PAPER No. 215.

RECONDITIONING OF MARALA WEIR.

By E. O. Cox, M. B. E., I. S. E., Superintending Engineer,

and R. B. L. Ganpat Rai, I. S. E., Executive Engineer.

Marala was the last of three similar wide-shuttered weirs on sand foundations constructed in the Punjab. Like Khanki and Rasul, it consisted of 8 bays of 500 feet with a set of undersluices on the left flank where the Upper Chenab Canal takes off. In order to show the need for reconditioning this work before a failure or partial failure actually took place as in cases of similar works elsewhere, it is proposed to deal, somewhat frankly, with the failure of the latter, the reason for these failures and the repairs and alterations carried out as a result of them; as it was largely because of those failures that it was decided to undertake the work at Marala last winter. Before doing so, it must be pointed out that weirs on sand foundations are make-shifts at best and can never be considered sound engineering structures. They are seldom used outside India and are only constructed at the Headworks of our canals from motives of economy and maintained intact by constant care and expense. Marala weir is, next to Khanki, the most important in the Province as on it depends the water supply to the Upper Chenab and Lower Bari Doab Canals, the combined net revenues from which are nearly a crore of rupees per year. If this weir was gapped in July at the beginning of the flood season, there would be little or nothing left of it by the end of August, and the *kharif* crops on the two Canals could not be matured nor the succeeding *rabi* sown, while a partial failure in September would seriously damage these crops.

Khanki Weir.

This was originally a flimsy structure constructed in 1891 without upstream and downstream cut-offs. Part of the crest subsided in 1892, and a further part in 1895. In the years 1896 to 1898, the upstream impervious floor was extended 42 feet and protected at the upstream end by a well line (20 feet deep) or wooden sheet pile line, but no downstream cut-off was put in then or later. Subsequently up to 1932, the work was only maintained intact at heavy cost by constant repairs. It withstood two record floods of about 7,50,000 cusecs discharge in successive years in 1928 and 1929, apparently without serious damage, but in August, 1932, a year of normal floods, part of the downstream glacis in bays 3 and 8 was undermined by " piping", and caved in, and the weir had to be almost entirely reconstructed in the next three working seasons at a cost of 38 lacs of rupees. This amount included the cost of depressing and gating bays 4 and 8 and constructing tunnels in the undersluice pocket to exclude silt from the Lower Chenab Canal. This weir, which is now provided with an impervious steel sheet pile cut-off downstream and arrows to turn up and dissipate the high velocity jet, which was responsible for the damage to the loose protection below in the past, is now reasonably safe against failures in future provided the work is adequately maintained and cavities, if they occur, are detected and filled in each winter, before they develop to such an extent as to cause the glacis or floor to cave in above them resulting in the weir being gapped. A full description of the failure of this work and the alterations and repairs carried out, is given in Punjab Engineering Congress Paper No. 195 (1935), " Reconstruction of the Khanki Weir" by R. B. A. N. Khosla, I. S. E. A cross section of the Weir before and after reconstruction is shown in Plate I.

Rasul Weir.

As a result of a flood of 8·75 lacs cusecs in August, 1929, which concentrated in the centre of the weir, parts of bays 2, 3 and 5 were washed away, while half of bay 4 completly disappeared. Repairs to the damaged bays only took two years to complete, and cost 35 lacs of rupees. In one of the bays, No. 7, which had apparently escaped damage in this flood an unsuspected cavity 275 feet by 50 feet was discovered between the crest (A) line of wells and that (B) half way down the glacis. This cavity is said to have formed when this bay was damaged in 1916 and when it was discovered and examined 14 years later, it was only covered with a flat arch of stone on end in lime mortar 15 inches thick. This instance shows how long a large cavity can exist before the inevitable and possibly disastrous collapse of the structure over it. The damage to Rasul Weir in 1929 was attributed at the time to swirls round the upstream groynes, but " piping" was far more likely to have been the root cause of the failure as it was the cause of the formation of the cavity in bay 7. The repairs to Rasul were carried out while Bligh's creep theory of weir design still held sway, as it was not till three years later that model experiments carried out in the Irrigation Research Institute, Lahore showed this theory was incorrect and dangerous. No deep downstream pile line or other cut-off exists below this weir and unless one is put and adequate means provided to detect cavities in time, this weir may fail again. A typical cross section of the weir is shown in Plate I.

Islam Weir.

In the early hours of the 19th September, 1929, when the discharge in the river was low, six bays of Islam, one of the modern gated weirs on the Sutlej, collapsed and were rebuilt at a cost of 37 lacs of rupees. This weir had a pile line 30·0 feet deep under but *not connected by an impervious joint to the crest* and no pile or other cut-off up or downstream of the impervious floor. This work was also designed on Bligh and in all probability the failure was due to " piping " and not to the causes given by the Islam Committee in their report. This committee dealt with the necessity of a downstream pile line in the following paragraph extracted from their report. " A line of sheet piles should always be provided at the end of the impervious floor. This is the most vulnerable point in the work and failure to hold it places the whole weir in danger." The words underlined above seem to show that the committee considered that the sole function of a downstream pile line was to buttress up the impermeable floor if and when the loose protection below it was carried away and a scour hole formed in consequence and not as well to dissipate residual pressure at the end of this floor. Unfortunately owing to the difficulty of driving piles through boulders, old gates and concrete deposited at this point during the failure, this pile line has not been driven as yet and till this is done the work cannot be considered safe.

Deg Fall.

This was constructed on a sandy bed in the Deg Diversion channel, Upper Chenab Canal in 1928. When the supply was first passed over the work, violent springs blowing sand appeared in the joints in the block area downstream which consisted of three lines of concrete blocks, 10·0′×10·0′. These joints were grouted up to flatten the hydraulic gradient but when the channel was opened and the head over the work increased to 4·0 feet, violent springs again appeared below the block area and shortly after a tunnel formed in the right half of the work under the R. C. floor 1·35 feet thick, the latter buckled and caved in and the fall collapsed with a head of 5·0 feet and a hydraulic gradient of over 1:20. This was one of the first weirs on sand foundations in the Punjab constructed without a deep downstream cut off and the first to fail. At a subsequent inquiry, the failure was attributed to the fact that the work was constructed in a scour hole subsequently filled up with fine sand but whatever doubt there may have been about the failure of other works described in this paper, there can be none whatever that in this case it was due to " piping". The work was abandoned and a new fall constructed 1,000 feet away seven years later. This was designed on modern lines, is surrounded with a box of sheet piles rigidly tied into the floor and provided with arrows and blocks to dissipate the energy of the falling water and pressure pipes to indicate cavities. The new work is thus as safe as it can possibly be. Plans and photographs of both falls are given in Punjab Engineering Congress paper No. 204 (1936), "The Deg Diversion and the Combined Fall and Aqueduct," by B. K. Kapur, Esquire, I. S. E., Executive Engineer.

The following two failures that occurred outside the Punjab are next described.

The Deoha Barrage—United Provinces.

This as originally constructed was a gated weir 500 feet long with a well line 20·0 feet deep under the crest but no upstream or downstream cut-offs. This partially failed in 1928 in a similar manner to the Anderson Weir described in the next paragraph, viz., the downstream floor cracked and a number of cavities were discovered below when the area round the cracks was dismantled. The damaged floor was replaced and a 20·0 feet steel sheet pile line put upstream. Within a year later, in September, when the work was again headed up, violent springs burst out downstream and a considerable part of the floor both upstream and downstream collapsed suddenly, before the gates could be opened to relieve the pressure. The hydraulic gradient at the time failure occurred was 1 in 30 or half that considered by Bligh to be safe. The floor was again repaired, a line of sheet piles 15·0 feet deep added down-stream and the weir has given no further trouble. This work also obviously failed through "piping".

Anderson Weir—Bengal.

This work 3750 feet long which was also designed according to Bligh and completed and opened only five years ago was similar to the Khanki and Marala Weirs, the main difference being that it had a high crest instead of shutters, no divide groynes and no deep downsteam cut-offs. It is interesting to note that in the design of this work in the 1914 project, up and downstream cut-offs were provided but these were omitted in the final sanctioned estimates as they would have caused an excess in the project and were not essential according to Bligh. After a record flood of 6·5 lacs cusecs in August, 1935, two parallel cracks were discovered extending across 4/5ths of the weir and dividing the downstream glacis into approximately three equal parts. As a good deal of the loose stone protection below the cracks remained intact and in position it is obvious that the damage was due to "piping". The weir has since been reconditioned on modern lines with up and downstream pile lines (the latter are Franki concrete sheet piles), energy dissipators in the form of staggered blocks downstream and pressure pipes to indicate cavities in future (to a limited extent). The discharge of the Damodar River drops to a trickle for six months in the year during which time the canal is closed so unlike the Punjab weirs it is always possible to make a thorough examination of the work in this period. A cross section of the weir before and after reconstruction is shown in Plate I. The upstream pile line is necessary because the river approaches the work in flood at an angle from the right and owing to the flimsy upstream loose protection and the absence of groynes, the upstream apron may be undermined and carried away in floods owing to cross flow.

In a fairly recent paper before the American Society of Civil Engineers entitled "Security from under seepage in masonry dams on earth foundations," by Lane, the author analysed the designs of 72 weirs out of which 24 had failed by "piping". He pointed out that failure had not occurred in a single case where deep up and downstream cut-offs had been provided. Four weirs in the Punjab, one in the United Provinces and one in Bengal on sand, all designed or remodelled according to Bligh, had failed unexpectedly through 'piping' between the years 1928 and 1935 and because of these failures and the History of Marala since it opened in 1912, described later, it was felt that the latter might also fail without any warning with disastrous results to the two canals depending on it for their supplies.

Comparison between the designs of Khanki, Rasul, Marala and Anderson Weirs.

It is instructive at this stage to compare the designs of four of these similar weirs, Khanki, Rasul, Marala and Anderson in some respects. These weirs were designed to stand the same maximum head of 10·0 feet. A cross section of each is shown in Plate I on which the discharges and up and downstream water levels in the greatest floods that have so far passed over them are also shown. In the case of Marala, the position and shape of the standing wave in bay 5 in the flood of August 1929 with a discharge of 130 cusecs per foot run is given. This wave as measured was 10·2 feet high and its trough extended well below the (B) line of wells. The depth of the wave in the same flood at Khanki was not measured but did not exceed 5·0 feet and this wave formed well-up the glacis. The Marala Weir, the design of which was based on those of Khanki and Rasul, has 3 well lines, well line (*A*) 24.0 feet deep on the upstream end, another (*B*) 18·5 feet deep half way down the glacis and a third (*C*) 16·0 feet deep at the downstream end of the impervious floor. Khanki had only one cut-off—a 20.0 feet deep well (or wooden sheet pile line) upstream put in as already pointed out in the years 1896 to 1898 after the crest had settled. Rasul had a deep well line under the crest, and another half way down the glacis while the Anderson Weir had no cutoffs at all. The lengths of impervious floor (or creep paths) in the case of each work are :—

Khanki	.. 183·0	Marala	.. 140·0
Rasul.	.. 134·0	Anderson	.. 114·0

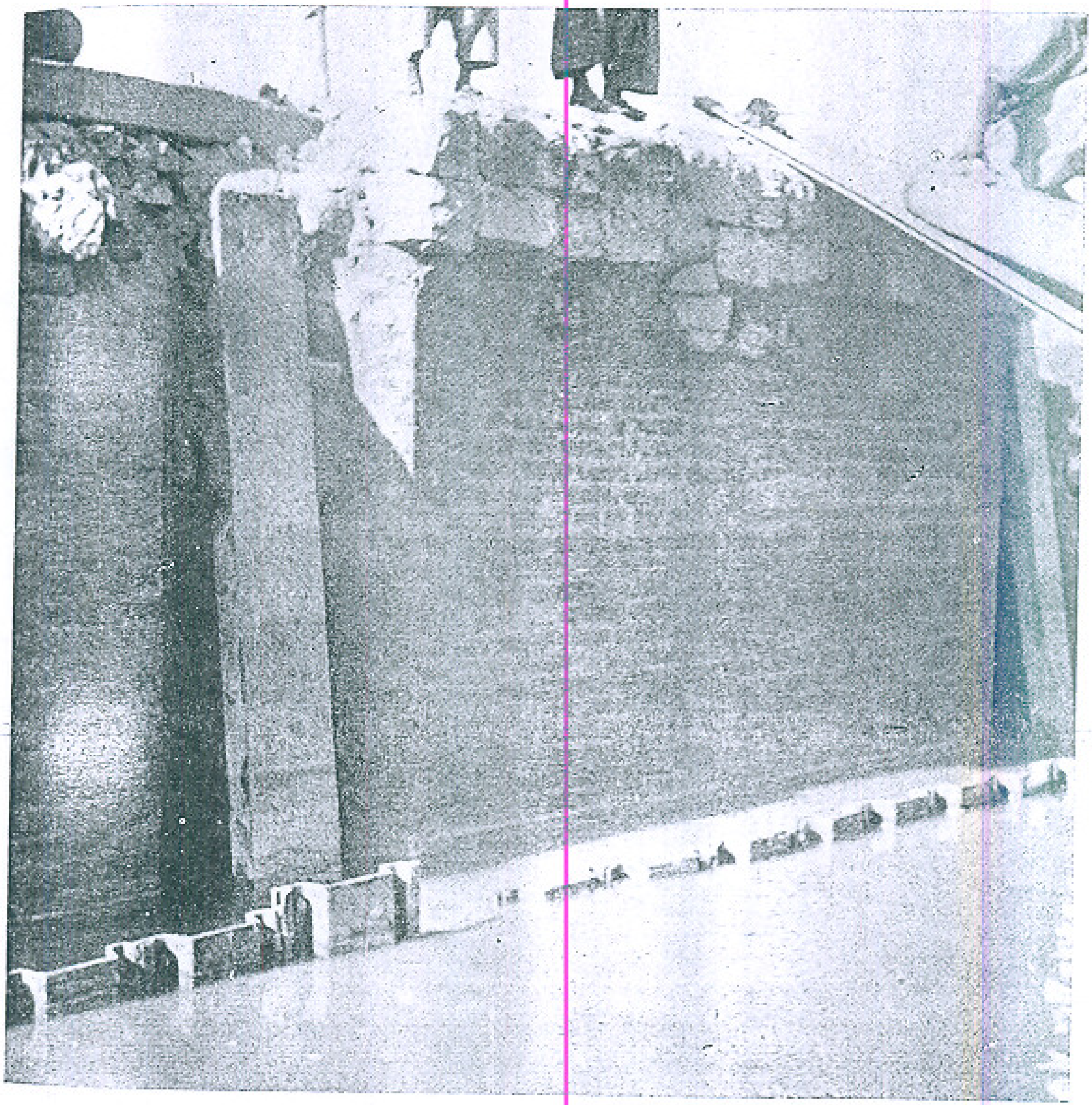
The upstream depth on the floor in floods at Rasul is much less than in corresponding floods in the case of the other three and this probably accounted for the swirls that carried away the upstream groynes and undermined the apron in the record flood of August 1929. The main defects at Marala were the flat slope of the downstream glacis and the comparatively high level at which the downstream loose protection was laid. This latter is shown by the following table :-

	Flood discharge.	Approx: discharge per foot run.	Downstream Depth
Khanki	7,50,000	170	19.9
Rasul	8,75,000	200	19.5
Marala	6,86,000	170	16.6
Anderson	6,50,000	155	22.3

There is nothing on record to show why the downstream floor at Marala was kept 3·0 feet to 4·0 feet higher than those at Khanki and Rasul. The sand at Marala is much coarser than at the site of the other two weirs and the amount of pumping required during construction consequently many times as great and with the pumping plant available it may have been impossible to lay the floor at a lower level. The slope of the downstream glacis—1 in 15—was the same as at Khanki and Rasul. Model experiments in recent years have shown that a slope of 1 in 4 or even 1 in 3 ending in a flat floor gives the best results as it keeps the standing wave under all conditions well up the work. As a result of the enormous standing waves that form in flood owing to this defect the semi-pervious glacis between the B and C lines of wells, the downstream groynes and the blocks and pitching stone beyond have been damaged or partly washed out over and over again and since 1912 have cost 5½ lacs of rupees to repair or replace. During the work carried out last winter, it was found that over half of the original concrete blocks had been washed away in the last 25 years and replaced by cement concrete.

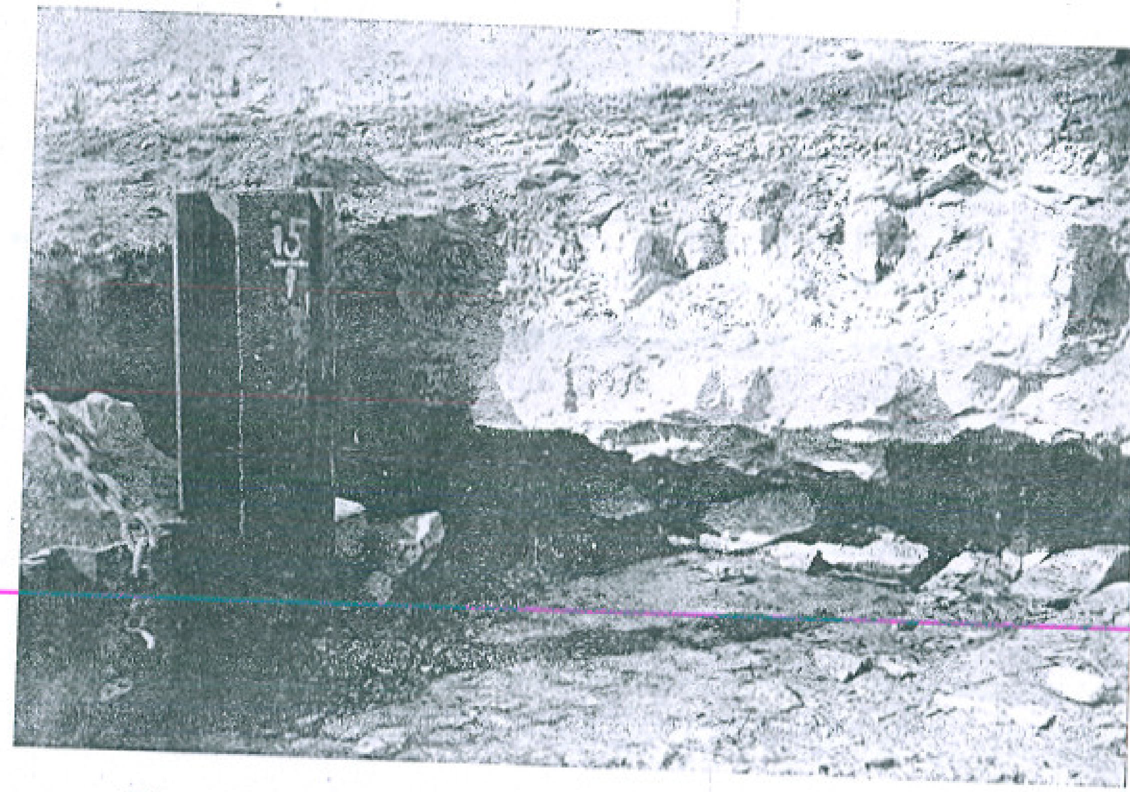
Plate II gives a cross section of the weir as originally constructed and also shows the crest raised 2·0 feet to R. L. 802·0 in 1924 and 1925. The weir was designed before Bligh's theory was recognised and used. The total length of the work was 320·0 feet out of which the impervious floor was 140·0 feet and the upstream and downstream loose protection 70·0 feet and 110·0 feet, respectively. The hydraulic gradient was 1 in 14 as against 1 in 15, recommended by Bligh. During the dismantling of the downstream glacis last winter gaps 3″ to 12″ in width were found in all the spaces between the wells in the B and C lines and the wooden piling. (Photo No. 1). The so-called semi-pervious glacis between the B and C lines of wells which was copied from Khanki and Rasul was also a source of weakness. There is nothing on record to show why this peculiar form of construction was adopted in these three weirs. The designers probably had a vague idea that this would release any residual pressure left below the B line without blowing sand and at the same time the glacis would be strong enough to stand

Photo No. 1.



Badly staunched well *Jhiri*. Nov. 1936.

Photo No. 2.



First pile in Bay No. 3 and hollow under old glacis between B and C lines of wells. Nov. 1936.

up to the dynamic action. It did neither. The section was 1·75 feet of rubble masonry in lime mortar on 1·5 feet of dry stone and as pointed out in the previous paragraph it was constantly damaged or removed in floods even as low as $2\frac{1}{2}$ lacs cusecs. When this part of the glacis was dismantled last winter it was found to be hollow from end to end. Photo No. 2 is typical of its state. If the gaps between the downstream wells had been properly closed off, the semi-pervious method of construction omitted and the downstream floor kept 3·0 feet to 4·0 feet lower the work would have been the soundest of any weir in the Punjab constructed before or since and given little trouble.

History of Marala Weir.

It is now proposed to deal with important points in the construction of the weir and its subsequent history as there is a good deal to learn from these and the history shows the strain a river weir has to stand. Construction started in the winter of 1908-09 and was completed in May, 1910. Marala was one of the few weirs built in the actual bed of the river and the work was accomplished under great difficulties, one of the greatest of which was unwatering. In February, 1909, a record winter freshet of 1,50,000 cusecs carried away all bunds and work was stopped till the succeeding November. In the glacis above the B line of wells, the bottom (flat) layer of masonry was apparently laid dry and a weak grout of lime *surkhi* and sand poured over it which did not completely fill the joints between the stone. This was evident from an examination of this part of the weir during dismantling last winter. The state of these open joints showed that water had been flowing freely through them over the sand below. In order to keep down the upstream water level and facilitate pumping and the subsequent diversion of the river over them while the remaining bays were being constructed the glacis in bays 1 to 6 was first built to a reduced section, the crest being kept at R. L. 797·5, *i.e.*, 2·5 feet below the final crest. In June 1909, while raising the reduced section to full height the Executive Engineer reported the existence of a number of transverse cracks in bay 3 one along the crest line and two between the crest and the B line of wells—and that the rubble masonry had settled 2″ to 3″ in some places below the crest. The Superintending Engineer in forwarding the Executive Engineer's report did not think those cracks and subsidences were of any importance "as *they occurred in what may be called the soling coat of the weir or in other words work which would not have been done if the work had been completed to the full section of the weir*" (*at first*). It was evidently considered at the time that the glacis although in lime mortar need not be more than 2·5 feet thick. This shows the rudimentary knowledge of pressure condition under a weir on sand when Marala was constructed.

The weir was first put into commission in April, 1912 and in the following October, after a monsoon of few and moderate floods, the glacis was found to be full of cracks and springs. Most of these were in the so-called semi-pervious section below the B line of wells but some were above it and even above the crest. In commenting on the damage in a report to the Chief Engineer the Superintending Engineer considered that "*the excess depth of wells (A line) upstream is an encouragement to piping because the spans between the wells partially closed off by timber piling to some extent prevent sand washed out being at once replaced.*" This amazing comment passed unchallenged and further shows how little the engineers at the time knew about the correct design of weirs on sand foundations. In dealing with the Superintending Engineer's report the Chief Engineer (Mr. Bennett) who was Superintending Engineer in charge during construction stated that in his opinion the springs were due to the interstices in the rubble masonry not having been completely filled up with mortar during construction. The cracks must be due to subsidence caused by piping or sand being blown through the interstices of the masonry. In a paper read before the Punjab Engineering Congress in 1913, Mr. Colyer the Sub-Divisional Officer in charge of Marala Headworks stated that in the winter of 1912-13 he grouted up 16,722 springs and 9,133 feet of cracks. The discharge of one of these springs was over a cusec and many of them were blowing sand. In summing up the discussion on this paper the President (Mr. R. E. Purves) stated that "it showed that the present knowledge of the Hydraulic Gradient in Canal Works was in its infancy" and moreover "the weir was in a thoroughly unsound condition in October 1912." This in spite of the fact that only the year before the Inspector General of Irrigation had stated it was of strong design and excellent workmanship.

In the following year fresh cracks and springs appeared and in 1917 after a flood of $5\frac{1}{2}$ lacs cusecs the stone on edge course (*kharwanja*) 15" thick in bay 6 was found to be uplifted or bulged in an area 90 feet$\times$15 feet above the B line of wells. After a good deal of discussion this was finally attributed to the back pressure from the standing wave acting under the *kharwanja* course which had an imperfect joint with the lower masonry. In subsequent years this bulging or "blistering" as it was called occurred almost all over the glacis between the crest and the C line of wells. After trying various methods of repair between the years 1932-36 almost half the *kharwanja* course between the crest and the B line of wells was removed and replaced in cement mortar after all open joints below had been grouted up under pressure. Moreover in order to try and stop the back pressure from the standing wave from acting back, a cut-off well of cement concrete 3·25 feet deep was put in the centre of the B line of wells in some of the bays. In 1922, the Executive Engineer drew attention to a serious depression that had existed for some years in bay 8 between the B and C lines of wells near the right flank where springs were very active. He concluded that those well lines were not arresting flow from under the weir and recommended a downstream steel sheet pile line. Next year he pointed out that most of the joints in the weir were open and that there were numerous springs in bay 1 from which he concluded that there were large cavities in this bay. In the winters of 1924-25, 1925-26 the crest of the weir was raised 2·0 feet to R. L. 802·0 and the opportunity was taken at the same time to examine and repair the upstream apron. This was found to be full of hollows and open joints 6″ to 9″ deep and over half a lac of rupees was spent in filling these joints alone.

In the record flood of 6,86,000 cusecs on 1st September 1928 and one almost equally great of 6,60,000 in the following year on the 29th August 1929 a good deal of damage was done below the weir. In the first flood, a good deal of the blocks and loose stone in bays 4,5,6 and 7 were carried away and groynes 4 and 6 overturned. In the following year, groyne 4 was again damaged, groyne 7 overturned and parts of the loose protection in bays 4, 5, 7 and 8 washed away. The damge in bay 4 in both years was particularly severe. In addition to the removal of the the loose protection in this bay the glacis between the B and C lines was carried away in a length of 150·0 feet. The repairs downstream of the weir in these two years cost over $3\frac{1}{2}$ lacs of rupees. Subsequently in a medium flood of 2,50,000 cusecs on the 15th July, 1930 an area 25 feet×15 feet below the B line was washed out as well as 250 feet length of the loose protection below. The repairs cost Rs. 90,000. This shows serious damage was not confined to high floods.

As a result of the damage in this year, the Chief Engineer called for a report on the following points :—

(*a*) Will the standing wave form on the glacis under all conditions ?

(*b*) Is the latter safe against uplift ?

(*c*) Is the velocity over the loose stone excessive ?

As regards these points it was pointed out in reply that under certain conditions the wave formed between the B and C lines and the section in this area was unsafe. Calculations made in 1931 showed this part of the glacis would have to be thickened to $6\frac{1}{2}$ feet and the glacis extended by 50 feet to make it safe for floods over 3 lacs cusecs. Next year, tests were made at Poona on a model of Marala Weir which are described in Punjab Engineering Congress Paper No. 170 (1933). In this paper Mr. Inglis advocated the construction of a baffle wall 4·0 feet high on the B line and a deflector 1·68 feet at the end of the blocks but his recommendations were not accepted.

A detailed examination of the weir in October 1934 showed its condition was far from satisfactory. Between the crest and the B line parts of bays 1, 3, 4 and 5 and the whole of bay 2 was " blistered". Pits were dug in every bay through the *kharwanja* course and fine sand was found packed between this course and the lower masonry and springs were working in every pit. Conditions were particularly disquieting in bay 2 where there were two longitudinal cracks and innumerable springs above the B line. An examination of the glacis below the B line, where as already stated above the trough of the wave formed in floods, showed that there were cavities almost from end to end. The same winter in order to try and determine whether these cavities also existed above the B line as suspected for many years, three holes at equal intervals in each bay were made by means of a Calyx drill just downstream of the crest block. The centre hole in bay 2 disclosed a cavity 7½″ deep which a pump discharging about a fifth of a cusec could not fill, while in one hole in bay 3, in three in bay 4 and in one in bay 7 there were cavities 2″ to 3″ deep. These cavities were however nothing like as great or as serious as those found in the same position at Khanki. During the reconditioning of Marala Weir last winter, pressure grouting was done at close intervals on either side of the crest block and comparatively little cement grout could be forced in. Also when the glacis above the B line was dismantled only one cavity 8 feet by 8 feet near the centre of bay 8 and just below the crest line was discovered. *A pressure pipe close by did not reveal the presence of this cavity.* Punjab Engineering Congress Paper No. 195 (1936) shows that cavities at Khanki were large and numerous and required enormous quantities of cement grout to fill them. The reason why there were not more and greater cavities at Marala between the crest and the B line of wells is not clear. One explanation is that the sand at Marala was too coarse to be moved by the residual pressure at the B line.

In view of the state of the weir in 1934, experiments were then carried out on a model in the Hydraulic Laboratory, Lahore. It was impossible to determine exactly what would be a fair representation of the conditions at Marala in the model but the following assumptions were made :—

(*a*) The well lines were leaking, (*b*) the top 1·5 feet of sand below the weir was coarse, (*c*) there was a hollow between the *kharwanja* course and the loose stone below between the B and C lines. Of these (*a*) and (*c*) were subsequently found to be correct.

As regards (*a*), observations in pressure pipes put in above and below the B line in 1934-35 showed that with a head of 8·0 feet over the weir, the drop in pressure across the B line was 0·54 feet (=7%) and this low drop indicated that this well line was not impervious. During the year 1935-36, three lines of observation pipes were put in in each bay of the weir at distances of 125, 250 and 375 feet from the left of each bay, the pipes in each line being just below the crest block and above and below the B line. Three more lines were put in, one in bay 6, 50 feet from the right, another in bay 7, 50 feet from the left and the third in bay 8, 50 feet from the left. The pipes in these lines were put in above and below the A line, the crest and the B line. Observations were made on a number of occasions, care being taken to see that the head over the weir had been steady for a considerable period before the observations. The two diagrams on Plate III show the results of observations made on the 10th February, 1936 and 22nd March, 1936 in bays 2 and 6, respectively. As the silt deposits upstream of the weir increase, under the present conditions, from left to right, the two sets of observations may be considered typical of the left and right halves of the weir. These observations showed that there was either no drop from the crest to the B line or that its extent was negligible, and that in bay 2, where a pipe had been put in above the C line also, the drop between the B and C line was small and there was a residual pressure of 26 per cent above the C line.

It appeared from these results that there were cavities under the floor in many of the bays. This combined with the high residual pressure above the C line and the recorded fact which was verified during the dismantling of the weir floor in bay 8 last winter that some of the wells in this line were only 4 to 5 feet deep led to the conclusion that the weir was in serious danger of collapse.

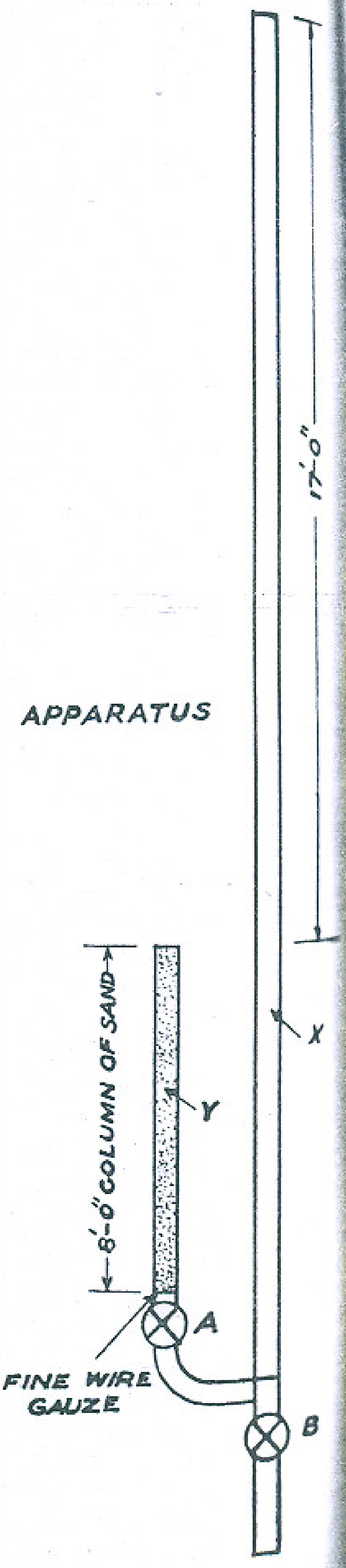
It also shows that pressure pipe observations on a weir which are the only practical method so far devised for detecting cavities without dismantling the work down to the sand, are not altogether reliable in a varying or coarse sand stratum like that at Marala, also unless these pipes are closely spaced, cavities between these may remain undetected. *It is vitally important to the safety of these weirs to devise an instrument which can conveniently and speedily detect cavities under them.* The Irrigation Research Institute are working on the design of such an instrument at present.

It has been shown that the weir was designed on wrong principles due to the elementary knowledge of hydraulic conditions. It was constructed with unsuitable mortar under very great difficulties, one bay partially subsided under no head during construction and since it was brought into operation in 1912, it had only been maintained intact at considerable expense. The whole of the impervious section from the crest to the B line of wells was full of cracks and open joints through which innumerable springs were working under small heads and the pressure pipe observations gave every indication that cavities existed below. Below the B line which had to stand the terrific pounding action of the standing wave, the glacis was too thin and cavities existed along it almost from end to end. Thus this weir appeared in immediate need of reconditioning to prevent an early collapse similar to those already described.

Purpose of Reconditioning.

It was first proposed to drive a sheet pile line 30·0 feet deep upstream and as close to the crest block as possible and tie it into the latter with an R. C. cap as at Khanki. Downstream, in view of the fact that the standing wave under flood conditions formed between the B and C lines of wells, the existing glacis was to be replaced by a cement concrete slab, ending in and tied to a 15·0 feet sheet pile line above and as close to the C line of wells as possible. The *kharwanja* course between the

B line of wells and the crest was to be removed and relayed in cement mortar after open joints and cavities below had been grouted up where this method of repair had not been carried out already. The usual energy dissipators, arrows and blocks and pressure pipes were to be provided. On further consideration, the upstream pile line and R.C. cap provided at Khanki were omitted as it was considered that the upstream well line 24·0 feet deep was sufficient to buttress up the apron and prevent it being undermined and carried away in floods and an impervious cut-off at this point was unnecessary as the maximum head allowed over the weir—10·0 feet—was small. In view of the fact that the masonry glacis 1.75 feet thick between the B and C line of wells had not blown up under the heads caused by the standing waves of 10·0 feet high or over in the flood of August, 1929, it was considered that a cement concrete slab 4·0 feet thick in this area would be ample but as an added precaution, the top 1·0 foot of this was to be proportioned at 1:2:4 and in this a reinforcement grid of ½″ bars 9″ apart provided and tied well down to the new pile line as well as the two well lines B and C.



Early in the year 1936, an experiment was performed at Marala to determine the exit gradient of the river sand. The apparatus used which is sketched in the margin was erected against weir groyne No. 1. *X* and *Y* were the two arms of a 2″ diameter pipe, fitted with two stopcocks *A* and *B*. A fine wire-gauze filter was fitted into the pipe above cock *A*. Cock *B* was simply a drain cock by manipulating which it was possible to adjust the level of water in the arm *X* of the pipe. The sand to be experimented upon was filled in the pipe *Y*, rods being used to ensure compactness. Except in one case, a column of sand 8 feet long was used and a head of water up to 17 feet could be brought to act on this column. The head was increased gradually and when pouring water into pipe *X*, Cock *A* was kept closed to eliminate water hammer. Just before blowing started the surface was noticed to heave up a little. Infiltration commenced with heads of 4 to 6 inches only which showed that the frictional resistance of an eight-foot column of sand was overcome with only this much head. Blowing was allowed to continue for 15 minutes in each case and the head when blowing ceased was also observed. It was found that this head was 2 to 5·5 feet lower than the head at which blowing had commenced.

Three grades of sand, fine, medium and coarse, having mean diameters 0·22, 0·28 and 0·43 of a millimeter, respectively, were tested. The results which are the mean of a number of observations are given below :-

S. No.	Description of sample.	Head in feet when blowing started.	Head in feet when blowing stopped.	Length of column of sand.	Exit gradient Col. 3 / Col. 5.
1	2	3	4	5	6
1	Fine sand Mean Dia. 0·22 mm.	9·77	7·03	8′	1·22
2	Medium sand Mean Dia. 0·28 mm.	14·0	12·03	8′	1·75
3	Coarse sand Mean Dia. 0·43 mm.	18·3	16·9	6·7′	2·73

The experiment thus showed that 1·2 to 2·7 feet head of water was required for every foot depth of sand before the latter started moving. Assuming a factor of safety of 2 and the percentage of residual head above well line C to be 30 or 3′ of head with 10′ over the weir, a 6′ curtain wall would be sufficient to prevent springs at this point. In order, however, to provide for possible scour a 15′ pile line was provided.

The profile of the standing wave personally observed by the Executive Engineer (R. B. A. N. Khosla) in bay 5 with a discharge of 130 cusecs per foot-run is shown in plate I. In addition to its great height of 10·2 feet it has an abnormally long flat trough extending from just above the C line to well above the B line. The wave under similar conditions of head and discharge in the model was sharper, only 7½ feet high and formed much further up the glacis although in the model the glacis was practically frictionless and on the prototype fairly rough. The reasons for these differences could not be explained at the time and have not been understood since although the matter is all important for future weir design and, in view of this difference, the actual observations on the weir had to be accepted and a gravity section $7\frac{1}{2}$ to 8·0 feet thick appeared to be necessary not alone in the area between the B and C lines but up to the crest. This entailed dismantling the whole glacis and rebuilding it 8·0 feet thick at enormous expense.

The matter was considered at a conference at Simla in July, 1936. Considerable doubt was thrown on the accuracy of the standing wave observations made in August, 1929, in view of their abnormal height and shape but Mr. Khosla who was present and had made them was positive that they had been made correctly. The next and main point discussed was why the thin glacis between the B and C lines had not blown up under unbalanced heads caused by waves in floods of over 3 lacs cusecs. The results of the discussion on this important point were not conclusive. It was agreed that the pressure acted simultaneously with the formation of the waves. The following opinions were expressed :—

(*i*) As the glacis below the B line was semi-pervious, pressure at the B line falls to zero. This was not accepted as pressure observations showed residual pressure below the C line.

(*ii*) The pressure was reduced as it passed through the interstices of the sand. This was also rejected as the pressure is static.

(*iii*) The waves causing the unbalanced head lasted too short a time to blow up the glacis. These waves only last six hours at the most and if the recent theory that subsoil flow is similar to that of a viscous or semi-viscous fluid is correct, it is reasonable to assume that the pressure would not act till the peak of the flood had passed and the depth of water on the glacis had increased sufficiently to resist the pressure. It was decided to take no risks and in order to reduce the height of the standing waves in flood and cause them to form further up the glacis, it was decided to test the following proposals on a model and accept the one which gave the best results.

(*a*) Baffles 2, 3 or 4·0′ high on the B line and deflectors on the C line in accordance with Punjab Engineering Congress Paper No. 170 (1933).

(*b*) A subsidiary Weir 2·0 feet or 3·0 feet high with its crest above the B line and a steep downstream glacis ending in a cistern 3·0 feet deep. Calculations showed that the latter would form a sharp well-defined wave on or just below the B line with discharges between 40 and 162 cusecs per foot run. The shape of this weir and the actual and calculated waves with the crest kept 2·0 feet high and discharges of 40 and 133·5 cusecs per foot run are shown on plate IV.

In the model tests no wave formed at all and the proposals were abandoned.

Finally it was decided to adopt the bold course of dismantling the existing glacis from a line, a few feet below the crest where the 1 in 4 meets the 1 in 15 slope, rebuild it to a slope of 1 in 4 ending in a floor 4·0 feet thick with its top 4·0 feet below the existing floor so as to give a depth in high flood about 1·0 feet greater than at Khanki. This necessitated the whole of the loose blocks and stone being removed and lowered 4.0 feet, the former being replaced where necessary. The standing waves caused at Khanki by the record floods in 1928 and 1929 which passed over Marala a few hours earlier were not actually measured but were not more than 5·0 feet high and it was reasonable to assume that with the extra depth at Marala after it was reconditioned, the waves in high flood in future would not be dangerously high.

Scheme of Reconditioning.

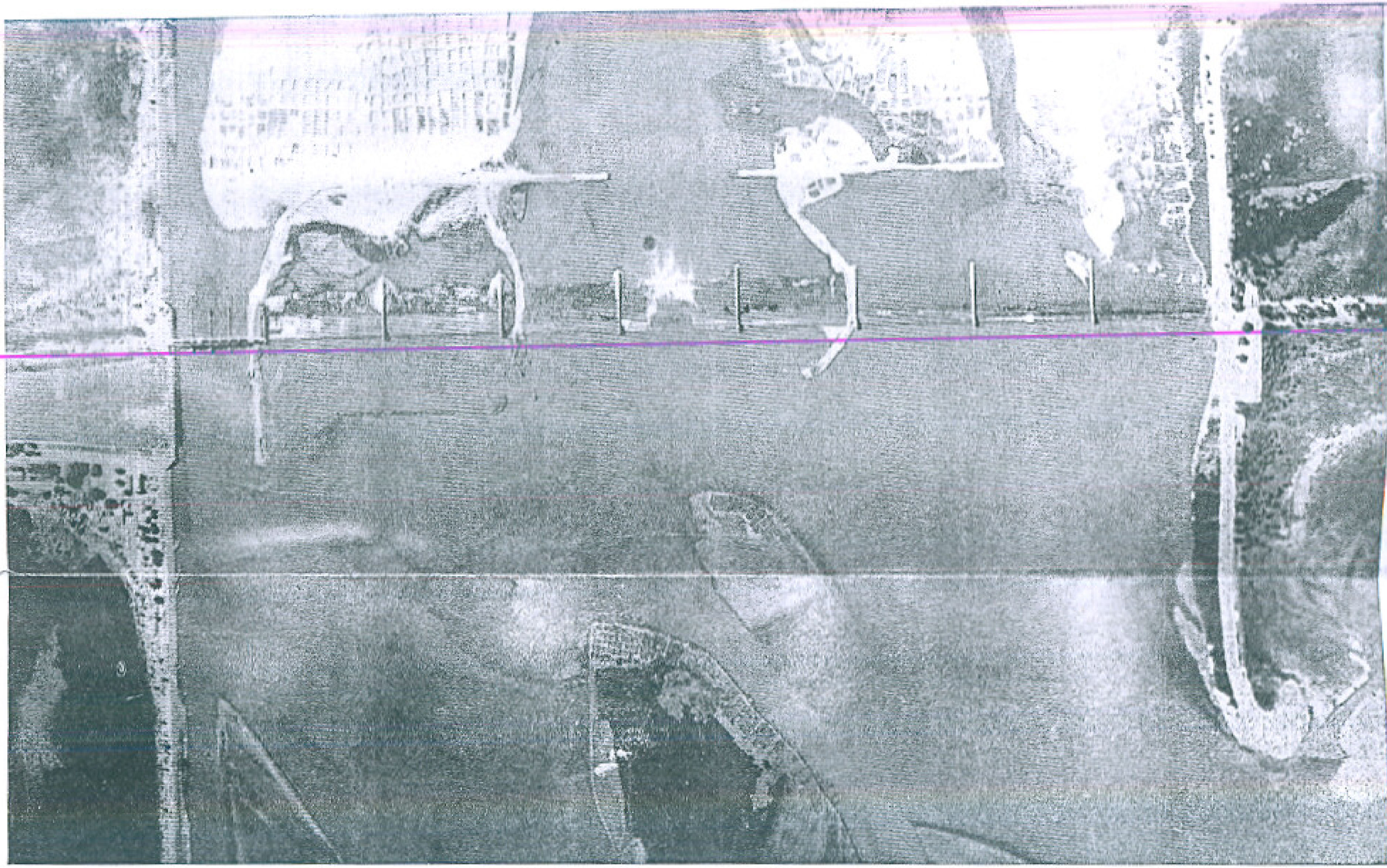
It has been stated above that in the original construction of the weir one of the greatest difficulties met with was unwatering. Owing to the coarseness of sand in the river bed pumping is heavy even under normal conditions. Winter freshets are another factor to be reckoned with. In a normal year, after the middle of December freshets in the Chenab river are fairly frequent and at times large and in planning a work of any magnitude in the river bed the manner of escaping these freshets over the weir and through the undersluices has to be given serious consideration, as not only do they throw an enormous strain on the pumping plant by increasing the head against which it has to work but by causing a breach in the ring bunds they may delay the work considerably if not stop it altogether for the rest of the working season (as in 1909). Another item which had to be considered was that during the period the work of reconditioning would be on, not only would the Upper Chenab Canal have to run but some water would have to be escaped below the weir for feeding the Lower Chenab Canal. And finally the question of time was of vital importance. The object aimed at was the completion of the work in one working season as spreading the work over two seasons meant an additional expenditure of three to four lacs ot rupees on works and establishment.

Three alternative proposals were considered, viz., (*i*) starting the work from bay 8 (right flank of the weir) and proceeding towards the left, (*ii*) starting from both ends and meeting in the centre, and (*iii*) starting from bay 1 (left flank of the weir) and proceeding towards the right.

All information available from the records regarding winter freshets was collected and studied with the object of arriving at a conclusion as regards their nature, frequency and incidence. This study showed that generally speaking, freshets were rare in the months of October and November, that they started about the middle of December and continued during the months of January, February and March with increasing frequency and size. It was found that whereas a freshet of 40,000 cusecs in December and of 80,000 cusecs in January was about the maximum that could be expected, discharges of 150,000 cusecs had actually passed down the river in February and March and that in the latter months, freshets of over 100,000 cusecs were fairly common. It was also noticed that these big freshets generally occurred as a result of prolonged spells of rainfall in the hills and that a freshet attained its peak at Marala about three days after rain had started at Riasi, 40 miles up the river.

Adverting to the three alternatives mentioned above, No. (ii) was ruled out on a number of considerations. It meant the splitting up of the available plant and the supervising staff. The plant was old and none too efficient and in case of a breakdown work in the section in which it was employed would have come to a standstill. It also meant working in the centre of the river during the freshet season and being surrounded by water on all sides during a freshet, a contingency which could not be viewed with equanimity. The choice thus lay between proposals Nos. (i) and (iii). It was realized that work in the left half of the weir would be more difficult than in the right. The left half of the weir is subject to direct attack from the Jammu Tawi, an affluent of the Chenab which joins the latter on the left bank above the weir and which is subject to sudden spates which come down with great velocity. This part of the weir is also subject to parallel flow on the upstream side because the main stream of the river is on the right at present and the canal has to be fed from it by means of a channel flowing parallel to the weir. Again lowering the water level in bays 1 and 2 would present more than ordinary difficulty because of the high head from the water level in the pocket against which work close to the left flank of the weir would have to be done. On the other hand, the right two bays of the weir occupy a sheltered position on account of being masked by the right upstream guide bund and are not exposed to much action even during freshets. Also the silt blanket which forms on the upstream of these bays renders unwatering a comparatively easy affair in these bays. Taking all this into consideration it was decided to start work from the left and proceed towards the right. Work would thus be done under the most benign conditions as the more difficult part of the work would be taken up during the earlier part of the working season when the worry inseparable from a river freshet in a work of this nature would be non-existent.

Another factor which led to this decision being arrived at was the existence of high shoals in the river both upstream and downstream of bays 1 and 2 at the end of September, 1936. Photo No. 3 which shows an aerial view of the Headworks taken about the middle of October, 1936 gives a good idea of the shoals downstream of the weir. These shoals unless utilized in the beginning of the season were liable to be carried away if there was an early freshet, and in particular the upstream shoal was going to be eroded in any case by the stream running parallel to the weir and feeding the canal. Thus the conditions which existed



Aerial view of Marala Head Works. October, 1936.

in the beginning of the season could not be expected to last till December or January when the ring bunds in these bays would be taken in hand if work were started from the right. The construction of these bunds then would be a much more difficult and expensive task as they would have to be taken up from much lower levels and built against heavy odds in the shape of river freshets.

A programme was accordingly drawn up on the assumption that work would be started from the left flank of the weir. A copy of this programme is given as Plate V. It will be seen that it was anticipated that work in the left half of the weir would be completed by December or in other words, before the freshet season started, and that the whole work would be finished in the beginning of March. This was on the assumption that nothing untoward happened. With the undersluices and bays 1 to 4 available for passing freshets down the river, work in the right half of the weir could be carried on practically without any risk, as bunds on one side of the river can be protected and strengthened more easily than in the centre. Floods in the Jammu Tawi could also be disposed of in that case without causing any undue heading up against the bunds.

Another advantage in this arrangement was that if something untoward happened resulting in work being delayed, work in bays 7 and 8 could continue till even late in the season because, as stated above, of the sheltered position of these bays. This would not be the case in the other proposal.

Taking all the *pros* and *cons* of the case into consideration it was therefore realised that the proposal of starting work from the left was undoubtedly the better of the two and that it was only by the adoption of this scheme that the ambitious aim kept in view of completing in one working season a work which would normally take two to complete could be achieved.

Layout of the work.

Plate VI shows the layout of the work. It shows the railway siding for unloading and its extension over the Regulator bridge, the temporary workshops, a small cement godown, the coal bins and the shingle and bajri stacks on the left and right flanks. The length of the unloading siding was about 300 feet and the site provided for it was very suitable and allowed of cement, coal, etc., being unloaded as these materials were received. For cement the main godown was in the old lime shed in the station area but a small godown was provided along side the siding to serve as a reserve to be drawn upon in case of emergency.

The width of roadway of the bridge over the undersluices was increased from 10 feet to 14 feet by temporarily widening it on the up-stream side in order to allow two strings of loaded camels to pass each other. Most of the materials, e.g., sheet piles, reinforcement bars, cement, steam coal, crude oil, etc., had to be carried to the work from the left bank and the widening of this bridge helped in relieving congestion and carriage being done smoothly.

As regards shingle, the total anticipated requirements were a little under 900,000 cubic feet and of this about 300,000 cubic feet were stacked on the left bank and the remainder on the right, or roughly the quantity required for 3 bays was stored on the left and for five bays on the right. This was because there was more storage space available on the right bank.

Plate VI also shows the ring bunds up and downstream of the weir. Work was done in three stages, bays 1, 2 and part of 3 being taken up first, the remainder of bay 3, bay 4 and part of bay 5 next and the remainder of bay 5 and bays 6, 7 and 8 last of all. The object of splitting up the work in the left half of the weir into two parts was to start work in bays 1 and 2 at the earliest opportunity. As stated above work in these bays was expected to be the most troublesome and it was considered essential to make an early start so as to be out of this part of the weir before the freshet season commenced.

Principal items of work.

The work of reconditioning consisted principally of the following items :—

(1) Driving of a 15 feet deep continous line of sheet piles above the C line of wells.

(2) Replacement of the semi-pervious sloping floor between the B and C lines of wells by a horizontal concrete floor 4′ thick, the new floor being depressed 4 feet below the original level.

(3) Reconstruction of the glacis above the B line of wells to a slope of 1 in 4 until it met the old glacis about 11 feet below the down-stream edge of the crest.

(4) Lowering of the block and loose stone protection below the C line by 4 feet.

and (5) Provision of two rows of raised and staggered blocks of size $5' \times 2' \times 2'$ on the horizontal floor between the B and C lines of wells and of three rows of such blocks in the block area downstream of the C line.

Plate VII shows the plan of a weir bay (No. 4) as reconditioned and Plate II the cross-sections of the weir before and after reconditioning.

Stated briefly, the following procedure was adopted in carrying out the work. After the ring bunds up and downstream had been linked and sufficiently strengthened, pumping was started followed by dismantling of the weir floor, excavation of the foundations, pile driving, concreting and stone masonry, in the order mentioned. Also as soon as the water level had been lowered sufficiently, dismantling of the loose stone apron was taken up followed by removal of the concrete blocks with the object of relaying the apron and the blocks 4 feet below the original level. The labour was so organised that the lowering of the block and loose stone protection preceded concreting, as it was found that work could go on most smoothly in this manner and at the same time the large amount of labour collected for the work (about 4,000 men and 1500 donkeys) could be kept constantly occupied. The loose stone apron after it had been lowered facilitated the work of removing and replacing the blocks as the latter could be stacked over the apron till the excavation and the foundation had been completed and they could be relaid. Again, after the stone apron and the blocks had been lowered, tramway tracks could be laid over their surface, thus enabling concrete from the mixers to be dumped near the site where it had to be finally deposited and reducing the lead by baskets to a minimum.

It is now proposed to describe in detail some of the items of work. The description will be confined to conditions peculiar to Marala as information of a general nature has already been included in two papers on more or less similar works recently read before this Congress, viz., Paper No. 195, Reconstruction of the Khanki Weir, and No. 204, The Deg Diversion and Combined Fall and Aqueduct.

Ring Bunds.

It has been stated above that the work was done in three stages. In the construction of ring bunds the following three points were kept in view:—

(*a*) that the bunds in the part of the weir enclosed should be strong enough to enable work in it to go on under conditions of reasonable security,

(*b*) that the bunds in the part of the weir to be next enclosed should be started well in time so as to enable work to progress, as far as possible, uninterruptedly,

and (*c*) that at all times sufficient escapage capacity should be available over the weir and through the undersluices for the passing of freshets in the river.

Bunds downstream of bays 1 and 2 were started in the last week of September 1936 and by the end of the following month, bunds upstream and downstream of these bays had been completed and those round bays 3, 4 and 5 were in progress. As regards the latter, a complete ring was formed by the third week of November and the bunds were completed to full section and revetted by the middle of December. During January, bunds were started up and downstream of bays 6, 7 and 8 in the first week and bunds up and downstream of bays 1 and 2 were cut in the second week and those in bays 3 and 4 towards the end of the month on completion of work in these bays. The bunds in bays 6 to 8 had been sufficiently strengthened by the end of the month to stand a freshet of 70,000 cusecs and were completed to full section and revetted by the middle of February.

The upstream bunds were located 300 feet and the downstream bunds 650 feet from the shutter line. These distances were suitable as while affording sufficient space for working and stacking of materials they did not make the pumping unduly heavy.

As regards the section, all bunds were made 15 feet wide at top and given a slope of 1 in 5 on the inside and 1 in 3 on the outside, additional *pushtas* being provided at low places so as to allow for a hydraulic gradient of 1 in 7 against floods. A freeboard of 3 feet above anticipated flood level was provided both upstream and downstream of the weir. On the upstream side, the lower part of the slope was pitched with a *pilchi* mattress loaded with spawls, the remainder of the slope up to flood level having a cross *pilchi* revetment. Above flood level the slope was pitched with 1 foot of spawls with the object of affording protection against wave action. On the downstream side, the whole slope was lined with 1 foot of spawls or rubbish obtained from dismantling the weir floor, etc.

In fixing the top R.L.'s of bunds the points taken into consideration were the time of the season when work in different bays would be in progress and the size of the biggest freshet that could then be expected in the river. From this and the waterway available for passing the freshet the corresponding R.L.'s of water surface up and downstream of the weir were estimated and an addition of 3 feet for freeboard gave the R. L.'s of top of bunds. During the first stage of the work, i. e., when work was in progress in bays 1 and 2, a freshet greater than 40,000 cusecs in discharge was not anticipated because, as already stated above, freshets in October and November are rare and those in December seldom if ever exceed 40,000 cusecs in discharge. There was to be a 24 days canal closure from the 20th of November but as the work of fitting new gates and gearing in the Head Regulator which had been going on for sometime before had to be completed during it, and as the opening of the undersluices would have interfered with this work, provision had to be made for passing a freshet, if any, over bays 6 to 8 of the weir only. It was considered that under these conditions, with a freshet of 40,000 cusecs, water level upstream and downstream would be about 807 and

801 respectively, and the top of the bunds was therefore kept at R.L.'s 810 and 804.

As regards bays 3,4 and left half of 5, work in these bays was to be carried on in January when freshets of the order of 80,000 cusecs in the river had been experienced before, and although the undersluices were then available for taking part of the freshet, bays 6 to 8 were enclosed by ring bunds. However, before this was done, work in bays 1 and 2 was completed and bunds cut. The following table will give an idea of the conditions then obtaining. The table has been framed on the assumption that both undersluices and weir bays will be discharging under free fall conditions but that only six out of the eight bays of the former will be effective. This is to provide for the obliquity of the current in the approach channel :—

Pond level (Crest level of weir 802)	Undersluices	Each weir bay.	Remarks.
	Cusecs.	Cusecs	In addition canal could take 6000 cusecs.
804	19,000	5,000	
805	22,000	9,000	
806	26,000	14,000	
807	30,000	19,000	
808	34,000	25,000	
809	38,000	31,000	
810	43,000	38,000	
811	47,000	46,000	
812	52,000	54,000	

With a pond level of 809 and the undersluices and bays 1 and 2 open, a freshet capacity of 100,000 cusecs would be available. There was however a shoal downstream of bays 1 and 2 at R. L. 799 and till this had been scoured, free fall conditions could not obtain. An initial velocity of 5 feet per second over this shoal with a downstream level of 807 would give 40 cusecs per foot run or 40,000 cusecs in bays 1 and 2 and adding to this 38,000 cusecs for the undersluices the combined discharging capacity would be 78,000 cusecs or say 80,000 cusecs. On these considerations a pond level of 809 was considered sufficient and the top of the bunds upstream and downstream was therefore kept at R. L.'s 812 and 806, the cross bund near groyne 2 being however kept at R. L. 809 on the downstream side. On the upstream side its top R. L. was 812.

As for work in the final stage, i.e., in bays 5 to 8, this had to be done in February and March, the period of large and frequent freshets. The bunds were therefore designed to stand up safely against a freshet of 150,000 cusecs. At the end of January, bunds in bays 3 and 4 had also been cut so that the whole of the left half of the weir and the undersluices were available for taking freshets. In the bund upstream of bays 1 and 2, three gaps of a total length of 600 feet had been provided, the bed R. L. of the gaps being 801, and the spawl and *pilchi* pitching on the upstream slope at the site of these gaps had been completely removed. The bund downstream of bay No. 1 and in a part of bay No. 2 had been removed down to R.L. 797, which was the general level of the bed here. Three gaps of a total length of 600 feet were made both in the upstream and the downstream bunds in bays 3 and 4, as done upstream of bays 1 and 2. With the gapping of the bunds described above it was considered that on the arrival of a big freshet, bays 1 to 4 would be at least 50 per cent effective to start with, or in other words, with a pond level of 809 and the undersluices open the initial discharging capacity would be 100,000 cusecs. A freshet of 100,000 cusecs or over takes 2 to 3 days to reach its peak by which time it was anticipated the shoal down stream of bays 1 and 2 would have scoured out and the remaining bunds above and below bays 1 to 4 washed away, allowing these bays to become fully effective when the total discharging capacity would increase to over 160,000 cusecs. Thus for the last stage of the work also a provision against a pond level of 809 was considered sufficient, the corresponding level downstream being 805. To allow for cross slope from the right to the left of the weir, the upstream water surface level was taken as 810, and the top of the bunds was thus fixed as $\frac{\text{upstream R. L. 813}}{\text{downstream R. L. 808}}$.

One of the factors which governed this programme and the design of the bunds was the mishap which occurred to the ring bunds at Rasul in April, 1930 during the course of repairs to that weir following the damage done by the record flood of August, 1929 and described in Paper No. 155 read before this Congress in its 1932 session. Pages 112 to 117 of the Proceedings for that year deal with expected freshets and the bunds as constructed and pages 125 and 126 with the abnormal freshet of 250,000 cusecs which passed down the river on the 8th and 9th April, 1930, *when the work was within a week of completion.* At the time bays 7 and 8 were open while bunds were still existing in bays 1 to 6, both upstream and downstream. As the river rose, the bunds in bay 6 were cut to bring this bay into action. Owing to a high wind half the width of the bund upsteam of bays 1 and 2 was eroded. As the river still rose, the upstream and downstream bunds in bays 1 and 2 were cut. The upstream cuts, however, developed much faster than the downstream, as a result of which the water level between the crest and the downstream bund rose to a considerable height, overtopped the downstream groyne and cross bund which was at R. L. 716—15 feet above the floor—and flooded the working area. As the river rose still further, the bund upstream of bay 5 was overtopped and breached and the breach spread rapidly, eroding the entire upstream and downstream bunds in bay 4 and most of them in bay 3. The flood caused considerable damage in bays 7 and 8 and resulted in heavy loss of stock, plant and machinery.

It is also mentioned on pages 116 and 117 that observations during the flood showed that anything less than one foot of spawls or ballast or shingle cannot be considered as adequate protection for a bund against wave action in the open river, and that the unprotected downstream bunds caused considerable anxiety during freshets due to erosion by waves.

It was realised that if the working area at Marala got flooded as a result either of the main or the cross bunds brea hing there would be such a set-back to the work that it could not be completed in one working season. In view of the experience gained at Rasul, every precaution was taken at Marala to avoid such a contingency. The main bunds up and downstream were made strong enough to stand safely the highest freshet that, judged from past experience, could be expected. The cross bunds in bays 3 and 5 downstream of the weir floor were kept two to three feet higher than the downstream bunds to provide against the danger of the former being over-topped and the working area being flooded during a freshet. The bunds in the left half of the weir were cut as soon as work in the part of the weir enclosed by them was completed. The downstream ends of the cross bunds were extended beyond the downstream bunds by about two chains in the form of spurs heavily armoured with *malba* and spawls. The object of these spurs was to prevent cross flow along and possible damage to the bunds downstream of bays 3 and 4 which lay in the deep channel. The spur in continuation of the cross bund to the right of groyne No. 2 also enabled bays 1 and 2 to be run with a discharge high enough to scour out the shoal below and establish free fall conditions, and the levelling off of the bund downstream of bay 1 was a further step in the same direction.

The bunds up and downstream of bays 3,4 and 5 had to be pushed on in conditions which were far from favourable. The deep channel of the river lay through these bays and the bunds had therefore to be advanced in long reaches where the depths were considerable. Again the direction of the current was also unfavourable and *sal balli* spurs had to be thrown out about a chain apart to divert the flow and enable the bunds to progress. For the upstream bunds a large number of boats was employed as the nearest sites for borrowing earth were the *belas* 1000 to 1200 feet above the weir. It was however found that boats alone did not give sufficient progress and they had to be supplemented by donkeys although the lead for the latter was about half a mile. The construction of the cross bund to the right of groyne 4 was also a difficult task as its alignment crossed the deep channel of the river where the bund had to be 50 feet high, and as the side slopes were 1 in 3 outside and 1 in 5 inside, the base of the bund in this reach was over 400 feet and the earthwork required enormous. Earth had to be obtained in the early part of the work from the shoal below bay 7—a lead of 20 to 25 chains—but later on when work was completed in bays 3 and 4, the earth was obtained from the upstream and downstream bunds in these bays.

Pumping.

Plate VI shows the position of the main pumping units installed both up and downstream of the weir. These consisted of centrifugal pumps of sizes varying from 10″ to 14″, worked by portable steam engines. For local pumping, the plant was either Petter crude oil pumping sets or electric sets working either in open sumps or tube wells. Arrangements for pumping had to be varied in the different bays to suit local conditions. These will now be briefly described.

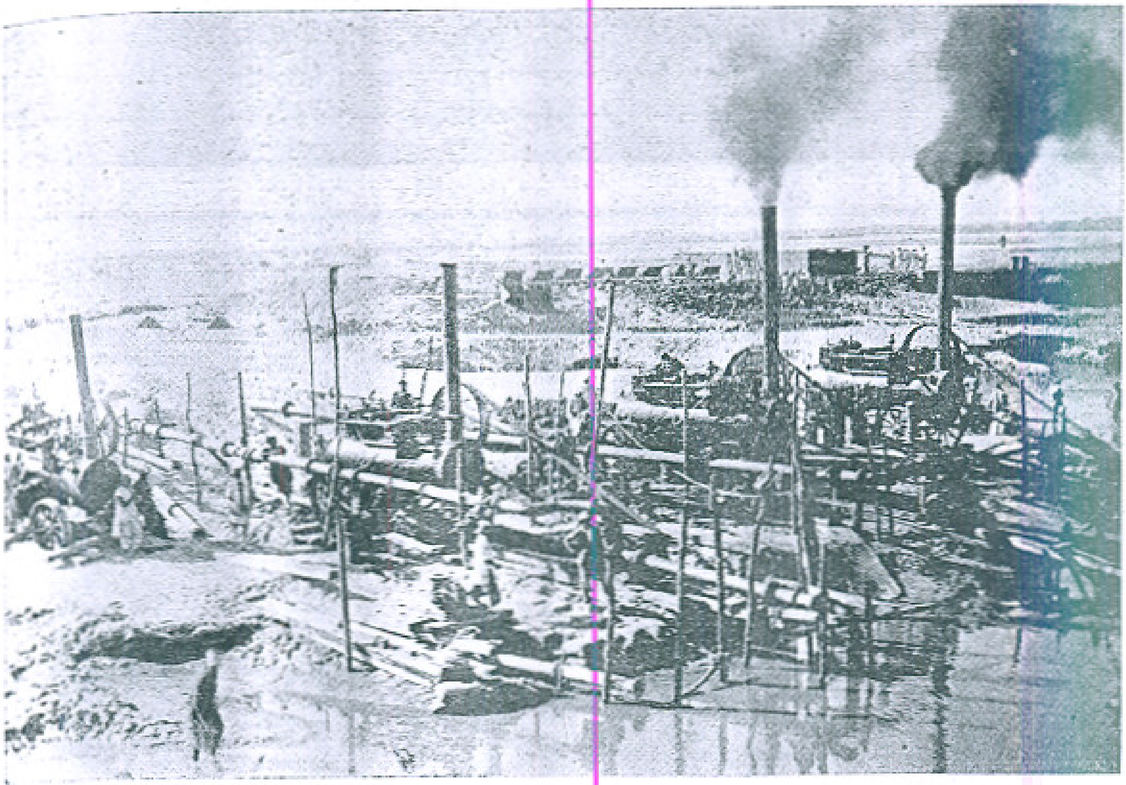
Bays 1 and 2.—In bays 1 and 2 there were large shoals both upstream and downstream of the weir. There was a deep scour hole with bottom R. L. 783 below groyne No. 1. This was utilized as a sump and a battery of pumps was installed on it (Photo No. 4). It was found however, that with four big pumps going downstream and one upstream and discharging about 25 cusecs on the aggregate, the water level could not be lowered below R. L. 787 against a level of 785·8 of bottom of concrete between the B and C lines of wells and of 784·8 in the curtain wall over the pile line. (In the remaining weir bays this deep curtain wall was eliminated by raising the top of the piles by one foot as model observations made in the Research Laboratory, Lahore showed that this could be done safely). Local pumping had therefore to be resorted to and in the left quarter of bay 1 where as already stated above conditions were particularly difficult owing to the proximity of the undersluices, as many as 6 pumps—three electric, one 8″ and two 4″ and three 6″ Petters—had to be installed before it was possible to unwater down to the correct level. A reference is here invited to Photo No. 5.

For local pumping, open sumps were used to start with and later on tube wells. The latter consisted of Essbee coir strainers 6″ inside diameter and each $8\frac{1}{2}$ feet long. Tests were made with 3, 2 and one length of strainers with a five feet length of blind pipe in each case. It was found that for attaining the object in view, *viz.*, dewatering the surface of the foundation pit with the tube wells spaced reasonably apart, the use of two lengths of strainers was the most economical. Tube wells with two lengths of strainers, spaced 50 feet apart and discharging about $\frac{3}{4}$ of a cusec each with a 4″ pump, were quite effective.

In view of the trouble that local pumping from open sumps gave in these bays it was not used in the rest of the weir. Where necessary it was confined to tube wells, the same strainers being used a number of times.

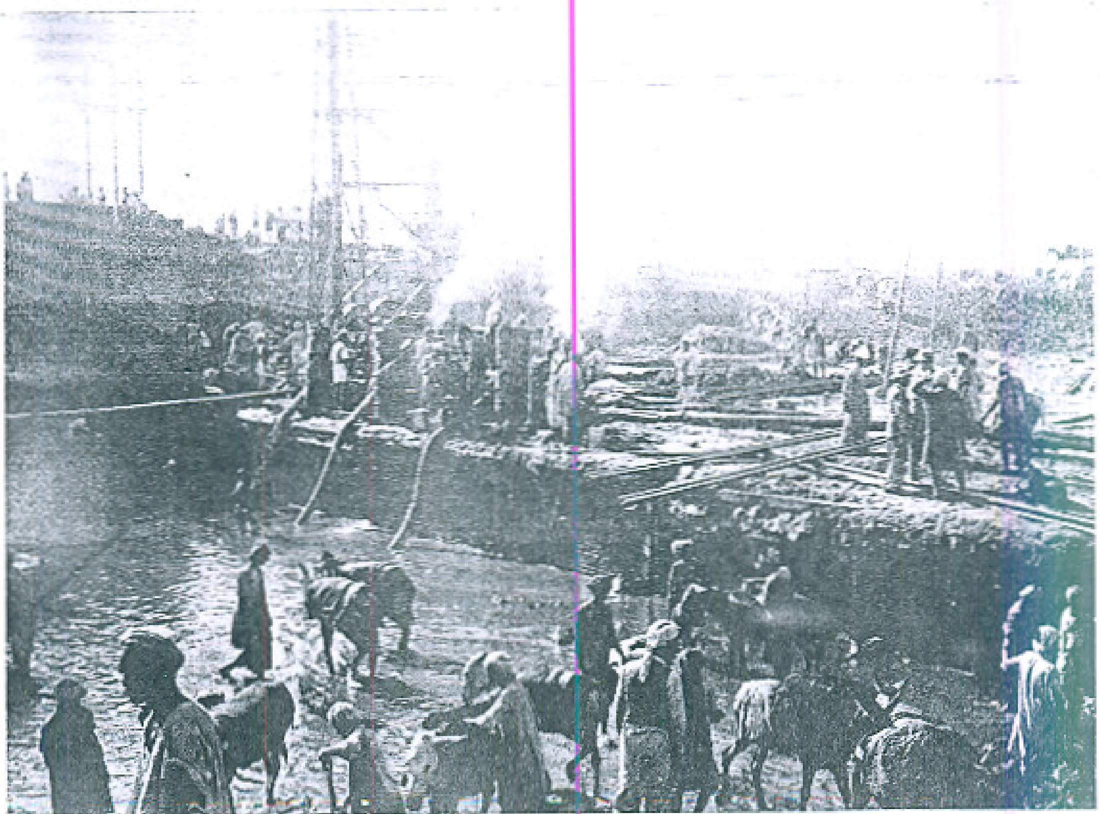
Bays 3 to 7.—Conditions in these bays differed materially from those in bays 1 and 2. Unlike the latter, there were no shoals in

Photo No. 4.



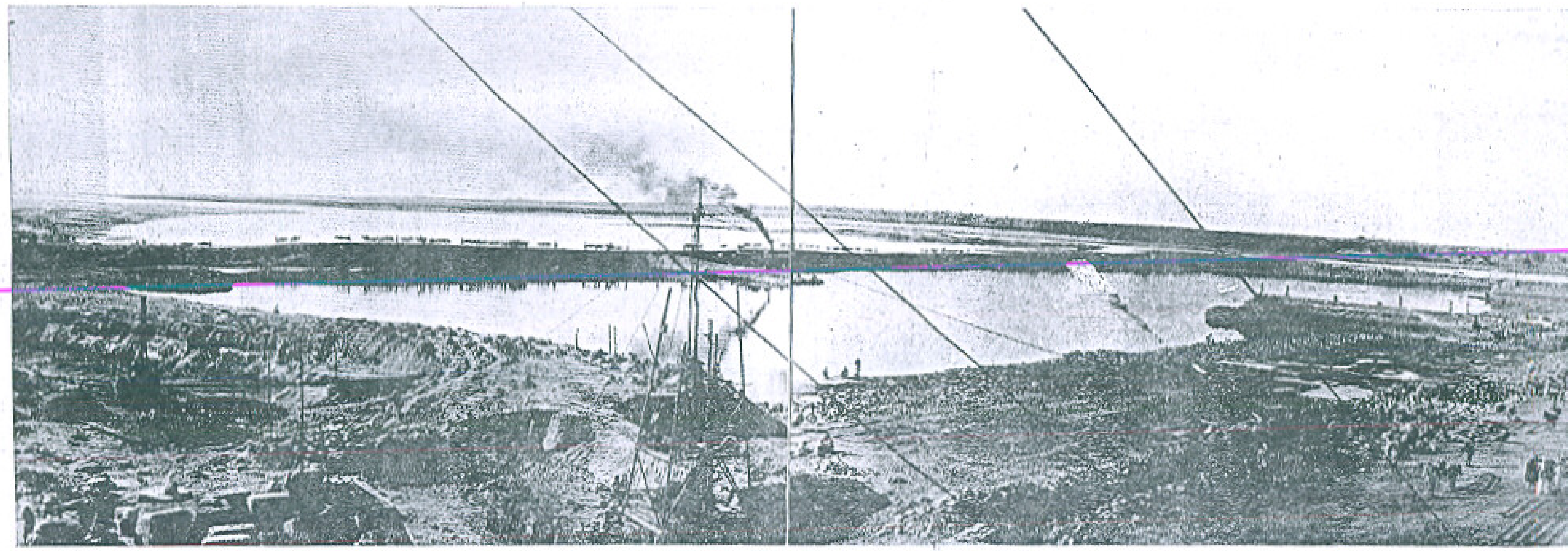
Battery of pumps downstream of Groyne No 1. Nov. 1936.

Photo No. 5.



Starting concrete in Bay No. 1 left flank. Mark concentration of local pumping. Date 17-11-36.

Photo No. 6.



Panoramic view of Bays 3, 4 and 5 showing the large and deep pool which it was necessary to pump before work could be commenced. Dec. 1936.

bays 3, 4 and 5. On the other hand, due to the fact that the deep channel of the river passed through these bays, there were deep scour holes both upstream and downstream—the deepest hole downstream in bay 4 being 34 feet deep below low river level (R. L. 760). It was therefore realised that pumping in these bays although difficult to start with would give no trouble once the water level had been depressed sufficiently. Photo No. 6 shows a panoramic view of these bays at the time pumping was started in them. Five big pumps were installed downstream of bays 3 to 5 and after intensive pumping lasting for three weeks during which the maximum discharge pumped was as much as 27 cusecs, the water level was lowered from R. L. 794 to R. L. 785·2 and to R. L. 784 after another week. As the level of the foundation for the concrete between the B and C lines of wells was 785·8, by having a cross drain in the centre of each bay it was possible to work in the dry from both ends of a bay and to do away entirely with local pumping except for the completion of the concrete in the centre of the bay where the two working faces were joined.

Owing to the absence of shoals, the portables and pumps downstream in bays 3 to 5 had to be erected quite close to the ring bunds to start with and then gradually advanced away from the bunds and installed over the deepest contours. As the water level downstream of the weir went down it was necessary to depress the water level upstream also in order to limit the head across the weir to a maximum of 10 feet as heads bigger than this are not considered safe. At this stage of the work pumping plant available was not sufficient and as a good working head was available over the weir, two 8″ siphons were installed in bay 5 and one in bay 6 for lowering the water level upstream of the crest. These siphons worked very satisfactorily and resulted in a saving of about Rs. 75 per working day in cost of pumping.

The procedure adopted in bays 6 and 7 was similar, as scour holes existed below these bays also and it was possible to lower the water surface sufficiently, thus doing away with the necessity of local pumping above the C line of wells when putting in the concrete.

Bay 8. Below bay 8 there was a shoal and as local pumping was found to be troublesome, expensive and a hindrance to progress, it was decided to sink two masonry wells in the shoal on one of which a portable and on the other a pump was mounted. The shoal was excavated for a considerable distance round the wells to create an artificial pond the water level in which was kept low enough to do without local pumping above the C lines of wells when the concrete was being placed. This pond is clearly visible in Photo No. 13. The arrangement worked quite satisfactorily and it was possible to lay concrete in this bay in the dry without any local pumping except in the portion close to the right flank where a few tube wells had to be sunk to deal with the heavy infiltration.

In the right half of the weir the delivery pipes from the main pumps were taken over the top of the downstream bunds. (The pipes for the two pumps in bay 6 can be seen in Photo No. 13) This was because during the time work in this part of the weir was in progress large and frequent freshets in the river were expected and if a leakage occurred round a delivery pipe resulting in a breach in the bund, the work could not have been completed during the remainder of the season. In February, 1909 a breach from this cause actually occurred in the bund upstream of bay 6 during a 150,000 cusecs freshet and work was stopped till the following November. In the left half of the weir, the delivery pipes had been kept a little above the normal winter water level in the river and taken through the downstream bunds because high freshets were not likely then.

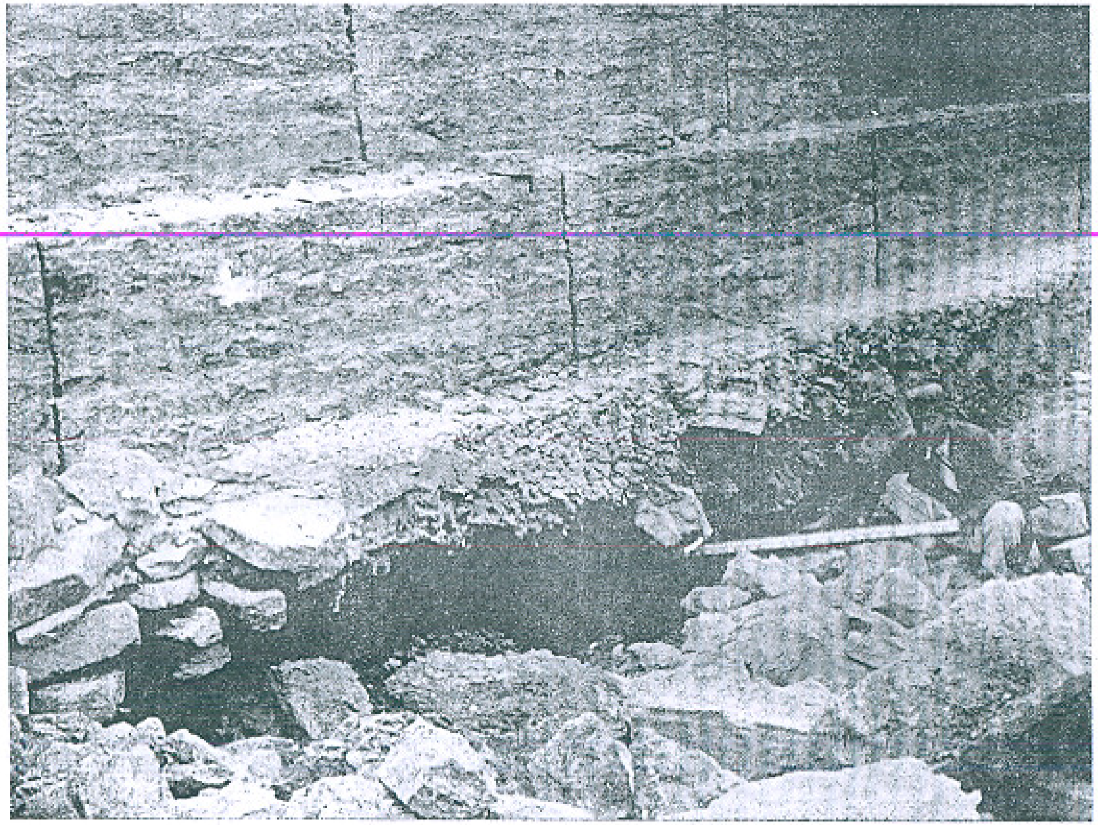
To prevent excessive inflow and sloughing of the downstream bunds which choked up the drains and sumps, *malba* bars were added at the inner toe of the bunds to act as filters. This was very successful.

In Plate IX is given a diagram showing the number of main pumps working and the discharge pumped on each day during the months of January, February and March, 1937. The maximum discharge pumped was 33 cusecs on the 19th and 20th January and the minimum 16 cusecs on the 28th and 29th of the same month. It varied of course with the extent of the area enclosed and the downstream water level which in turn was affected by freshets in the river and the programme of distribution of the river supplies between the Upper and Lower Chenab Canals. As a rough approximation it may be stated that with an area 1000 feet by 1000 feet enclosed by ring bunds and conditions normal, a discharge of 25 cusecs had to be pumped out to keep the water level inside the ring downstream of the weir depressed 10 to 12 feet below the downstream river level, or that a discharge of 1 cusec had to be pumped per acre of area enclosed.

Pile Driving.

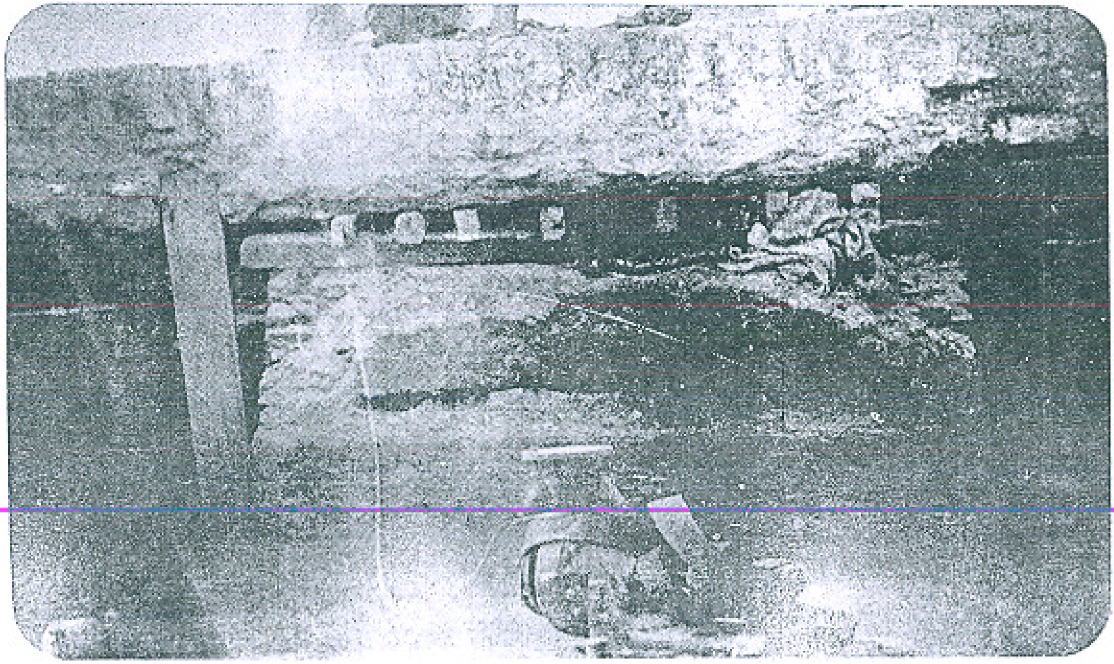
As already stated, the driving of a 15 feet deep line of sheet piles above the C line of wells was an important item in the reconditioning of the weir. It was originally proposed to have the piles four feet above the upstream edge of the wells in the C line but in view of the extent of the overhang of the hammer of the pile driver beyond the track over which the pile driver moved on the C line, it was decided that two feet would be a more convenient distance. Plate VII shows the position of the pile line in a weir bay. Near the left flank the line was given a right angle turn downstream and was taken just past the fish ladder so as to abut against the foundation wells under the right flank wall of the undersluices. (Plate No. VIII). On the right flank of the weir it abutted against a well under the right flank wall. In addition, as shown in Plate VII, a line of piles was driven under groyne No. 4. This groyne had failed in both the record floods of 1928 and 1929. On dismantling the block and loose stone protection on either side, it was found that the foundations of the groyne had been undermined. (Photo No. 7).

Photo No. 7.



Six feet cavity under Groyne No. 4.
Date of photograph. 10-12-36.

Photo No. 8.



Tilted wells in C line in Bay No. 4. Dec. 1936.

Photo No. 12.

Universal sheet piles driven in a gap in B line of wells.
Three of the wells were missing.—Date 15-2-37.

It was decided to rebuild it on a concrete slab 2·0 feet thick resting on a line of piles 15·0 feet deep.

The type generally used was Ransome uniform (D) as used in the reconstruction of the Khanki Weir and at the Deg Fall, but where it was necessary to drive piles through stone, the type known as "Universal" was used as it is considerably heavier in section. Stone was generally met in those reaches where damage had been done in previous years to the glacis between the B and C lines of wells. With the aid of a water jet borings were made about five feet apart in the line in which the piles had to be driven and the reaches in which stone was lying buried thus determined. Where stone was found within three feet of the foundation level even Universal piles got bent in the process of driving. At such places arrangements were made to dig out the stone so as to ensure that the pile was driven through sand for a depth of at least 3 feet. A bull-headed rail driven by the hammer of the pile driver was a great help in loosening and breaking the stone. It was found that this depth in sand gave the pile the necessary grip to enable it to pierce through stone if met further down. In view of the risk of disengagement of clutches in such reaches the excavation was completed and the piles were then driven to the final level in one operation, no dolleying being done subsequently.

For the reasons mentioned above, Universal piles had to be driven in a length of about 150 feet in the right half of bay 4 where the glacis between the B and C lines of wells had been completely washed away in the record flood of 1929 and where some wells in the C line had become tilted. (Photo No. 8). As already stated, groyne No. 4 had been damaged twice before and here also in a length of about 50 feet at the downstream end, Universal piles had to be driven. Again on dismantling the weir floor in bay 5 it was found that three wells in the B line on which the safety of the old weir depended were missing. These wells, it appeared, were omitted originally owing to the presence of stone, the remnant of an old construction bund, in the river bed, and for the same reason new wells could not be sunk here. As there was considerable sloughing of wet sand between the crest and this gap which might have undermined the crest, it was decided to put in a line of Universal piles across the gap a little below the downstream edge of the B line and join it to the latter. (Photo No. 12).

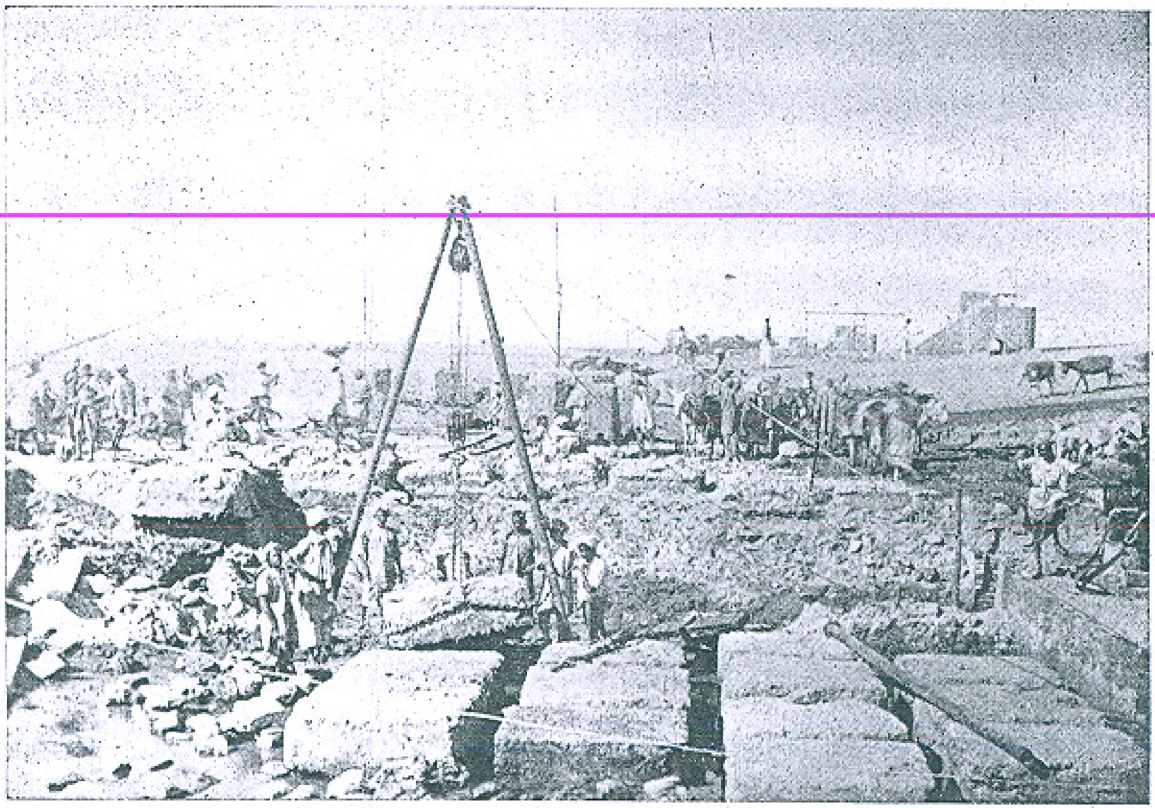
In bays 1 to 3, the pile drivers had been erected on the C line of wells. In the rest of the weir the machines were tracked over the finished excavation between the B and C lines of wells. This not only allowed uninterrupted dismantling over the C line but also expedited progress by facilitating the laying of the track for the pile driver to move on. The maximum progress on any one day was 207 Nos. 15′ deep Ransome piles driven, which is probably a record.

Lowering of Block Area and Stone Apron.

In the old weir the block area consisted of 10 rows of $5' \times 5' \times 2'$ lime concrete blocks, the spacing between the blocks being one foot both longitudinally and transversally. As already mentioned above, due to the flat slope of the old glacis and the comparatively high level of the block and loose stone apron below, some part or other of the block area was damaged in each flood, the subsequent repairs consisting of replacement by lime or cement concrete blocks of equal or bigger size, by concrete laid *en masse* or by stone confined in wooden crates and covered with a raft of cement concrete. The lowering of the block area by 4 feet as a part of the reconditioning of the weir therefore presented many interesting problems. The old concrete blocks weighed from 3 to 3½ tons each and removing and relaying them at the lowered level was a problem in itself, the extent of which can be judged from the fact that about 17,000 tons of concrete blocks had to be removed. A start was made with a pair of sheer legs (Photo No. 10) but the process was slow and expensive as it was found that with 20 to 25 coolies working on a pair of sheer legs less than 5 blocks could be completely handled in one day at a cost of Rs. 4 each and as there were 800 blocks in each bay the work could not have been completed in one working season by that method. It was then proposed to construct 4 gantries to straddle the bays but this too was rejected as too slow and expensive. Fortunately Mr. Munro, Executive Engineer, Dragline and Pumping Division undertook to do this work with two old Dragline Excavators working on caterpillar wheels. (Photo No. 11). This greatly expedited the work as with proper organization each machine could easily handle 50 blocks a day. The working cost was also brought down very considerably. The machines worked for over four months without a break-down and their use removed a difficulty which at one time appeared well nigh insurmountable considering that from the very beginning the aim was to finish the work in one working season.

In bays 4 and 5 it was found that the majority of the blocks had been washed away and replaced by mass cement concrete while many of the lime concrete blocks were damaged and useless owing to the poor quality of the surkhi sand lime mortar. The missing and damaged blocks were replaced by blocks built in stone masonry after an immense amount of labour had been spent in dismantling this raft of cement concrete, every bit of which had to be blasted with gelignite or black powder by night, broken up by crow bars, chisels and hammers during the day and removed by donkeys. As the work progressed further it was found that conditions in bays 6, 7 and 8 were even worse, the number of blocks fit to be used again being about one-seventh the total number required. This involved not only very difficult and expensive dismantling of cement concrete but also the building of new blocks over a larger area. In the interest of speed and economy it was decided to build these

Photo No. 10



Lifting 3-ton block by sheer legs. November, 1936.