PAPER No. 147.

DAMAGED FALLS ON THE KHADIR BRANCH OF THE PAKPATTAN CANAL.

By

E. L. Prothero, Executive Engineer, P. W. D. (Irrigation).

1. The Khadir Branch takes out of the Pakpattan Canal on the left side at a distance of 112,000 feet from the head. Its full supply discharge is 2,218 cusecs during the Kharif season only. Its general alignment is parallel to the Sutlej River. It has a length of about 63 miles in the course of which there are 10 masonry falls. These falls were originally of all similar design, *viz*., a long crested weir of about half the channel width and a depth over the crest of approximately 75 per cent. of the full supply depth. The expansion downstream was 1 in 5, and the talus below the crest was built in steps down to the level of the channel bed below the fall. The pucca masonry extended only to the point where the side expansion below the work met the downstream bed width. Beyond this line, concrete blocks were laid at a slope of 1 in 5 to a level 3 feet below that of the downstream bed. From this point, the concrete block protection was carried horizontally for a short extra distance, and was protected at the end by a shallow curtain wall.

2. The branch was opened for irrigation in the Kharif of 1928, and as soon as an appreciable discharge was let into the branch, the following were observable:—

(i) Below each fall, a jet formed in the stream and considerable reverse flow occurred on each side.

(ii) The steps which were in no case longer than 3·45 feet were found to be insufficiently long to intercept the natural path of the falling water. As a consequence, a high velocity jet travelled along the pucca floor with its energy undestroyed by the steps as had been intended.

(iii) The jet was not uniform, was unstable and was found subsequently to impinge first on one side, and then on the other.

(iv) Considerable action was observed, in the majority of instances, below the pucca floor. This resulted in serious scour of the banks which, in a few instances, encroached upon the patrol road.

3. When the branch was closed in October, 1928, the condition of 6 out of the 10 falls was found to be very serious. A hard clay stratum existed below all these falls, and where it had been necessary to cut through this stratum in order to lay the depressed pitching, the bed scour was found to be very serious; in one case, the maximum scour attained a depth of 20 feet.

In the fall at R. D. 143,000, the clay had not been cut through, and it was interesting to note that the vertical clay wall at the end of the depressed pitching was found to be almost unaffected-indeed, at the end of the 1929 flow season, this was still in much the same condition.

From the above, it would appear that economy in design can be effected where the sub-soil is good solid clay. But where clay does not exist, or has to be cut through in order to lay depressed pitching, heavy bed scour must be expected, unless other means are taken to destroy surplus energy.

4. Detailed examination of all the falls indicated that the standard design was faulty in the following respects :—

(1) The downstream expansion at 1 in 5 was far too rapid where contraction of the waterway had been carried to the extent of these designs. So rapid an expansion precludes adherence of the stream lines to the masonry and gives rise to jets. Not only is uniform distribution at the exit impossible under such circumstances, but back flow at one or both sides is certain to result.

(2) The design failed to afford any effectual means of destroying surplus energy. The surplus energy could, therefore, only be dissipated in the standing wave whose position and size were, in consequence, less favourable than had been anticipated. But, the standing wave being naturally inefficient in this respect, action persisted below it, resulting in the damage to be described.

5. During the winter closure of 1928-29, damaged portions of the falls were repaired, and various steps taken to rectify the defects noted above. It was decided to try a different method in several cases in order that the most effective remedy might be ascertained.

6. **Fall at R. D. 68,170.**

Discharge	.. 1,605 cusecs.
Difference between upstream and downstream levels	.. 2·5 ft.

In this case, reinforced "friction blocks," *triangular in plan and 2·4 feet high, were let into the downstream floor. Five rows of these blocks were put in and arranged as shown in Plates I, IX and X. In addition to this, bricks in wire *trangars* were laid from the edge of the depressed pitching to the bottom of the deepest scour below the floor. The effect of the "friction blocks" in breaking up the high velocity jet and in destroying surplus energy was not quite as satisfactory as had been hoped. Turbulence beyond the pucca floor persisted, and back flow

* The term "friction block" is used to denote an obstruction placed in a stream whose primary object is to divert the stream lines in such a manner that they re-act one upon another so causing excessive internal friction and consuming surplus energy.

at the sides was not entirly eliminated. Nevertheless, at the end of the flow season of 1929, no further damage to the masonry work had occurred, and there was some improvement in the scour downstream of the fall.

7. **Fall at R. D. 114,000.**

Discharge	.. 1,370 cusecs.
Difference between upstream and down-stream full supply level	.. 3·5 ft.

The method described for the fall at R. D. 68,170 was adopted in this case also. The pucca floor below this fall was longer so that 12 rows of " friction blocks " could be inserted. The effect in this case was very similar, but the turbulence was kept on the pucca floor, although a central jet still persisted beyond the pucca work. The back flow, though reduced, resulted in side scour not being eliminated.

Levels taken at the end of the season showed great improvement in the bed scour (*vide* Levels on Plate No. II) and no further damage to the work occurred. It may be remarked here, that some trees passed over this fall and knocked out 7 " friction blocks," mostly in the front row.

8. **Fal at R. D. 127,635.**

Discharge	.. 1,378 cusecs.
Difference between upstream and down-stream levels	.. 1 ft.

This fall has the smallest difference in levels, but suffered from a maximum scour of 20 ft. This scour r trogressed until the concrete blocks had all fallen in.

The usual repairs and replacements were done in this case also. Ten thin reinforced concrete partition walls 3″ thick were built immediately below the crest for a distance of 15 feet. The top level of these partition walls was only 1 foot above crest level.

Up to a discharge of 800 cusecs, the effect was most encouraging. No jet formed and side scour was decreased, back flow being almost entirely absent.

But as the discharge increased above 800 cusecs, the useful effect of these walls became less apparent, uneven distribution of discharge at exit re-appeared and, consequently, back flow at the sides.

These smooth partition walls increase the wetted perimeter, and so add considerably to the total internal friction of the stream. It appears probable that by raising the height to full supply level and increasing their length, as found necessary, all jetting at any stated discharge can be entirely eliminated.

Levels taken at the end of the 1929 flow season showed that over 1 ft. of silt had been deposited in the scour hole below the fall.

9. **Fall at R. D. 176,500.**

Discharge	.. 1,243 cusecs.
Difference between upstream and downstream levels	.. 3·94 ft

The scour below this fall at the end of the 1928 flow season was over 13 ft. There was heavy side scour in addition. A deep cistern was constructed immediately downstream of the pucca floor: length 21·4 ft. depth 10 ft. below designed bed level. This cistern was based on Mr. Montagu's theories, and should have been placed immediately below the downstream talus, but this alteration, however desirable, would have involved excessive expenditure.

The effect of this method in regard to quelling disturbance was besr of all. There was very little action apparent below the cistern, side scour improved, but back flow was not entirely eliminated.

Observations at the end of the 1929 flow season showed that there was no damage to the work, practically no silt was left in the cistern, and that the scour showed marked improvement (*vide* Levels on Plate No. IV)

10. **Fall at R. D. 201,850.**

Discharge	.. 1,138 cusecs.
Difference between upstream and downstream levels	.. 4·3 ft.

Damage below this fall was less than in the cases previously described. In this instance, the steps of the talus were lengthened as shown on Plate No. V. The object of this manœuvre was to ensure that the steps intercepted the "gravity parabola" (*i.e.* the curve traced by a body having horizontal velocity and falling vertically under the influence of gravity).

During the 1929 flow season, the first step was found to be effective and the action upon it considerable, indicating a partial destruction of surplus energy. Back flow persisted, resulting in side scour which could not be prevented. Maximum turbulence took place at a greater distance, below the crest of the fall. Nevertheless, at the end of the 1929 flow season, some improvement in the scour downstream of the work was found.

11. **Fall at R. D. 241,000.**

Discharge	.. 1,042 cusecs.
Difference between upstream and downtream levels	.. 2 ft.

The original design of this fall differed from the others. The downstream floor was depressed 1 ft. below the designed bed and ended in a baffle wall which was 1 ft. above designed bed level. Downstream of the baffle wall the concrete blocks were laid.

There was no bridge at this site, and consequently there were no piers in the flume which was 32 ft. wide. The maximum scour below this work was 15·6 ft., and had taken place further downstream than in the cases previously described.

Experiments which have been carried out elsewhere seem to indicate that a baffle wall, placed immediately below the trough of the standing wave, is effective in destroying the energy of the high velocity jet. These experiments indicate that this baffle wall had been built in the wrong place. However, it was decided at this site to test the result of raising this baffle wall by 2 ft.

When the branch was re-opened in 1929, the concrete blocks below the baffle wall were damaged by the subsidiary fall created by the baffle wall itself. During the flow season, considerable action was observable below this baffle, and there was considerable back flow. Examination at the end of the 1929 season, showed that considerable silt had deposited in the scour hole, contrary to expectation, and that there was a certain amount of damage to the block protection.

12. It will be noted that all the methods tried have been successful in checking further damage, and so have effected their principal object. While the deep cistern has been most effective in producing smooth flow at exit, the thin divide walls appear to be most successful in eliminating back flow and jetting.

The general inference is that a fall should be combined with a roughened cistern correctly placed with two or three thin partition walls. Too much weight, however, should not be given to this conclusion, as the observations upon which it is based are made upon modifications of an originally faulty design.

13. It will be clear from what has gone before, that the original trouble arose from excessive side restriction. Bearing this in mind, the Author has designed and built a number of control points in the Khadir Division, the principal features of which are little or no side contraction and a roughened cistern below the talus. Observation of these works on distributaries carrying about 200 cusecs has shown that little or no side or bed scour has taken place ; the distribution of discharge at exit is almost uniform, protection below the cistern is not required, and the falls themselves are cheap to construct. It is only when such a work must be combined with a bridge that the initial cost increases, owing to the longer span involved.

14. It is believed in some quarters, that wide and consequently, high crests result in silting of the bed at low supplies. Should this be the case, their general application on the Sutlej Valley P oject, with its necessarily varying supplies, contains an element of danger. Examples of this type of design on other canals tend to refute this theory. For example, the syphon spillway at Renala on the Lower Bari Doab Canal where the surface level automatically remains constant at all stages of discharge, so far as the Author is aware, has given rise to no such trouble. The bed of the canal upstream of this syphon is almost ideal, an ideal that most channels attempt rather unsuccessfully to attain.

15. Rightly or wrongly, this fear of silting the upstream bed during low supplies affects design. For instance, the original proposals for a high-crested weir of full bed width for the meter flume at R. D. 2,500, Khadir Branch, was rejected in favour of a design of 3 bays, the central one at bed level and 26 ft. wide; the crests of the two side bays are 3·4 ft. above the central crest and 7 ft. wide. The bed width of the Khadir Branch at this point is 88 ft.

The two piers separating the three bays are truncated. The crests end with a direct fall into a cistern 4 ft. deep and 40 ft. long. No cistern or roughness could counteract the effects of such a design. When the Khadir Branch was re-opened after constructing this meter flume, three or four distinct standing waves formed below the central bay. On each side, very heavy back flow resulted. The side pitching below the fall fell in, and bricks in *trangars* had to be laid down hurriedly to check the very serious bed scour. Fortunately, the clay stratum at this site is very thick and tenacious or the work could not have stood without considerable additions and repairs.

16. While observing the action created below the meter flume, the alternative method of having the central crest higher than the side crests suggested itself to the Author. The fall at R. D. 1,43,000 was selected for experiment in this direction.

This fall consisted of four bays of 8 ft. Four karries $6'' \times 6''$ were inserted in all four bays and float observations were made to determine the extent of the jet and back flow. This back flow persisted upstream as far as the standing wave.

One karrie was then taken out of each of the two side bays. This had little effect. These karries were then inserted into the central bays and fresh float observations showed considerable improvement in the condition of back flow.

One more karrie was removed from each of the side bays and put into the central bays. Back flow was practically eliminated. On removing one more karrie from each of the side bays, excessive flow took place along the sides, showing quite clearly that there is a limit to the difference of crest levels in adjoining bays. Moreover, this limit appears to depend on the discharge and depth obtained at each particular fall. No doubt, some rough working rules could be determined in a laboratory, but, in general, the Author is averse to any attempt on these lines.

17. **Conclusions.**—In summarising the impressions which his observations have left, the Author desires it to be clearly understood that in no case have his modifications been the result of mathematical treatment, save in so far as he used Mr. Montagu's empiric rules for the length and depth of cistern The conclusions and recommendations are qualitative in nature:—

(i) Wherever other considerations permit, side contraction should be avoided and the crest of the fall should be the full bed width of the channel. This avoids the necessity of an expansion downstream which, at the present stage of our knowledge, is not susceptible of accurate theoretical treatment.

(ii) The standing wave which forms below falls, while destroying a considerable portion of surplus energy, is naturally imperfect in this respect and, consequently, the surplus energy remaining in the water must be screened out by some means.

(iii) This surplus energy can be destroyed successfully by rows of "friction blocks" so placed as to split up the high velocity jet, as mentioned in the footnote of para. 6. In parenthesis, it is claimed for the design of "friction block" evolved in this Division, that it offers minimum direct resistance to flow of the stream, and so necessitates minimum maintenance.

(iv) The destruction of energy below a fall apppears to require naturally, a depth in excess of the ordinary full supply depth of the channel.

Where this depth does not exist, scour must take place. It would appear reasonable to anticipate this scour by constructing a cistern immediately below the talus of the fall, wherein the turbulence may be localised and from which the stream may issue at normal velocity.

(v) Where constriction is found to be necessary, whether from reasons of economy or other consideration, thin partition walls should be constructed, *vide* paragraph 8, to ensure uniform distribution of discharge on departure from the work. Such walls have the additional merit of increasing the wetted perimeter, with consequential increase of internal friction.

(vi) Variations of crest level should be avoided, whenever possible. On the rare occasions when such a design cannot be avoided, the higher crests should be in the centre, with the lowest at the sides. Differences in crest width should not be great, and cisterns combined with partition walls should be designed amply large enough to deal with the action which is certain to result downstream.

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PLATE NO 1

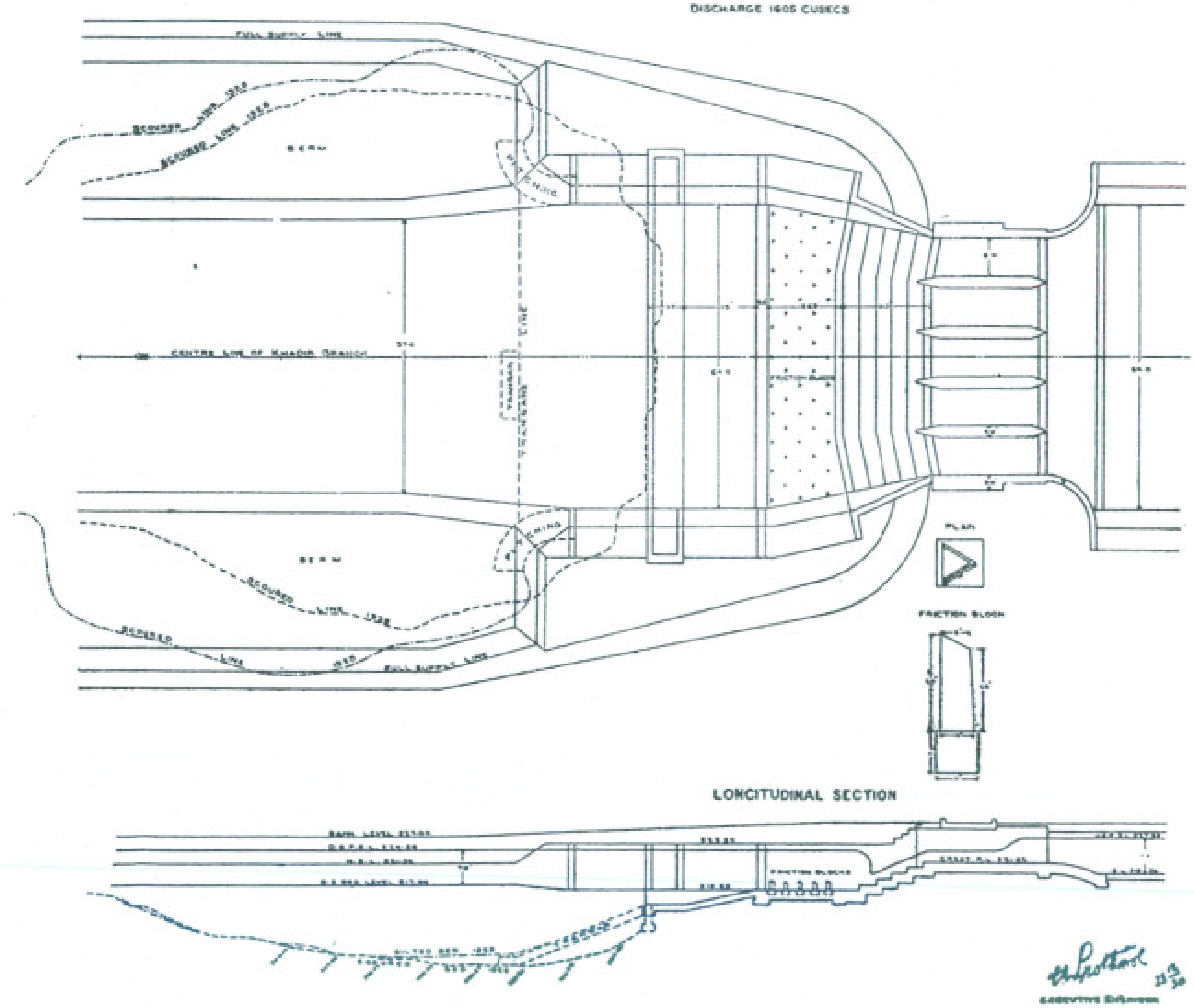
KHADIR DIVISION, S. V. P.

PLAN OF 2·5 REGULATING FALL WITH V.R. BRIDGE

AT R.D. 68170 OF KHADIR BRANCH

SCALE = 1/400

DISCHARGE 1605 CUSECS



PAPER No. 147.

PLATE NO. 11.

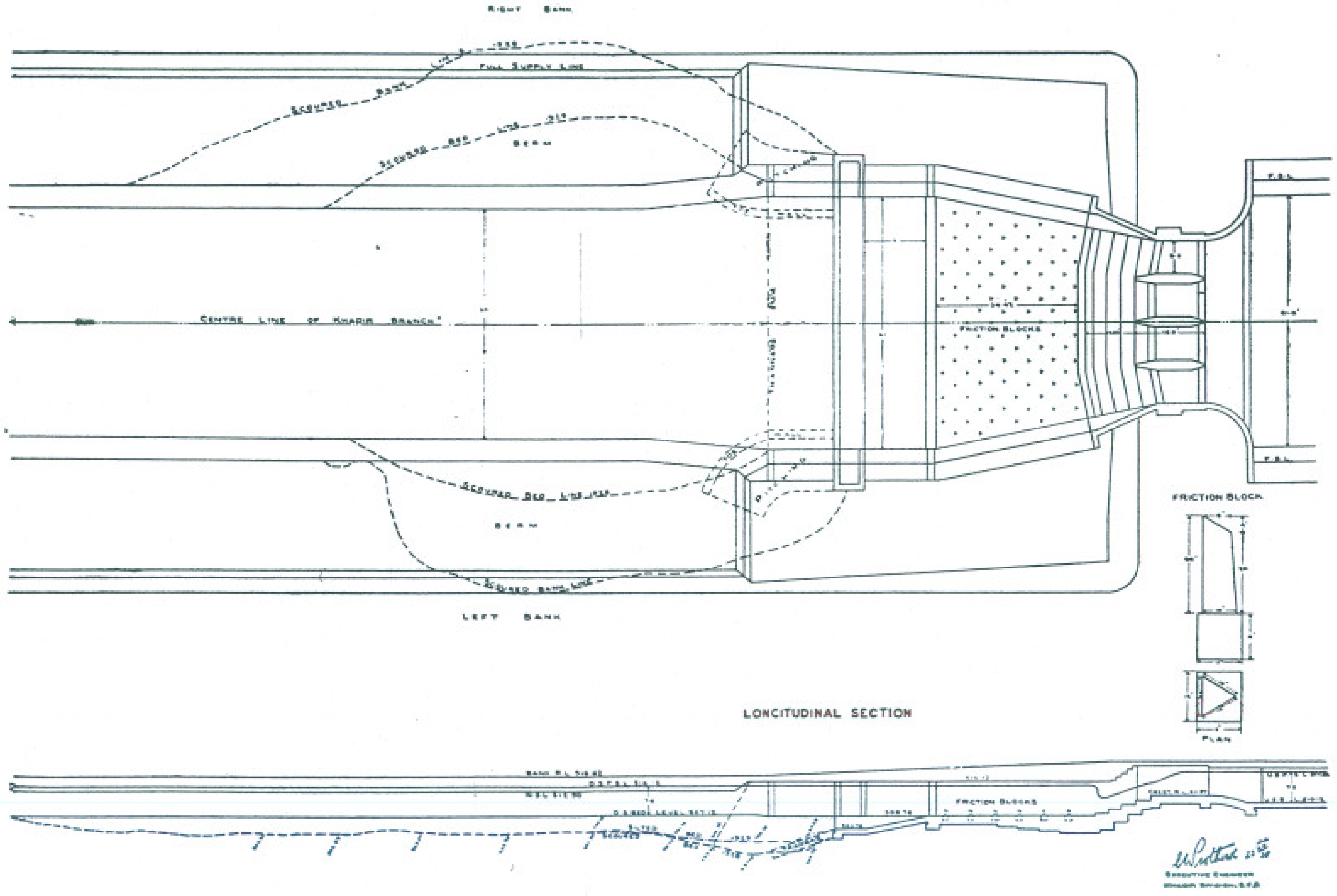
KHADIR DIVISION. S.V.P.

PLAN OF 3·5' REGULATING FALL

AT R.D. 114000 OF KHADIR BRANCH

SCALE = 1/420

DISCHARGE 1378 CUSECS



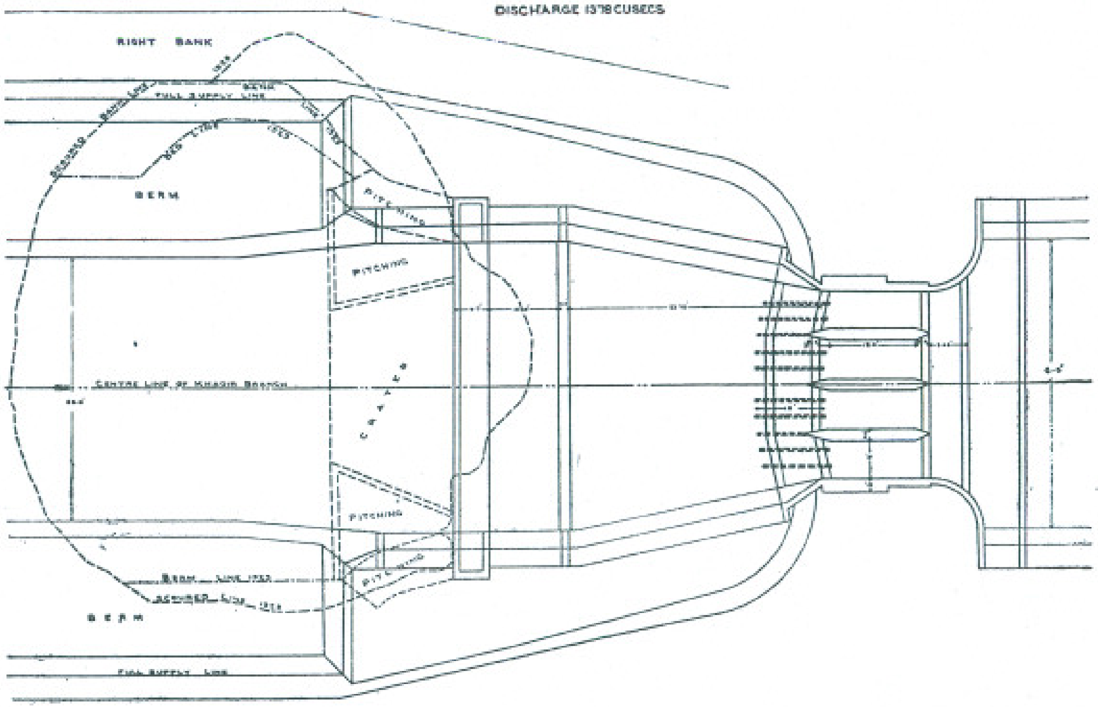
KHADIR DIVISION, S.V.P.

PLAN OF 1-0' REGULATING FALL WITH V.R. BRIDGE

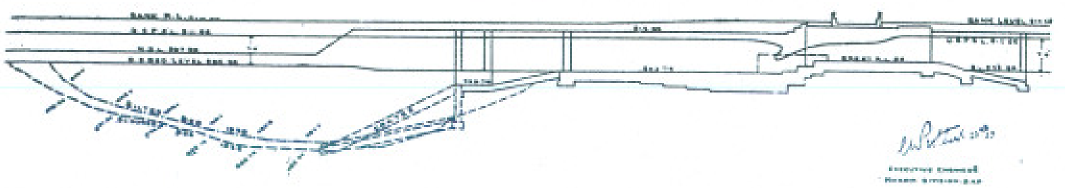
AT R.D. 127635 OF KHADIR BRANCH

SCALE = 1/420

DISCHARGE 1378 CUSECS



LONGITUDINAL SECTION



PAPER No. 147.

PLATE No IV

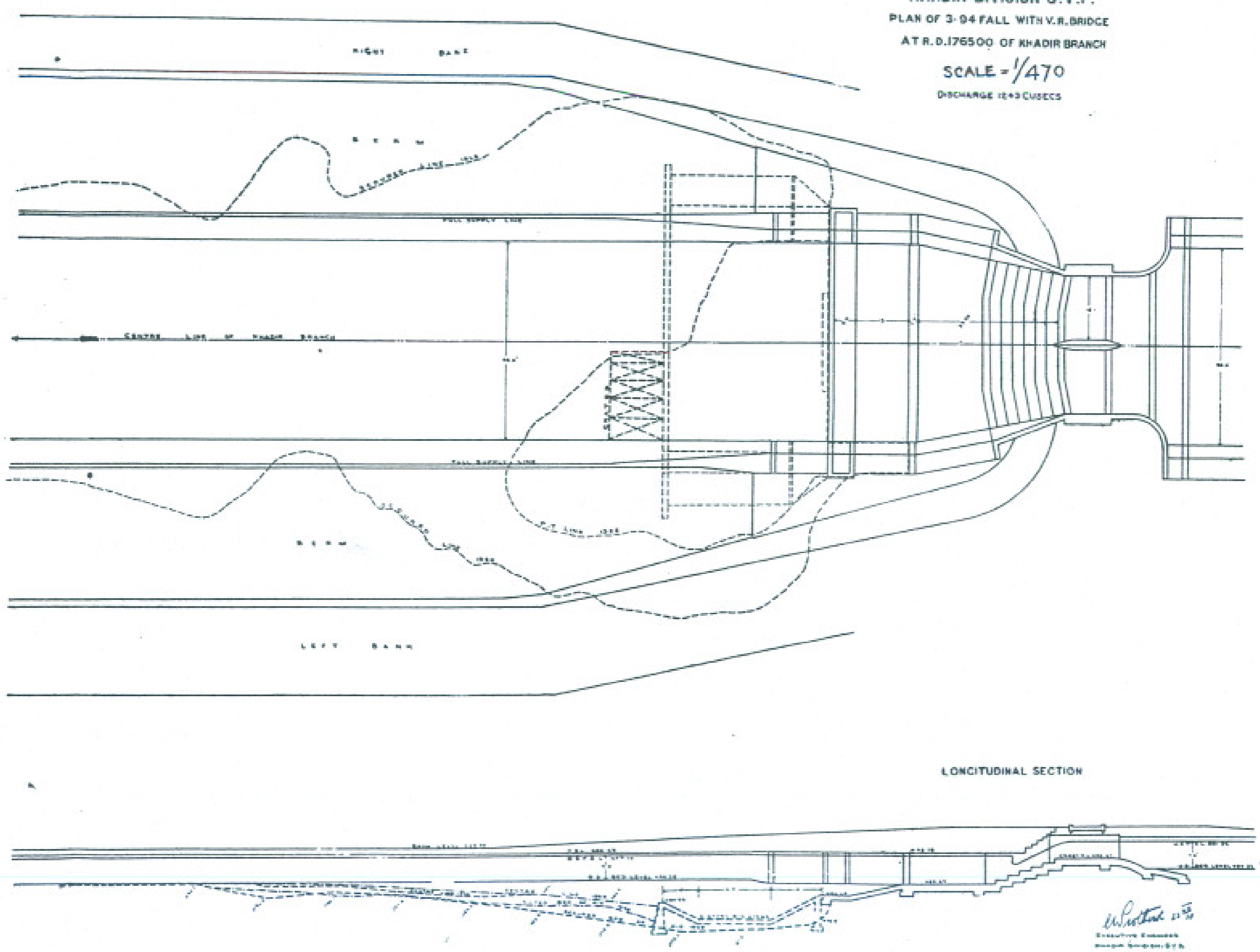
KHADIR DIVISION S.V.P.

PLAN OF 3·94 FALL WITH V.R. BRIDGE

AT R.D. 176500 OF KHADIR BRANCH

SCALE = 1/470

DISCHARGE 1243 CUSECS



PAPER No. 147.

PLATE NO V

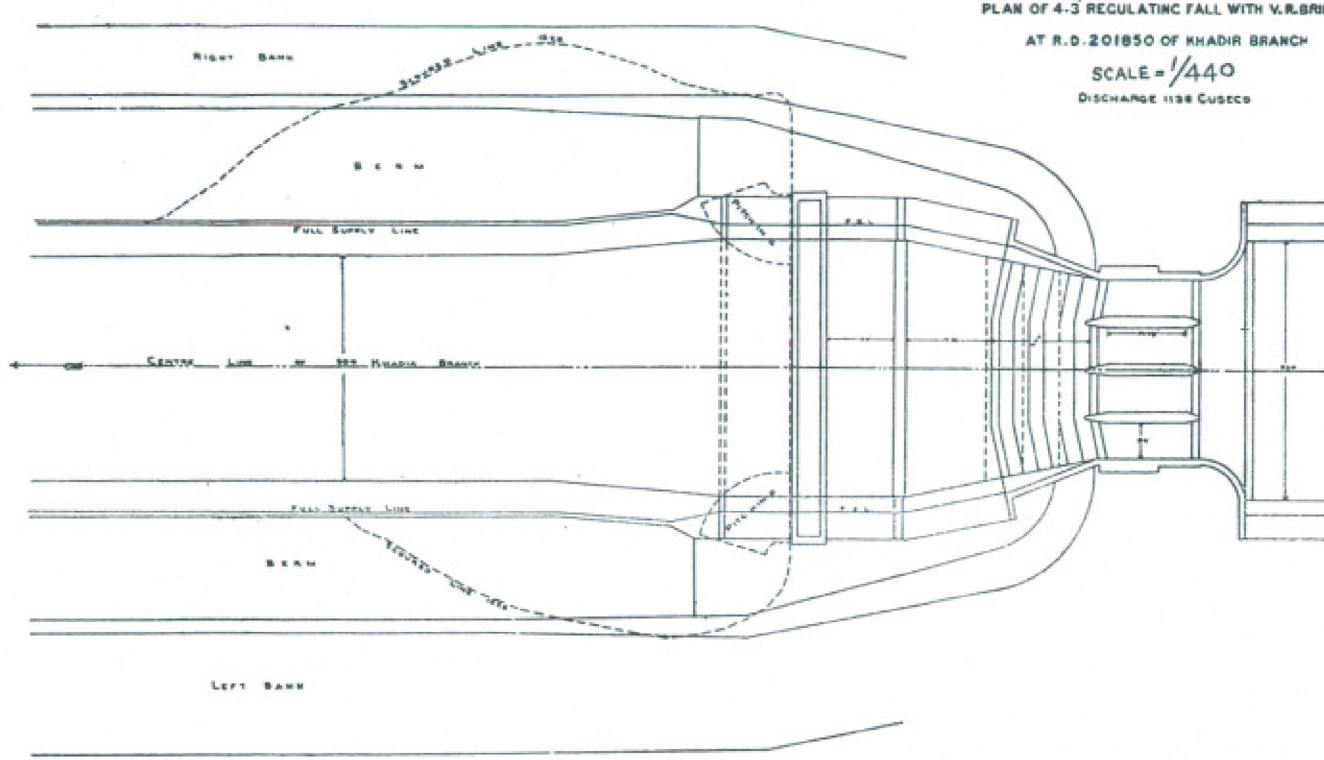
KHADIR DIVISION. S. V. P.

PLAN OF 4-3' REGULATING FALL WITH V.R.BRIDGE

AT R.D. 201850 OF KHADIR BRANCH

SCALE = 1/440

DISCHARGE 1138 CUSECS



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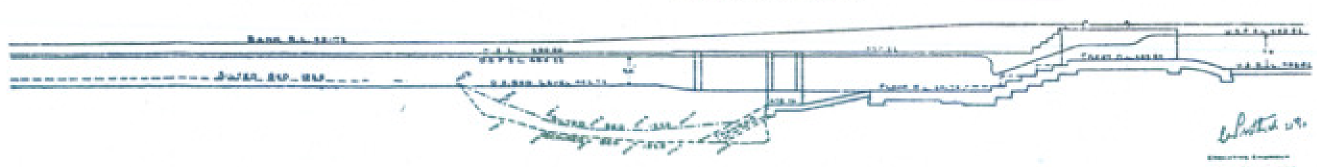
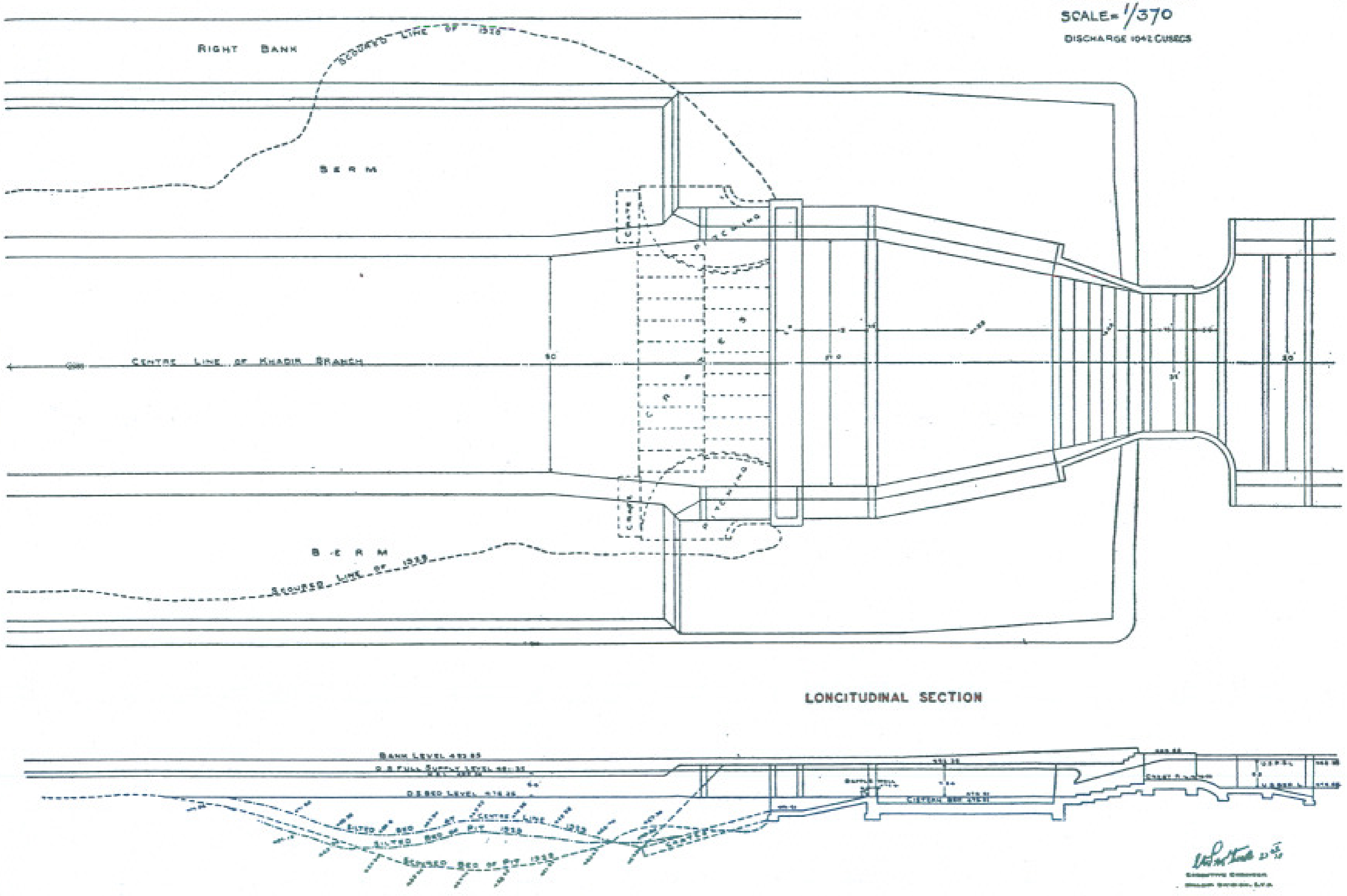


Paper No. 147.

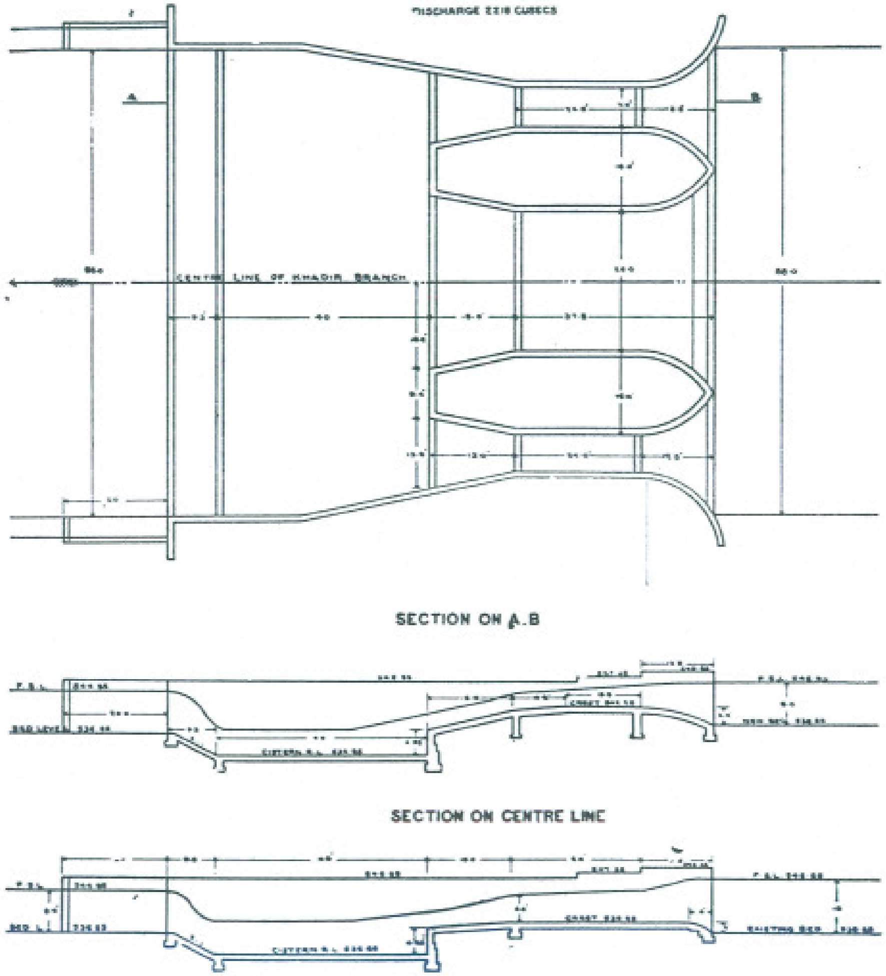
PLATE VI.

KHADIR DIVISION, S.V.P.
PLAN OF 2-0 METER FALL AT R.D. 241000
OF KHADIR BRANCH
SCALE = 1/370
DISCHARGE 1042 CUSECS



KHADIR DIVISION S.V.P

PLAN OF METER FLUME AT R.D. 2500
OF KHADIR BRANCH
SCALE = 1/375
DISCHARGE 2218 CUSECS



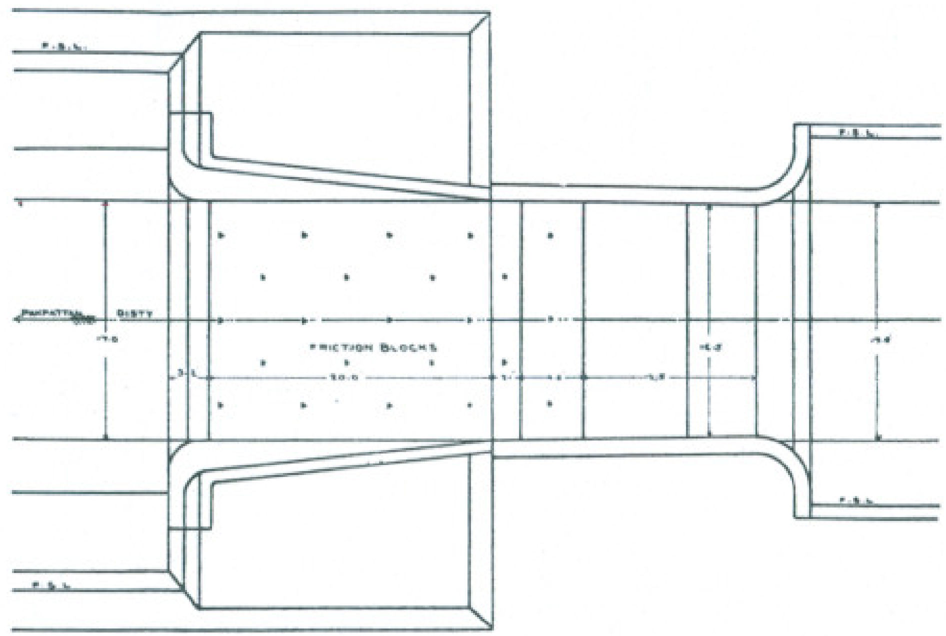
Executive Engineer
Khadir Division, S.V.P.

KHADIR DIVISION S.V.P.

PLAN OF 1.0' FALL AT R.D. 35700 OF PAKPATTAN DISTRIBUTARY

SCALE = 1/140

DISCHARGE 144 CUSECS



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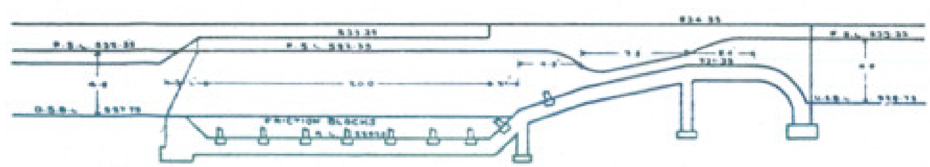

E. W. Prothero
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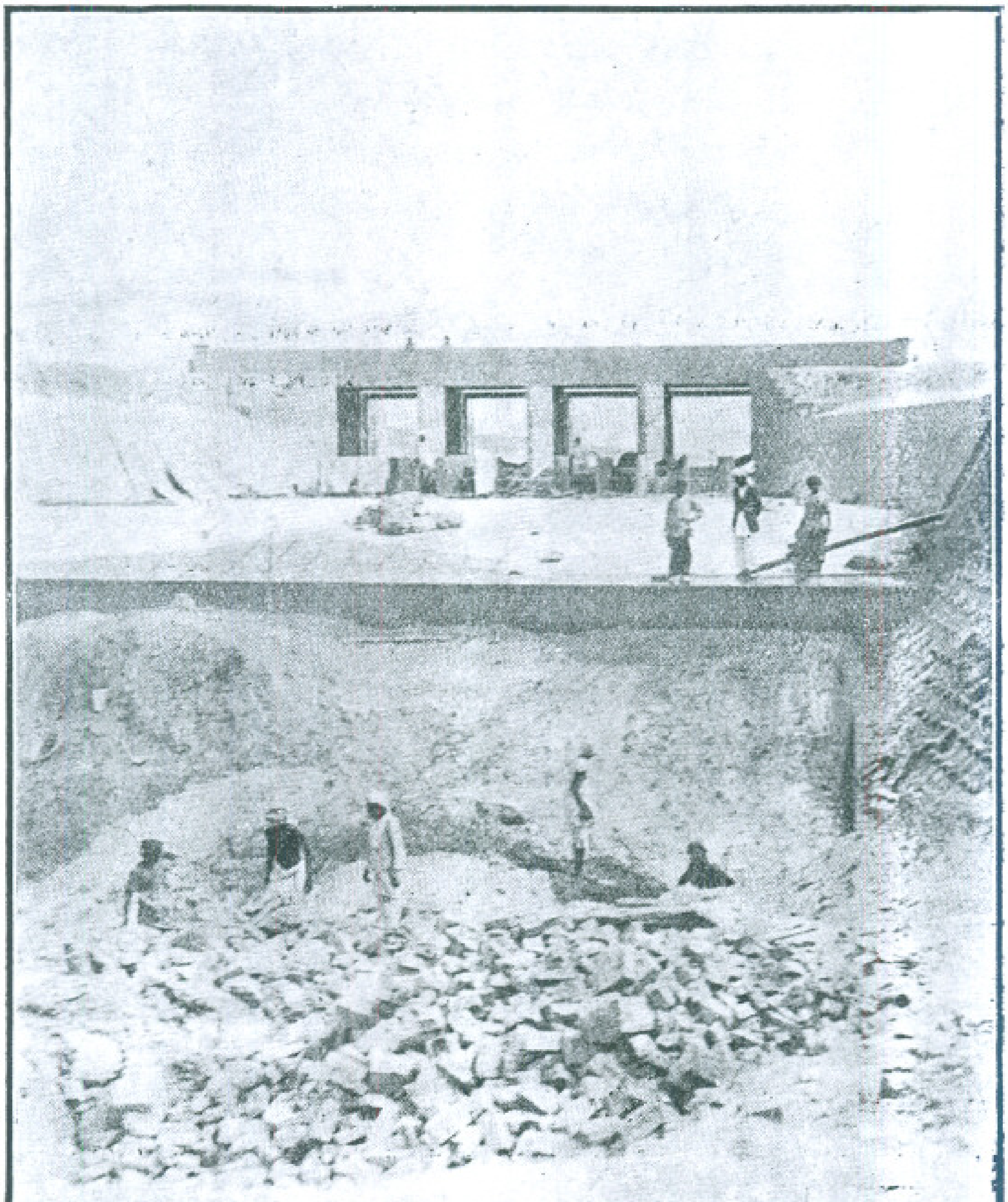
FALL AT R.D. 68170 OF KHADIR BRANCH.
REPAIRS IN PROGRESS.

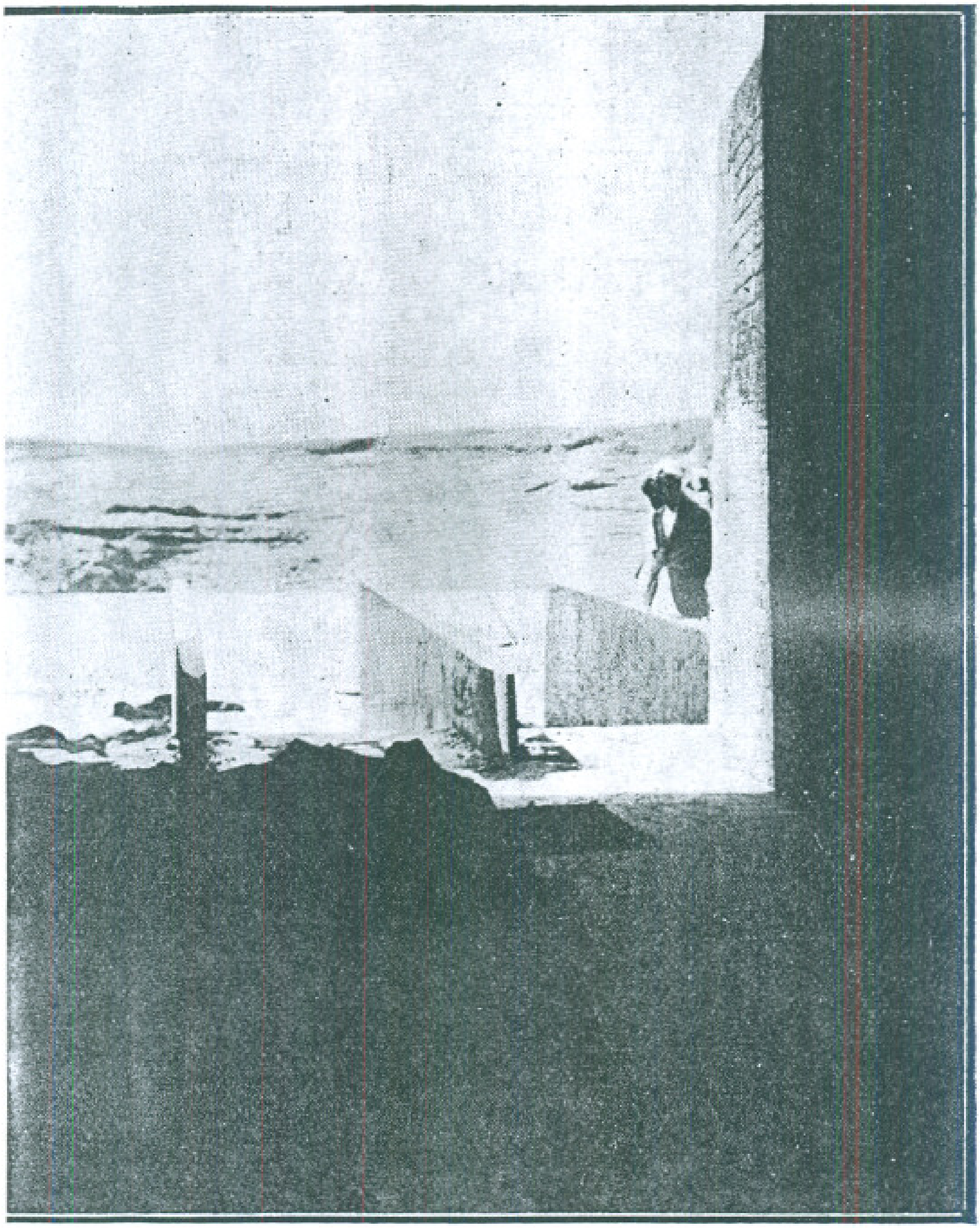
FALL AT R. D. 68170 OF KHADIR BRANCH, LOOKING UPSTREAM.
REPAIRS IN PROGRESS.

FALL AT R. D. 114000 OF KHADIR BRANCH.
REPAIRS IN PROGRESS.

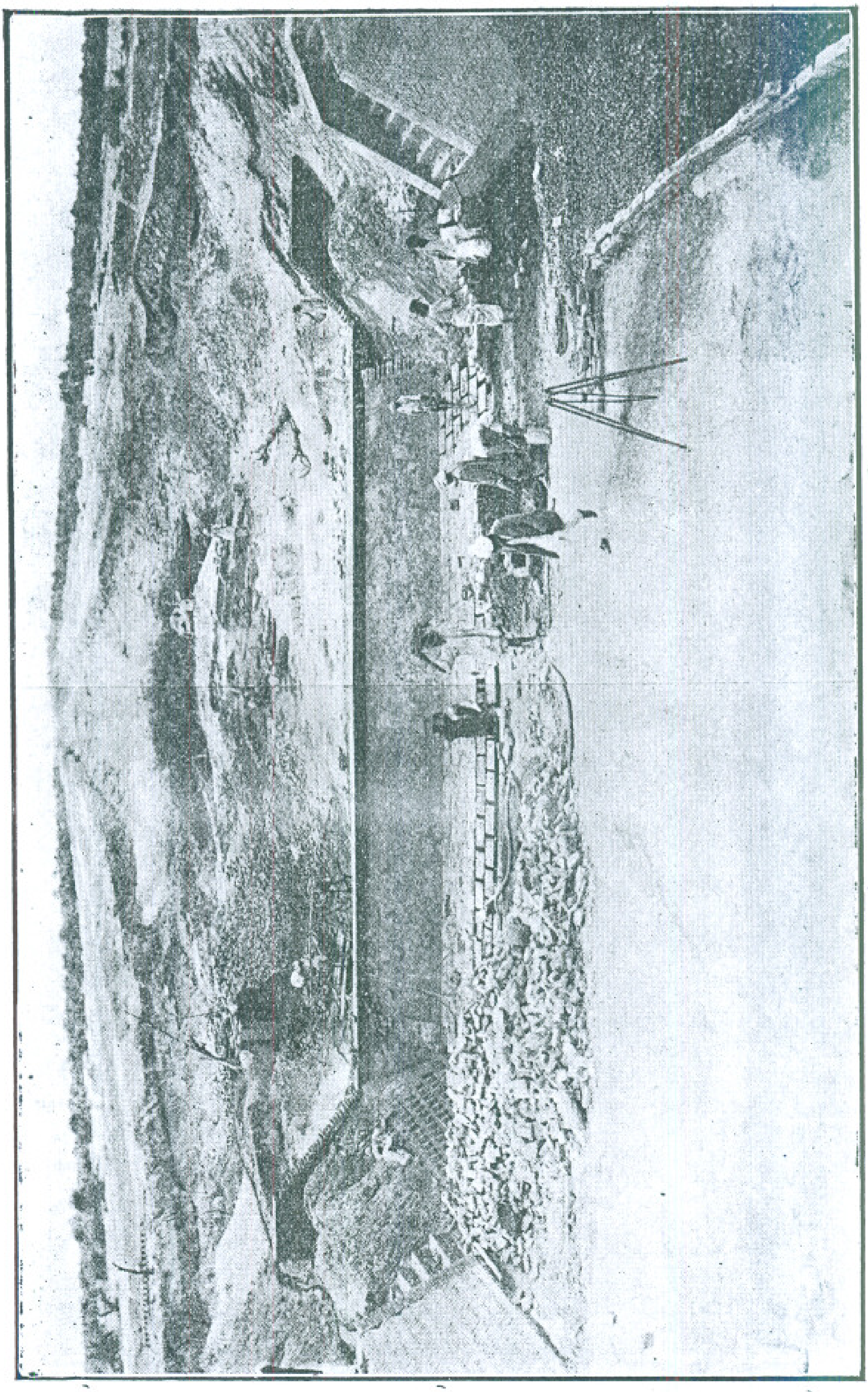
FALL AT R. D. 127635 OF KHADIR BRANCH.
REPAIRS IN PROGRESS.



FALL AT R. D. 127635 OF KHADIR BRANCH.
SHEWING NEW R. C. VANES.



FALL AT R. D. 143000 OF KHADIR BRANCH. NO DAMAGE.
NOTE CLAY STILL STANDING.



DISCUSSION.

The Author, introducing his paper, said that first of all he wished to apologize for putting before the Congress what many would consider to be, and was, really, a very simple paper.

He said that he had done so:—

firstly, to place on record, damage that had happened to certain falls in his charge, the methods of repair and the results thereof,

secondly, to bring out certain conclusions that he had inferred from those results, and

thirdly, to draw attention to the necessity of standardising, as far as possible, the design of canal falls.

It was clear, he thought, that in all those cases the damage was due to original faulty design as explained in para. 4 (1) and (2) of the paper, and it was more than probable that had there been a deep stratum of clay at all those falls, there would have been no such damage and the impression would have remained that the design of these falls was sound. In support of this statement he referred the members to the case of fall R. D. 143,000, Plate 14, and added that it would be noticed that the clay had been left undisturbed after the flow seasons 1928, 1929 and that even now after the flow season 1930 it was in the same condition.

He added he would go further and state that in his opinion many falls in the Punjab, were standing undamaged, more on account of a fortuitous choice of site, rather than from the infallibility of the design.

He did not claim that there was any thing new in his paper; for example, conclusion (4) had long been recognised but had become overlooked in recent years.

Dyers had recognised the necessity of a cistern and had found the necessary depth experimentally by floating bottles over falls and noting the depth at which they were not broken. The dimensions usually adopted were:—

$$\text{depth of cistern} = \text{upstream depth} + \frac{\text{difference between upstream and downstream line.}}{3}$$

and length=5 depth.

These formulae ignored the effect of the fluming ratio, that is the ratio of the bed width to width crest of weir.

According to Montagu, $D = H_L \times \sqrt{H} \times \sqrt{F_o}$

$$\text{and } L = X \times 3\,(1 + \sqrt{H})$$

These formulae gave rather a long cistern in some cases and it had been found that this could be shortened by suitable roughening, by means of friction blocks as described in the footnote, page 116.

He said that there might be many present in the Congress who remembered the old needle falls, the principle of which was to destroy the energy generated by means of the mutal interference of the three streams of water. This was just what it was claimed the friction blocks did when suitably placed (see conclusion iii).

Why, in course of time cisterns had been abandoned, he did not know, since holes were to be found below every natural waterfall.

During recent years, the attention of engineers in the Punjab Irrigation Branch had been concentrated on means of metering canal supplies at falls, and as a result, the broad crested weirs of various designs had come into use.

MR. G. LACEY, said that Mr. Protheroe was to be congratulated on the presentation of an interesting and valuable paper. In America full publicity was given to failures or partial failures and it was thus made possible for engineers in general to profit by the experience of others; the courage and originality of those who constructed such works should not be forgotten.

The heavy damage that had occurred on these works could hardly be ascribed to neglect of well established engineering principles; it would be more correct to state that in respect of large flumed works, as described in the paper, practice had outstripped theory. He felt therefore that the Congress should be particularly grateful to the Author, who following the example of another country, had written a faithful record of a courageous experiment which might have proved less expensive had it been conducted on a smaller scale.

In the construction of the falls on the Sarda Canal, they had been more conservative. The principle adopted was that of limiting, so far as was possible, the energy destroyed per foot width of fall crest. It was hoped by providing a nearly vertical drop that the action due to turbulence would be confined to the masonry floor of the fall and would not extend to any great degree to the unprotected canal bed below the supplementary floor protection. A few falls of the notch type had been constructed, but the great majority were ordinary raised crests, and in either case, the width of the crest was never made less than the bed width. By this means parallel flow was ensured.

These falls had so far worked very well, and those that he had inspected during a closure, after two years' running, showed that wherever the original clay had been undisturbed for excavation, it had stood up to action in the most remarkable manner. Time would show how long that natural protection would survive the action on it. Where there was a sandy bed, without any clay downstream, there was naturally action, but not of the excessive kind described in the paper.

It was frequently argued that a broad crested fall led to silting upstream, and that a fall designed in such a manner that the water surface remained sensibly parallel to the bed, within the working range of discharges, greatly reduced this risk. It was interesting to investigate the theory on which this point of view was based.

In most large canals, if discharge diagrams based on Kutter's formula were correct, the discharge per foot run varied very approximately as the vertical depth D, raised to the two-thirds power; Kennedy's formula assigned to the critical depth a power of 0·64 which was very nearly two-thirds. In theory therefore, a canal operated at constant slope could be made non-silting over a very large range of discharges. He submitted that in practice this state of affairs did not exist. In his view the smaller discharge demanded a greater slope, and as that enhanced slope did not prevail, silt was thrown down. This was inevitable unless a notch was designed that gave an increased slope at low supplies and such a notch would lead to loss of command. In every canal therefore silt must be thrown down above falls at low supplies; it was of course picked up again when the canal discharge was increased.

He had observed that channels which carried silt became remarkably regular upstream of falls and if data were sought of normal channels, the best place to investigate was a reach upstream of a fall. On the Sarda Canal where some of the channels, in order to avoid disturbing the underlying clay, had been made more than usually wide, he had detected upstream of the falls, a tendency to berm at the sides and to scour in the centre.

That was departing somewhat from the subject of the paper but the fact was possibly worth placing on record. He fully appreciated that the great variation of discharge on the Pakpattan canal falls made the design of any kind of fall a difficult matter, and the soil, so far as he was able to judge from the paper, appeared to be exceptionally devoid of clay.

MR. M. D. MITHAL, said that he had gone through the paper and agreed with the Author in many respects.

As regards the Fall at R. D. 127,000, there were some sort of waves running parallel to the stream line which he had added after the design, the result being that for a certain discharge there was no back flow, but when the height over the crest increased, the back flow began and continued to grow. The speaker explained by a diagram that if the divide walls on the downstream side were not all parallel to each other and that if the side ones were deflected a little bit towards the sides, there would possibly not be any back flow.

He quoted the example of the falls on the Fordwah branch, where the conditions were very much the same as those on the Khadir Branch and the Canal discharge was 2,500 cusecs. Although the strata was mostly sand, no damage occurred on them though the channels had been running for the last 3 or 4 years. However, in no case were the crest widths reduced to less than 60 per cent. of the upstream bed width.

Mr. S. L. Malhotra, said that little provision existed in the original design of practically all the falls described by the Author, to destroy the horizontal velocity generated by the fall, while the narrow waterway and sharp expansion downstream helped considerably to augment the formation of the high velocity jet, causing the damage and deep scour described in the paper. Evidently, the shallow cistern below the pacca floor lined by concrete blocks, was ineffective in destroying the energy of the high velocity jet. The baffle wall in the last fall was too low and became useful only after raising, after the first season.

The speaker had a similar experience on two falls on the Main Branch of the Eastern Canal at R. D. 215,500 and 224,000. The waterway in these cases was constricted to about half the bed width and the downstream splay of wings was nearly 1 in 3. At the end of the stepped talus, there was a cistern, two feet deep, with a baffle wall. Due to the sharp downstream expansion, there was a tremendous back velocity at the sides, which caused deep pot-holes in the cistern floor by churning of bricks and bats left in the cistern or thrown in by village boys.

Below the baffle wall, there was a cistern, four feet deep and twenty feet long, lined on sides and floor with reinforced brickwork, three inches deep. The baffle wall, being probably low, failed to kill the horizontal velocity of the jet and there was very serious side scour encroaching on the banks. The soil being sandy, no amount of bushing and stacking could resist the scour. This serious scour was brought to the notice of Mr. Burkitt, who proposed to extend the reinforced brickwork pitching by another 30 feet and adding another baffle wall at the downstream end of the original cistern, thus forming another cistern of the Montagu type as provided by Mr. Protheroe in one of his falls. Owing to the speaker's transfer during the construction of the second baffle wall, he could not observe the effect of these, but he had since come to know that the scouring had ceased.

Another fall at R. D. 196,000 of the same channel had a long and high crest, with waterway about two-thirds of the bed width. This fall had a similar cistern below the talus, with a baffle wall and a second cistern below it. Practically no damage occurred on this fall and there was no back velocity. This fall had all the good points mentioned by the Author, *viz.*, very little side contraction, a long cistern below the talus, a baffle wall serving the purpose of friction blocks and a second cistern below the baffle wall.

Under instructions of Mr. Burkitt, the falls on the distributaries and the more recent ones on the main channel had been designed with the following features, agreeing with the conclusions arrived at by the Author—

(*a*) water way about $\frac{3}{4}$ths of the bed width, thus avoiding excessive constriction.

(*b*) a glacis, stepped at 1 in 3, at the downstream end of the crest which, though not actually cutting the gravity parabola, had some effect in breaking the jet.

(*c*) a cistern at least two feet deep below the talus and of length fixed empirically in relation to discharge and fall.

(*d*) side walls splayed out at least at 1 in 5.

(*e*) a baffle wall at the downstream end of the cistern to kill horizontal velocity. The height of the baffle wall was fixed with no afflux condition at share discharge.

(*f*) a cistern downstream of the baffle wall, of depth and length fixed empirically, sufficient to destroy any residual velocity below the baffle wall.

(*g*) in most cases, the falls were combined with bridges of short spans. The downstream noses of piers tapered at 1 in 10 to a zero point practically, thus the ends of the piers projected beyond the talus. This served the purpose of partition walls mentioned by Mr. Protheroe, by increasing the wetted perimeter and localising the action of the jet into different compartments.

Two falls built on the Upper and Lower Sohag Branches had shown no scour at all. In the case of the fall R. D. 13,000 Upper Sohag Branch, the existing downstream bed being much below the designed, a subsidiary fall below the bafflc wall was formed, which had, however, no scouring action, due to the safe depth and length of the cistern below the baffle wall.

Regarding side scour, excellent results had been got by use of "pilchhi" pitching on the Dipalpur Canal. The "pilchhi" was laid in alternate layers with earth, with thick ends of stems projecting into the channel, and formed an elastic and rough lining. All further side damage had been stopped on the Regulator at R. D. 264,000 of the Dipalpur Canal and other similar falls. This was being tried on the Ghumariwala fall, R. D. 112,000, of the Pakpattan Canals and appeared to have succeeded very well so far.

Mr. T. A. W. Foy, remarked that it was stated on page 117 of the paper that the partition walls were only successful for a limited discharge. The Author had suggested that if they were carried to above the full supply level they would be more effective. The speaker was of opinion that would merely transfer the action further downstream.

In para. 11 on page 119 the Author had proposed a baffle wall in a certain position. The trouble was that if this was correct for full supply, it was definitely wrong for two-thirds supply and caused worse action downstream. This also was another case of transferring the site of damage downstream.

In para. 14, the Author had tended to belittle the possibility of silting up of the channel upstream of a raised crest. During this summer, the speaker had analysed the effect of the substitution of a raised crest at Rasul for a shuttered weir. The crest was of a mean height of 3·7 feet. The annual river survey sections, taken 2,000 feet upstream of the weir during the last 10 years which had elapsed since the building of the crest, showed a mean silting up of 2 feet of the channel upstream of the weir. In the opinion of the speaker, the whole trouble that had arisen with new falls was due to the policy of expecting nine penny worth of value for four pence, and in consequence skimping the design. It should be recognised that a fall was an expensive affair and the introduction of falls into the design of a channel should be done sparingly. In this connection, it would, on many channels, be economical to design each bridge as a drowned fall constricted to take up say 0·3 feet loss of head. As the bridges had to be given protection, the slight extra expenditure would be justified in the saving on a high fall.

With reference to paragraph 17 of the Author's conclusions, the speaker did not agree with the proposal for no side contractions on the following grounds :—

(*i*) A high raised crest caused silting upstream.

(*ii*) This silting on the upstream side, caused the channel to take up a wider and shallower section, with consequent attack on the berms. Berm attack was most expensive to cure and a wide shallow channel aggravated silting troubles.

(*iii*) In waterlogged regions, the presence of these raised crests prevented the channel acting as a drain, during closures.

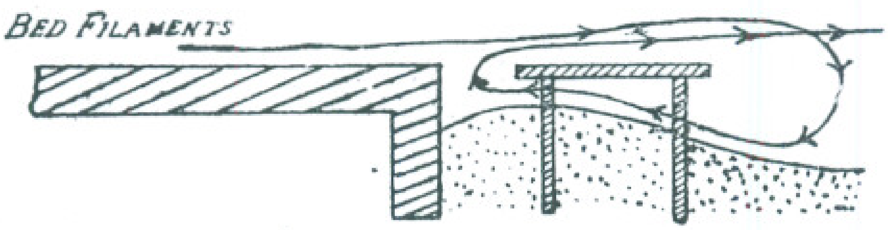
This was a valuable function. The Lower Jhelum Canal in the first 5 miles collected seepage varying from 300 to 100 cusecs depending on the length of the closure.

On the above grounds the speaker rejected the high uniform crest for canal falls, as a standard design.

MR. C. C. INGLIS, stated that he had been carrying out experiments with models of falls from which it was clear that the scour which occurred below flumes, was mainly due to the diverging sides and to a lesser extent, to the side slopes. The former caused return flow at the sides and hence vortices with vertical axes which eroded the banks, while the side slopes caused the bed roller (with horizontal axis, which normally formed at the downstream end of a pavement) to be unstable and to form spiral eddies which dived down and scooped out the silt in the corners between the side slopes and the dropwall. Too rapid expansion was by far the more serious.

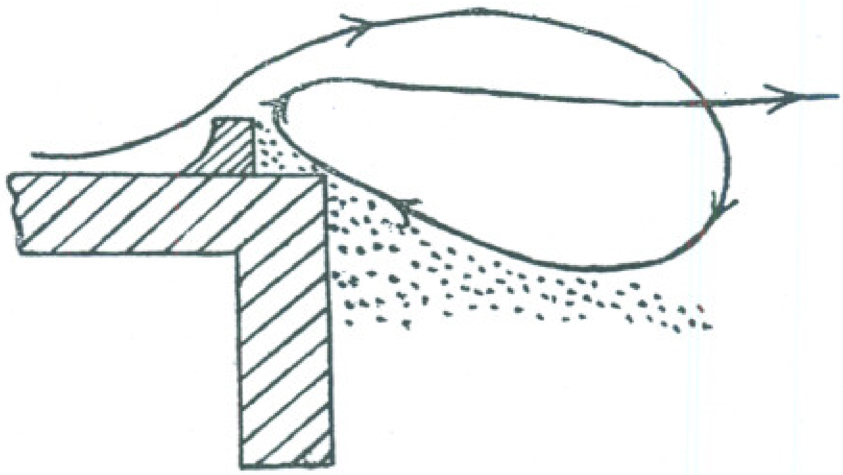
One of the large falls of the Sukkur Barrage Project had been designed with an expansion of 1 in 5 at the two sides. This was before it was realised that the expansion depended on the breadth ; depth ratio. To set this right, radial extensions of the piers were tried. The model experiments to test these vanes were carried out in Karachi by Mr. Hawes, Executive Engineer, Research (Sind). These showed that the best results were obtained with vanes which diverged less sharply than radially. This was because the velocity at the sides must necessarily be reduced more than in mid-stream. It was also found that only the two end vanes were required. (*i.e.*, in extension of the first pier on either side). These caused the water between the remaining piers to fan out naturally. The danger of scour caused by spiral flow at the end of the pavement was being provided against by placing "tarungars" on the bed.

It had been stated that the three reasons why fluming had been adopted were for cheapness, proportionality and measurement. All the three could be attained without the evils arising from excessive side divergence, by constructing an island in the middle of the canal, which would cause the 'set' of the two streams to meet at the downstream end of the island where the excess energy would be dissipated in the middle of the canal. This would also prevent the stream from "setting" towards one of the banks. Where there was no expansion and the flow was parallel to the axis of the stream it was comparatively simple to prevent bed scour. This could be achieved by using Rehbock's dentated sills or a floor fixed downstream of the pavement, at the same level, leaving a gap between, *vide* sketch (see also Mr. Mair's Paper read



before the Bombay Engineering Congress 1930). The effect of this was to cause return flow underneath the floor which piled up the silt beneath the floor, thus preventing damage to the pavement and drop wall.

A third method which was more simple than either of these was to construct a 'deflector' equal to 1/12th the 'full supply depth' downstream. This caused a return flow which piled up the silt against the 'deflector.' This design had been fully tested with models and was very effective, in stopping scour and it also prevented the stream from



'hunting.' All these designs were successful with parallel flow; but none of them fully met the conditions at the sides below an expanding flume.

It was undoubtedly desirable to sink the pavement below the canal bed level, for 3 reasons :—

(*i*) it increased the section and so reduced the mean velocity;

(*ii*) it increased the 'depth: breadth' ratio—which was very important; and,

(*iii*) it made it possible to 'comb out' residual eddies by a contraction at the end of the pavement.

Deepening would, however, be ineffective if the divergences were too sharp.

It was also necessary to emphasise that the drop wall at the downstream end of the pavement should be carried to a depth not less than two-thirds the channel depth,—to prevent undermining and also to reduce the danger of 'piping,' which was greatly magnified by downstream scour.

Though a weir caused some bed silting in its immediate vicinity, weirs could be designed so that at full discharge there was some 'draw down' and the scouring effect at full supply then neutralised the silting effect at low supplies. The objection that such a weir tended to raise the subsoil water table by storing water during closures could be eliminated by leaving holes in the weir—which, the speaker understood, was the practice in the United Provinces.

Mr. H. W. Nicholson, advocated the cause of the old notched falls as they were the best so far evolved. He referred to Sir John Benton, whose genius was responsible for the production of these falls on the Sirhind Canal, and said that because latter day engineers had become more accountants than engineers, the present day fantastic ideas concerning falls had come into being. He also referred to Bligh's design.

The speaker thought the real trouble lay in the fact that, as in the case of the Sutlej Valley Canals, efforts were made to save on capital expenditure, which led to unsafe but cheap designs, thus enhancing the cost of subsequent repairs and maintenance. On the Sutlej Valley Canals, it had taken only four years to wipe out the savings made on the capital cost.

He pointed out that a 10 feet fall was better than a 2 feet fall, with which the scouring downstream was greater, and that it was very easy to accelerate water but very difficult to decelerate it, without doing damage. He considered that they were going in a sort of circle. This circle was now nearing full turn and they would revert to the old notched falls very soon, as they were still the best solution.

Mr. Ishar Das, said that the paper was a very interesting one. He agreed with Mr. Nicholson's remarks and had found that notched falls were quite good on the Upper Swat Canal, for a higher discharge than 500 cusecs, where downstream cisterns were provided. He was of opinion that different sorts of falls suited different conditions. The main object was to avoid scour in channels and he asked that Mr. Colyer should throw further light on the matter as the latter had designed dissipators for channels, on account of which great improvement had taken place, except in a few cases. In certain cases of flumed falls, the speaker had observed that in channels of about 150 cusecs, where crest width was about 7-8ths of the bed width and the crest was raised so much that H was only 1·1 against D=3·2, there was no silt deposit upstream of the crest. When studying the action of the filaments of the coming jet on the friction blocks he had noticed that when the jet came, the filaments were broken, and vertical columns of water were formed to arrest the onward jet, and water came out of the cisterns in stable flow. Therefore for small discharges, friction blocks were very useful. He had discussed the subject with Mr. Inglis who had agreed that in the case of friction blocks, there was a sort of vibration set up by the impinging jets which weakened the life of the blocks. For higher discharges, bigger friction blocks were necessary and those might be unsuitable. He considered that up to 2,000 cusecs there would be no difficulty with broad crested flumes with D/S cisterns and friction blocks, but beyond that limit, he advised the use of notched falls with cisterns and friction blocks. The friction blocks added to the wetted perimeter which was useful for the dissipation of the energy.

Mr. C. A. Colyer, said that he had risen to speak because he was responsible for the "biff-wall" which had come in for a good deal of criticism. Although the "biff-wall" had solved the problem of damage below falls in many cases, he did not consider that any one device was going to solve the whole problem.

Mr. Montagu had once remarked that he had spent his time pulling out biff-walls which Mr. Colyer had put in, but nevertheless, the speaker had recently seen one of these very walls after six years' working, and had found it to be functioning very satisfactorily.

He regretted that he had not been invited to join the Committee appointed on the Sutlej Valley Project, which he understood had turned down the "biff-wall." He agreed that one standard design could not possibly cover all the varying conditions prevalent in different places, and considered that conditions on the Sutlej Valley Canals offered a unique chance of testing several different devices.

MR. N. BODDINGTON, said that one remark, in particular, during the discussion, made him think. This remark was to the effect that the chief difficulty to be overcome was the dissipation of energy. Energy was a very valuable commodity and to dissipate it merely for the sake of its dissipation appeared uneconomical. He suggested that there were many possible uses for this energy and if it were converted into electricity, this different form of the same energy could be used for unwatering the waterlogged land adjacent to canals, thereby increasing the canal supply, reclaiming bad land and preventing other land from deterioration.

He recognised that the energy would not always be available, as canals had to be closed for repairs and other reasons but, during times of closure, waterlogging did not increase, so no argument on the score of intermittent supply would prevail against his suggestion.

He believed that the cost would not be excessive, especially if adherence to a standard type of plant, was enforced.

THE AUTHOR, replying to the discussion, said that never had he hoped the paper would meet with such a reception. The members had still to decide however on the best form of a fall to be designed. The Author thought that Mr. Lacey agreed with him in every way, but had different experiences to relate. Mr. Lacey also thought that there should be a high crest.

Mr. Mithal had spoken about the slopes of the glacis which actually were slightly different, and then he had gone on to cases where the fluming ratio was about 60 per cent. This, the Author considered might have been due to the choice of site, and therefore, no inherent quality of design could be claimed.

Mr. Malhotra had mentioned certain cases where damage had occurred and stated they had put in some pitching and again when more damage occurred, the same procedure had been repeated. This was a very common history of the falls in the Punjab, for when it was not known what to do, they simply added another 100 feet of pitching.

To Mr. Foy's question, Mr. Nicholson had already replied the greatest damage caused was in the case of the 2 feet falls, and not the larger falls, where a scour of 20 feet was found.

Mr. Inglis, in his remarks describing his experiments, had pointed out that so many divide walls were not required, and had suggested that one at each end would be sufficient. These walls however were only put in as an experiment. The falls had been repaired in different ways.

Regarding the utilisation of energy from falls, the Author understood that this question had already been investigated and quoted the example of Renala Hydro Electric plant, which was working quite satisfactorily. Owing to closures which would be longer and oftener in future, this method of utilisation of energy, however, might not be very satisfactory. Mr. Nicholson had asked what was wrong with the notched falls. The Author quite agreed with him and thought that in the maze of different things such as proportionality, flexibility, etc., the old notched falls and broad crested weirs had been lost sight of. When a design was prepared, a certain level was adopted, but unfortunately owing to retrogression, the conditions downstream did not remain the same. Mr. Colyer had pointed out that in one or two cases "biff-walls" were still standing, and he had said also, that no standardization of design was possible. This gave point to the object with which the Author's paper had been written, which was to see what designs could be adopted for the future. When there were about half a dozen designs which were fundamentally correct, it could not be said how these could be standardized. In conclusion, the Author said the Punjab Irrigation Department had as many different designs as there were Executive Engineers, and that it was high time it came back, to re-consider the old ways.

R. B. DEWAN AMAR NATH NANDA, who was presiding, said that the Congress was very much indebted to Mr. Inglis, who was a great engineer in his own Province, for his words of wisdom expressed in connection with this paper.