PAPER No. 214

PROTECTION AGAINST SCOUR BELOW RIVER AND CANAL WORKS.

By Harbans Lal Uppal, M. Sc., Ph. D., Research Officer and
N. N. Bhandari, B. A., Research Assistant.

1. Introduction.

The protection of stream beds below weirs and canal falls is one of the most important problems of river hydraulics. Huge sums are spent annually in protecting the bed below over-falls and on the maintenance of these works without getting satisfactory results in almost all cases.

A quarter of a century back the hydraulic jump or the standing wave[1] was regarded to be a satisfactory means of the dissipation of kinematic energy which resulted from the falling water. Later on it was found that only a small portion of the kinematic energy was dissipated in the formation of the standing wave, the major portion remaining as such. This caused an uneven distribution of velocities below the standing wave resulting in deep scour holes at the downstream end of the work. The scouring action, which is the result of the high velocity jet and is developed when the discharge takes place either over weirs or through gates, is a constant worry to the engineer charged with the maintenance of such structures.

However sound the design of work may be, a certain depth of scour is bound to occur below the downstream end due to the occurrence of residual eddies. The action of the current is illustrated below.

FORMATION OF A HOLE BY SCOUR

The depth of scour for any discharge per foot run can be calculated theoretically from Kennedy's [2] silt formula $V_o = 0{\cdot}84 d^{0{\cdot}64}$, or $d = 1{\cdot}11\, q^{0{\cdot}61}$ where d is the depth of scour. It may also be determined by Lacey's [3] formula $R = 0{\cdot}7305 \frac{V_o^2}{f}$ or $0{\cdot}7305 \left\{ \frac{Q}{3{\cdot}8f} \right\}^{\frac{1}{3}}$ where R is the depth of scour and f is the silt factor.

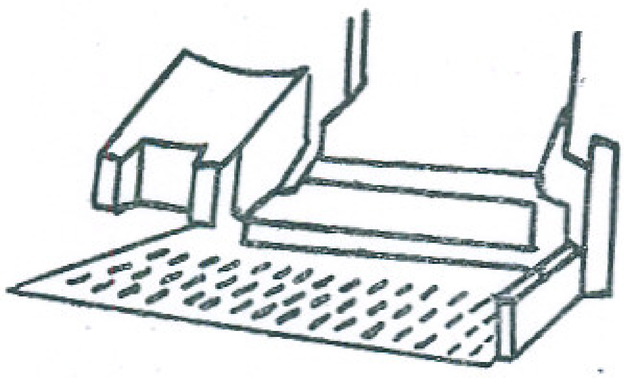
A large number of cases have occurred where due to the formation of extraordinary deep scour-holes downstream, the structures collapsed resulting in a considerable loss of money and even lives.

In our own country severe damage to several works and failure of a number of them took place due to the same reason. Below are cited some of the outstanding cases.

Name of Work	*Depth of scour below the downstream floor level.*		*Cost of Repairs.*
Merala	.. 54 feet	1929-30.	Rs. 1,35,978
Khanki	.. 33 feet	1934-35.	Rs. 3,00,000
Panjnad	.. 35 feet	1934-35.	Rs. 75,000
Islam	.. Very deep scour and consequently the failure of Islam Weir followed.		
Ferozepur	.. 20 feet		
Rasul	.. Very deep scour resulting in the failure of certain bays of the weir.		

2. History of Energy Dissipators.

The trouble was felt at all places where the structures were built on fine sand foundations and a search began to be made for some sort of devices which when constructed on the floor of the weir would reduce the scour. Puchner and Hofbauer [4] in 1914 carried out, in a glass flume, some experiments on protection against scour. They found during the reconstruction of a raft-chute that a movable hinged platform substantially filled up the scour hole that had existed at the foot of the chute. The platform consisted of square timbers fastened tight together. At the downstream part of the platform each alternate plank was omitted so as to allow the sand and gravel to pass through. It presented a comblike appearance.



Wood Platform for Scour Prevention.

One of the most important investigations in this direction was that by Riegel and Biebe [5]. They examined several devices on a number of different works. In the first series of these tests they studded the floor with knobs, boulders and small piers. The main conclusions derived from these tests were that the velocities below the standing wave were diminished when the floor was roughened and the standing wave occurred sooner with the blocks than without them under the same downstream water level conditions. It was, however, observed by them that under increased discharge and high downstream level the devices were little effective. In the next series the tests were extended to the use of baffle piers and spraying devices. Different designs of baffle piers were adopted but it was found that no single arrangement was suitable for all discharges. The tests on spraying devices were not carried to completion as these devices were found to be inferior to the standing wave.

Rhebock [6] at Karlsruhe made a series of tests on a number of devices for preventing the scour below stream beds, below spill-ways and weirs. As a result of his investigation he found that a dentated sill was valuable in reducing the scour. The device consisted of a roof-like sill with alternate teeth with their vertical faces upstream and with gently sloping faces on the downstream side. The height of the sill was about 1-10th the height of the over-fall.

Colyer [7] after several years of observations on certain canal falls developed a biff wall which when constructed at the downstream end of the cistern of a flumed fall successfully dissipated the kinematic energy and reduced the scour. Three different shapes, *viz.*, rectangular, upstream face curved, and upstream face stepped were examined by him. The height of the biff wall was such that it just caused an independent fall, the biff acting as a weir.

Steel and Munro [8] investigated models of the diversion dams for Pit No. 3 and Pit No. 4 hydroelectric projects of the Pacific Gas and Electric Company. The object of these experiments was to determine the most satisfactory means of destroying the energy of the water at the foot of the dam and thus protecting the bed and the bank against scour.

They examined several types of stilling devices. The devices which gave most satisfactory results were two rows of baffle piers constructed on the concrete floor below the bucket of the dam. The upper row of the piers acted as splitters, the lower row having curved upstream faces serving as deflectors.

Protheroe [9] on some falls on the Khadir Branch constructed pier-shaped blocks or "friction blocks" so placed as to split up the high velocity jet causing greater internal friction and consumption of surplus energy. The blocks showed only slight improvement in the distribution of velocities downstream of the standing wave. The turbulence beyond the pucca floor persisted and the side scour continued.

Inglis [10] at Poona carried out a long series of tests with several devices for the dissipation of surplus energy below falls. He found that the addition of a baffle wall at the position of the standing wave was a satisfactory means of obtaining an even distribution of bed velocities. The baffle was found to be effective over a wide range of downstream water-levels. The special pavement for the baffle was designed according to the formula : $\frac{d_x}{d_2}=\left\{\frac{h_2}{D}\right\}^{1\cdot 3}$ for parallel sided fall, where

d_2=Depth of water at toe of fall (assuming that no standing wave has formed).

d_x =Depth of water downstream of standing wave above baffle pavement level in a parallel sided channel.

$D=D_1+h_v$=Upstream depth of water above sill of S. W. F. + head due to velocity of approach.

h_2=Difference of level of water upstream of, and at the toe of the fall, assuming no standing wave, i. e., the effective head for downstream velocity V_2.

The optimum height and the position of the baffle were determined. In the case of a curved downstream glacis the height of the baffle fixed by Inglis was equal to the depth of water at the toe of the fall assuming that no standing wave was formed, i.e., $h_b=d_2$. In the case of straight glacis the height of the baffle was kept at 1·5 times the depth, i.e., 1·5 d_2. In some cases the top level of the baffle was as high as the sill of the fall.

Regarding the optimum position of the baffle from the toe of the glacis a safe range was found to be from $3d_2$ to $9d_2$.

A curved upstream face with radius equal to and ending at two-thirds the height of the baffle was preferred to a rectangular one.

A deflector was also investigated by Inglis and found to be useful in the reduction of bed scour. The height of the deflector was kept between 1-12th and 1-15th the depth of water on the downstream floor.

In the year 1932 the late Mr. Nicholson [11] constructed a set of arrows on the floor of Bay No. 2, Khanki Weir for protecting the bed against scour. The length of the arms and the angle between the arms were not based on any calculations. The design was more or less the outcome of intuition. Gunn [12] in 1934 made certain tests on these arrows in the Hydraulic Laboratory, Irrigation Research Institute, Lahore.

The latest work on this subject is by Stevens [13] on scour prevention below Bonneville Dam. On a model of the dam to a scale 1:36 a number of experiments were made on different combinations of deck aprons, baffles, etc. The arrangement adopted consisted of wedge shaped baffle blocks 6 feet × 6 feet and 1:1 slope.

A perusal of the foregoing literature on the subject shows that devices developed from time to time for the prevention of scour did not prove to be effective for all the conditions of flow. Secondly, the tests carried out mostly did not comprise examination of weirs where the volume of discharge was tremendous. Most of the investigators confined their attention to the falls which in most cases were flumed and were provided with a cistern, i.e., factors which are helpful to the working of the devices. In order to make an exhaustive study of the means of protection downstream of hydraulic works, model experiments were started. A special feature of these tests was an examination of almost all types of works, i.e., Weirs, Undersluices, Head-regulators, Rapids, Falls and Level-crossings. While weirs were given special consideration, the falls on some of the distributaries were also examined.

A detailed comparative study of all types of devices suggested from time to time was made. The devices found most efficient were further tested on a large number of models of different forms. This ensured their wide application.

3. Apparatus.

(*a*) *The Experimental Flume.*—The tests were carried out in a glass flume $2\frac{1}{2}$ feet wide and $2\frac{1}{2}$ feet deep. The total length of the

FIG. 1(a)
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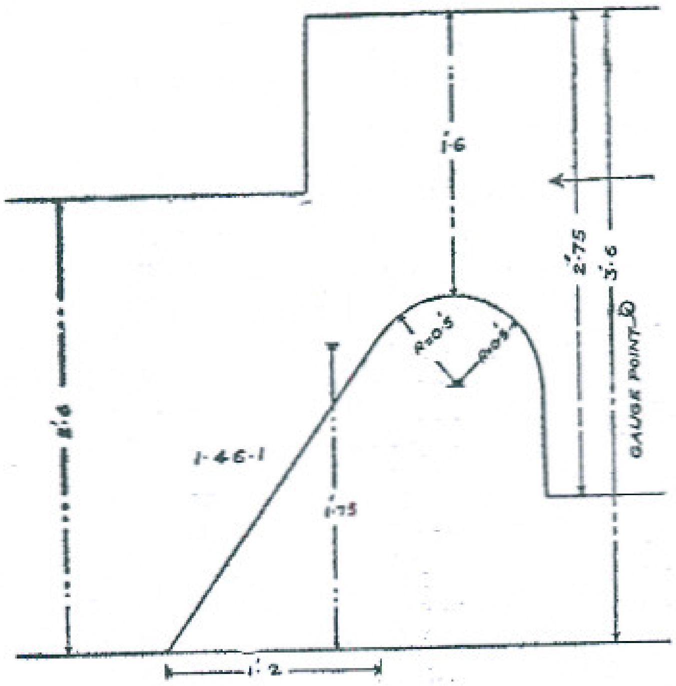
SECTION SHOWING THE ROUND CRESTED WEIR FOR THE MEASUREMENT OF DISCHARGE



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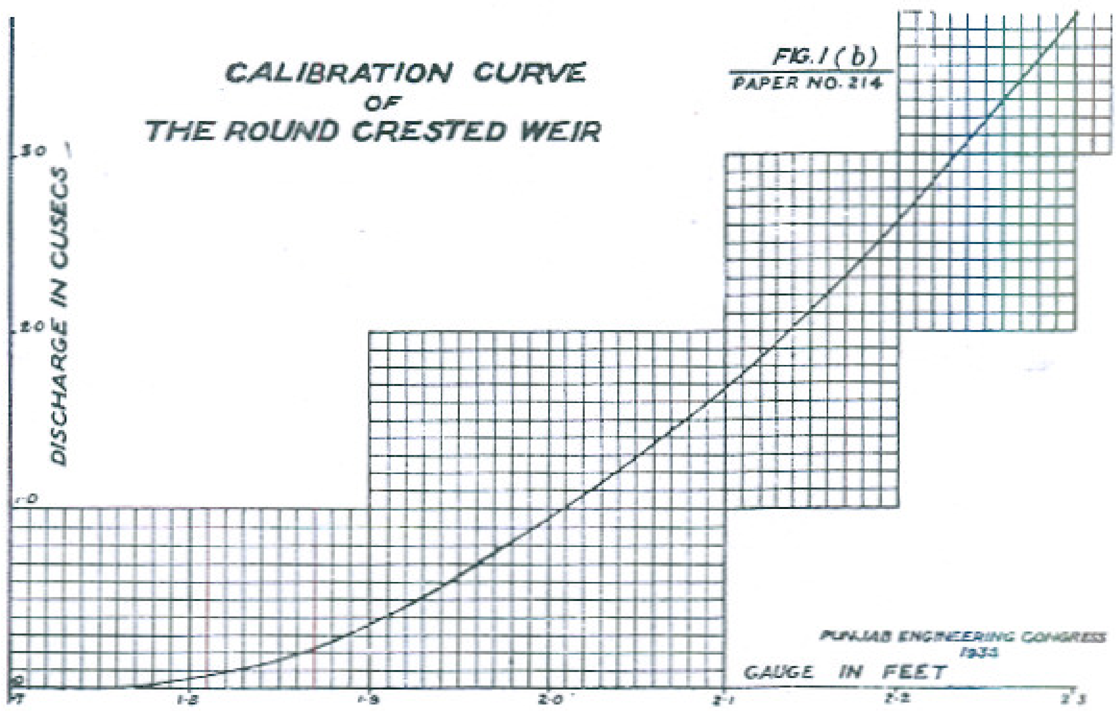
CALIBRATION CURVE
OF
THE ROUND CRESTED WEIR
FIG. 1 (b)
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DISCHARGE IN CUSECS
3·0
2·0
1·0
GAUGE IN FEET
1·8
1·9
2·0
2·1
2·2
2·3
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flume was 60 feet while the length of the glass portion was 40 fee only. The water was supplied from an over-head tank 20′×10′×(provided with a spill-over for maintaining a constant head. The tota length of the spill-over was 12 feet divided into 3 parts of 4 fee each.

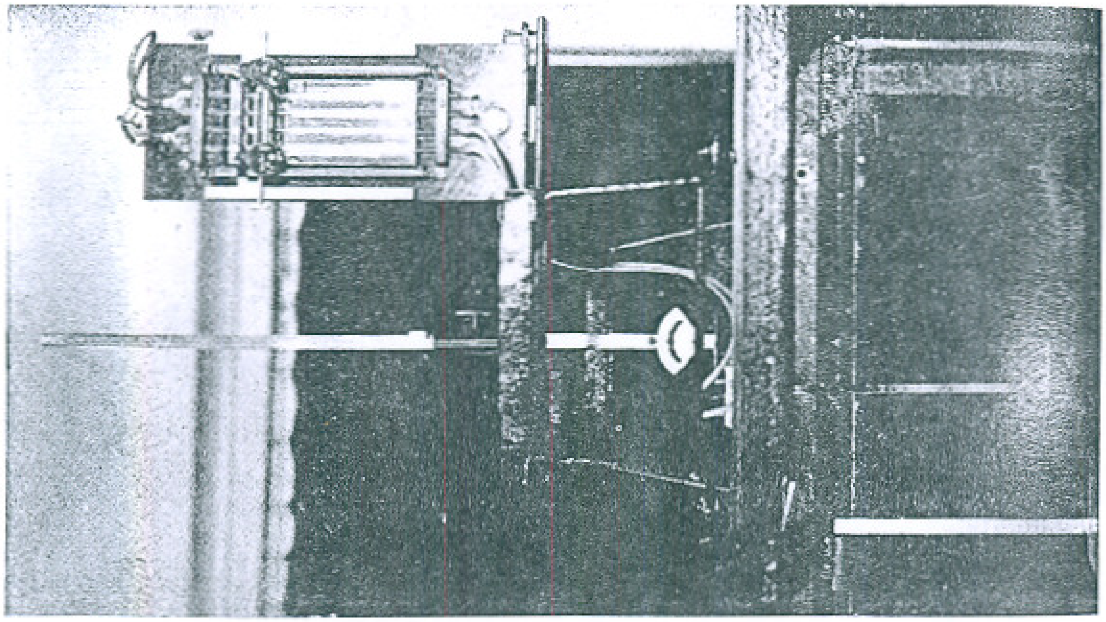
The pumping set consisted of four hydraulic pumps with a tota discharge of 8 cusecs. The water from the flume discharged into a underground tunnel which was joined to the pumps so that the wate could be brought back and lifted up to the over-head tank. At the down stream end of the flume a gate was fitted which could be raised o lowered in order to maintain a correct level of water downstrean of the model.

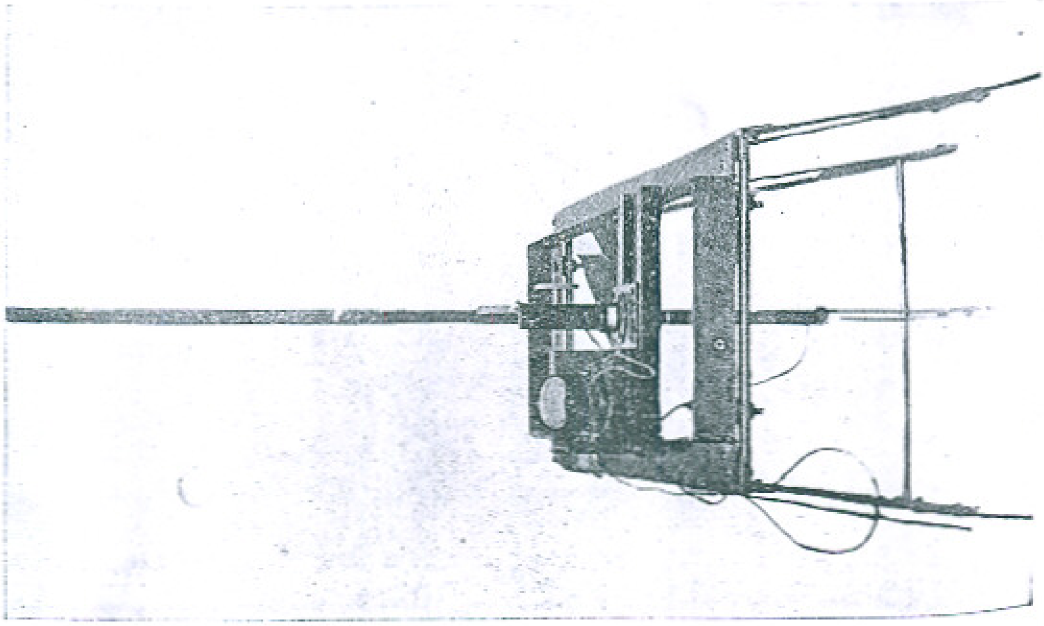
(*b*) *Measuring Weir.*—The discharge was measured by means of a round crested weir fitted at the upstream end of the flume. This was made of steel plate. The crest of the weir was an arc on a radius of 0·5 feet. The downstream of the crest had a slope of 1·46 : 1 while the upstream portion below the crest was vertical. The height of the crest from the upstream bed was 1·15′ and from the downstream bed level it was 2 feet.

The approach channel was 2·5 feet wide and 2·75 feet deep thus causing a maximum head of 1·6 feet on the weir crest. The weir is illustrated in Fig. 1(*a*).

(*c*) *Gauge Well for the Measurement of Head.*—For the measurement of head above the crest a gauge-well 3ft.×1ft.×1ft. with steel back and glass sides was situated at a distance of 10 feet from the crest. It was connected to the approach channel through a lead pipe $\frac{1}{2}''$ in diameter. The connecting point was made absolutely flush with the inside wall of the channel. The readings of the water level in the gauge-well were taken by means of a spitzen-tester point gauge fitted with a vernier scale. The point gauge was capable of reading up to 1-1000th of a foot. When the point of the needle just touched the water level a star-like mark appeared on the surface. This was considered to be the correct point of contact and the readings were taken. The surface of water in the gauge well was illuminated from the top in order to facilitate the observations.

(*d*) *Electric water level recorder.*—The accuracy of the instrument was further enhanced by fitting up an electrical arrangement for determining the point of contact between the point-gauge and the water surface. A micro-ammeter was put in the electrical circuit. The deflection of the pointer of the micro-ammeter signalled the contact of the gauge point with water surface whereupon readings on vertical scale were recorded. Readings taken by this method are free of observer's personal error.





(*e*) *Construction of the models.*—The models were constructed of seasoned teak wood and then fitted in the flume. The scales adopted varied from 1/10 to 1/40 of the actual, depending upon the magnitude of the discharge. The maximum constant discharge which could be run in the flume was about 5 cusecs. The models of flumed falls were given proper contraction and their sloping sides were built in glass inside the experimental flume.

(*f*) *Bed material.*—It has been shown by experiments carried out in Germany and in America that the shape of the scour hole is independent of the grade of the material used. However, the depth of the scour will depend upon the size of the particles. The coarse bed material will take a longer time to develop the scour than the finer one. Different grades of coarse sand and bajri were tried in order to select a material which gave a decent scour in a reasonable time and at the same time it was not so fine as to be immediately washed away to the pumps. It was found that the most suitable material was one that passed through a sieve of $\frac{1}{8}''$ but was retained on $\frac{1}{16}''$ sieve.

The tests carried out included :—

(*i*) the determination of the water surface profile,

(*ii*) the observation of velocity along vertical sections and the determination of the line of maximum velocity,

(*iii*) the measurement of depth of scour,

(*iv*) the photographs showing the action of water.

(*g*) *Universal Pitot Tube.*—The velocity observations were taken by means of a Universal pitot-tube manufactured by Messrs. Franz Kneller and Co., Karlsruhe. With the help of the point gauge fixed to the pitot tube the observations could be taken at any depth. Similarly the presence of the tilting devices enabled the velocity observations to be taken at any angle to the direction of flow. The photograph illustrating the whole arrangement is shown in Photo I.

(*h*) *Point Gauge.*—The water surface observations and the surveys of the scoured bed were made by point-gauges fitted with micro-ammeters for the automatic record of the surface of contact. By the help of the electrical arrangement the bed could be surveyed in running water. Both the point-gauge and the pitot-tube were mounted on carriers with their legs straight-edged. The flume for a length of 30 feet was fitted with straight edges so that the pitot-tube and the point-gauge could slide over the entire length of the model in a perfectly horizontal section in both directions. The photographs were taken by still and movie cameras, suitable illumination having been provided.

4. Examination of different types of Energy Dissipators.

A large number of different devices were investigated. These included (i) devices used by the previous investigators, and (ii) new types which suggested themselves during the course of investigation. A detailed study of each type of dissipator was made. Exhaustive tests under varying conditions of flow were carried out. In all about 340 tests were made. *The object of these tests was to find out a type of energy dissipator which worked satisfactorily under all conditions of flow.* So far no such suitable device had been discovered. The following types were investigated :—

I. Extension of the downstream horizontal apron as a measure for the reduction of scour.

II. (*a*) Baffle Wall,
 (*i*) Different heights, & (*ii*) Different positions.
 (*b*) Baffle wall with Deflector.
 (*c*) Deflector alone of different heights.

III. (*a*) Arrows alone.
 (*b*) Arrows with blocks.

IV. Blocks alone.

V. Dentated sill.

VI. Different forms of blocks were examined with a view to reducing their cost and increasing the efficiency :—

(*i*) Rectangular.
(*ii*) Triangular.
(*iii*) Upstream face curved.
(*iv*) Downstream face curved.
(*v*) Baffle piers.
(*vi*) Blocks with holes in the centre for the passage of water.

The tests were carried out on models of different works. Some of these are mentioned below :—

1. Khanki Weir.
 (*i*) Open weir,
 (*ii*) Undersluiced bays IV and VIII.
2. Panjnad Weir and Annexe.
3. Deg Diversion Fall, Upper Chenab Canal.
4. Merala Weir.
5. Ferozepur Weir.

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CROSS SECTION KHANKI WEIR

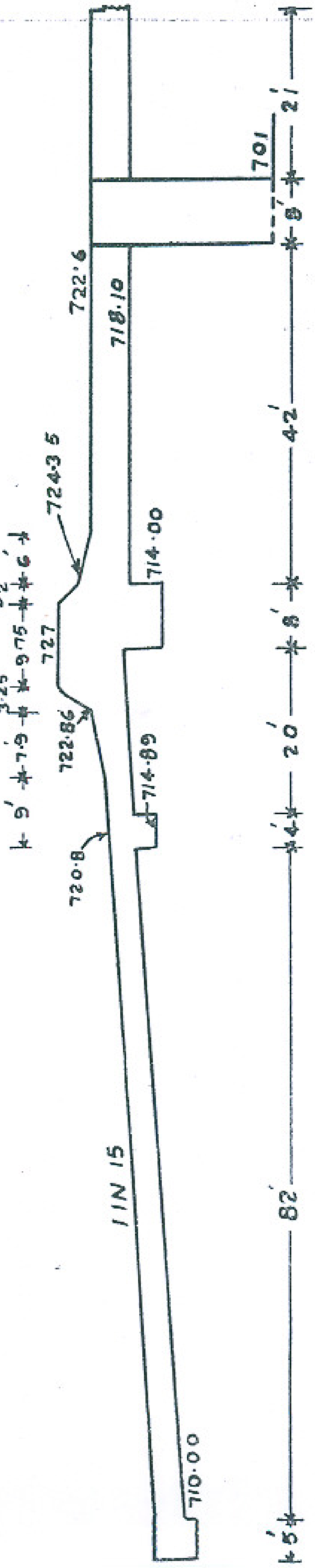

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FIG. 3
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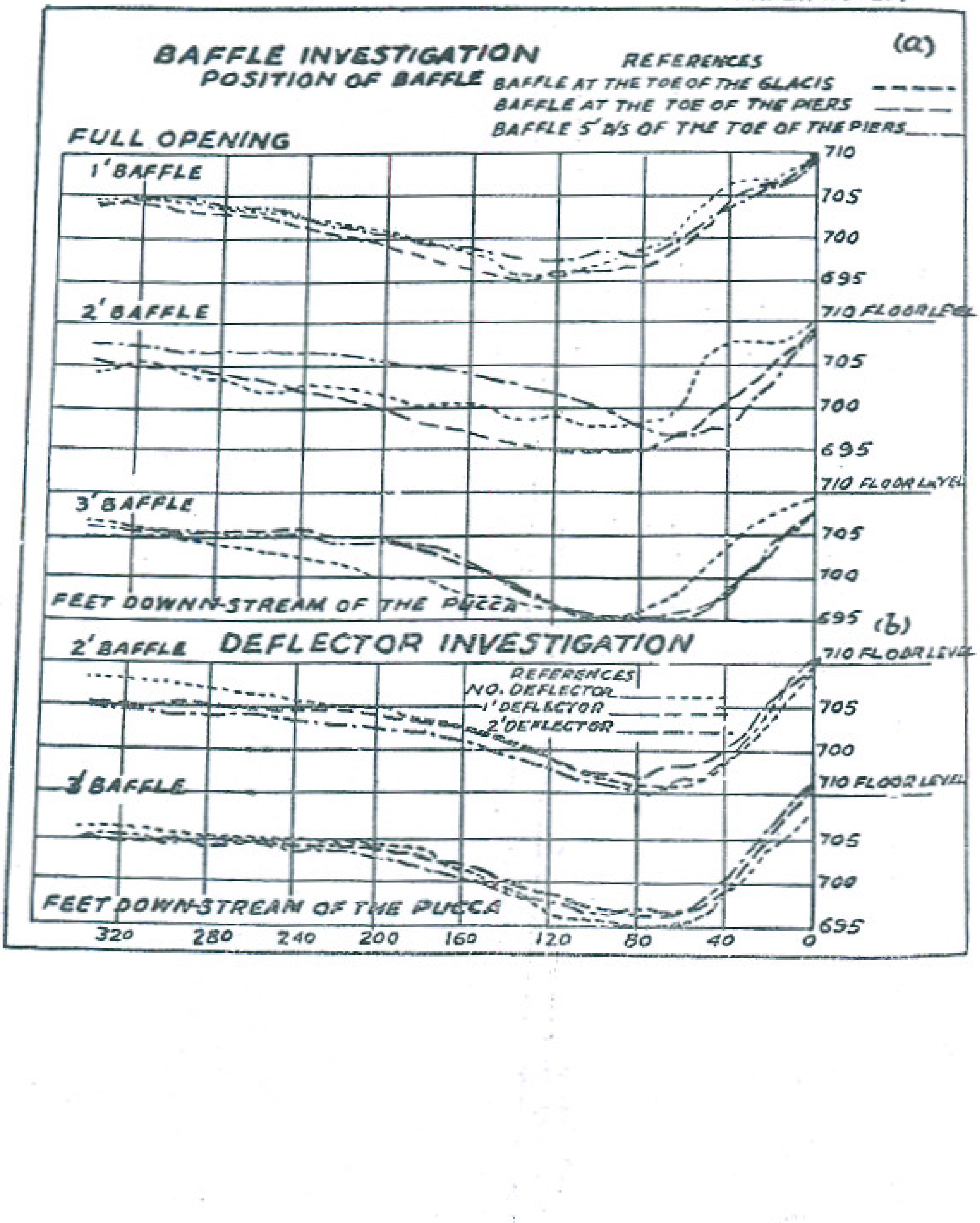

FIG. 4
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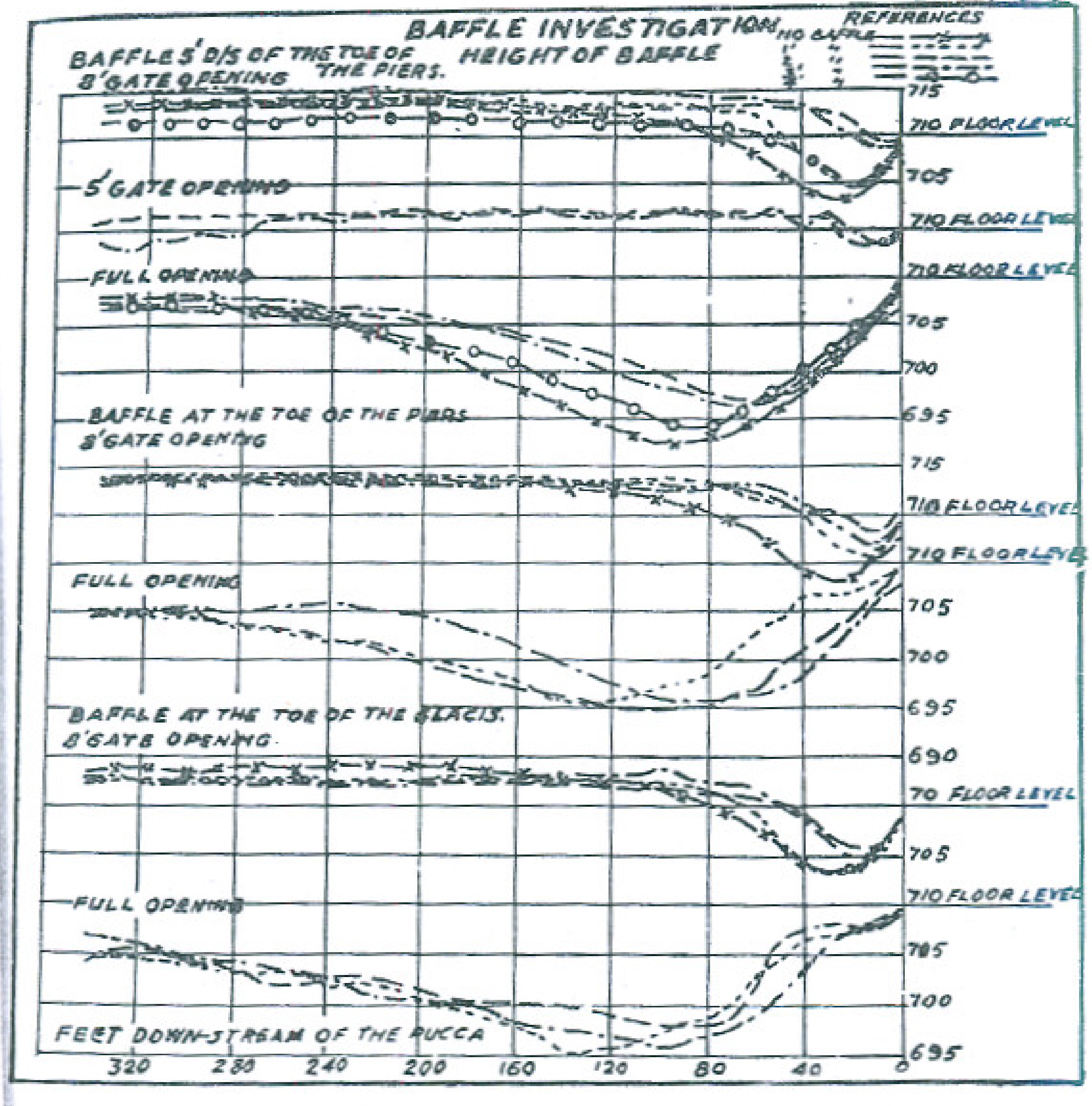


6. Anderson Undersluices.
7. Islam Weir.
8. Salampur Feeder, Upper Bari Doab Canal.
9. Jaba Level Crossing, Upper Jhelum Canal.
10. Sarda Barrage.

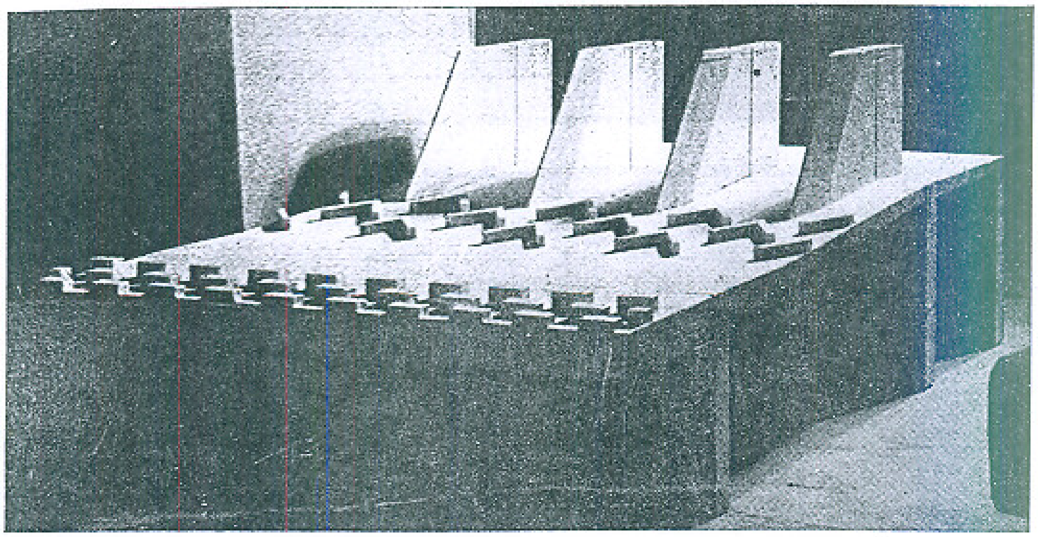
Photos III-XI show the models fitted with energy dissipators.

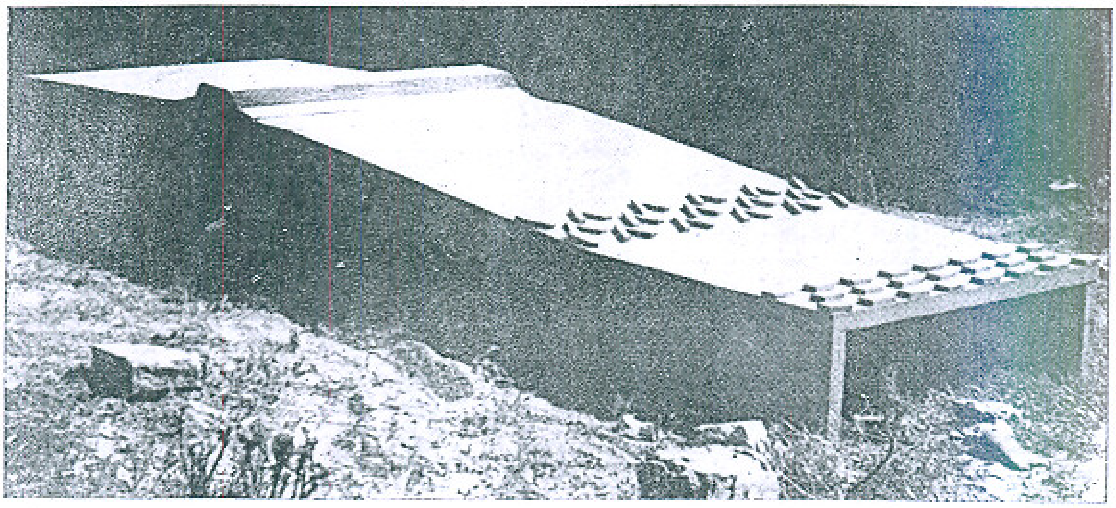
I. *Extension of the Downstream Horizontal Apron.*—Different lengths of the downstream apron were examined in order to investigate the effect of the length of the apron on the depth of scour downstream of the apron. It was found that no appreciable reduction in the depth of scour was caused by longer lengths of aprons. The extension of aprons from 30 feet to 55 feet on Rupar and Khanki Weir models reduced the scour by about 1 foot. Similarly at Marh Chiniot Drain Rapid, reduction in the horizontal floor of 30 feet had little effect on the scour.

II. *Baffle Wall.*—The first series of experiments was carried out on Khanki Weir model. The section through the weir is shown in Fig. 2. The discharges used were 36,000, 62,500 and 1,10,000 cusecs through the bay which was 500 feet overall width. The tests were first made with the baffle wall alone and then in combination with the deflector. In some cases the deflector alone was also examined. Different heights of the baffle wall and the deflector wall were tested. The optimum position of the baffle wall on the floor of the weir was also determined. As many as fifteen different arrangements were examined. The bed was surveyed in each case after running the model for four hours. The velocity sections were also observed for all the cases and the line of maximum velocity was drawn. The bed surveys obtained for different cases of baffle wall of different heights and at different positions, alone and in combination with deflector wall are shown in Fig. 3. Similar tests were carried out on a model of the bays with gated span. The results are shown in Fig. 4.

An examination of Figs. 3 and 4 showed that a baffle of medium height of 2 feet was better than 4 feet or 1 foot baffle. Again the position of the baffle at 5 feet downstream of the pier noses was more effective than any other position. The deflector wall up to a height of 2 feet did not materially reduce the scour. This is shown in Fig. 3 (*b*).

One great difficulty in applying a baffle wall to a weir was that the best position and height for a low discharge was the worst for a high discharge and *vice versa*. Similarly the presence of a deflector reduced the scour to some extent in the immediate neighbourhood of the pucca work but extended the scour much farther downstream.





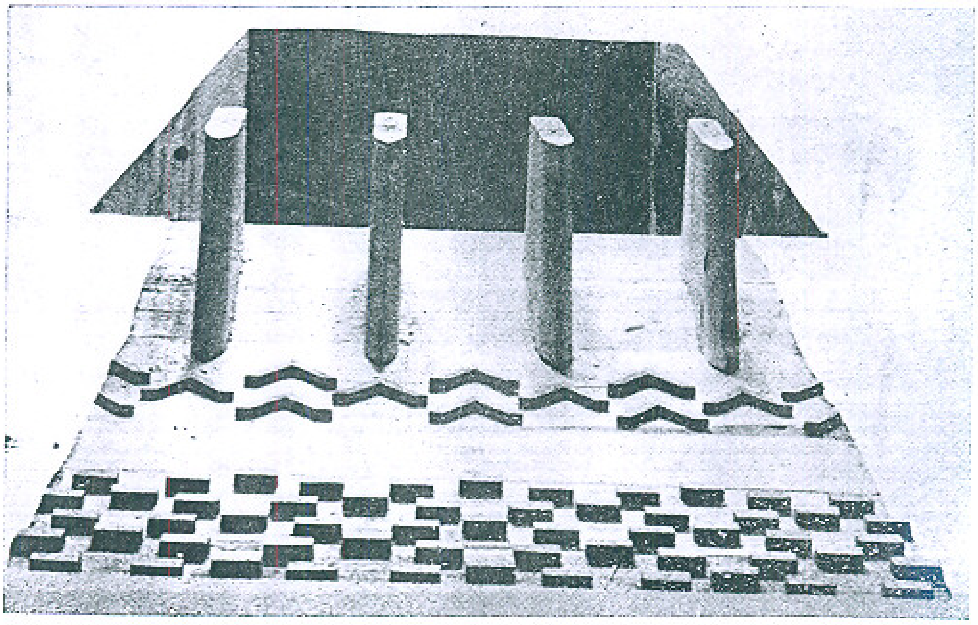


Photo No. II.

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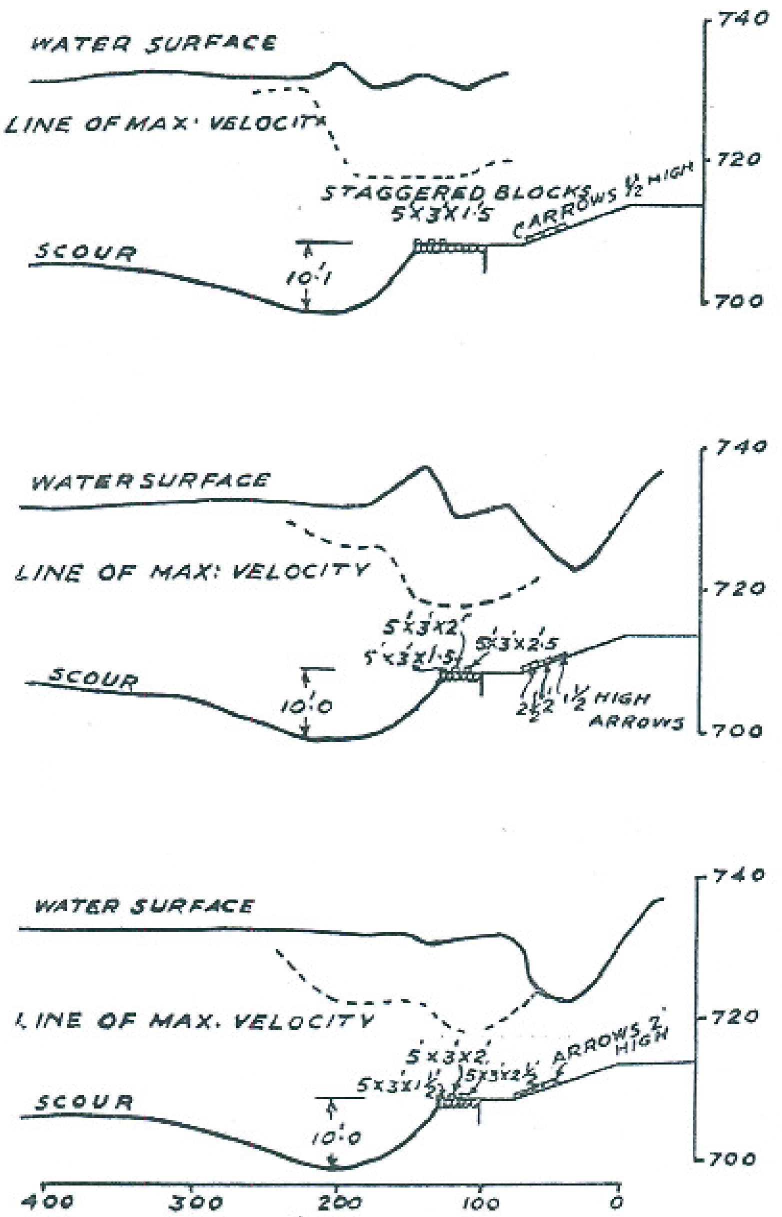
FIG. 5
MAXIMUM FLOOD LEVEL



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III (*a*) *Arrows.*—Next, the arrows were constructed. These consisted of low walled arms with an angle of 60° between the arms. The length of arms were approximately 12 feet. They were placed in 3 rows on the floor. The arrangement is shown in Photo II. It was found that the arrows to some extent threw the high velocity jet on to the top surface thus reducing the bed velocities. The depth of scour was reduced but not to any appreciable extent. The construction of arrows alone was not found to be very satisfactory from the point of view of reduction of scour.

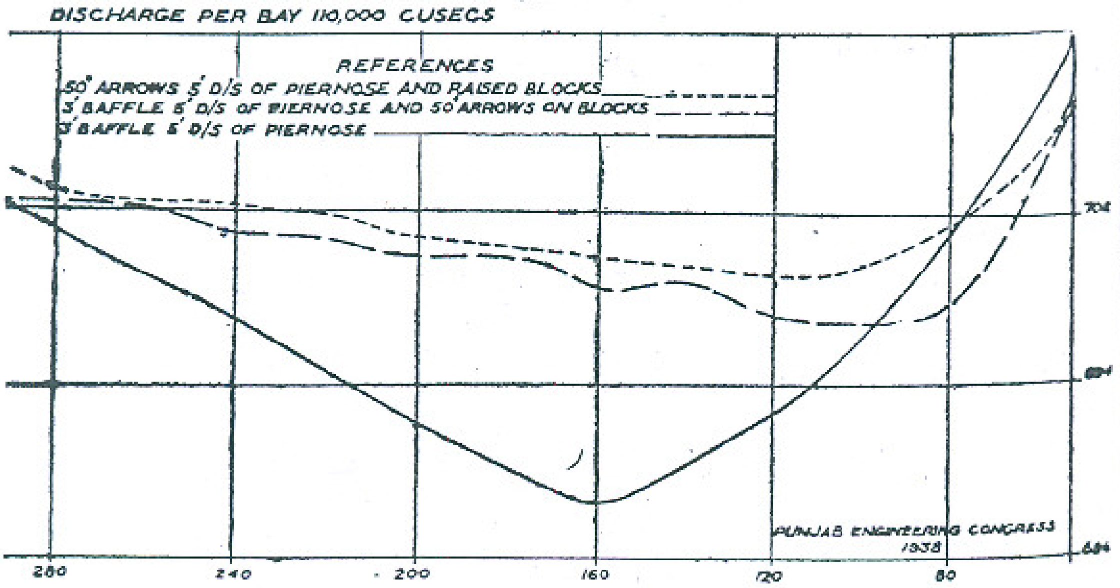
III (*b*) *Arrows and Blocks.*—On the block portion the raised blocks were constructed in conjunction with arrows. The blocks were rectangular in shape and were staggered. The arrangement of the blocks is also shown in Photo II.

The observations obtained are shown in Appendix I and plotted in Fig. 5.

It will be seen from columns 9 and 10, Appendix I that a combination of arrows and blocks gives much better results than arrows alone.

A comparison of the results obtained by the use of baffle alone, baffle in combination with arrows and arrows in combination with blocks is made in Fig. 6. It will be seen that *arrows and blocks gave much better results than the baffle and deflector wall.*

Fig 6.



The arrows and blocks having shown to be better than the baffle and the deflector wall were constructed on other bays of the weir also. They were also examined on a model of Khanki Weir, Bay VIII during

KHANKI WEIR
BAY VIII
ARRANGEMENT OF ARROWS & CONTROL BLOCKS

FIG. 7
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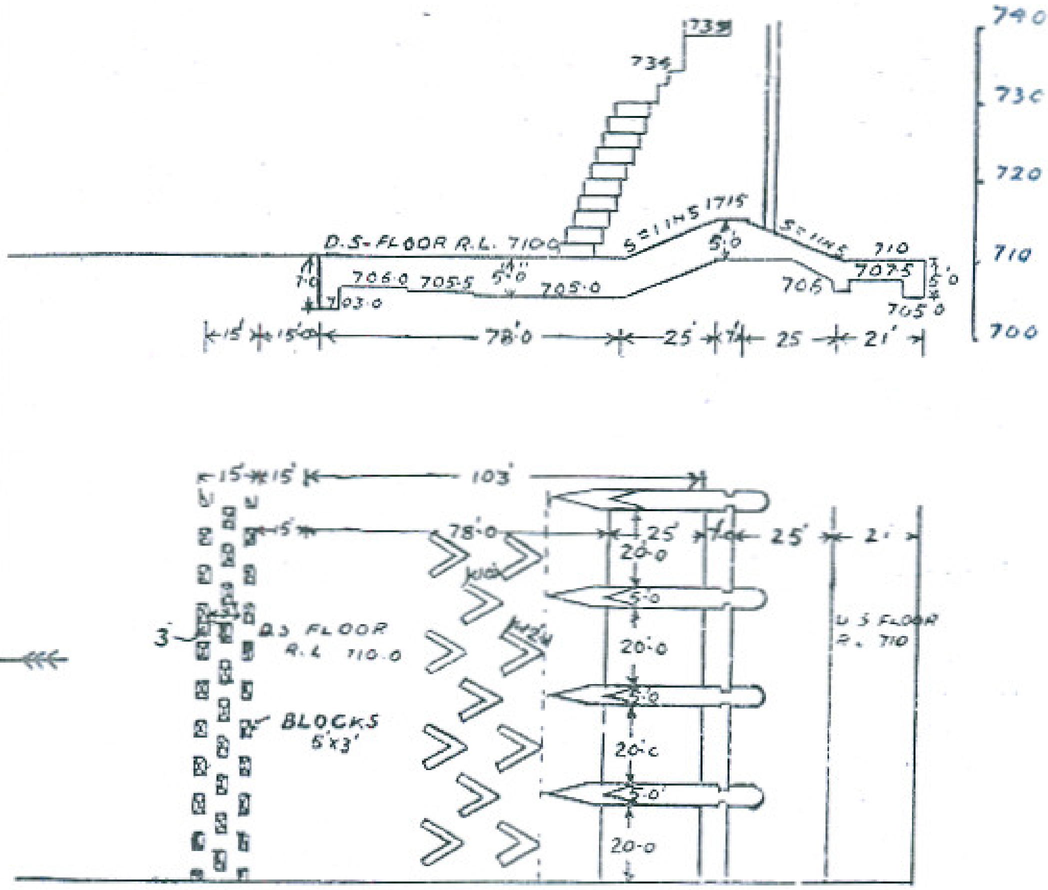

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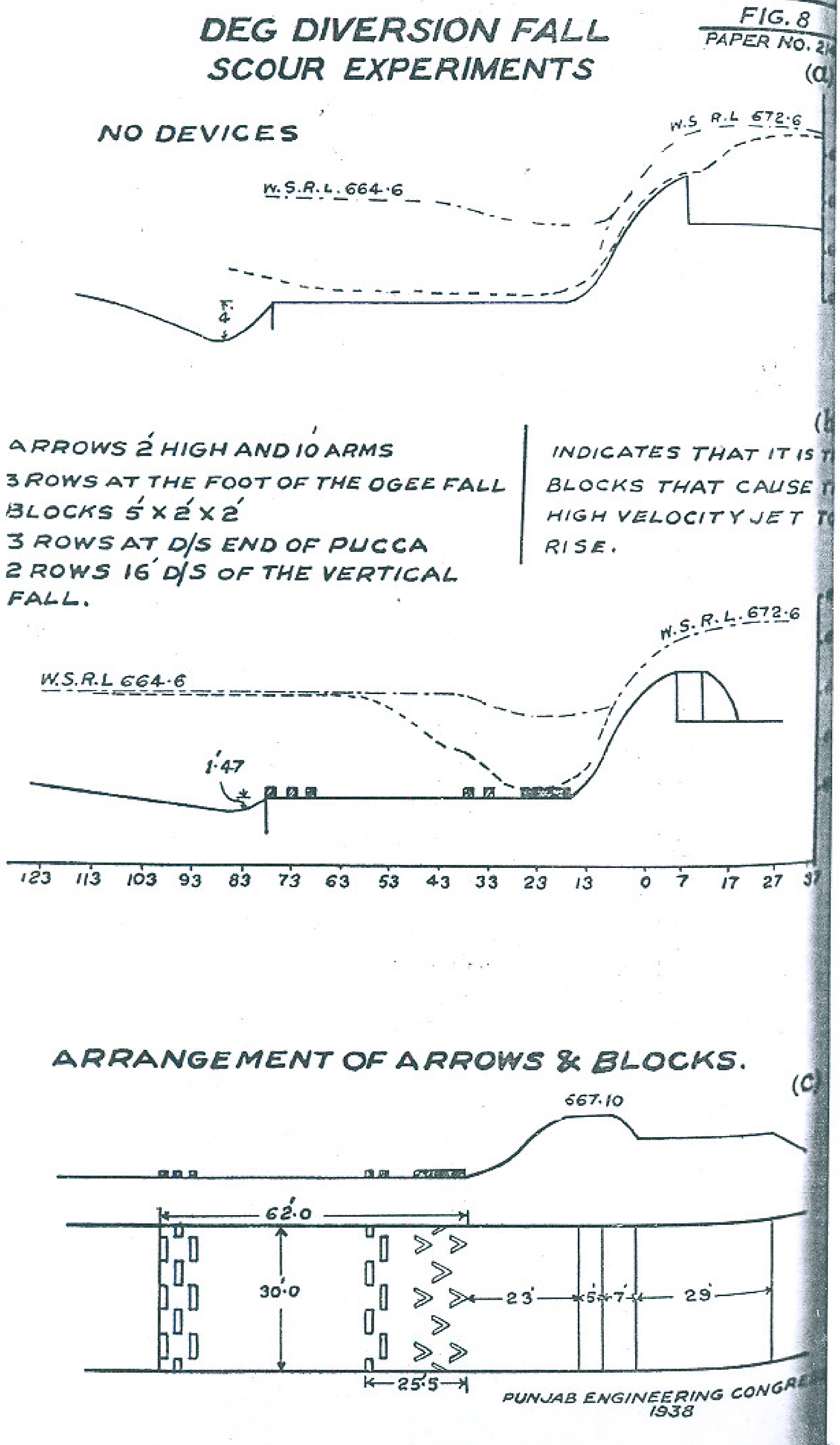
DEG DIVERSION FALL
SCOUR EXPERIMENTS
FIG. 8
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(a)
NO DEVICES
W.S. R.L. 672·6
W.S.R.L. 664·6
4'
(b
ARROWS 2' HIGH AND 10' ARMS
3 ROWS AT THE FOOT OF THE OGEE FALL
BLOCKS 5' X 2' X 2'
3 ROWS AT D/S END OF PUCCA
2 ROWS 16' D/S OF THE VERTICAL FALL.
INDICATES THAT IT IS
BLOCKS THAT CAUSE
HIGH VELOCITY JET
RISE.
W.S. R.L. 672·6
W.S.R.L 664·6
1'·47
123 113 103 93 83 73 63 53 43 33 23 13 0 7 17 27 37
ARRANGEMENT OF ARROWS & BLOCKS.
(c)
667.10
62'·0
30'·0
23'
5'
7'
29'
25'·5
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PANJNAD WEIR ANNEXE

DISCHARGE 7 LACS CUSECS

FIG. 9

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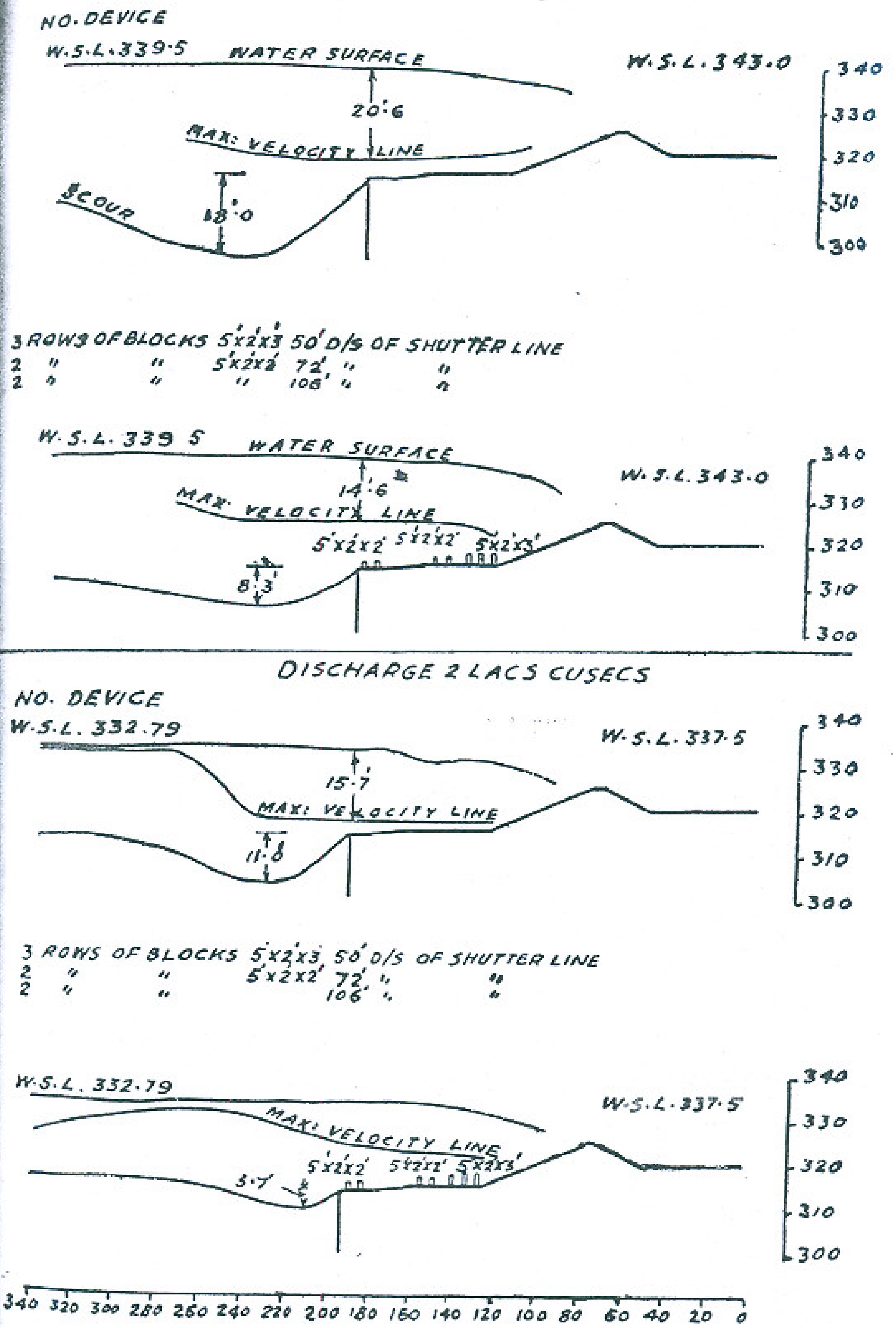

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FIG. 10
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PANJNAD WEIR ANNEX

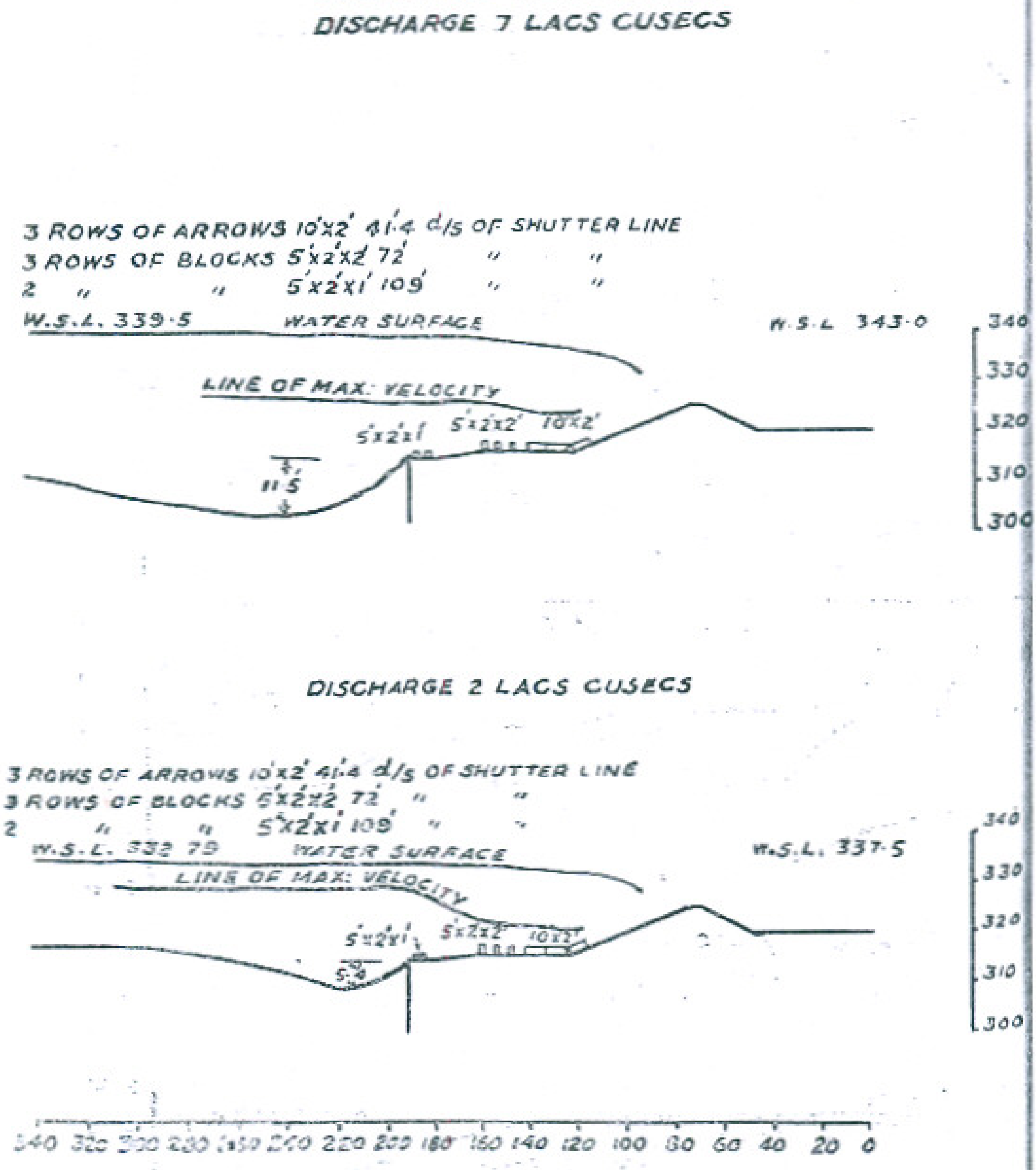

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FIG. 10 (CONTD).
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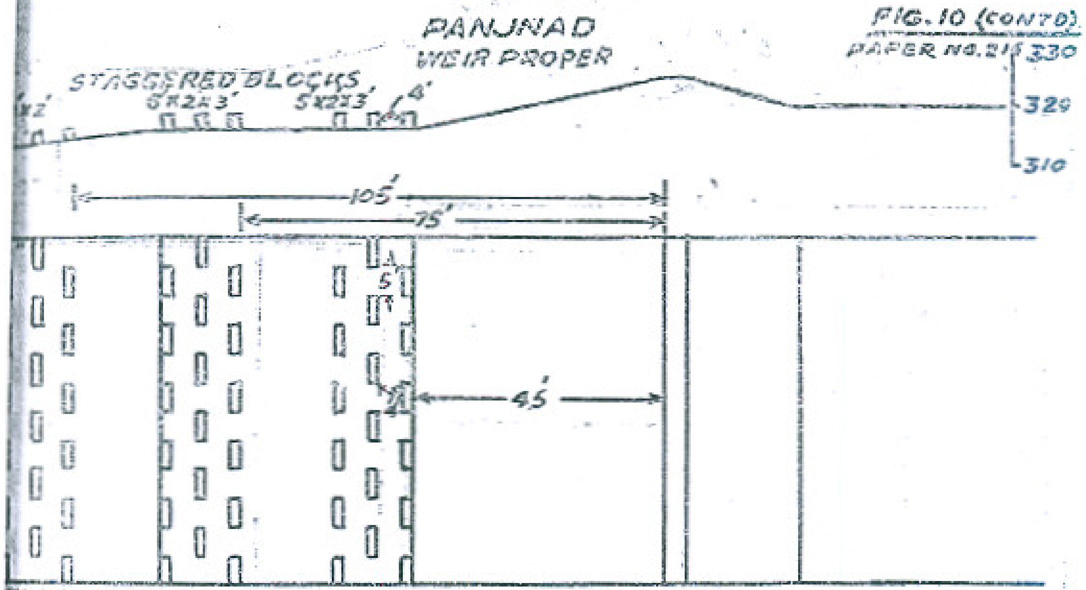

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