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CONTROL OF FLOW ON CURVES IN OPEN CHANNELS

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Introduction

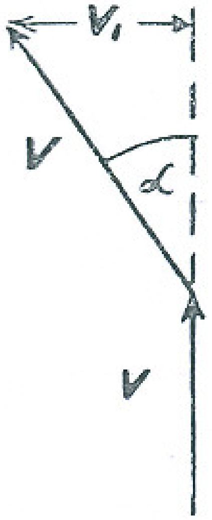
It is well known that the flow of silt-laden water around curves in open channels leads to an abnormal distribution both of silt and of velocity across the section of the channel, and that this, in turn, may cause shoaling, scouring and erosion and give rise to serious difficulties.

It is the purpose of this paper to examine exactly what happens when water flows round a curve and consider the remedies available to deal with the effects of curvature. The latter part of the paper is concerned with a device for controlling the flow around curves or for correcting badly distributed flow, however caused; the device is believed to be novel, at least in so far as its application is concerned.

Flow of Water around a Curve

The nature of flow around a curve in an open channel is well known and there is more than one way of explaining what happens, but the following explanation is as satisfactory as most, and is convenient with regard to what follows.

FIG. I



Referring to Fig. I, a stream of water diverted through an angle α, and maintaining the same velocity may be considered as having a lateral velocity $V_1 = V \sin \alpha$ imposed upon it, and the energy in terms of head required to divert the flow is that required to produce this velocity or

$$\frac{V_1{}^2}{2g}=\frac{V^2}{2g}\sin^2\alpha \ldots\ldots (1)$$

Theoretically in frictionless motion no energy would be required, but the above is a rational assumption while empirical rules vary from $\frac{V^2}{2g}\text{Sin } \alpha$ to $\frac{V^2}{2g}\sin^2\frac{\alpha}{2}$, the point in the present argument being that energy is actually required and this varies with $\frac{V^2}{2g}$ multiplied by a function of the angle.

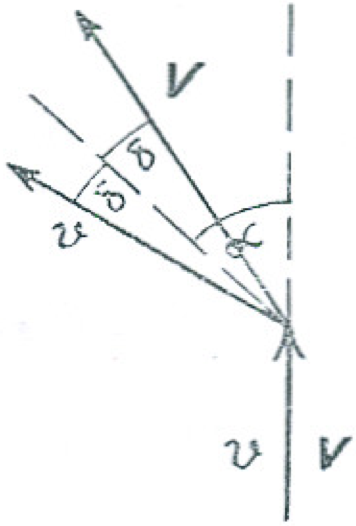


FIG. II

Now, referring to Fig. II, suppose that two streams of water carrying the same discharge but with different velocities V & v are flowing together, and the combined streams are forced to change direction so that the mean change is through the angle α. If both streams turned through the same angle, the energy required to produce the change would be :

$$\tfrac{1}{2}\left\{\frac{V^2}{2g}\sin^2\alpha+\frac{v^2}{2g}\sin^2\alpha\right\}\ldots\ldots (2)$$

If, however, one stream at velocity V is permitted to change through an angle $(\alpha - \delta)$ and the other at velocity v through an angle $(\alpha+\delta)$, the mean change of direction will be the same, and the energy required will be :

$$\tfrac{1}{2}\left\{\frac{V^2}{2g}\sin^2(\alpha-\delta)+\frac{v^2}{2g}\sin^2(\alpha+\delta)\right\}\ldots.(3)$$

It is a well known principle that, whenever there is any choice in the matter, flowing water will always take the path of least resistance, or the total energy required to produce any change will be a minimum, that is, the value of δ will be such as to make the expression (3) a minimum or

$$V^2 \sin^2 (\propto - \delta) + v^2 \sin^2 (\propto + \delta) \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

will be a minimum.

For a minimum value when $V > v$ it can be shown that δ must have a positive value $\ngtr \propto$, that is to say, that the stream with the greater velocity will turn through a smaller angle than the low velocity stream. Without entering into complicated mathematics, a simple numerical example will demonstrate the fact :

Example :

Let $V = 2$, $v = 1$ and $\propto = 30°$ then if $\delta = 0$ and the two streams keep together, the expression(4) becomes :

$$4 \left(\tfrac{1}{2}\right)^2 + 1 \left(\tfrac{1}{2}\right)^2 = \frac{5}{4}$$

If, on the other hand, $\propto = \delta = 30°$ or the high velocity stream keeps on straight, then expression (4) becomes : $4 \, (0)^2 + 1 \left(\frac{\sqrt{3}}{2}\right)^2 = \frac{3}{4}$ or the energy required is only 0.6 of that required for the streams to keep together.

Hence, when flowing water passes round a curve, the high velocity streamlines will travel as straight as possible and pass to the outer side of the curve, while the lower velocity filaments will turn through a greater angle than the average and pass to the inner side of the curve. Thus the curve will be negotiated with the minimum expenditure of energy or head.

In the ordinary open channel the higher velocities are in the upper part of the stream, and the low velocities mostly near the bottom, so that in passing round a curve, the high velocity surface water travels to the outer edge of the curve and the bottom water turns more or less sharply towards the inside of the curve ; thus the stream as a whole rotates with a corkscrew motion. The amount of rotation will depend on the original differences of velocity in the stream and the degree of curvature ; on the ordinary mild curve the corkscrew motion will not be strong.

This explains why rotation takes place, but does not give the whole picture. Normally water is forced round a curve by a rigid side wall, pitching, or berm, and it is the lateral pressure on the side that causes the change of direction of the whole stream, that is, the pressure on the outer side of the curve must be greater than on the inner side; the pressures are changed by the momentum of the stream. If the pressure against one side is greater than on the other, the level of the surface must be higher on the side with the greater pressure, *viz.*, the outer side. This difference of level across the stream forces water to flow across the channel to the inner side of the curve, and as shown above, the water that is moved across must be the relatively low velocity bottom water. Thus in addition to the corkscrew movement we have the phenomenon of a high surface level and high velocity on the outer side, and a relatively low surface and low velocity on the inner side of the curve.

Silt Movement on Curves—Rigid Bed

In a silt-laden channel where most of the silt travels in the low velocity water near the bottom, it follows that most of the silt moves across the channel towards the inside of the curve; where velocities are lower, the normal effect of the same is that a shoal is formed; conversely, on the outer side of the curve there is a high velocity and a relatively small amount of silt with a consequent tendency to scour. This, however, is a general statement, but in particular cases variations arise, and, in fact, as will be shown later, the statement is not wholly true except in so far as general tendencies are concerned.

In a curved channel with a rigid bed and sides, scour cannot take place, but silt is drawn strongly towards the inside of the curve and shoaling often occurs. If, however, velocities are high enough for the degree of curvature and the silt load, there may be no shoal, but in such cases there is usually considerable turbulence and a strong corkscrew action which throws the silt up into the upper fast-moving jets, and to a large extent the silt is redistributed; even so, the amount of silt carried per unit volume of water is much greater somewhere near the inner edge of the curve. It is, however, just possible for nearly all the silt to travel in a fairly narrow width along the inside of the curve without shoaling, and the author has actually created the necessary conditions on a model, but the adjustment is very fine and the curve must be very gentle with a minimum of turbulence.

Where there is shoaling in a rigid channel, there is usually some redistribution of silt due to turbulence, while the flow of silt is the greatest along and near the edge of the shoal, the velocity over the shoal itself being too low to carry a very heavy silt load. The shoal is kept stable due to the fact that a great deal of the silt approaching the shoal and on the edge of the shoal is lifted by turbulence and the corkscrew motion producing vertical jets along the edge of the shoal; the silt that is lifted is carried away towards the outside of the curve by the upper layers of water. The top of the shoal becomes stable when the velocity and turbulence over it is sufficient to carry the relatively small amount of silt reaching that position.

Silt Movement on Curves—Unrestricted Bed

In a channel of fairly constant discharge and entirely free to form its own bed out of the normal silt supply, there is, of course, scouring and shoaling on a curve, but this continues only until a state of stability is reached and the channel, instead of being roughly rectangular, becomes more or less wedge-shaped in section, with the deep portion on the outside of the curve. Now the corkscrew motion of the water continues as before, but is strongest in the deep portion and becomes weaker towards the shallow inner side of the curve, with the result that vertical eddies are strongest where scour begins to give place to shoaling; the corkscrew currents are indicated in Fig. III.

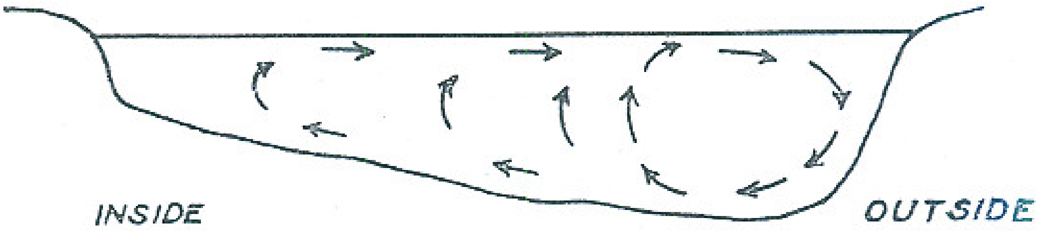


FIG. III

Silt in the deep part of the channel is drawn towards the shoal, but, instead of passing right on to the shoal, is caught up by the corkscrew motion and the relatively high turbulence in this region, reaches the higher velocity water near the surface and is carried back to the outside before it can settle down again; some silt passes on to the shoal and the vertical eddies, though weaker, pick up silt and return it at least part of the way back to the outside; some silt will, of course, get beyond vertical eddies of sufficient strength to return it, and will be carried forward on the shoal. Thus the silt is mostly being picked up into fairly high suspension and thrown back to the outside of the curve as fast as it is drawn along the bed towards the shoal, so that the shallow water is enabled to carry forward the relatively small silt supply reaching the higher parts of the shoal. In such a channel, then, there must be a somewhat greater quantity of silt per unit volume of water, carried forward in the deep water near the outside than in the shallows along the inside of the curve.

This latter statement may be disputed, but it seems that it must be true if the channel is to be stable, for otherwise the inside of the curve would quickly silt up solid, which, of course, it does if the curve is too sharp or the channel too wide. If the channel settles down to a fairly stable wedge shape in section, the outer side of the curve has a relatively high velocity and turbulence and, therefore, has a high silt-carrying capacity, and to be stable must carry silt up to full capacity or, otherwise, scour further; conversely, on the inside of the curve there is relatively low velocity and low turbulence with low silt capacity, hence the water must carry only a relatively low silt charge or else silt up further.

This is borne out by actual silt observations on stable curves on a silted bed and an example is given in Plate I where the results of observations on a curve at the Kasba Syphon on the Upper Jhelum Canal are plotted; the silt samples were taken with the standard bottle sampler at 0.8 of the depth so that a fair proportion of the coarse bed silt was found in all samples. The total silt (that is, all silt over 0.07 mms. diameter) is plotted in a firm line while the coarse silt over 0.20 mms. diameter is shown dotted; soundings are plotted below.

Even so, experience may appear to contradict these conclusions, since outlets and minor offtakes on the inside of a curve usually have silt trouble while canals taking out of the deep water side of a river are usually fairly silt-free. But outlets and minor offtakes are usually built in relation to the normal section of a straight channel and become more or less submerged in the shoal, while a river is by no means stable and, certainly, has nothing like a constant discharge. The most reasonable explanation for canal heads being best situated by a deep water channel seems to be that the river scours during floods, but at other times the deep channel is silting up, so that the canal has a primitive form of still pond regulation.

Harmful Effects and Remedies

A sharp curve is almost invariably protected with a rigid bed and sides of masonry or pitching, but, even so, the effects of the curve always tend to persist in the earthen channel beyond. Jetting, once established, tends to go beyond the permanent works and expend energy on scouring the bed and eroding the berms, while shoaling may also continue for some distance.

This is amply illustrated by the case of the sharp curve at R. D. 46,000 of Bhiwani Distributary shown in Plate II. Here a channel of 203 cusecs, after passing over a control point, takes a sharp left-hand turn of 53° between masonry walls, followed by a fairly sharp expansion between pitched sides; the floor is protected with masonry and pitching. A divide wall had been built to reduce the effect of the curve and had been recently extended, but, even so, there was heavy shoaling as indicated on the plan. The jets from the two parts of the channel combined and cut into the right bank, made a deep scour hole, and further turned back across the channel with a lesser effect on the left bank further downstream; the jetting action is indicated by arrows on the plan.

The remedies proposed and considered for this work cover most of the possibilities of such cases in general:

(*a*) Protection of the banks with bushing, pitching or loose bats. Bushing is only a temporary expedient, while pitching or loose bats would probably be effective if they did not divert the jet elsewhere. In any case protection does not reduce the action, and certainly does not restrict shoaling.

(*b*) Divide walls certainly limit the action, but in this particular case it was not reasonably possible to extend the principle by putting in other divide walls, while a further lengthening seemed futile. It was, however, considered that an extension at a slight angle to the remainder might separate the two jets, and this would be possible, but the two jets and shoaling would remain.

(*c*) Friction blocks in the path of the jet. Suitable blocks might destroy some of the energy of the jet, but would be unlikely to affect shoaling. Actually a number of blocks $0.8\times0.8\times1.25$ ft. high were put in the jet near the end of the divide wall, but the effect appeared to be nil, and the blocks were removed as useless.

(*d*) Baffle wall across the stream. It is well known that converging streamlines tend to steady the flow, and it can be shown that a general increase of velocity must tend to equalise velocities across the stream; even so the velocity of the jets would be increased to some extent and it is doubtful if the net result would be any real advantage. This was not actually tried, and in any case would hardly have stopped the shoaling.

(*e*) Side projections to divert the jet or the flow in general. The principle involved is to make the boundary restriction or side wall on the outside of the curve turn through a slightly greater angle than the stream as a whole, thus making the jet pass to the centre of the flow. The proposed extension of the divide wall at a slight angle, mentioned above, is an example. The principle was actually applied in another form, and $9''\times9''$ pillars were built against the outer side walls as dotted on the plan (Plate III). These were actually fairly effective and on account of their crude nature broke up the jets to a large extent, but they produced objectionably violent turbulence, swirls and eddies. The difficulty about applying the principle is that it is almost impossible to forecast the result, and in any case some jetting and shoaling is almost certain to remain.

(*f*) Silt Vanes. King's Silt Vanes would change the silt distribution and probably stop shoaling, but a jet would be likely to persist, if not be encouraged, to pass the downstream end of the vanes. Actually, vanes very similar to King's Silt Vanes were put in, although they were designed not so much to divert silt as to divert flow and to dissipate the jet. These vanes are shown on the plan (Plate III), and the effect of these was remarkable.

Vanes on Bhiwani Distributary

The design of vanes finally adopted was somewhat similar to King's Silt Vanes, except that they were straight and each vane ran right into the side-wall at one end or the other, so that in effect each pair of vanes presented a continuous obstruction to flow and the whole supply was forced to pass over the top of the vanes.

The vanes were 1.5 ft. high, the channel having a full supply depth of 3.9 ft., so that the height of the vanes was a little over one-third of the depth. The vanes were spaced 2.5 ft. apart and were placed at about 60° to the normal section.

On the face of it, these vanes were likely to make matters worse since there was already a concentration of flow on the right side or outside of the curve, and clearly the vanes would divert more flow to the same side. Admittedly this obvious effect seemed as if it might outweigh any other action of the vanes, but although there must have been some flow along the vanes, and it was intended that there should be, the main effect of the vanes was to divert the flow as a whole towards the left or inner side of the curve and to break up the jet, thus making the flow fairly evenly distributed across the width of the channel. The small flow along the vanes carried silt with it, so that the silt distribution was improved, which, combined with the even distribution of flow of water, stopped all scouring, shoaling, jetting and erosion, the earthen channel becoming almost as even as if there had been no curve at all. It was anticipated that there would be some dead water close to the inside of the curve (left side) and near the vanes, but in fact there was no slack water anywhere.

It was anticipated that the vanes would not be of exactly the correct strength, and in fact in the left bay they were too powerful and in the right bay not sufficiently effective as regards distribution of flow; in both bays they were too powerful in their effect on silt distribution. An adjustment was made by making the vanes 1.25 ft. and 1.75 ft. high in the left and right bays respectively, and removing the downstream half of the D. S. vane in both cases; the part removed is shown dotted on the plan (Plate III). The cross-section on Plate III shows the silted bed of the channel and velocity distribution after the final adjustment of the vanes; considering that the section was taken only 10 feet from the end of the bed pitching, the variations in bed levels and velocities are not unduly marked.

The reason why the vanes should cause the flow to change direction is given in detail below, but the general principle is that the water is forced to turn in order to obtain sufficient sectional area of flow to cross the vanes without undue increase of velocity. From another point of view the vanes may be regarded as reversing the normal corkscrew motion of a curve.

The vanes created a slight increase of turbulence which, together with the slight increase of velocity (converging streamlines), had some effect in helping to equalise velocities and distribute the flow evenly. The jet was broken up since the greater part of it was diverted and only a part of it was able to continue in its original direction.

Diversion of Flow by a Diagonal Vane

The change of direction, when water flows across a diagonal vane and the magnitude of the diversion produced, is now explained with reference to Fig. IV.

Suppose a diagonal vane is constructed across a stream at an angle θ to the normal section and to such a height that if the flow were diverted to cross the vane at right angles, there would be no change of velocity, that is, the sectional area measured above and along the length of vane is the same as the normal section of flow in the approach channel.

Imagine a stream of water travelling at velocity V and approaching a vane AB at an angle (90°—θ) at the point 0.

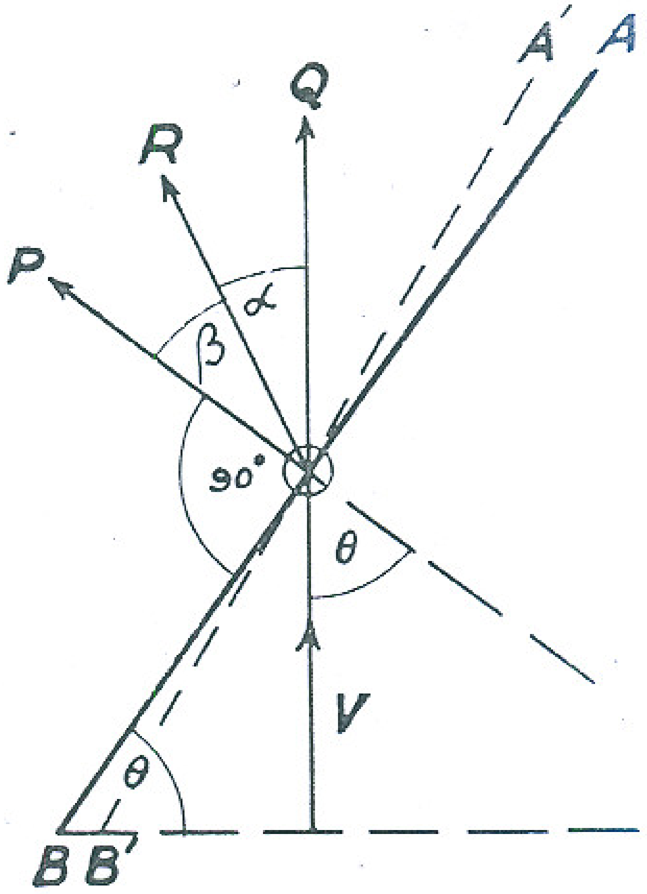


FIG. IV

If the water travelled on straight in direction 0Q, energy would be required to produce the increased velocity necessary to pass diagonally over the vane, but no energy would be required on account of change of direction.

If, on the other hand, the flow turned at right angle to the vane in the direction OP, there would be no change of velocity, but energy would be required to produce the directional change.

The actual direction of flow would be somewhere between these two extremes, say in the direction OR, such that the energy required to cross the vane (for increase of velocity and change of direction) would be a minimum. This is an established hydraulic principle and, in simple language, means that the flow will take the path of least resistance.

The energy (in terms of head) required to divert the flow through the angle α may be taken as the energy to produce a velocity of ($V \sin \alpha$) or $E = \frac{V^2}{2g} \mathrm{Sin}^2 \alpha$.

The velocity over the vane will be increased from the value V to v, where $v = V \sec \beta$ and the energy required to produce this increase of velocity will be ;

$$\epsilon = \frac{v^2}{2g} - \frac{V^2}{2g} = \frac{V^2 \sec^2 \beta}{2g} - \frac{V^2}{2g}$$

$$= \frac{V^2}{2g} \tan^2 \beta$$

Now since $E + \epsilon$ is to be a minimum—

$\frac{V^2}{2g} \sin^2 \alpha + \frac{V^2}{2g} \tan^2 \beta$ is to be a minimum—

and $\sin^2 \alpha + \tan^2 \beta$ is to be a minimum—

Since $\alpha + \beta = \theta$, an angle fixed by design, by differentiation and equating to zero, the value of β could be determined from the resulting equation :

$$\mathrm{Tan}^5\beta - \mathrm{Sin}\, 2\theta\, \mathrm{Tan}^2\beta - (2\cos 2\theta + 1)\, \mathrm{Tan}\beta + \mathrm{Sin}\, 2\theta = 0.$$

The stream would be diverted through the angle $\alpha = \theta - \beta$.

Supposing now that the height of the vane were to remain the same as before, but the vane were constructed along the line A′ B′. The sectional area presented to flow in the direction OP would be the same as before, and apparently the vane A′ B′ would divert the flow to the same extent as the vane AB. This is not exactly true, and there would be some slight difference, but provided the angle A′OA is not unduly large the difference is very small. Thus, provided that the angle θ is not less than that required by theory, for all practical purposes the change of direction of flow is controlled entirely by the height of the vane.

Practical Considerations

The exact determination of the angle of diversion from the equation given above would be unduly involved and serve no practical purpose, since α can be found with sufficient accuracy by simpler methods.

A rough approximation is immediately apparent, since for angles up to about 30° the SIN and TAN are roughly equal and the expression SIN $^2\alpha +$ TAN $^2\beta$ may be written :

$$\mathrm{SIN}\,^2\alpha + \mathrm{SIN}\,^2\beta.$$

For this expression to be a minimum $\alpha = \beta = \frac{1}{2}\theta$ and this result is in fact near enough for all practical purposes.

A more accurate result can be obtained for particular values of θ by working out values of SIN $^2\alpha +$ TAN $^2\beta$ with the help of mathematical tables ; this has been done for $\theta = 30°$, 45° and 60° and plotted in Plate IV. From these graphs it will be seen that the minimum values of the expression in each case are at a point where $\alpha > \beta$ or $\alpha > \frac{1}{2}\theta$, but it will also be noted that for a fair range of α, the value of SIN $^2\alpha$ $+$ TAN$^2\beta$ is very nearly the same, or, in other words, the forces involved in maintaining flow at the exact theoretical angle α are very small, and any incidental factors would in practice make α depart from the theoretical value. Further, the actual head required to divert the flow is not necessarily exactly $\frac{V^2}{2g}$ SIN $^2\alpha$, but if the head required be taken as $\frac{V^2}{2g}$ SIN α or $\frac{V^2}{2g}$ SIN$^2 \frac{\alpha}{2}$, the flow would theoretically be diverted through an even greater angle, as will be seen from the curves dotted on Plate IV for a vane at 60°.

Mention has been made of the fact that the vane tends to divert some of the bottom water and silt along the vane in the contrary direction to that in which the flow as a whole is to be diverted ; shock may also have some effect on the whole flow and both these factors may tend to reduce the value of α in practice. Further, the width of the top of a vane consisting of a thin wall would require the water to change direction suddenly ; this is another form of shock which would tend to reduce the actual value of α.

With these considerations in view it is unlikely that the actual value of α would exceed $\frac{1}{2}\theta$ and practical results indicate that the actual angle of diversion is generally somewhat less than this, and may be taken as varying with the height of the vane since low vanes seem to be relatively ineffective. As a rough approximation the actual angle of diversion α may be taken as $H\theta$, where H is the height of the vane relative to the total depth of water. It is true that shock could be largely eliminated by building the vane with a rounded approach curve and a wide crest on the lines of a broad-crested weir, but the expense would not usually be justified and the vane would cease to perform the useful function of redistributing silt.

It has been shown that, provided the theoretical value of θ is exceeded, the height of the vane controls the angle of diversion α, and for purposes of design, the data given in Table I of the Appendix may be found useful.

From practical considerations it is not desirable to build vanes higher than half the depth of the channel, and should a change of direction exceeding 30° be required, it would be better to carry out the operation in two or more stages.

The table shows data for a vane as low as one-tenth of the depth, but if it is necesary to divert the flow at all, vanes of less height than one quarter of the depth are not likely to serve any useful purpose. The reason for this is that although low vanes may divert the flow, the forces acting are very small, while a diversion of less than 10° is not likely to be of any real value except perhaps in some unusual circumtances.

In any particular case it is not always easy to determine exactly to what extent the flow should be diverted, and, therfore, it is desirable to build the vane at an angle somewhat greater than the theoretical value of θ, usually to the full 60°, and to make the height of the vane to suit estimated requirements. The actual amount of diversion can then be adjusted by raising or lowering the vane as found necessary. Similarly, when the vanes have been built and adjusted satisfactorily, it is not easy to determine the actual angle of diversion with any exactitude, so that data of the actual angle of diversion produced by vanes can only be on an approximate basis.

It should be noted that the full effect of diversion vanes is not apparent until the channel has been in flow for a week or 10 days, since it takes a little time for shoals to be removed and scour holes to fill up.

Other Applications of Diversion Vanes

It was intended to build a series of vanes on a curve in an unprotected earthen channel as a purely experimental measure to see if it were possible to pass the supply round a curve in a channel of normal rectangular section without erosion of the berm on the outer side of the curve or shoaling on the inner side, and also to obtain a more exact determination of the actual angle of diversion produced by vanes. For various reasons the experiment was not carried out, but in any case it would not have been of great practical importance, since, as shown above, exact determination of the angle of diversion is not essential, while the cost of vanes in such a case would probably be greater than the cost of protecting the berm.

A vane was, however, built to deal with a common case of jetting on an ordinary small regulator, the jet originally passing along one side of quite a gentle expansion, causing scour on one side and shoaling on the other. It is true that the jet was caused by the sharp curve upstream of the standing wave weir, but the weir and wave did not even out the flow and silt distribution. A plan of the work on Durjanpur Minor Head with a discharge of 40 cusecs is shown in Plate V together with cross-sections taken at the end of the pitching before and after the construction of the vane. In this case the single vane was built at 45° of ample strength and continuous from side to side without any gap to pass leakage water, as this could be done without interfering with the supply of the minor. The vane was built 0.9 ft. high, but it was found necessary to increase the height to 1.05 ft. to make it sufficiently effective.

Experiments with diversion vanes to deal with central or unstable jetting have not been carried out, but their application to such cases would seem to be possible. Nor have vanes of uneven height been tried, but a vane highest at the point of maximum jetting and lowest where flow is slack would possibly be even more effective than a vane of the same height throughout.

Summary and Conclusions

(1) Flow round a curve produces a rotary or corkscrew movement which results in a redistribution of velocity with the higher velocities on the outside and lower velocities on the inside of the curve, producing scour and shoaling respectively.

(2) Where the channel has a rigid bed and sides the rotation usually produces a concentration of silt near the inside of the curve which aggravates the scouring and shoaling action.

(3) Where the channel is entirely free to form its own bed in the normal silt supply and the channel settles down to a stable, roughly wedge-shaped section, then the rotation and turbulence maintain a more or less normal silt distribution, the flow of silt being somewhat greater towards the outside rather than the inside of the curve.

(4) Various methods of dealing with the conditions set up downstream of a curve and expansion are discussed and it is suggested that the most satisfactory method is to correct the distribution of flow and silt by means of a diagonal vane or vanes. These diversion vanes bear some resemblance to King's Silt Vanes, but are designed primarily for the diversion of flow rather than the diversion of silt.

(5) At first sight, diversion vanes are built the wrong way round, but the main effect of a vane is to divert the flow across rather than parallel to the vane. There is, however, some flow along the vane which has an effect on silt distribution, so that the net effect is to nullify the effects of a curve and prevent jetting, scouring and shoaling.

(6) The diversion of flow by a diagonal vane is shown to be susceptible to theoretical treatment, but for various practical reasons the actual amount of diversion is somewhat less than that indicated by theory. The angle through which flow is diverted is shown to be almost entirely dependent on the height of the vane relative to the total depth of water.

(7) Two examples of diversion vanes in practice are given to show that a suitable vane is capable of correcting the effects of a curve; a single vane meets the case in ordinary circumstances.

(8) The principle of the diversion vane might possibly be adapted to deal with other conditions than those of the two cases described, but for the present such adaptations must be treated as experimental.

APPENDIX

TABLE I

Θ Required angle of vane to normal (Minimum value)	H Height of vane as proportion of total depth of water	$\propto$ Probable angle of diversion of flow $H\Theta$
26°	0.10	2½°
36°	0.20	7°
41°	0.25	10°
45°	0.30	13°
48°	0.33	16°
50°	0.35	18°
53°	0.40	22°
60°	0.50	30°

PLATE I
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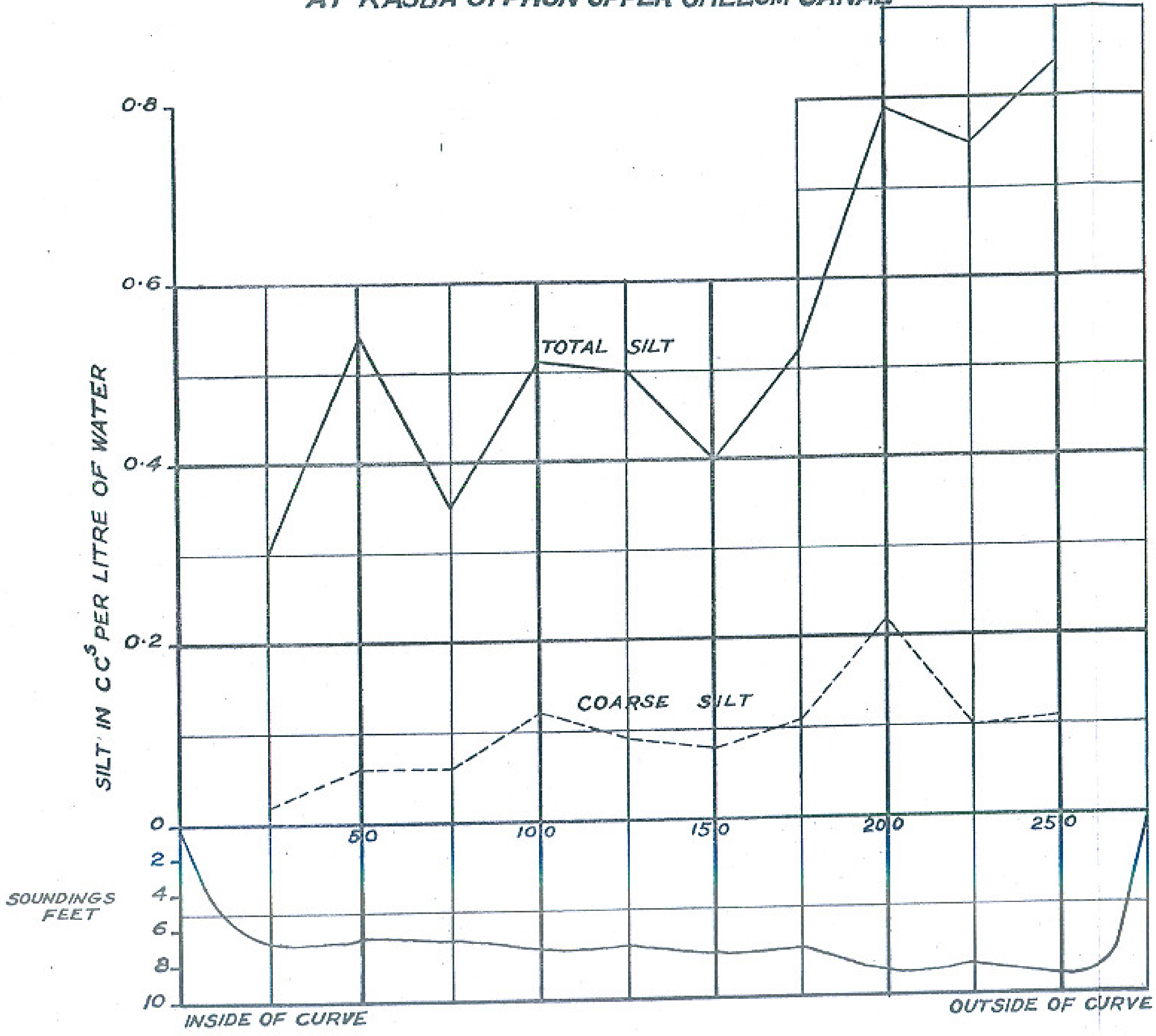
DISTRIBUTION OF SILT ACROSS A CURVE
AT KASBA SYPHON UPPER JHELUM CANAL



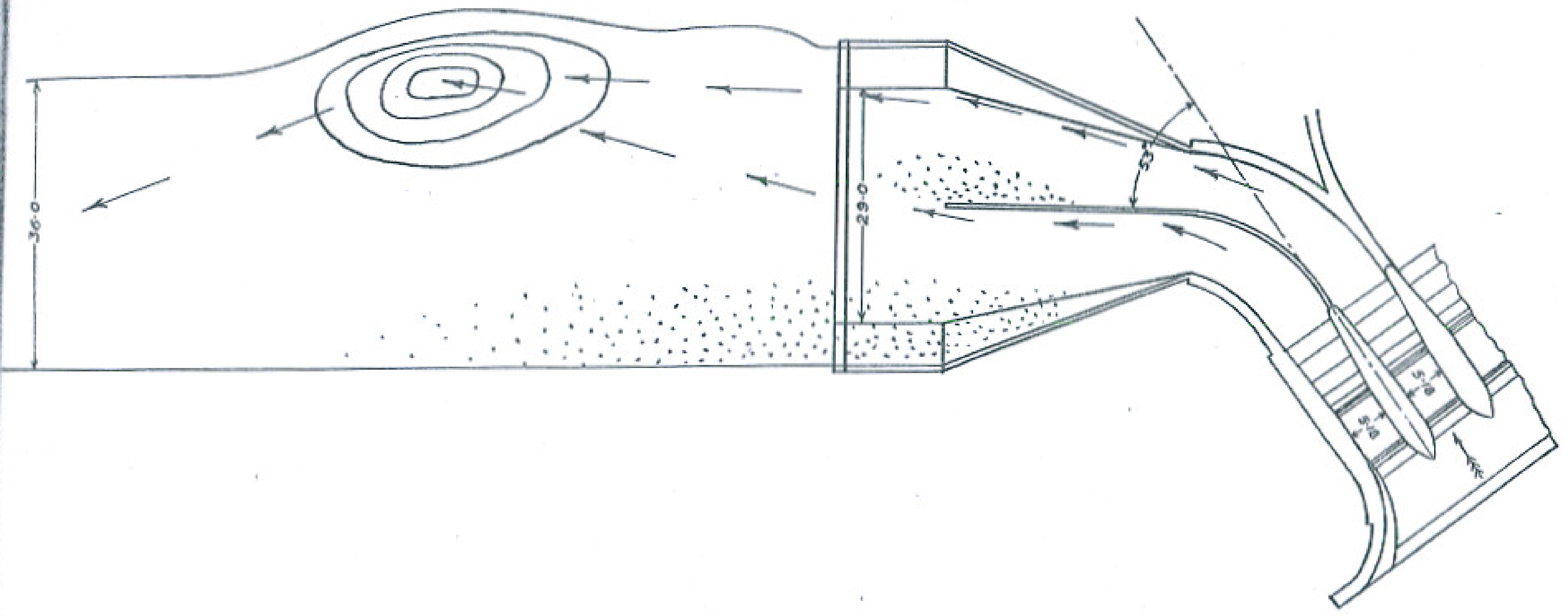
PUNJAB ENGINEERING CONGRES
1941.

PLATE II
PAPER NO. 242

CURVE AT R.D. 46,000 BHIWANI DISTRIBUTARY W. J. CANAL

SHOWING SHOALING JETTING AND SCOUR

SCALE 1/200

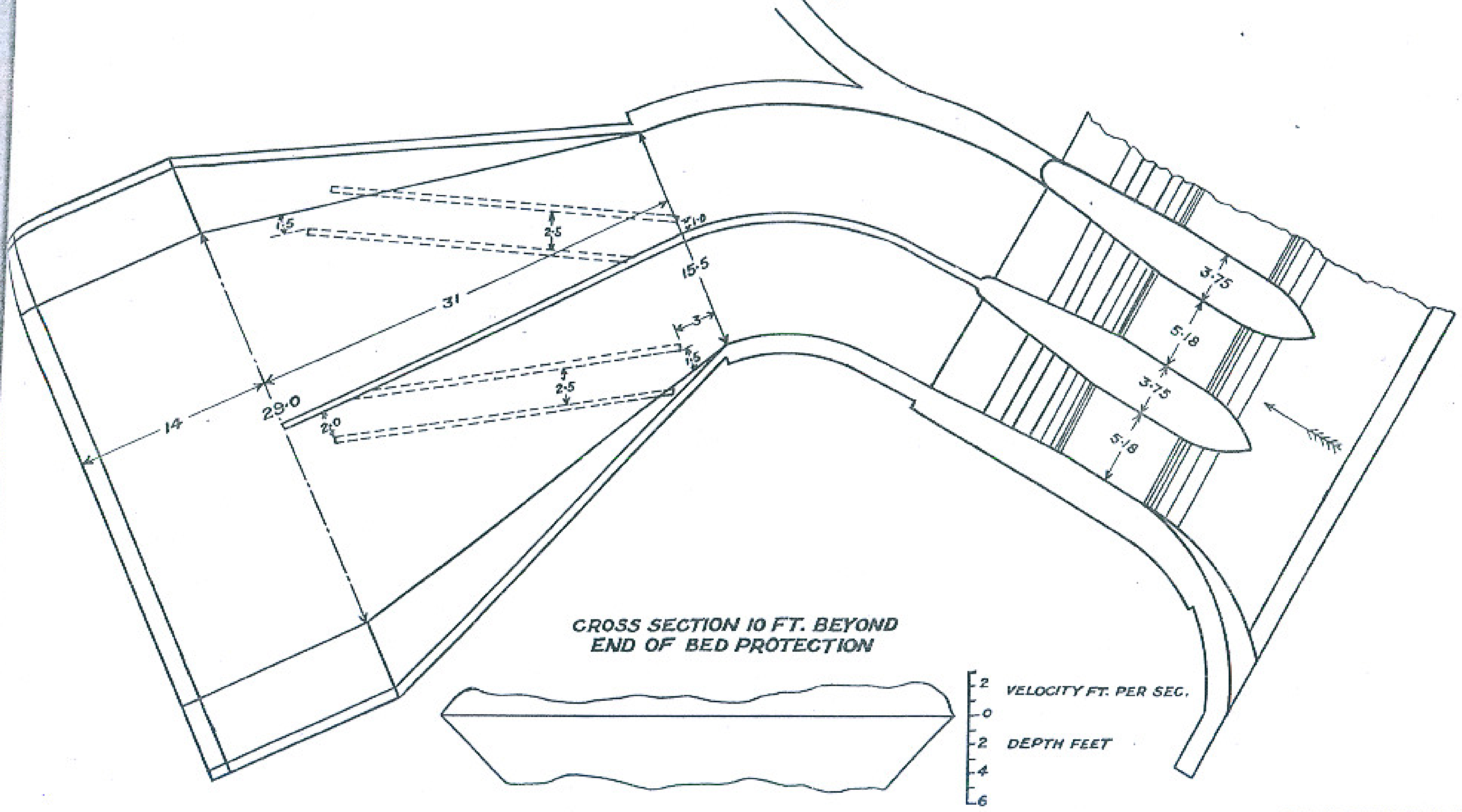


PUNJAB ENGINEERING CONGRESS
1941.

PLATE III
PAPER NO. 242

CURVE AT R.D. 46,000 BHIWANI DISTRIBUTARY W. J. CANAL

SHOWING DIVERSION VANES
SCALE 1/100



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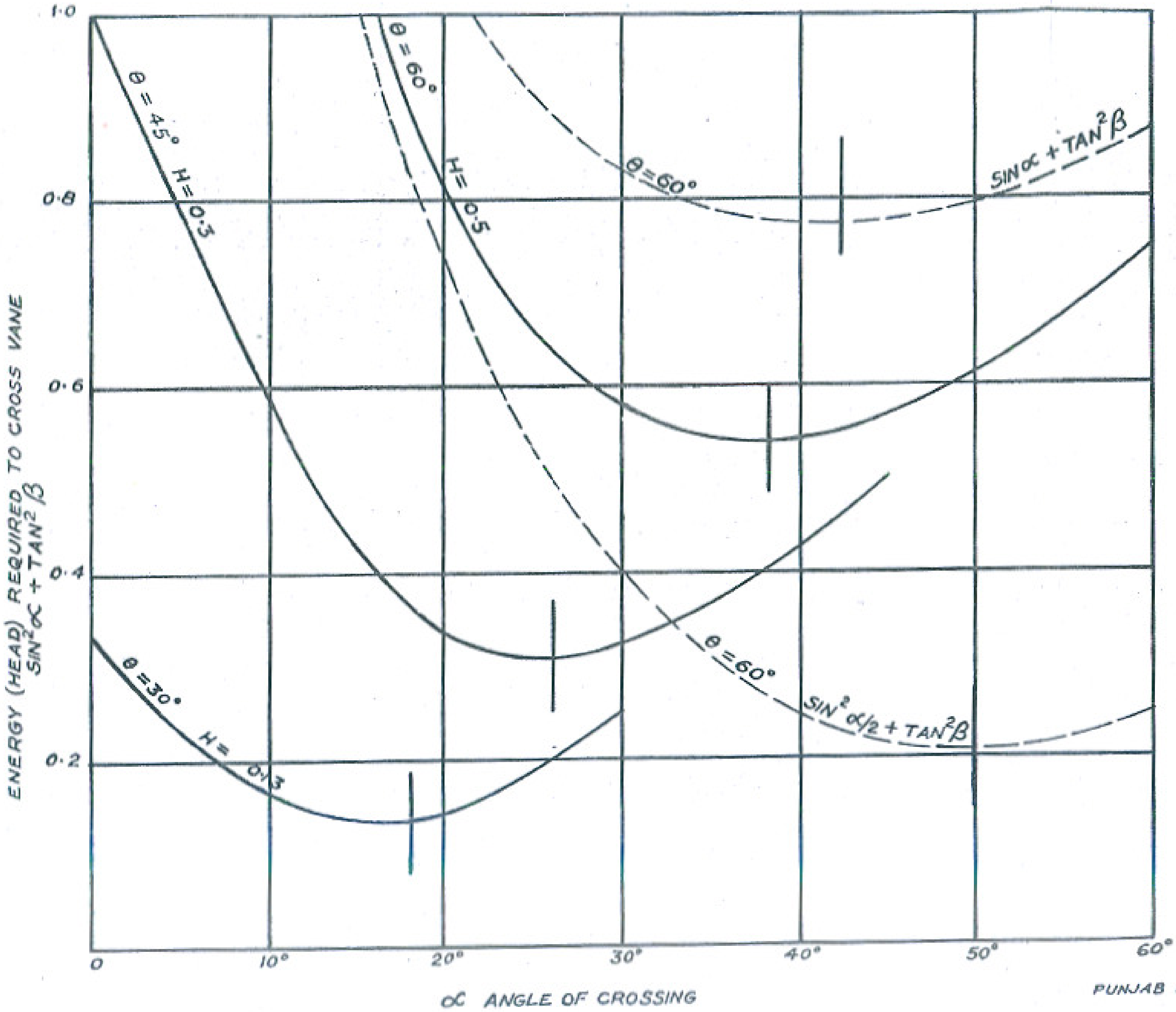
1941.

PLATE IV
PAPER NO. 242

GRAPH OF ENERGY TO CROSS VANE



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REGULATOR OF DURJANPUR MINOR W. J. (

SHOWING DIVERSION VANE AND ITS EFFECT

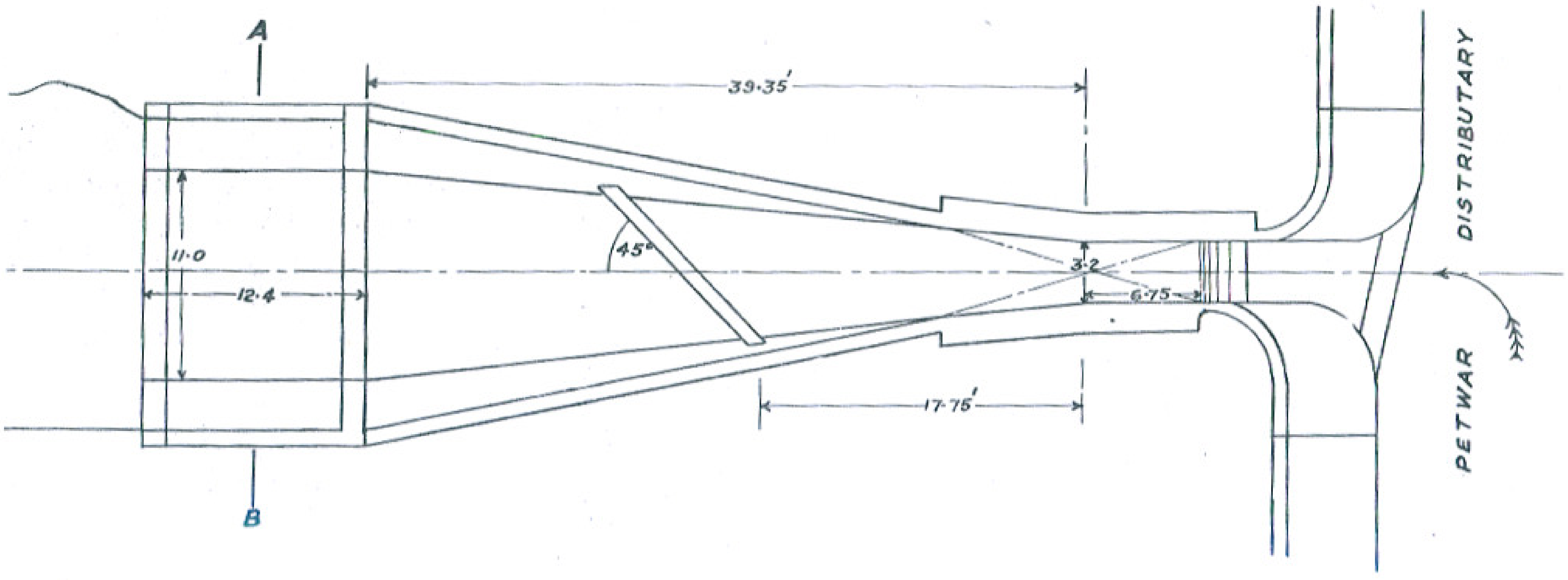
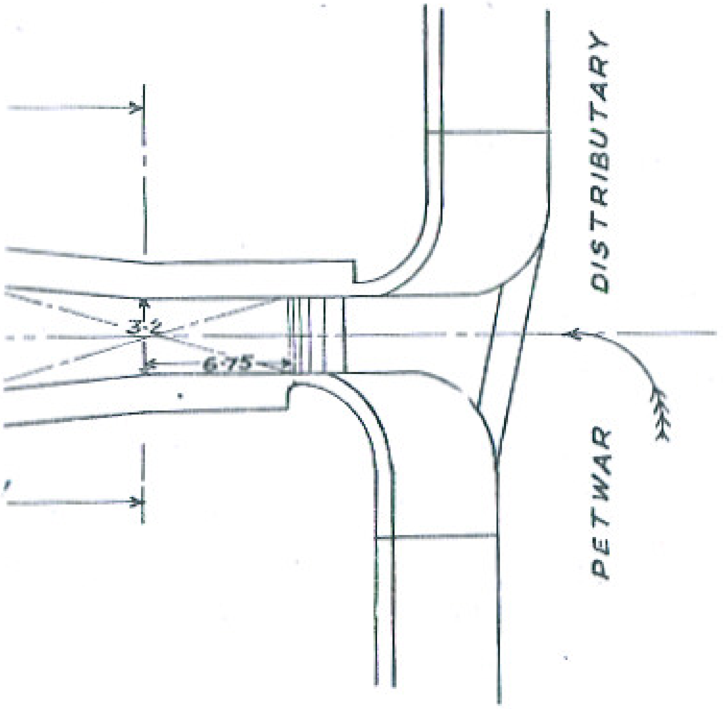
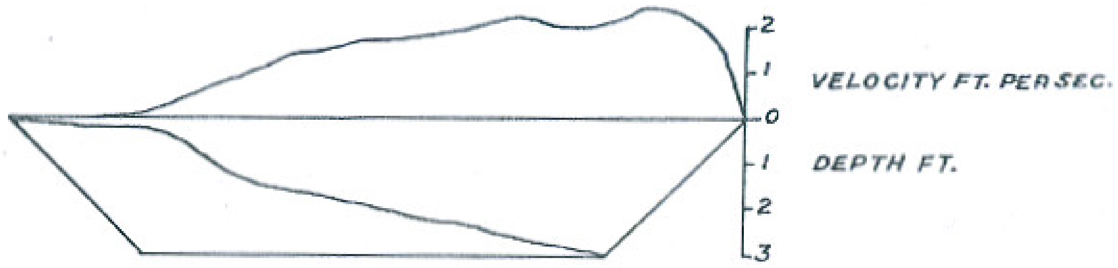


PLATE V
PAPER NO. 242

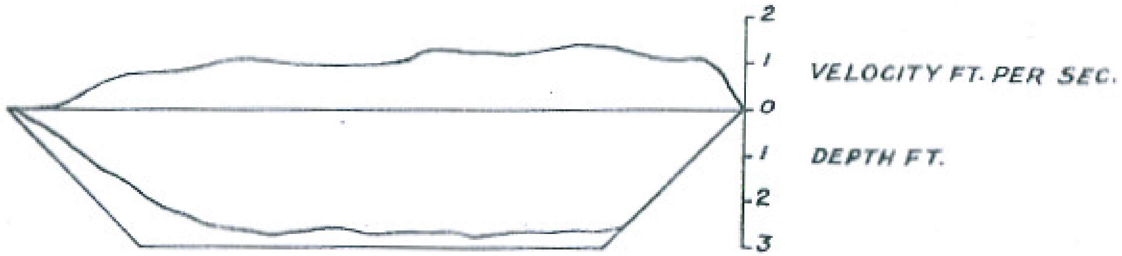
F DURJANPUR MINOR W. J. CANAL
G DIVERSION VANE AND ITS EFFECT



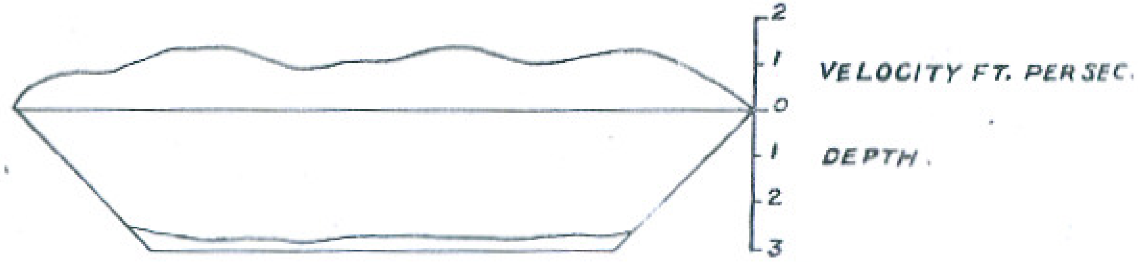
CROSS SECTIONS AT A. B.



WITHOUT VANE



WITH VANE 0·9 FT. HIGH



WITH VANE 1·05 FT. HIGH

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DISCUSSION

Mr. A. N. Wilson, the Author, said that there are one or two errors in printing which may have made the paper difficult to follow.

On page 24 under the heading "Silt Movement on Curves—Rigid Bed," in the first sentence the first semi-colon should be a comma only, and the words "the same" in the second line should be replaced by the word "which." The sentence will then read: "In a silt laden channel where most of the silt travels in the low velocity water near the bottom, it follows that most of the silt moves across the channel towards the inside of the curve, where velocities are lower, the normal effect of which is that a shoal is formed;"

Referring to Plate III the 9″×9″ pillars mentioned in para (*e*) on page 27 have been omitted. Similarly, the portion of the vanes dismantled as mentioned near the bottom of page 28, is not clear from the plan as the whole of the vanes have been shown dotted. These errors and omissions have been corrected in the plan now on view.

Mr. G. R. Sawhney congratulated the Author on writing a paper on a rather important phenomena concerning open channels, and added that the effect of curves on the working of earthen channels was fully known and very successfully made use of long ago in Sher Shah's time, but that it was a pity that for some unknown reasons this phenomena had so far been ignored.

He remarked that the introduction of vanes for putting right the earthen channels in curved reaches was a rather novel method, but it was likely to be expensive, and suggested that with energy varying with $\frac{V^2}{2g}$ multiple of the angle, the trouble could be very nearly cured by making curves with suitable angles. Designing faulty head reaches and then trying to experiment and introduce novelties to make the channels work without giving any trouble in such reaches was, in his opinion, simply probing in the dark. Why not re-align the channel properly, he asked, and solve these everlasting troubles? He went on to relate that similar trouble, as was being met at R. D. 56,000 Bhiwani Distributary, but with much more damaging effect, was being caused in the head reach of Hussainabad Distributary on the Lower Bari Doab Canal; thousands of rupees were being spent on its silt clearance and finding cures or a solution for this trouble, but nothing seemed to succeed until the faulty head reach was re-aligned and the head of the Distributary shifted upstream, and ever since this had been done the channel had worked very satisfactorily.

He congratulated the Author for his having actually created the necessary conditions on a rather sensitive model to make it just possible for nearly all the silt to travel in a fairly narrow width alongside the curve and thus stop shoaling, but was very doubtful if such good results would be obtained in practice in the channels. Experiments and tests, he said, were no doubt very necessary and helpful in the advancement of any science, but this model mania was invariably leading us astray because until we could disect the sand particles proportionally to the dimensions of our models the results and conclusions derived from the working of such models may not necessarily be correct and for this reason we should be more cautious in introducing a model and taking the results of one or two experiments as positive solution of every serious trouble we meet in the working of our channels.

He thought that the silt vanes did not seem to change the silt distribution but seemed to act as catch-pits and that soon after they had done their work as catch-pits the same trouble would again start in most cases; also that we rarely have much head available to lose, which would be consumed in filling up the catch-pits.

Mr. C. C. Inglis congratulated the Author on the extremely neat and simple method he had evolved for controlling flow downstream of a curve in a lined channel, and added that he could not understand, however, why the Author was surprised at the result.

He then went on to consider flow round a normal curve, and stated: "The top water follows the outside of the curve, but at about $\frac{1}{3}$rd depth 'diving flow' occurs and bed water flows to the inner, convex, bank; and if you want to draw off top water, relatively free from bed silt, you excavate your channel head on the outside of the curve; and if you want to draw off still less bed sand, you construct a raised sill at a little more than $\frac{1}{3}$rd depth. In the above case, you are setting out to exclude bed sand; but if, on the contrary, you desire to take as much bed sand as you could into the offtaking channel, you should reverse the process, which is exactly what the Author has done.

"This figure is only diagrammatic, and the efficiency is affected by the position of the groyne relative to the curve and the ratio of discharge in the parent and offtaking channels; a factor which has a marked effect on bed sand movement."

Referring to the paper he said, on page 25 the Author says:

> "Silt in the deep part of the channel is drawn towards the shoal; but, instead of passing right on to the shoal, is caught up by the corkscrew motion and the relatively high turbulence. Thus the silt is mostly being picked up into fairly high suspension and thrown back to the outside of the curve as fast as it is drawn along the bed towards the shoal so that the shallow water is enabled to carry forward the relatively small silt supply reaching the high parts of the shoal. In such a channel then there must be a somewhat greater quantity of silt per unit volumes of water near the outside than in the shallows along the inside of the curve."

and added that from this it was clear that the Author considered that silt charge was mainly a function of velocity and that because the velocity was higher at the outside of the curve than at the inside, that therefore the silt concentration must be higher. This, he said, ignores the fact that "rate of change of velocity,"—*i.e.* "velocity gradient"—is the dominant factor in silt transport and that, consequently, there was no need to assume any corkscrew action as, in fact, the term "corkscrew" was an unfortunate one in this connection; because there was normally no corkscrew motion, but only a partial rotary movement which reversed before any corkscrew action occurred; and even where eddies created turbulence, this enabled the flow round the inside of the curve to carry more silt; but did not normally create corkscrew flow.

Again on page 26, added Mr. Inglis, the Author says:

> "Experience may appear to contradict these conclusions, since outlets and minor offtakes on the inside of a curve usually have silt trouble, while canals taking out of the deep water side of a river are usually fairly silt free. But outlets and minor offtakes are usually built in relation to the normal section of a straight channel and become more or less submerged in the shoal, while a river is by no means stable and, certainly, has nothing like a constant discharge. The most reasonable explanation for canal heads being best situated by a deep water channel seems to be that the river scours during floods, but at other times the deep channel is silting up, so that the canal has a primitive form of still-pond regulation."

and remarked that this statement was completely unjustifiable and wrong; and that if the Author would read Bombay P. W. D. Technical Papers Nos. 52 and 59 and Annual Reports of the Central Irrigation and Hydrodynamic Research Station for 1937-38, 1938-39 and 1939-40, he would find that even though curvature of flow is not the only factor controlling silt movement, it is undoubtedly the major factor.

L. Ishar Dass remarked that in the Railways, superelevation was given on curves to counteract the centrifugal forces, and that the same principle had been applied by him in more than one place with success, by keeping the bed on the outside of the curve about 0·5 foot higher than the inside, and pitching the bed and the sides. Lesser depth of water on the outer side of the curve, he added, should have reduced velocity but side and friction depth inside should mean more velocity inside but that the centrifugal action of the curve made the velocity uniform, with the result that in this place where there used to be heavy silt-heaps, not a handful of silt was found. This he said was in a case of distributary of about 46 cusecs. He further added that a curve with a small discharge was also similarly treated with success, and that precise calculation for determining superelevation for different discharges and different curvatures will probably be more useful.

The **Author** in replying to the discussion said that Mr. Sawhney's remark that diversion vanes in earthen channels would be unduly expensive was probably correct, as suggested in the paper.

Re-alignment of channels and rebuilding of masonry works to remove curves was in his opinion a possible solution but a very expensive one which would be unnecessary if the flow at the masonry work could be corrected by the simple and inexpensive method of building one or two diversion vanes. The cost of vanes on Biwani Distributary, he said, was Rs. 60 only, whereas re-alignment and reconstruction of masonry works would have cost several thousand rupees.

He rejoined that the result obtained on a model was mentioned in the paper only to show that certain conditions were possible, and added that models could certainly produce valuable results provided the basic principles were understood ; and that there was no need to "disect the sand particles."

He further stated that the paper was not concerned with "silt vanes" as such, but that neither silt vanes nor diversion vanes acted as "Catch-pits," nor did either require any measurable head.

Replying to Mr. Inglis, he remarked that he (Mr. Inglis) apparently regarded the action of diversion vanes as anything but surprising. He added that now that their effects had been demonstrated, they may appear obvious, but it seemed doubtful if the results could have been forecast with any degree of certainty.

It is true, he stated, that a diversion vane works as a rather inefficient silt vane, but although this was of some importance, it was desirable that there should not be too great an effect on silt, since the main purpose for which a diversion vane was designed was to cause a change in direction of the flow as a whole with an even silt distribution. Therefore, he added, if the object were to force silt into an offtaking channel, silt vanes designed on the principles set forth by King (P. E. C., paper No.s 62 and 169) would be more suitable, whereas a diversion vane designed primarily to change the direction of flow might be relatively inefficient.

He went on to assert that it cannot be agreed that the quotation from page 25 of the paper means that silt charge was merely a function of velocity ; and that in fact there was no mention of velocity in the quotation, while it was clearly stated that silt "is caught up by the corkscrew motion and the relatively high turbulence" clearly silt charge is dependant on velocity, depth, turbulence and velocity gradient, but in any part of a given section of a stable silted channel free to scour its own bed, all these factors were inter-dependent, so that where there was a concentration of flow there was also relatively high velocity, high turbulence, greater depth, greater velocity gradient and greater silt carrying capacity, and *vice versa*. Further, he added the quotation was merely a probable explanation of the observed facts that on a curve entirely without bed restriction, the section became stable and more or less wedge-shaped, and that the silt charge per unit volume of water was greatest somewhere towards the outer side of the curve ; and remarked that the theory may have its imperfections, but it seemed a reasonable explanation of the known facts.

To him it seemed immaterial whether the motion be termed "Corkscrew" or "Partial rotary" movement, so long as the idea of rotation plus forward movement be accepted. The amount of rotation, he said, would of course depend on the curve and be very slight on a gentle curve, but so long as the movement existed the facts could not be explained adequately without taking this factor into consideration.

With all due respect to the Bombay P. W. D. Technical papers Nos. 52 and 59 and the Annual Reports of the Central Irrigation and Hydrodynamic Research Station for 1937 to 1940, he suggested that none of the observed data was in conflict with the statements made in the paper or the quotation from page 26, although some of the conclusions drawn may be actually or apparently conflicting. He added : "The Bombay papers deal primarily with silt drawn into offtaking channels, and curvature of flow has a very great influence on the amount of silt drawn into offtakes, nor is this denied either in the quotation or elsewhere in the paper." The statement that the quotation is "completely injustifiable and wrong" could, therefore, only mean that the explanation was not accepted. The explanation, he conceded, may be imperfect, but the alternative explanation of why curvature effects the silt drawn into offtakes, appeared to be the conventional and unduly simplified hypothesis that the main flow of silt is invariably close to the inner side of a curve, and if true this would be a very satisfactory explanation. Unfortunately, however, he added, the main flow of silt on a curve may be anywhere from towards the outer side, to close to the inner edge of the curve, depending on conditions. As a general rule, it appeared to him that the nearer the curve approached a normal wedge shape in section, the further the main silt flow receded from the inner edge, while the more nearly the section was forced to a rectangular shape, the closer the silt flow tended to hug the inner edge of the curve. He admitted that large quantities of silt could easily be drawn towards the inner side of a curve by slight interference, but added that on the other hand very special conditions had to be set up to maintain a rectangular section free from shoals or undue turbulence and corkscrew action, and thus bring nearly all the silt close to the inner side of the curve.

He further stated that in case the criticism meant a denial that in a channel entirely free to form its own bed the silt charge tended to be greatest in the deep water towards the outer side of the curve, some further explanation may be necessary and explained as follows : "Let it be supposed that the silt charge were greater near the inner edge of the curve, and accepting the undeniable fact of a more or less wedge-shaped section, then for the curve to be stable in section it would be necessary for there to be a high velocity-turbulence relation in the shallow water on the inner side, while the deep water on the outer side would have to be relatively placid. Without any elaborate measurements, it is only necessary to watch the surface of a normal silted channel on a curve to see that such conditions do not exist, but on the contrary the shallow water on the inside is relatively non-turbulent, while the deep outer side has relatively high velocity and turbulence ; in fact, often there is a regular boiling motion compared with the almost imperceptible turbulence over the shoal. However, the only really effective argument on the point is actual observations of silt charge."

Replying to L. Ishar Dass's suggestion that superelevation of the bed has a similar effect to a diversion vane, he said that admittedly the Author had only tried this once on a small scale, and that although the results were by no means satisfactory, it might be possible to produce a suitable design, but that this would probably be expensive and uncertain in its effects unless the technique were fully developed. That superelevation would effectively turn the flow seemed probable to him, but in his opinion the effect on silt distribution seemed unlikely to be favourable.