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DISSIPATION OF ENERGY BELOW CANAL FALLS.

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Data on which note is based.

This note was prepared for the Central Board of Irrigation under the orders of the Chief Engineer, which also called for notes from Messrs. Fenwick, Protheroe and Jagan Nath Juneja, with a view to their opinion being embodied therein. At the author's suggestion opinions were also obtained from Messrs. Gunn, Khosla and Brown. A lengthy note by Mr. Colyer, embodying the results of a departmental enquiry conducted by him last year was also placed at the author's disposal. This enquiry embraced reports from all sixteen circles and one Independent Division of the Punjab and North-West Frontier Province and in addition some officers specially interested were requested to supply notes.

Mr. Colyer's conclusions after studying this data are reproduced below :—

(1) The perfect fall has yet to be designed.

(2) In cases where accurate metering is not required, the trapezoidal notch is the best form of fall, if somewhat expensive.

(3) In all cases a cistern, either counter-sunk, or formed by a transverse wall above bed-level, is necessary, the former type being preferable to, but more costly than, the latter.

(4) Aeration by means of grids is extremely effective but can only be used where establishment is maintained to keep the grids continually free from floating jungle.

(5) Where a high degree of aeration is impracticable, the cistern should end in a vertical, or better still a re-entrant wall, this giving better results if raised above downstream bed-level.

(6) The provision of friction-blocks or dentations in a cistern increases its efficiency.

(7) Stream-lining and gradual expansion within economic limits does not effectively prevent scour, but is helpful if supported by one or more of the other methods mentioned above.

(8) Partition walls built on the glacis so as to diverge slightly from the axis of the stream in a radial manner, effectively moderate cross-flow, but their design for large discharges needs further investigation, and deserves closer study.

At the present stage of experience in the Punjab the various means of prevention of scour below falls, may be placed approximately, and tentatively, in the following order of merit :—

(1) Trapezoidal notches with grids to aerate the jet, and a deep and long cistern.

(2) Trapezoidal notches with a deep and long cistern ending in a baffle-wall.

(3) Rectangular notches or Broad Crested Weirs without a glacis, discharging through an aerating grid into a deep, long cistern.

(4) Rectangular Notches or Broad Crested Weirs with an approximately parabolic glacis leading to a dentated cistern ending in a re-entrant baffle-wall, radial partition walls being built down the glacis in the case of contracted weirs.

The opinions received from other officers are summarized below :

Mr. Fenwick confines himself to giving an opinion on the modification of a contracted glacis fall consisting of providing it with a high baffle-wall and radial diaphragms on the glacis. His conclusions on this are that the baffle-wall distributes the flow uniformly but itself sets up a very bad action below it at certain stages. The diaphragms are helpful but it is doubtful if they are necessary in addition to the baffle.

Mr. Juneja advocates the superiority of the notched fall over Broad Crested flumed falls. Also instances cases where troublesome flumed falls have been improved by the use of baffle-walls and extension of protection.

Mr. Protheroe emphasises the divergence of opinion on fall design in the department and also the danger of drawing conclusions from designs which have been successful at certain sites, pointing out that variation in soil has more to do with this than the design. Refers to his opinions previously expressed in his Congress paper and adds that he now considers that such devices as friction-blocks and baffle-walls cannot give satisfactory results if the fall is improperly designed.

Advocates as the best type a fall with the following characteristics :

1. Broad Crested Weir with no side contraction.
2. Glacis with 1 to 1 slope down to depth sufficient for wave and 1 in 5 or 1 in 10 beyond.
3. A depressed cistern.
4. Longitudinal diaphragms.

Mr. Gunn considers the most economical type of fall is one which breaks up jets at an early stage and at the same time provides for a sufficient volume of water to be contained within the ends of the pakka work to allow the energy of turbulence to dissipate itself.

Mr. Khosla points out the difference in action between a broad and narrow crest advocating the latter. Describes the beneficial result of grids and friction-blocks in the case of the Bambanwala Fall Upper Chenab Canal. Deprecates fluming and advocates the Rehbock cill and the baffle-wall provided it does not extend above bed-level.

Mr. Brown points out the two types of fall existing in nature, the waterfall with short deep pool and the rapid with long one. Advocates the vertical drop type as preferable and instances the trouble caused by low head falls where the jet is necessarily nearly horizontal in support of his contention.

He advocates the following principles :—

(*a*) The jet should descend as steeply as possible.

(*b*) No contraction.

(*c*) If feasible the use of a grid.

(*d*) Cistern of full bed width.

(*e*) The use of friction-blocks.

He also considers that the size of cistern depends on the height of fall, depth of flow, nature of soil and the angle the falling water makes with the horizontal ; and that baffle-walls and diaphragms are unnecessary if the fall is properly designed, but may be necessary to distribute the flow in the case of a diverging glacis.

General Principles.

Before commenting on the various forms of fall and the devices designed to expedite energy dissipation in connection therewith, it is necessary to understand clearly the function of a fall and the means by which this can be accomplished.

The function of the fall is to lower a certain discharge of water by a certain distance and to deliver it at the lower level free of kinetic energy in excess of that of normal flow.

Assuming no useful work to be done by the fall this involves the dissipation of the energy set free by the falling water, a measure of which is the product of the discharge and the height of the fall measured vertically from the upstream to the downstream water surface level.

The process of energy dissipation is as follows : The energy which upstream of the fall is in the potential form is first converted to the kinetic form in the falling jet. In this stage flow is stream-line, *i. e.*, generally parallel at all points on the cross section. On arriving at the lower level the stream-line flow is broken up into turbulent or eddy flow, *i. e.*, the jet splits up into various small streams flowing in different directions.

The energy which is then still kinetic is evident in the velocity of these stream lines. As the energy is dissipated the velocity of this motion is reduced until it is not in excess of that of normal flow, at which stage the energy set free by the fall is completely dissipated.

Since energy is indestructible, that dissipated must appear in one of three forms :

(*a*) Sound energy represented by the noise produced.

(*b*) Work done in eroding the boundaries of the stream, and

(*c*) Heat caused by friction—

(1) between the water and the air bounding it.

(2) between the water and its solid boundaries.

(3) between water and water owing to its internal movement.

(4) within the water due to its elastic compression and expansion.

(5) within the boundaries due to their elastic compression and expansion.

(6) internal friction in enclosed air due to its compression and expansion.

(7) friction between enclosed air and water.

Of the above the energy utilized is negligible in the case of (*a*) and (*b*) and in the case of (*c*).

(1) is only appreciable where the discharge is arranged in the form of a number of small streams as in the case of the Glenfield and Kennedy dissipator ;

(2) is small as is shown by the small loss of energy in stream-line flow. Also the solid boundaries vary as the square of the linear dimension only ;

(4) and (5) are necessarily small owing to the high elasticity of still water under compression ;

(3) is generally admitted to be the principle avenue of dissipation of energy. The fact that the energy dissipated in this case is proportional to the volume makes it more important than (2). It is obvious that the smaller the individual eddies and the greater their number the greater will be their inter-action and consequently their capacity for absorption of energy. Anything in the nature of large whirlpools is to be avoided, since such eddies absorb little energy themselves and occupy valuable space which would otherwise be employed in efficient dissipation.

The importance of (6) has not, the author thinks, been generally realized. The energy required to compress air is very considerable. To compress 1 cubic foot of atmospheric air isothermally to a head of H feet of water requires an expenditure of energy equal to :

$$F = 4880 \log \frac{H+34}{34} \text{ foot lbs.}$$

$$\text{If } H = 5. \quad F = 290.$$

This is almost equal to the energy released by a cubic foot of water falling 5 feet = 311 ft. lbs.

Air enclosed by a jet at a fall is generally carried to the bottom of the cistern and consequently compressed to a considerable head and though the energy used in this is, of course, in part released as the air expands in rising to the surface again, a part is lost in friction in each process. As in passing through the turbulence of a cistern, the air is subject to rapidly varying pressure and energy is lost in friction at each variation, it is probable that the total energy consumed in this way is very considerable. Unfortunately however, the amount of air enclosed is generally small as is evident from the small super elevation of the aerated water.

(7) is probably not very important though the frictional losses attendant on the passage of numerous small bubbles of air through water is comparable with those occurring in the passage of drops of water through air, *vide* 1.

To summarize the chief objects desired in fall design are :—

(*a*) To enclose as much air as possible in the water.

(*b*) To break up the jet into small eddies as soon as possible.

The Overfall.

Bearing these in mind we will now consider the different features of falls and their value in producing the best type of action. Working from upstream we will start with the different types of overfall. In this there are two features that tend to assist in breaking up the jet, *i. e.*—

(*a*) Interaction of jets.

(*b*) Verticality of jet.

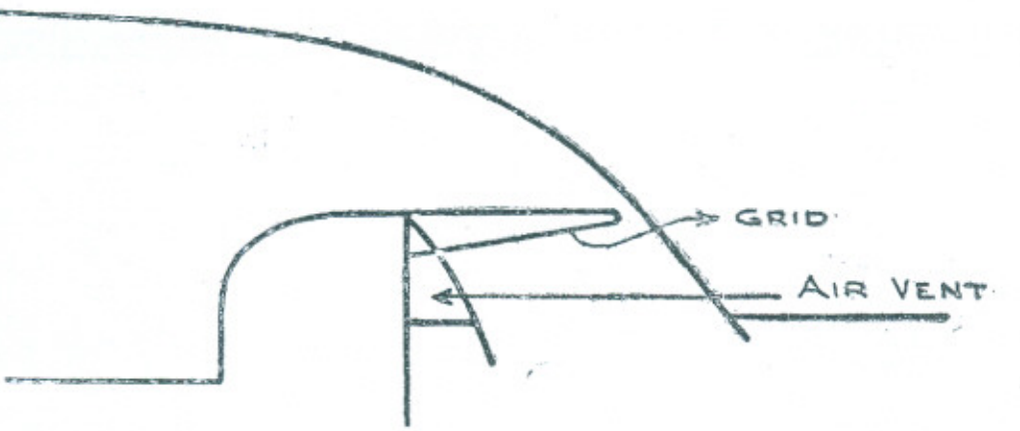
The advantage of enclosing air has been argued above. As the air is chiefly carried into the cistern along the surface of the jet, the greater the surface the more air enclosed. This would indicate the advantage of spreading the jet out as much as possible, *i. e.*, providing a continuous overfall along the full width of the crest. It must be remembered, however, that the jet has two surfaces and arrangements be made to aerate the under-side.

An arrangement which ensures a large surface of jet and also adequate aeration is the notched fall. The virtue of the trapezoidal notch commonly used in the Punjab appears to lie in its sharp or stream lined

sides, not in its trapezoidal shape. The shape of the sides produces convergent approach flow with consequent reactionary divergent flow in the jet, which spreads the jet over the full width of waterway and produces interaction with adjacent jets. The lip of the fall also assists in spreading the jet. There seems to be no reason why a similar rectangular notch should not be constructed.

Another arrangement which secures efficient aeration is the standing wave; here the breaking wave engulfs air in comparatively large quantities though on one surface of the jet only.

The best arrangement for air induction, however, is undoubtedly the grid. This secures a very large jet surface with consequent air induction and also a large amount of interaction. The objection to its use is its tendency to catch floating jungle with consequent danger of breaches. Its use has therefore been confined to sites where staff was available for clearing it. This feature might, however, be obviated by arranging for the jet to pass over the grid at a gentle angle and to envelope it completely so that any floating matter must pass clear of it. In this case aeration would be arranged from the underside. Thus:—



The efficiency of this device can also be enhanced to any degree by increasing the number of members of the grid.

Another device which might be used for energy dissipation through aeration is the spillway syphon. The gentle action below the Renala syphon at low supplies is very striking as is also the amount of air present. This device might well be used for cases of low falls where the grid is impracticable.

Jet inclination and glacis.

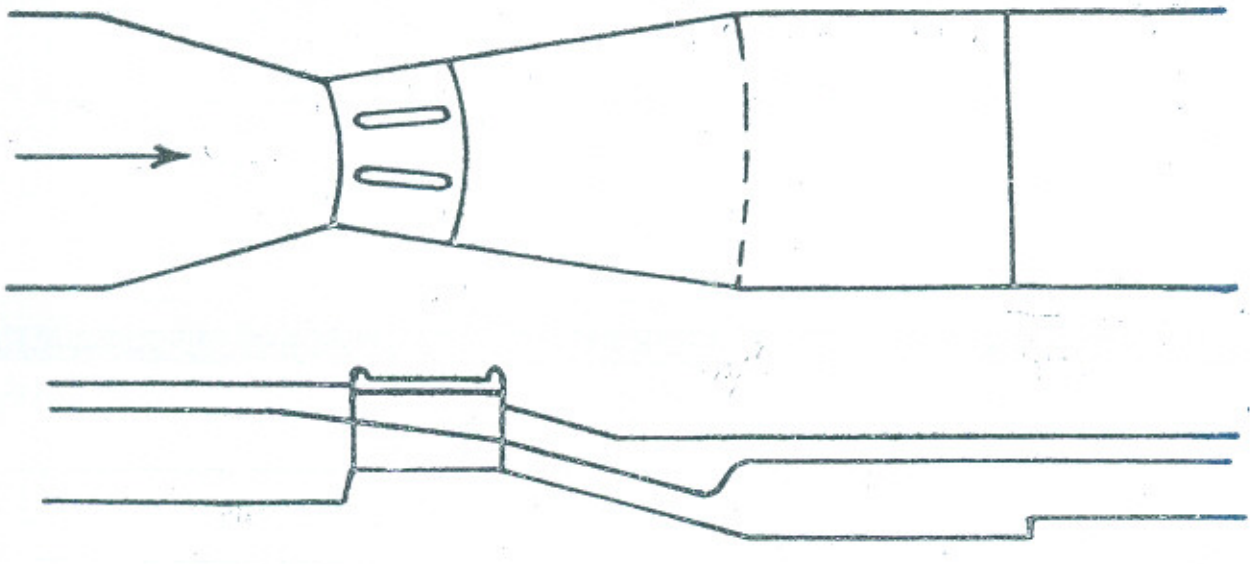
The merits of jet verticality seem to lie in the fact that the more vertically the jet enters the cistern, the more the change of direction to the horizontal is likely to break it up. A sharp crested weir will give a slightly more vertical jet than a broad one, and a continuous overfall is to be preferred to notches, particularly broad crested ones in this respect.

Under the head of jet inclination comes the question of direct drop *versus* sloping glacis. Opinions generally favour the direct drop though there is quite a considerable minority in favour of the glacis. The aerating properties of the standing wave are undoubtedly an argument in favour of the glacis, which also is useful in cheapening construction by avoiding the cost of the drop-wall. This advantage is particularly important when designing according to Bligh where a certain length of impervious floor is necessary.

There are two types of glacis intermediate between the direct drop and the plain slope, where the profile is made up of curves or varying slopes, the distinction depending on whether the surface is generally concave or convex upwards. Of these the former is, in the author's opinion, to be preferred, since it ensures the adequate aeration and jet dispersal of the standing wave. The latter is distinctly inferior to the direct drop since the aeration of the underside of the jet is impossible.

Attempts have been made to obtain energy losses before the jet enters the cistern by roughening the glacis. On the S. V. P. a stepped form of glacis was used for this purpose but it is generally admitted to have been valueless. Even on the Upper Bari Doab Canal falls where long glacis at a slope of 1 in 15 consist of grouted boulder pitching, it is doubtful if the effect of the roughness is great. The standing waves formed on these rapids are of normal height.

Attempts were also made on the Sutlej Valley Project in the case of flumed works to spread the jet uniformly after contraction by making the glacis of conical form. These, however, have not generally been successful. An alternative method of effecting this which has not, so far as the author is aware, been tried, would be to bow the crest of the fall. Thus :—



In this case the bridge would either follow the curve of the crest or the side spans would be skew. In any case the piers should be radial.

Another method of securing uniform distribution in the cistern is the use of radial vertical diaphragms on the glacis. These mechanically distribute the jet uniformly over the width of the cistern at entry.

While on the subject of jet distribution it may be mentioned that on the Sutlej Valley Canals where falls have been contracted from 30 to 40% the rate of expansion of their side walls, generally 1 in 5 has been too abrupt to secure uniform distribution at the wave, and consequently additions of one type or another have in many cases, had to be made for this purpose. A more gentle expansion than 1 in 5 would lead to heavy expense.

The Cistern.

Obviously every fall must comprise a cistern of some kind. By a cistern is meant the portion of the water-way below the fall, the boundaries of which are protected. The function of the cistern is twofold, firstly, to convert the initial descending jet or jets into turbulent or eddy flow and, secondly, to allow of sufficient time for the turbulence to settle down to that of normal flow. It is useful to distinguish between these two processes the former of which may be termed " dispersion" and the second " stilling " and the portions of the cistern in which they take place may be termed the " dispersion chamber " and the "stilling chamber," respectively. The former process obviously takes place at the U. S. end of the cistern and the second at the D. S. end though of course the two processes overlap.

While no distinction has been made between the two processes in the past, it has been customary in the Punjab to construct the upper portion of the cistern, which is subject to the action of the undispersed jet of masonry, while the lower part is usually bounded by flexible protection such as pitching of concrete blocks, stone or brickwork. The boundary between the two portions has however frequently been fixed by other considerations such as the length of impervious floor required for the hydraulic gradient. Having recognised the difference in the functions served by the two portions it would seem obvious that all devices intended to assist the breaking up of the jet, should be confined to the dispersion chamber. If such devices are placed in the stilling chamber the fall will automatically conserve sufficient energy to overcome them, and this energy will be converted to eddy motion at a stage when it will be too late for the eddies to subside within protected boundaries.

Size of Cistern.

The size of the cistern must evidently be such as to allow the water to remain in it for a time sufficient for the two processes to be carried out. The relation between cistern volume (C), discharge (Q), and the mean time the water will remain within the cistern boundaries (T) is given by $T = \frac{C}{Q}$.

The time required for dispersion and stilling is obviously a function of the fall, *i. e.*, the difference between the U. S. and D. S. levels=F. The greater the fall the longer the time required. It is not directly proportional however, as the greater the fall the greater the velocity of the jet and the eddies and consequently the initial rate of dissipation of energy. A rough idea of the way in which the time varies with F can be obtained from the following mathematical analysis, in which the following assumptions are made:

(*a*) That the mean initial velocity set up in the cistern is proportional to $\sqrt{F} = K_1 \sqrt{F}$. Since neglecting losses in the jet the total energy in the cistern must be equal to that of the fall $= QF = Q\frac{V^2}{2g}$ where V is the velocity of the jet entering the cistern, and the initial energy in the cistern is proportional to Σqv^2 where q is the discharge and v the velocity of any stream-line this assumption would seem to be justified.

(*b*) That the retardation of the eddy velocity varies as some power of the velocity between 1 and 2.

In these two limiting cases we have:

(1) $\frac{dv}{dT} = Kv$ (2) $\frac{dv}{dT} = Kv^2$

$dT = \frac{K}{v} dv$ $dT = \frac{K}{v^2} dv$

$T = K \log \frac{v_o}{v}$ $T = K\left(\frac{1}{v} - \frac{1}{v_o}\right)$

where v_o is the initial velocity and v the velocity at the end of time T. Assuming that v=1 marks the stilling of the turbulence.

(1) $T = K \log V_o$ (2) $T = K\left(1 - \frac{1}{V_o}\right)$

$= K \log K_1\sqrt{F}$ $= K\left(1 - \frac{1}{K_1\sqrt{F}}\right)$

$= K (\log K_1 + \frac{1}{2} \log F)$.

If $K_1 = \sqrt{2g} = 8$, *i. e.*, if the mean eddy velocity = the velocity of the jet at entry,

for F=1.

(1) $T_1 = K (0{\cdot}903)$ (2) $T_1 = (0{\cdot}875)$.

and for F=9.

$T_9 = K (0{\cdot}903 - 0{\cdot}477)$ $T_9 = K\left(1 - \frac{1}{24}\right)$

$= 1{\cdot}38\ K$ $= 0{\cdot}958\ K$

$\frac{T_9}{T_1} = 1{\cdot}53.$ $\frac{T_9}{T_1} = 1{\cdot}09.$

Table showing for different types of falls average values of K_D, K_S and K in the formula $C=KQF^{0.33}$ where C. is cistern capacity Q. discharge, F. fall and K constant. K_D and K_S are constants applicable to the dispersion and stilling chambers respectively $K=K_D + K_S$.

Group No.	Number Averaged.	TYPE.				K_D.	K_S.	K.
		Overfall.	Glacis.	Cistern.	Soil.			
I. Upper Bari Doab Canal Main Line.	7	Uncontracted Broad Crest.	1 in 15 slope roughened.	Undepressed ..	Shingle ..	..	..	10·2
II. Do. ..	2	Uncontracted Narrow Crest.	Direct fall ..	Depressed ..	Good ..	5·2	8·7	13·9
III. Lower Jhelum Canal (Rasul Meter).	1	Uncontracted Broad Crest.	Glacis ..	Undepressed ..	Good ..	10·2	4·6	14·8
IV. Upper Jhelum Canal G. B.	..	Uncontracted Notches.	Direct fall ..	Depressed ..	Good ..	5·2	13·3	18·5
V. Upper Chenab Canal M. L. L.	4	Uncontracted Narrow Crest.	Direct fall ..	Depressed ..	Average ..	6·5	11·8	18·3
VI. Sutlej Valley Project.	9	Uncontracted Broad Crest.	Stepped Glacis	Undepressed ..	Poor ..	7·4	11·2	18·7
VII. Sutlej Valley Project.	2	Contracted Narrow Crest.	Direct fall ..	Undepressed	Poor ..	9·4	13·8	23·2
VIII. Lower Bari Doab Canal.	9	Uncontracted Narrow Crest.	Direct fall ..	Depressed ..	Poor ..	11·3	14·4	25·7
IX. Lower Jhelum Canal	4	Uncontracted Narrow Crest (R. Bridges).	Direct fall ..	Depressed ..	Good ..	13·9	22·6	35·6
X. Sirhind Canal. ..	8	Contracted Notches.	Direct fall ..	Depressed ..	Average ..	16·2	20·6	36·8

These figures indicate how little is the effect of F on the cistern capacity. They would suggest a formula for the latter of the form :

$$C = K\,QF^{n}$$ where n is about O.1.

For a cistern to work efficiently it is essential that all the water passing through it should remain in it for the same time. To this end any concentrated jets, or large eddies which may result in part of the water passing rapidly through the cistern are to be avoided. The best of cisterns, however, will not entirely eliminate this action which is more liable to arise with high heads than with low, consequently a value of n in the above formula higher than O.1 is required. An analysis of the data of 33 Punjab falls of over 1,000 cs. capacity as actually constructed or modified after construction indicates a value of $n=0{\cdot}33$. Accepting this index the value of K and its component K_D and K_S, *i.e.*, the corresponding constants applied to the dispersal chamber and the stilling tank respectively are worked out in Appendix A for groups of falls of different types. A summary of the results with mean value of K_D K_S and K for each group is given in the interleaved table. Remembering that the examples averaged must contain items the dimensions of which are in excess of requirements, that K_D is independent of soil conditions and depends principally on the form of overfall, and that K_S depends on soil conditions only, assuming the dispersion chamber to have done its work efficiently, the following values are recommended for design :—

K_D	Type of overfall.
4·0	Uncontracted. Grid.
5·0	Uncontracted. Sharp crest or notches. Direct fall.
6·0	Uncontracted. Broad crested notches or glacis.
8·0	Contracted 30 to 40%.
K_S	Type of soil.
5·0	Shingle.
8·0	Good clay.
10·0	Average Punjab soil.
15·0—20·0	Poor soil—light silt.

Shape of Cistern.

The width of the cistern will generally be made equal to the downstream bed width. In the case of falls with contracted crest widths, it is necessary to spread the water over the full width as soon as possible and certainly before the end of the dispersion chamber. It is preferable that this spreading should be complete before the jet enters the cistern, so as to give a uniform distribution of flow from the beginning.

A jet confined at entry to a portion of the width only tends to set up large eddies in the unoccupied width and hence reduces the general efficiency of the cistern.

On the Sirhind Canal there are examples of falls with cisterns of width greater than the bed width where the above tendency is very noticeable.

Generally speaking the deeper the cistern the better. In any case the depth in the dispersion chamber must be sufficient to support the standing wave, the simplest way of calculating which is to use the curve issued by the Punjab Irrigation Research Laboratory. The calculation should be made irrespective of whether the fall has a glacis or a direct drop as it is quite possible in the latter case for the jet, deflected from the floor of the cistern to set up a standing wave. In making the calculation allowance should be made for possible retrogression of d. s. levels. Also, in the case of channels liable to run with low supplies the position of the wave for these conditions should be investigated as F.S. conditions are not always the worst. When the crest width is contracted relative to that of the cistern, unless effective arrangements have been made to spread the jet prior to its entry into the cistern, the contracted width should be assumed to persist in the cistern.

The effect of not providing sufficient depth for the standing wave is of course to cause the jet to cross the cistern without breaking up and consequently render it completely useless.

Apart from providing sufficient margin for the wave, additional depth is useful in that the reduction of efficiency is not so great in the case of retrogression occurring.

Punjab practice seems to favour an additional depth of about $\frac{D}{3}$ where D is the full supply depth, cisterns as deep (below F. S. L.) as 1·75 D occur however.

The author would advocate providing an additional depth up to $\frac{D}{3}$ in the dispersion chamber where this can be done without abnormal expense : *i. e.*, where spring level is low and no unwatering is involved. In the stilling chamber he would conform to the normal waterway of the channel unless there is reason to anticipate retrogression when the final anticipated section of the channel would be adopted.

Mechanical devices in the cistern.

In the following paragraphs are described various devices designed to assist mechanically the dispersion of the jet. As stated above all such devices should be confined to the dispersion chamber and not used in the stilling chamber.

Assuming a fall to be properly designed it is very doubtful if any mechanical aids to breaking up the jet are necessary. The natural tendency of a stream possessed of more energy than needed for its normal flow to set up such eddy action as is necessary to absorb the surplus is well known. Examples are the standing wave and sudden increase of section. The tendency of the action to take an undesirable form where there is concentration of flow over a portion of the section is however also well known.

The author's conclusion is that such devices are unnecessary where the design is such as to secure uniform distribution of the flow over the cistern width from the beginning. Where this cannot be secured, *i. e.*, in contracted weirs or with broad crested notches they are useful.

Roughening of the cistern boundaries is a very old device commonly carried out in brick pitching by setting headers projecting beyond the face of the work. In large works elongated concrete blocks have been used in the same way and a special form of block designed to produce the maximum interference with the waterway at least cost has been produced by Mr. Montagu. Blocks of this form are sometimes referred to as friction-blocks. They appear to be useful in preventing the formation of large eddies.

The Baffle Wall.

Originated by Mr. Colyer, consists of a vertical or overhanging end to the dispersion chamber. Mr. Colyer's explanation of its action as the author understands it is that it turns the jet back on itself and thus causes interference and increased frictional losses. A more rational explanation would seem to be that it breaks up any horizontal jet at the bottom of the cistern which persists as far as its end. For this purpose it would appear to be advisable to place it as close to the point of entry as possible, a practice followed successfully in the case of the Rehbock dentated cill and the "tooth" device by Bombay Engineers (we have no experience in the Punjab of these devices which are therefore not described in this note). There is considerable evidence to the effect that the application of this device has proved useful, particularly where the overfall is such as to produce uneven entry into the dispersion chamber. It has however in certain cases caused trouble by heading up low supplies and thus causing additional eddies in the stilling chamber.

Mr. Colyer considers that the action of this device is enhanced if it protrudes above the bed but this is contested by other officers. The author's conclusion is that if the dissipation chamber is depressed a

vertical end to it is desirable. If the depression is slight or non-existant a low transverse baffle-wall of height not more than $\frac{D}{4}$ placed just downstream of the wave is advantageous, particularly in the case of contracted works. The height of the baffle should always be limited to that which will cause no afflux with the lowest supplies habitually run. The formula $Q=2H^{1.5}$ may be used for calculating this.

Longitudinal diaphragms have been used in the dispersion chamber with a view to preventing the formation of large eddies. This action is purely mechanical.

Summary.

The author's conclusions are, firstly, with regard to the overfall :—

(*a*) Any contraction of the total crest width is inadvisable and if indulged in must involve additional expense in the cistern.

Where unavoidable, arrangements should be made to spread the jet uniformly over the cistern at entry. This can best be done by bowing the crest of the fall or by radial diaphragms on the glacis.

(*b*) For a given total crest width the different types of overfall in order of merit are :—

(1) Continuous overfall through grid.

(2) Sharp sided notches, with lips, arranged so that the jets overlap in the cistern.

(3) Continuous overfall, sharp crest.

(4) Continuous overfall, broad crest.

(5) Broad crested and sided notches.

(*c*) All types of overfall should be designed to give the maximum aeration, particular care being given to securing access of air to the underside of the jet. In the case of low falls where this is difficult the spillway syphon principle should be tried, low falls are however extremely uneconomical and should be avoided wherever possible.

The direct drop is preferable to the sloping glacis. Of intermediate types a profile concave on the upper face is preferred to a convex one.

The cistern.

Should be considered in two parts: the dispersal chamber and the stilling chamber. The former should embody the following features :—

(*a*) The width should be full downstream bed width.

(*b*) Its bottom should be depressed as much as possible consistent with economy of construction up to $\frac{D}{3}$ below d. s. bed-level. It should invariably be sufficient to carry the standing wave having regard to (1) low supplies, (2) possible retrogression, (3) concentrated jets.

(*c*) If depressed its downstream end should be vertical.

(*d*) The size of the dispersion chamber should be calculated from the formula—

$$C_D = K_D \, Q \, F^{0 \cdot 33}$$

where C_D is the capacity below F. S. L. in cubic feet (having regard to possible retrogression). The capacity is of course measured downstream of the wave in glacis falls.

Q is the discharge of the channel in cusecs.

F is the fall in feet.

K_D is a constant.

The author would suggest 5·0 as the normal value of K_D applicable to a direct drop fall with sharp sided notches or a continuous overfall of the sharp or broad crested variety. To this he would apply the following factors in the cases noted against each :—

0·80 Grid.

1·20 Broad crested notches or sloping glacis.

1·60 Contracted crest width.

(*e*) Where the dispersion chamber is not depressed a baffle-wall of height not exceeding $\frac{D}{4}$ and consistent with a depth on it given by $q = 2 \, h^{1 \cdot 5}$ for the lowest supply habitually run may advantageously be placed at about a distance D downstream of the wave in the case of glacis falls and of the point of impact of the jet, in the case of direct drop falls.

(*f*) Friction-blocks or longitudinal diaphragms may be advantageously used in the dispersion chamber in the case of broad crested notches or contracted crest falls.

The Stilling Chamber should be of the same section as the normal water-way or with slightly greater depth if future retrogression is anticipated.

It should contain no mechanical devices for jet dispersion. Its size should be calculated by the formula—

$$C_s = K_s \quad Q\ F^{0\cdot33}$$

where K_s is a constant depending on the type of soil or silt only.

The following values are suggested :

K_s	Type of soil.
5·0	Shingle.
8·0	Good clay.
10·0	Average Punjab soil.
15·0--20 0	Poor soil and light silt.

Appendix A.

CALCULATION OF K_D K_S AND K.

Branch.	R. D.	Q.	F.	C_D	C_S	K_D	K_S	K.
I. UPPER BARI DOAB CANAL. (Rapids).								
M. L. ..	11,000	4,835	4·0		97,000			12·
,, ..	16,000	4,828	7·6		95,000			10·0
,, ..	18,500	4,824	7·5		92,000			9·7
,, ..	20,000	4,818	7·2		91,000			9·9
,, ..	22,500	4,815	9·0		91,000			9·1
,, ..	24,500	4,812	8·1		91,000			9·4
,, ..	26,500	4,809	8·0		91,000			9·5
						Total		70·2
						Mean		10.0
II. UPPER BARI DOAB CANAL. (Direct Falls).								
,, ..	101,072	6,453	8·5	79,000	146,000	5·9	11·0	16·9
,, ..	114,110	6,433	10·3	63,000	91,000	4·5	6·5	11·0
					Total	10.4	17.5	27.9
					Mean	5.2	8.7	13.9
III. LOWER JHELUM CANAL. (Rasul Meter Flume).								
M. L. ..	1,000	4,169	3·5	64,000	30,000	10·2	4·6	14·8
IV. UPPER JHELUM CANAL. (Uncontracted Notches).								
G. B. ..	6,003	2,033	8·0	26,000	13,000	6·4	3·2	9·6
,, ..	21,000	1,864	2·5	14,000	25,000	5·5	9·8	15·3
,, ..	35,065	1,496	2·2	9,600	14,000	5·1	7·0	12·1
,, ..	63,000	1,197	1·88	8,000	30,000	5·4	20·4	25·8
,, ..	75,000	1,016	3·0	5,000	24,000	3·5	16·1	19·6
,, ..	86,000	1,005	1·0	5,700	23,000	5·6	23·2	28·8
					Total	31·5	79·7	111·2
					Mean	5·2	13·3	18·5

CALCULATION OF K_D K_S AND K.

Branch.		R. D.	Q.	F.	C_D	C_S	K_D	K_S	K.
V. UPPER CHENAB CANAL. (UNCONTRACTED NARROW CREST).									
M. L. L.	..	0	11,700	2·6	170,000	150,000	10·6	9·3	14·9
,,	..	71,000	10,028	8·5	75,000	64,000	3·7	7·3	11·0
,,	..	2,21,000	8,542	10·0	73,000	103,000	4·0	9·6	13·6
,,	..	251,000	8,145	2·35	81,000	145,000	7·7	21·0	28·7
						Total	26·0	47·2	73·2
						Mean	6·5	11·8	18·3
VI. SUTLEJ VALLEY PROJECT. (CONTRACTED BROAD CREST).									
D. C.	..	131,000	2,280	2·5	15,500	26,500	5·0	8·7	13·7
,,	..	112,000	2,280	5·8	18,000	21,000	4·3	5·1	9·4
,,	..	215,000	7,600	4·0	14,700	19,000	5·7	7·5	13·2
,,	..	192,000	1,900	3·0	17,600	38,000	6·4	13·4	20·3
,,	..	162,000	2,000	4·0	14,500	33,000	4·5	10·4	14·9
M. C.	..	169,000	3,760	4·12	36,000	176,000	6·0	22·5	28·5
,,	..	140,000	3,800	3·0	32,000	115,000	5·8	21·0	27·8
P. C.	..	176,000	1,243	3·9	25,000	11,000	12·7	5·6	18·3
,,	..	68,000	1,605	2·5	35,000	13,100	16·3	6·0	22·3
						Total	66·7	100·7	168·4
						Mean	7·4	110·2	18·2

CALCULATION OF K_D K_S AND K.

Branch.	R. D.	Q.	F.	C_D	C_S	K_D	K_S	K
VII. SUTLEJ VALLEY PROJECT. (Uncontracted Narrow Crest).								
P. C. U. ..	52,000	7,100	2·89	101,000	113,000	10·0	11·0	21·0
,, ..	112,000	5,040	10·9	88,000	76,000	7·9	6·8	14·7
P. C. L. ..	75,000	2,730	1·4	30,000	59,000	9·8	19·4	29·2
,, ..	26,650	3,050	1·2	32,000	59,000	9·8	18·2	28·0
					Total	37·5	55·4	92·9
					Mean	9·4	13·9	23·2
VIII. LOWER BARI DOAB CANAL. (Uncontracted Narrow Crest).								
M. L. ..	196,954	5,227	2·0	68,000	12,100	10·3	18·4	28·7
,, ..	297,000	4,558	3·0	70,000	103,000	10·7	15·7	26·4
,, ..	473,000	2,774	3·5	50,000	63,000	11·9	15·0	26·9
,, ..	329,000	4,104	8·0	88,000	87,000	10·8	10·6	21·4
,, ..	161,754	5,343	2·0	80,500	119,000	12·0	16·6	28·6
,, ..	258,654	4,558	4·0	84,000	104,000	11·3	14·4	25·7
,, ..	585,900	1,401	3·25	25,000	30,000	12·0	14·5	26·5
,, ..	601,200	1,341	7·75	30,000	29,000	11·3	10·9	22·2
,, ..	640,200	1,188	4·0	22,000	26,000	11·7	13·8	25·5
					Total	102·0	129·9	231·9
					Mean	11·3	14·4	25·7

CALCULATION OF K_D K_S AND K.

Branch.		R. D.	Q.	F.	C_D	C_S	K_D	K_S	K.
IX. LOWER JHELUM CANAL. (UNCONTRACTED NARROW CREST).									
N. B.	..	64,000	1,697	3·15	42,000	..	16·8	..	..
,,	..	95,870	1,697	1·84	28,000	55,000	14·3	28·5	42·8
,,	..	103,270	1,490	3·1	27,000	39,000	12·2	17·8	30·0
,,	..	146,250	1,375	3·8	29,000	50,000	12·5	21·5	34·0
						Total	55·8	67·8	106·8
						Mean	13·9	22·6	35·6
X. SIRHIND CANAL. (CONTRACTED NOTCHES).									
A. B.	..	404,000	1,133	5·6	42,000	36,000	20·6	17·6	38·2
,,	..	360,000	1,404	7·26	441,000	61,000	16·2	22·4	38·6
,,	..	289,000	1,900	9·3	57,600	83,400	14·2	21·0	35·2
,,	..	254,000	2,083	10·1	64,000	167,000	10·4	27·0	37·4
,,	..	105,000	2,807	8·0	84,000	..	14·8	..	..
,,	..	157,000	2,538	6·0	80,000	..	17·4	..	..
B. B.	..	109.000	2,091	6·0	65,000	..	17·1	..	..
,,	..	23,000	2,700	7·5	102,000	80,000	19·2	15·1	34·3
						Total	129·9	103·1	183·7
						Mean	15·2	20·6	36·8

DISCUSSION.

In introducing his paper the author apologized for inflicting two papers on the Congress in one session, his only excuse being that this paper was not written for the Congress, but, under the orders of Government, for the Central Board of Irrigation. The Council of the Punjab Engineering Congress did him a great honour in desiring to place the paper before the Congress and that he could hardly refuse.

Under the circumstances in which the paper had been written it should not have contained anything original; it was required to review Punjab practice. He was afraid, however, that a certain amount of what might be termed "Unbaked Theory" had crept into it. For example, the idea of bowing the crest of a fall and the use of the syphon for aerating low falls.

For the attempted explanation of the action of aeration he thought he need not apologize. The value of aeration was admitted by those who had considered it and whether his explanation of the way it worked was correct or not was a matter of minor importance. The main point was to obtain the general recognition of the value of that factor in the dissipation of energy in order that it might receive due weight in design.

Regarding the formula he suggested for the cistern capacity; he had seen this referred to by various people as an "empirical formula." He would however like to emphasize that it had a rational basis. This comprised the facts:—

(*a*) That a certain known amount of energy had to be dissipated by a fall;

(*b*) That time is required for the dissipation of the energy; and

(*c*) That the rate of dissipation depends on the height of the fall.

The relation assumed between the rate of dissipation and height of fall was of course empirical and was calculated to correspond with Punjab practice, hence the index 0·33 and the co-efficients.

A word of warning was perhaps necessary as regards the use of these empirical factors. Firstly, as regards the index. The mathematical analysis indicated a very small figure for this which was increased to

correspond with practice. This was on the safe side for high falls but was the reverse for low ones. It might be advisable to use the simple formula :

$$C = K\ Q.$$

where K is less than unity.

Now as regards the co-efficients, these had been deliberately kept below average values as only in this way could economy be secured. The capacities given by the formula could not therefore be expected to give entirely trouble-free works. It was better however that they should occasionally have to extend the protection below a fall than that their designs as a whole should be unnecessarily strong and expensive.

Mr. Nand Gopal said that the method of dealing with the question adopted by Mr. Haigh was ingenious and comprehensive. After a close study of the paper he has some doubts which he would ask the author to kindly clear up. He had applied the formula devised by Mr. Haigh to existing falls on the Upper Chenab Canal Main Line Lower and found that different values of the constant K_D were obtained according as the dispersion chamber was taken up to the end of the slope in the cistern or to the beginning of it. The former gave higher values for K_D than the latter. This was natural and perhaps immaterial so long as the values were above the recommended figure of 5. This however did not happen and while in the former case K_D worked out higher than 5, in the latter it came out less. He would like to know if Mr. Haigh would recommend any modifications to existing falls in order to remedy this defect. It would of course be very problematic if the dispersion chamber could or should be extended particularly when it was so difficult to draw a line in actual conditions by observation between dispersion and stilling operation. It was noticed however, that values of K_S increase or decrease inversely by the same amount as K_D reduces, the value of K ($=K_D+K_S$) remaining unaltered. If, therefore, the desired effect could be attained by having a greater value of K_S, this could be done by extending the flexible protection but if not then some form of dissipation of energy in the dispersion chamber was necessary. The speaker enquired what form would be the best for that.

While observing the actual conditions of falls, it was noticed that only one fall showed satisfactory conditions and for this the value of K was 33. Other falls for which K worked out from about 16 to 21 erosion was seen extending up to 1000 feet and over, while the soil could not be deemed any different from average Punjab soil for which Mr. Haigh has recommended a value of K=15 only. It appeared to him that value of K was much below what it should be and perhaps 25 or 30 was near correct. For one case of poor soil with more sand, the erosion went on for over 1500 feet and for such cases the value of K should in his opinion be 30 to 35 against about 20 recommended by Mr. Haigh. The speaker asked if the author would kindly give his views on these points.

Mr. Colyer speaking on Mr. Haigh's paper, stated that on pages 4, 13 and 15, Mr. Haigh had referred to what the speaker had called a 'biff-wall,' as a 'baffle-wall.' In his paper on the same subject for the Central Board of Irrigation, Mr. Colyer had emphasized that a 'biff-wall' was definitely different, and should be distinguished, from the baffle-wall, because baffle piers were simply a means of baffling or obstructing flow, whereas the biff-wall caused a distinct 'biff'; you could not go *round* it, you had to go *back*. It caused the water to be thrown back upon itself, and this had a great deal to do with the dissipation of energy.

On page 3, talking of Mr. Brown, the author said that he went to nature. It was perfectly open to him to go to nature, but the point was that they were trying to defeat nature. If they went to nature in the matter of canals, they would have to face the formation of creeks, high banks and shoals, etc. They should try not to keep to nature but to Engineering, which had been described as 'harnessing the forces of nature.' The speaker remarked that incidentally Mr. Brown's experiments were not a fair test of the 'biff-wall,' as Mr. Colyer's own design had not been included in them.

On pages 4 and 5 Mr. Haigh had dealt with the aeration of the jet. In the speaker's opinion, aeration of the jet was one of the most important factors in the dissipation of energy, and it could be supplied by induction pipes, that is to say by placing pipes under the nape of the jet, thus introducing more air, and increasing the dissipation of energy. This effect of aeration of the jet was brought home to him very forcibly at the bifurcation of the Upper Bari Doab Canal, where jets shooting clear of rectangular notches, were intercepted by grids, causing almost perfect aeration. He had some photographs of devices for producing aeration on various canals, but unfortunately circumstances did not permit them to be shown there. Aeration caused the breaking up of the jet, which as Mr. Haigh pointed out was one of the two main factors in energy-dissipation.

Mr. Haigh had recognized that a continuous overfall was even better than trapezoidal notches. He had done a very good thing in differentiating and separating the functions of dispersion and of stilling chambers, and in reducing his observations to a formula which, even if not yet perfect, was an inducement to other engineers to design these dissipators on a rational basis.

Mr. Colyer referred to a very interesting case of jet-penetration on the Sirhind Canal which he had already mentioned in his paper for the Central Board of Irrigation. There was a fall which had a cistern probably double the width of the actual fall which consisted of rectangular notches. This fall gave a lot of trouble until the cistern was tightened up laterally, after which the trouble ceased. He agreed that by using a vertical-ended cistern as Mr. Haigh recommended, better

dissipation was obtained, but even better results were obtained with a cistern ending in a re-entrant section. Mr. Haigh had objected to the protrusion of these biff-walls and the speaker explained that the protrusion above bed was merely a cheap way of deepening the cistern.

Another controversial point was the correct height for a biff-wall and his experiments showed that the formation of a *small* additional standing-wave considerably reduced the pulsating action which ruined so many banks.

Referring to the summary on page 14, item A, about contraction of the width, he stated that if they could not afford to build a cistern, the best thing was to raise the biff-wall above downstream level and provide it with a glacis sloping down at say, 1 in 3. It was a question of economy whether to raise the biff-wall, or to depress the cistern. In either case he held strongly that it should not be simply vertical but should be of the re-entrant type.

Referring to his notes prepared for the Central Board of Irrigation, from information obtained from 16 Circles and from 9 selected officers having special knowledge of the subject, he had been surprised to find such a lot of evidence recorded in favour of the 'Biff-wall' (*vide* Punjab Irrigation Paper Class 'A' No. 30) as a means of dissipating energy below canal falls.

Mr. Gerald Lacey suggested that the best way to dissipate the energy of a fall was to insert a turbine, generate power and use it. This method had recently been developed to some extent in the United Provinces.

Mr. R. K. Khanna said that the subject of dissipation of energy below canal falls had received considerable attention lately, but he believed that its consideration had not been based on proper scientific reasoning. Too much stress had been laid on the opinions of individual engineers and what they thought to be the best method of dissipation of energy without considering whether their opinions had a reasonable basis or not. The result had been that by far the greater part of the potential energy of falls had generally been allowed to be converted into forward velocity of flow below the falls and engineers had been ineffectively trying to dissipate the energy of flow by means of "Biff" walls and such like devices. This was like letting loose a wild monster and then trying to appease it by patting it.

A much more rational way of tackling the problem would be to try to prevent the conversion of potential energy of fall into forward velocity. A very simple way of doing it would be to split up the flow of water, as it was falling, into two equal and opposing streams, such that one half of the energy of the fall destroyed the other half before the water

reached the low level channel. This arrangement is shown diagrammatically in Fig. 1.

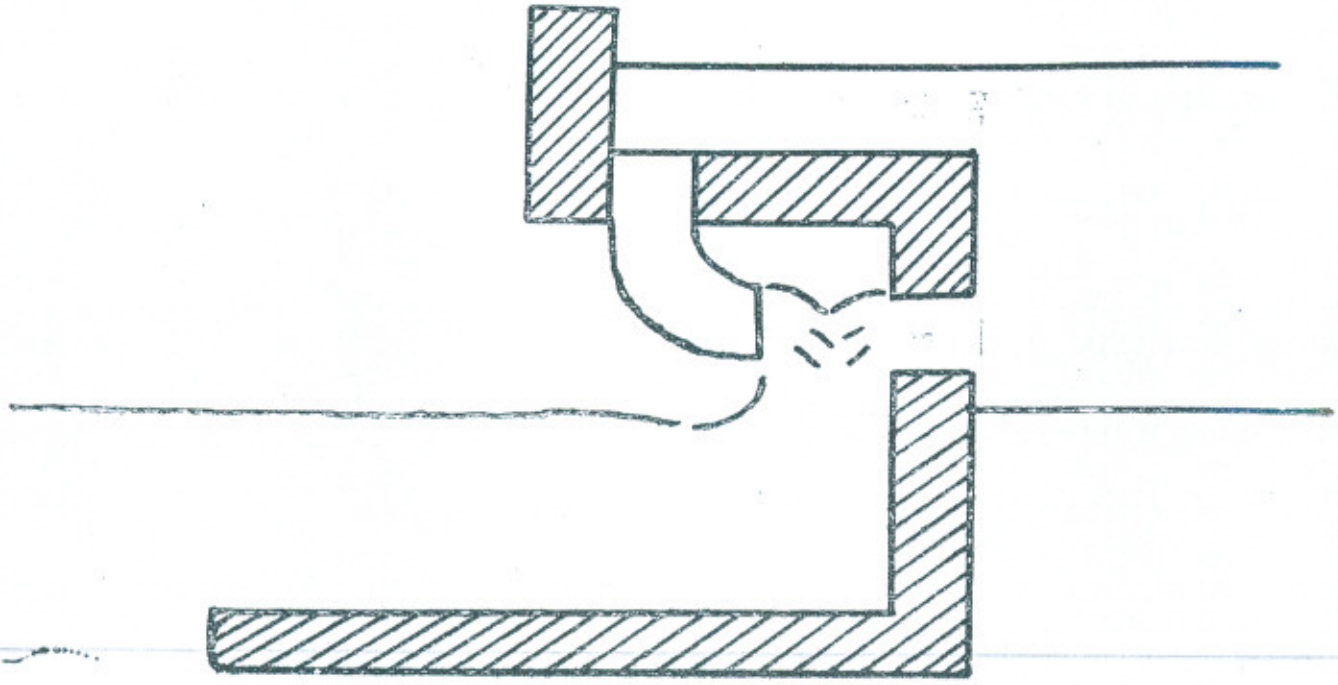


Fig. 1.

Similarly they should be able to dissipate by far the greater portion of the energy of any canal falls by means of the arrangement shown in Fig. 2. With this water would flow out of the orifices *A*, *B* and *C*, and the greater part of the energy would be dissipated at the points X and Y.

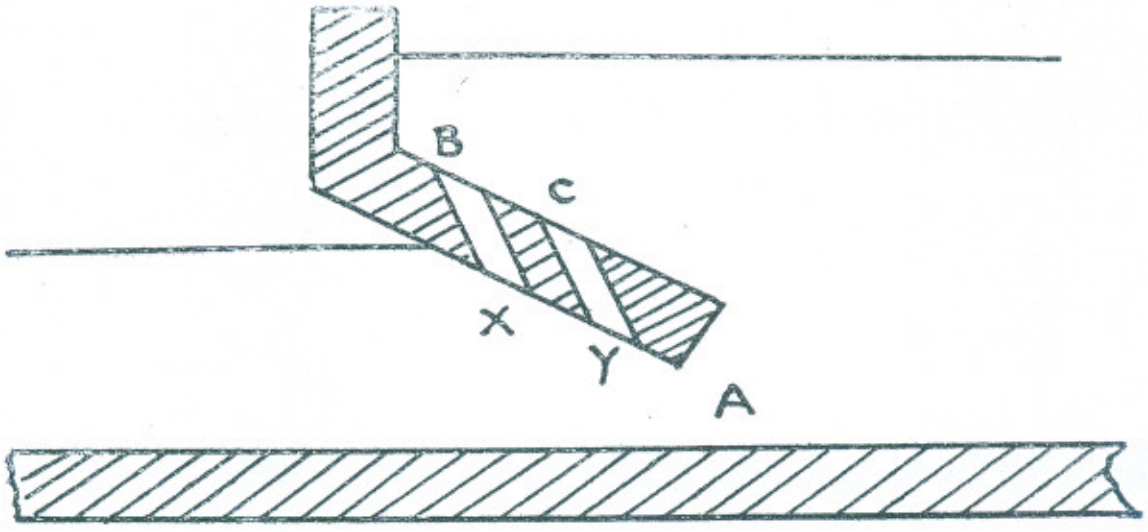


Fig. 2.

These were however merely illustrations of the principle on which suitable designs of works could be made. His real object was to point out that water in falling should acquire as little forward velocity as possible, and that most of the energy of the fall should be dissipated

within as short a distance as possible below the fall by mutual friction between the particles. This could be done by making the water fall over a sharp crested weir, extending over the full width of the channel.

Change in the direction of flow of water only was greatly helpful in dissipating the energy of falls.

Another simple way of dissipating the energy of a fall within a very short distance below the fall was to have an orifice directed upwards. Water in rushing through the orifice would form a sort of hump and partly by the mutual friction of the particles of water and partly by its back flow from the hump by far the greater portion of energy would be dissipated within a short space.

Besides the prevention of conversion of potential energy into forward velocity which could be effected by any of the methods indicated above it was of importance that water in falling should cover the whole width of the channel below the fall by which means eddying and churning action which was detrimental to the safety of works was avoided. Generally speaking the requirements of canal falls were :—

(1) That the potential energy of water should not be converted into forward velocity below the fall.

(2) The whole quantity of water should pass over as wide a weir or through as wide an orifice as possible ; and should if possible be split up into two or more smaller streams within the body of the fall, in order to destroy the energy by the inter-action of the jets.

As an alternative to the above requirements the orifice type of fall with an upturned direction of flow he might suggest combined weir and orifice type as indicated in the sketch Fig. 3.

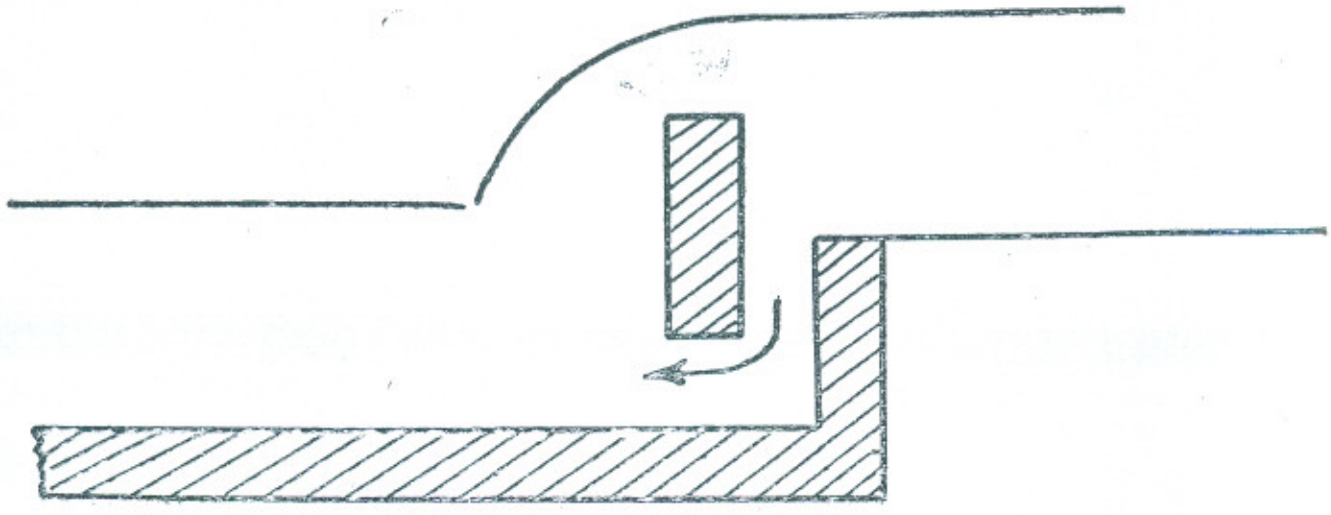


Fig. 3.

The Author in replying to the discussion regretted that it had had to be cut short owing to the time available being limited.

Referring to Mr. Nand Gopal's remarks, he said that it was difficult in practice to determine the limits of the dispersion chamber. It was really a matter for observation of the limits where the main forward jet or jets of the fall had dispersed. In his analysis he had assumed the dispersion chamber to be limited by the extent of the rigid protection as this was safe. If the jets persisted beyond this the fall would certainly give trouble. The chamber defined in this way might well be greater than requirements however.

Similarly the stilling chamber (which in the Paper had been taken as the balance of the cistern) might be defined as that portion of the cistern where its cross section is not less than the normal cross section of the stream and which does not contain any mechanical devices for jet dispersion. The stilling chamber as thus defined might well overlap the dispersion chamber. In this case he suggested that any lower portion might be considered to be dispersion or stilling chamber according as it is in the upper or lower half of the whole cistern.

Trouble in the case of existing falls could only be put down to inadequate extent of dispersion chamber where it started from the upper end of the flexible protection. In other cases it was first necessary to see that the stilling chamber was adequate and if not to make it so.

If trouble still persisted he would then endeavour to improve the efficiency of the dispersion chamber by aeration, mechanical dispersion, etc.

In the cases cited by L. Nand Gopal the stilling chamber was obviously inadequate.

In cases where side erosion persisted for long distance below a fall he thought the trouble was to be sought more in the design of the channel than in the fall.

Referring to Mr. Colyer's remarks he regretted that Mr. Colyer objected to the change of nomenclature. Higher authority had however objected to the lack of dignity in the term " biff wall " and personally he could not see much difference between the functions of Mr. Colyer's device and the baffle wall developed in Bombay. The latter however, appeared to be much more efficient by reasons of its positioning which conformed to that suggested in the paper.

He was glad to hear Mr. Colyer support his advocacy of aeration and the continuous overfall. The example quoted by Mr. Colyer for the Sirhind Canal was very interesting.

Referring to Mr. Lacey's remarks he thought that no one would seriously deny Mr. Lacey's contention.

Referring to Mr. Khanna he said that the suggestions put forward were very ingenious. He was afraid, however, that when Mr. Khanna came to put his ideas into practice he would find difficulties. Orifice falls were only practicable where a permanent staff existed to keep them clean and to secure the effective interaction of jets in the manner suggested would mean a very expensive design.

CORRESPONDENCE.

Mr. Ishwar Das in writing pointed out that many canal falls were combined with bridges which were usually placed upstream of the crest of the fall.

In the recent remodelling of distributaries in Shahpur Division, Lower Jhelum Canal, the waterway of the bridges had been utilized as the fall cistern. The results were so satisfactory that he was tempted to recommend their use very widely.

The advantages of this as he saw them were :—

1. With the bridge orifice submerged the entrained air is passed through the length of the waterway under pressure. This is evident as the air can be seen emerging at the downstream end.

2. The water is in contact with solid boundaries on all sides thus securing maximum friction between the water and its solid boundaries.

3. The piers of the bridge act as longitudinal diaphrams and prevent the formation of large eddies.

Incidently it might be said that building the bridges downstream instead of upstream would save initial expenditure and recurring maintenance charges of high ramps and approaches.

The second point he would bring to notice was the excellent design of falls adopted on the Lower Jhelum Canal and associated with the name of Mr. A. W. M. Jesson.

The design which had been singularly successful was simple and straightforward. Its chief characteristics were :—

1. Crest length the same as the downstream bed width of the channel, giving a low intensity of discharge per foot and straight stream line flow.

2. No cistern.

3. All the debris left after construction was utilized in filling downstream forming a very rough flexible apron on the downstream bed and sides.

The author's comments on this are that while he agrees that the protected portion of the waterway under a bridge would generally provide an ample cistern for a distributary fall, he could not support the

advocacy of submerged bridges for the purpose. The idea that the submergence increases the dissipation of energy through aeration is fallacious. The air will rise to the surface in the same distance in either case, and after leaving the water no further dissipation of energy is possible. The submergence reduces the volume of the cistern or alternatively increases its cost and the disadvantages frcm the point of view of danger of blocking are considerable.

In conclusion, the author would like to place on record an experiment made by Mr. E. S. Crump *apropos* of the statement on page 93 of the paper that the virtue of the trapezoidal notch seemed to lie on its sharp edge rather than in its notched shape. Mr. Crump demonstrated by fitting suitable lips to broad sided rectangular notches that the lip is the chief agent in producing the typical jet of the notched fall.