into the canal and cleared of crest was there. daily again within a

It is of importance to diagnose the silt-difficulty at Rupar correctly; and to that end it is important that we should start with a sound theory, and a clear conception of the nature of the forces that cause scour or deposit of silt by currents of water. A man may cure himself of an illness by swallowing the entire contents of a medicine chest, but he will not advance the cause of medical science thereby, if he cannot say which particular medicines have been responsible for his cure. He may even do much harm if he attributes the cure to the wrong pill-box. To the author it seems obvious that the simplest and most certain remedy for silt-entry into a canal-head, is to reduce the velocity of entry to such an extent that silt of an objectionable coarseness cannot be carried by that velocity. If this reduction of velocity be accomplished, silt will no more be able to enter the canal, than flies can enter a wire-gauze meat-safe; and, that being so, it is a waste of time and energy to speculate upon the effects of less obvious remedies. The mean velocity of entry can be limited most surely by passing the current over a sill with "free" overfall; and for any particular grade of silt, or shingle, it is only necessary to make the sill long enough, and the depth of overflow shallow enough, in order to keep the velocity within the desired limit.

At Rupar the length of the sill of the canal-head was increased from 195 feet to 273 feet, an increase of forty per cent.; and the new permanent sill, seven feet high, and the movable sill, higher still, which reduced the velocity and altered the conditions of inflow, must be credited mainly with the cure of the silt trouble there.

The still-pond device, doubtless, contributed to the cure, but, if the sill had been increased still more in length, it alone could have accomplished the whole cure.

To those who attribute the silt-excluding effect of a high sill to its skimming "top-water" comparatively free of silt, the author would point out that this is only a half truth; and that *top water*, actuated by a high velocity, may carry just as heavy silt as *bottom water* of a lower velocity.

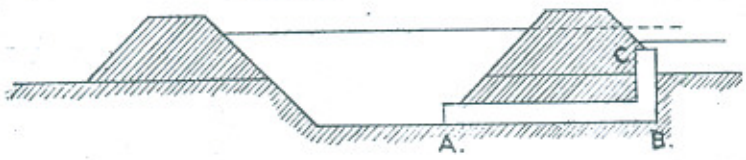
It is true that the Rupar silt experiments showed that the higher layers of currents contained less coarse silt than the lower ers of the same currents; but Mr. Jeffery, Superintending er, wrote as follows in 1897 in his report on these :—"I was struck, whilst personally watching the significant fact that when there is coarse sand in ity brought up by the pump from mid-depth

stream varies considerably with the speed the pump is orked at."

It follows from this experiment that water passing over a igh sill would carry silt or shingle of any required degree of oarseness if the velocity of the stream over the sill were high nough. *Per contra*, water may be taken from the bottom of a ieavily silt laden stream, and may carry no silt with it, provided : be drawn off with a velocity sufficiently low.

Thus in Fig. VIII, water, free from silt, might be drawn)ff from the bottom of a silt-laden stream, through a pipe ABC

FIG. VIII



provided the tail end of the pipe discharged at so high a level that the velocity of discharge was too low to carry the silt. Silt, of any given grades of coarseness, will drop through still water with a certain velocity ; and water flowing vertically upwards through a pipe, with less than that velocity, will not be able to carry with it that particular grade of silt.

The Lower Chenab Canal

After the Sirhind Canal, the next great perennial canal undertaken in the Punjab was the Lower Chenab Canal. At first this canal was not provided with regular Head Works, such as a masonry weir across the river, to control it at the offtake ; the idea being to provide the latter subsequently when the canal had begun to earn revenue. Under this conception the canal was dug with its bed level about 2·5 feet lower than the average low-water-surface level of the river at Garhi Gola, the point of offtake. It was supposed that the canal would not be affected by silt-deposits, and that it would even be able to irrigate during the rabi or winter season. This sanguine hypothesis was soon shattered.

The canal was opened for the first time in May 1887. and in a few weeks was choked with silt in its head-reach. Turbid water, entering the canal during high stages of the river's flow, deposited shoals in the canal up to a level higher than that of the river's lower stages. The canal was closed and cleared of silt ; but on being reopened it silted up rapidly again within a

fortnight. The crops dependent upon it failed that year, and in the succeeding years, in spite of all that could be done to save them. The construction of the regular Head Works was then undertaken (1890-92.).

The Head Works at Khanki.

The Head Works were located at Khanki, on the river Chenab, about five miles upstream of Garhi Gola, and eleven miles downstream of the Railway Bridge at Wazirabad. The canal, which had already been dug to a gradient of 1 in 6,250, was extended upstream to Khanki at the same gradient, which gave it a bed level of 713·4 at the head According to the design of 1889 it was surmised, from experience of the Sirhind Canal, at Rupar, that silt to a depth of five feet might be deposited on the canal-bed at its head ; and, as it was calculated that a depth of four feet of water would be required over the shoal to give the canal its maximum supply of 2,100 cusecs, this fixed the full supply level of the canal at 713·4 + 6 + 4 = 723·4, at the head.

In order to furnish this supply Col. Ottley designed the crest of the masonry weir to be at 721· 0, with hinged shutters 2·5 feet high fixed to it, so as to pond up the water surface to 723·5.

These facts serve to illustrate the state of canal science at that time and shew that the silt trouble at Rupar had not yet been fully realized.

When the time for construction arrived, the canal bed at the head was put at 714·3 instead of 713·4 ; the full supply level of the canal at 724·7 ; the crest of the weir (at left flank) at 722·2 ; and the hinged shutters on crest of weir were made four feet high so as to hold up the river water surface to 726·2, if necessary. These shutters were afterwards replaced by others six feet high, to hold up the water to 728·2 ; this having been found necessary. The sill of the intake, or canal head, was built at first to a level of 717·0 ; and the floor of the under-sluices to 715·0 or 7·2 feet below the crest of the weir, and fitted with gates which were ultimately remodelled to hold up the water to 728·0.

The width of waterway given to the undersluices was 240 feet, exactly the same as in the case of the existing head works at Rupar and Madhopur ; and apparenty designed without any other principle than that of imitation.

The main features of the design of the canal head and weir at Khanki are exhibited in Plate V.

While the channel of the Lower Chenab Canal was new and smooth it carried its water with a relatively high velocity, and even scoured its bed ; but as its surface became rougher, from erosion, the growth of weeds, and silt, its coefficient of velocity fell lower. In the course of time also its capacity was greatly enhanced by widening its channel ; and its full supply, which was originally 2,350 cusecs, was gradually increased to 10,700 cusecs. The waterway of the intake, or canal head, however, remained as before ; which meant that the *velocity of entry was greatly increased*, bringing into the canal quantities of silt in excess of its carrying-on capacity. The weir and sluices in the river, also, gave insufficient control of the canal head, and it became necessary to increase the height of the weir shutters and of the sluice gates. Still the shoals in the river continued to give trouble. At the turn of the season the river threatened occasionally to flow at a distance from the canal head, instead of past its face, and the reputation of the local engineers not infrequently hung on the success or failure of hasty expedients, adopted in the face of emergencies, but which ought to have been avoidable by the permanent features of a rationally designed head works.

The sill of the canal head at Khanki was 234 feet long, and only two feet above the bed of the river as represented by the floor of the weir sluices. The full supply level of the canal rose to 725·8 ; whilst the normal summer level of the river's flow varied from 728·3 to 730·5 : that is to say, when the river's flow was most heavily charged with silt, it entered the canal under a head of pressure varying from 2·5 to 4·7 feet, implying entrant mean velocities of from nine to twelve feet per second. If the entrant mean velocity were, say, ten feet per second, and the discharge of the canal, say, 10,000 cusecs, the vertical dimension of the orifice of entry would be about four feet, and the *maximum* velocity of entry would be about fifteen feet per second at a level of only about four feet above river-bed. But the permanent sill of the canal head was sometimes supplemented by a temporary sill of planks which had the effect of increasing its height by from one to four feet. On the other hand, if the canal were taking less than full supply, the head of pressure through the orifice might be from four to seven feet, instead of from 2·5 to 4·7 feet, only ; and the mean velocity of entry might be as much as fourteen feet per second. In any case it would seem that under ordinary summer conditions the silt laden water of the river might often be entering the canal with a *maximum* velocity of, say, fifteen feet per second, at a level

not more than six feet abcve river bed ; and, in the light of the theory already set forth by the author in this paper, it is easy to see that under such conditions, the silt brought into the canal might be much in excess of the carrying capacity of the canal currents, whose mean velocity might be not more than three feet per second in a nine foot depth of water.

Silt Troubles.

In the circumstances, it is not surprising to find that Mr. W B. Gordon, C. I. E., Chief Engineer, in a note, dated 7th July 1910, wrote of this canal as follows :—"The silt carried into the canal in 1907 and 1909 has led to serious difficulties, not only at the head of the canal, but also in the branches and distributary systems. The important Gugera Branch, which should take nearly half the total supply of the canal, can now take in only seventy-five per cent. of its theoretical supply. On the Jhang Branch also, silt deposit has given rise to serious inconvenience. Last year the necessary clearance of this branch involved a closure of twelve days' duration and an expenditure of Rs. 85.000."

It has been mentioned that Mr. Kennedy asserted that the raising of the canal head sill at Rupar on the Sutlej river, had "done no good", and that the solution of the silt problem there was entirely due to the device of ponding up the flow in front of the canal head and regulating it by means of the shutters on the far end of the weir. It has also been shown that this latter device, when applied to the case of the Ravi at Madhopur by Mr. Kennedy himself, failed conspicuously ; and Mr. Gordon, in his note, dated 7th July 1910, has recorded a similar failure at the Chenab Canal works at Khanki, in the following terms :—"During the flood season of 1908, in marked contrast to that of 1907, but little silt was deposited in the canal ; and as the result of the season's working the Superintending Engineer considered that it might be possible to exclude silt from the canal by careful attention to the working of the shutters and undersluices, and by measures for improving the regime of the river with the object of diverting the main stream to the right flank. The experience of the following year has, however, conclusively shown that however carefully the shutters and undersluices may be worked, the main stream is liable to force its way over to the left flank, close to the canal regulator, carrying with it large volumes of silt."