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Use of Short Triangular Vanes for Efficient Design of Wide-angle Open-channel Expansions

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The root cause of unsatisfactory hydraulic performance of a wide-angle expansion is the separation of boundary-layer and subsequent generation of stall. The separation leads to high loss in head and gives rise to non-uniformity in the exit velocity distribution, which results in scour and uneven flow in the tail channel. Either by merely increasing the length or by adopting some complicated streamlined shape for the expansion walls, the objectionable features cannot be avoided successfully while at the same time the fact remains that the design becomes uneconomical. The design of a wide-angle expansion in sub-critical flow should, therefore, be examined from another view point, namely, controlling the boundary layer flow. The authors tested a number of devices and found that the use of a pair of triangular vanes converging downstream and placed symmetrically at the commencement of expansion yielded very encouraging results. After testing different orientations and geometry, the vanes have been developed for a given expansion. The criteria for satisfactory performance were developed in terms of: (i) hydraulic efficiency, (ii) exit bed shear distribution, and (iii) separation pattern. Nine different flows were tested and the optimum values of height, length, spacing and inclination of the vanes have been found. Design curves have been prepared to arrive at the optimum dimensions of the vanes for best performance. The results have been compared with other standard designs.

INTRODUCTION

The design of open-channel expansions is a problem of common occurrence in the execution of irrigation and hydraulic structures. In the field of aeronautics and mechanical engineering, problems of flow expansions in pressure conduits have been tackled analytically by employing the principles of boundary layer separation whereas in the field of open-channel, the approaches so far are mostly empirical in nature. However, the devices found effective in aeronautics are not directly applicable to open-channel expansions, and hence separate investigations are necessary.

In open-channel, the first major investigation in respect of contracting and expanding transition is of Hinds[1]. Hinds' warped type expanding transition is very popular, even now, particularly for major types of hydraulic structures, such as, aqueducts, syphons, etc.

The hyperbolic transition of Mitra[2], later modified by Chaturvedi[3] by exponential curve, are popular in India. The designs are based on certain hypothesis, similar to Hinds', in respect of length, water surface profile and variation of velocity.

Adoption of appurtenances in an expansion so as to spread the flow and avoid scour in tail channel was initiated by Rao[4], in Poondi Research Station, Madras. They used triangular vanes and bed deflectors for such purpose. Simons[5] of United States Department of the Interior used wedges for spreading the flow. The headloss was considerably high. Smith and Yu[6] developed baffles of rectangular section for achieving uniform distribution of velocity after expansions. The headloss, in this case too, was considerable and wake developed behind each of the baffles. Mazumder[7] adopted a streamlined expansion having a shape similar to the boundary of the eddy in a sudden expansion. The performance was tested for five different lengths and for several discharges and depths of flow.

THE PROBLEM

In open channels, using gradual rate of flaring implies a great length of the walls which may prove prohibitively costly in comparison with the savings achieved through constriction. It is also seen[7] that the performance of such expansions of long length is not up to the expectatation. Not only is the head recovery poor but also the velocity distribution at the exit of the expansion is extremely non-uniform. Moreover, the flow is seen to separate from the boundary giving rise to undesirable eddies and rough flow in the tail channel. By giving some complicated shape of the expansion walls, very little improvement in performance takes place. Non-uniformity of the velocity distribution at exit results in erosion of tail channel for a considerable length beyond the exit of the expansion.

FLOW CHARACTERISTICS IN A WIDE-ANGLE EXPANSION

A wide-angle expansion, in subcritical flow, is associated with strong adverse pressure gradient in the direction of flow. According to Prandtl, the viscous drag on the boundary-layer fluid on which the external

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pressure gradient is impressed, is unable to overcome the combined resistance due to friction and pressure; the kinetic energy of the particles soon gets exhausted, the particles separate from the boundary and move in a reverse direction, that is, opposite to the main flow. The surface of separation has a high velocity gradient and is extremely unstable and gives rise to turbulence. Substantial portion of the kinetic energy of the mean motion drains away through production of turbulence which is subsequently convected, diffused and dissipated. As revealed from the measurements of Gibson[8], Chaturvedi[9] and others, beyond a certain angle the effect of frictional resistance offered by the boundary is practically nil and the headloss is entirely due to turbulence, known popularly as 'form loss'. The other effects of separation are distortion of velocity profile, disturbance and vibration due to eddies.

USE OF APPURTENANCES FOR WIDE-ANGLE EXPANSIONS

An expansion may be designed for achieving any one or more of the following performances: (i) high recovery of head so that afflux is minimum, (ii) uniform distribution of velocity at exit so that there is no erosion in the tail-channel, and (iii) smooth flow in the tail channel free from eddies. Although such objectives may be partially fulfilled by providing a long length of expansion, the difficulties with such design have already been pointed out. It is felt, therefore, that some kind of appurtenances should be used in an effort to curtail the length, simplify the construction and at the same time improve the performance. The methods devised by several workers in this respect have already been described. The authors also conducted a series of experiments using different types of appurtenances. From the comparative results of the preliminary experiments, it was found that the pair of triangular vanes converging downstream in plan and placed symmetrically near the commencement of expansion (Fig 1) gave very encouraging results. Such vanes[3] were initially used in Poondi (Madras). However, the detailed investigations in respect of such vanes were beyond the scope of present studies.

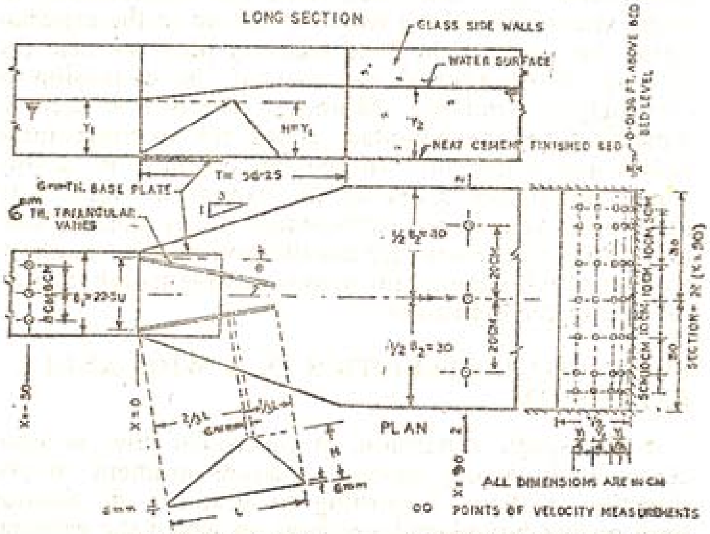


Fig 1 Expansion provided with typical triangular vanes (showing the various parameters of vanes tested for finding their optimum values)

PERFORMANCE OF EXPANSION PROVIDED WITH APPURTENANCES

HYDRAULIC EFFICIENCY

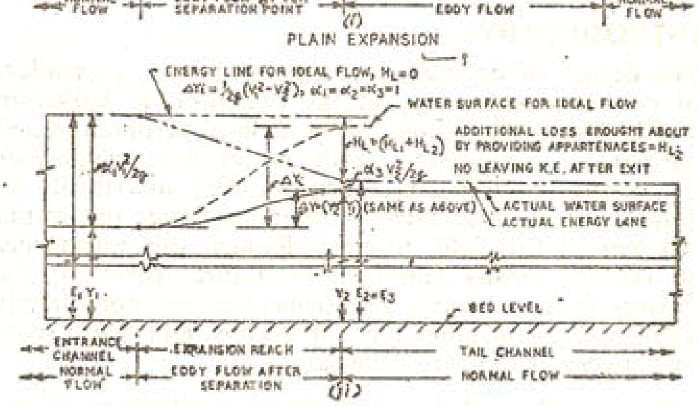
Since both the headlosses inside and outside the expansion H_{L_1} and H_{L_2} in the tail channel [Fig 2(i)] are to be taken into account, the following definition of efficiency of an expansion is introduced as the ratio of actual recovery of head to the total loss in kinetic energy:

$$\eta_P' = \frac{(Y_2 - Y_1)}{\left(\frac{\alpha_1 v_1^2}{2g} - \frac{\alpha_3 v_2^2}{2g}\right)} \tag{1}$$

where α_3 is the value of energy correction factor at a section in tail channel in which the flow is normal and parallel to walls. Assuming $\alpha_1 \approx \alpha_3 \approx 1$, equation (1) reduces to

$$\eta_P = \frac{(Y_2 - Y_1)}{\left(\frac{v_1^2}{2g} - \frac{v_2^2}{2g}\right)} = \frac{\Delta Y}{\Delta Y_i} \tag{2}$$

where ΔY and ΔY_i are the head recoveries corresponding to actual and ideal flow conditions [(Fig 2(ii)].



Expansion provided with appurtenances

Fig 2

It may be noted here that the usual form of expressing headloss in an expansion is to use an outlet loss coefficient, C_o, defined as:

$$C_O = \frac{H_L}{\left(\frac{v_1^2}{2g} - \frac{v_2^2}{2g}\right)} \tag{3}$$

It may easily be shown that where the value of η_P is expressed in percentage

$$C_O = \left(1 - \frac{\eta_P}{100}\right) \tag{4}$$

STANDARD DEVIATION OF EXIT BED-SHEAR DISTRIBUTION AND SCOUR IN TAIL CHANNEL

In Fig 2(i), the energy line (drawn chain dotted) corresponds to plain expansion, without any appurtenances. Greater the value of $H_{L_2} = \frac{(\alpha_2 - \alpha_3) V_2^2}{2g}$, the greater will be the non-uniformity in velocity distribution and more scour in the tail channel, if unlined. Now, by providing suitable appurtenances, it may be possible to dissipate the extra kinetic energy H_{L2}, within the reach of expansion itself, so that the total headloss inside will be equal to the sum of H_{L1} and H_{L2}. Fig 2(ii) shows the energy line for such an expansion, provided with appurtenances. Since there is no surplus kinetic energy after exit, the energy line runs parallel to the water surface right from the exit of the expansion. Since the head recovery, ΔY, is the same as in Fig 2(i), from equation (2) the hydraulic efficiency, η_P attains the same value in both the expansions. Thus, if hydraulic efficiency alone is taken as the comparing index, the performance of both the expansions appear to be identically the same. However, this is not actually so. In the plain expansion, the tail channel is exposed to scour which is totally absent in the expansion provided with appurtenances. The action of the appurtenance is to render the flow uniform and establish the normal velocity distribution obtaining in a canal right from the exit section.

Besides hydraulic efficiency, the second most important criterion for performance in an unlined channel, therefore, is the scour. The rational way of bringing the scour effect is, to consider the bed-shear distribution at exit of the expansion. Keeping the normal uniform flow in view, any deviation of the actual bed-shear distribution from the normal one corresponding to uniform parallel flow is considered to be undesirable. Because if the deviation of the actual distribution from the normal one is greater, more will be the scour. A parameter σ defined as the standard deviation of the actual bed-shear distribution from normal one was used for comparing the relative performance of expansions provided with appurtenances in different forms and orientations. The term σ is defined as

$$\sigma = \left[\frac{1}{N}\left\{\sum_{X=1}^{X=N}\left(\frac{T_{ox}}{\bar{\tau}_n} - 1\right)^2\right\}\right]^{\frac{1}{2}} \qquad (5)$$

where τ_o is the actual bed shear at any point in the exit section and $\bar{\tau}_n$ the mean normal bed-shear corresponding to uniform flow.

SEPARATION AND SMOOTHNESS OF FLOW IN THE TAIL CHANNEL

Another important criterion of performance is the smoothness of flow in the tail channel. This is governed by separation and stall characteristics of the expansion. Greater the stall, the more disturbed and uneven will be the flow.

It is neither practicable nor desirable to define a single term taking all the criteria of efficiency together. Because, the relative importance of the several criteria may differ from place to place, it was decided to study : (i) hydraulic efficiency, (ii) standard deviation of the exit bed-shear distribution, and (iii) the stall characteristics, and develop the optimum geometry of the vanes for each individual criterion separately.

EXPERIMENTATION

LABORATORY SET-UP

The experiments were conducted in hydraulics laboratory at Indian Institute of Technology, Kharagpur, in a flume measuring 9 m long, 60 cm wide and 67 cm in height. A wooden flume (22.5 cm wide) ends in an expansion having 3:1 side splay. The bed and sides of the expansion and the bed of the tail channel was finished smooth by neat cement plaster (Fig 1).

COMPUTATION OF HYDRAULIC EFFICIENCY

The actual recovery of head ΔY was found by accurately measuring the water surface profile. The values of the ideal recovery in head, ΔY_i, were calculated for different flows by solving a cubical equation in Y_2.

COMPUTATION OF EXIT BED-SHEAR DISTRIBUTION AND STANDARD DEVIATION

The bed-shear, τ_o-values near the exit end of the expansion (at $x = 90$ cm) were determined by using Prandtl-Karman universal resistance law,

$$\frac{u}{u_*} = 5.75 \log \frac{y\,u}{\nu} + 5.5 \qquad (6)$$

where u is the velocity at any depth y above the bed within the boundary layer and $u_* = \sqrt{\frac{\tau_o}{P}}$.

The mean bed-shear $\bar{\tau}_n$ corresponding to normal uniform flow in a 60 cm wide flume having the same boundary conditions as at exit of the expansion tested, were also determined by using equation (6). Non-dimensional plots of $\frac{\tau_o}{\tau_n}$ were made [Fig 3(iii)] and choosing seven standard ordinates of the non-dimensional bed-shear distribution, the standard deviation, σ, of the actual bed-shear distribution from the normal one was computed by using equation (5)

$$\sigma = \left[\frac{1}{7}\left\{\sum_{X=1}^{X=7}\left(\frac{\tau_{ox}}{\bar{\tau}_n} - 1\right)^2\right\}\right]$$

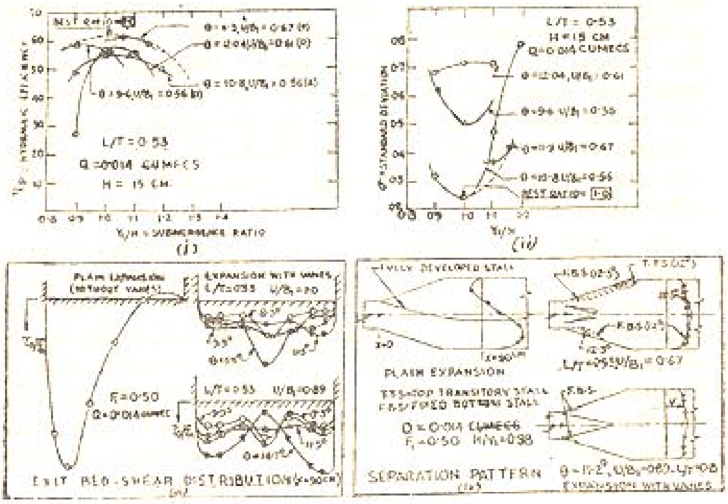


Fig 3

MEASUREMENT OF SEPARATION AND STALLING PATTERN

The formation and gradual decay of stall in the expansion could be controlled by using different orientations of the vanes. The zones of stall on top and bottom could be traced by injecting potassium permanganate solution with a fine-nozzled pipette [Fig 3(iv)].

DISCUSSION OF RESULTS

OPTIMUM SUBMERGENCE RATIO

The hydraulic efficiency and standard deviation for the various submergences of vanes having different orientations are drawn in Fig 3(i) and 3(ii) respectively.

It may be noted that the best performance occurs at a submergence $\left(\frac{Y_1}{H}\right)$ ratio of unity. Curves similar to Fig 3 drawn for the other lengths and heights of the vanes and for the different flows tested, confirmed the above results.

From the study of stalling pattern at various submergences also, it was found that the best result could be achieved at unit submergence. It was decided, therefore, that the subsequent study for other geometry of the vanes should be made keeping the submergence as unity, that is, the height, H (at apex in Fig 1) of the vane should be same as Y_1, the depth of flow at entry.

OPTIMUM LENGTH $\left(\frac{L}{T}\right)$ SPACING $\left(\frac{U}{B_1}\right)$ AND INCLINATION θ OF THE VANES AND THEIR PERFORMANCE

It is not possible to present here all the performance curves of hydraulic efficiency, bed-shear distribution standard deviation, the energy correction factors, the stalling pattern and the scour pattern corresponding to the several geometries and flow conditions tested. Fig 3(iii) and 3(iv) are drawn to illustrate the improvement in bed-shear distribution and stalling pattern by providing vanes as indicated. The variation of hydraulic efficiency and standard deviation with different parameters of vanes are shown in Fig 4 for one typical flow. These curves are used for determining the optimum length, spacing and inclination of the vanes for the given flow. The performance of the wide-angle expansion provided with triangular vanes have been compared with other conventional designs in Fig 5.

DESIGN CURVES FOR THE OPTIMUM GEOMETRY OF VANES

A set of design curves (Fig 6 and 7) have been prepared from the performance curves (similar to Fig 4) so that the optimum length, spacing and inclinations of the vanes for maximum hydraulic efficiency or for minimum standard deviation may be easily found for any given flow condition. The height of the vanes, as already stated, is given by the depth of flow at entry. The curves are drawn in non-dimensional form and are self-explanatory.

The hydraulic efficiency which is extremely small (only 23.6% on average) for plain straight expansion (3:1 splay) is increased to a great extent (71% on average) by providing vanes and is greater than the maximum value of efficiency (66 % on average) obtained in plain curved expansion at optimum length (lying between 7:1 to 9:1 average splay). Velocity and bed-shear distributions which are highly distorted (average value of $\sigma = 2.5$) and cause large amount of scour in tail channel (Fig 8) in case of plain expansion, are improved remarkably (average value of $\sigma = 0.25$) and attained almost the same value as in normal flow, even from the exit of the expansion (Fig 9). Very encouraging results are obtained in respect of separation and stalling of flow. Without vanes, the flow is found to separate right at entry and stall violently (Fig 10). With vanes, however, it was possible to completely eliminate the separation and stalling thereby (Fig 11). The recommended design is simple (straight walls) and economic (3:1 side splay) and needs only a pair of short triangular shaped flat vanes placed inside the expansion as proposed.

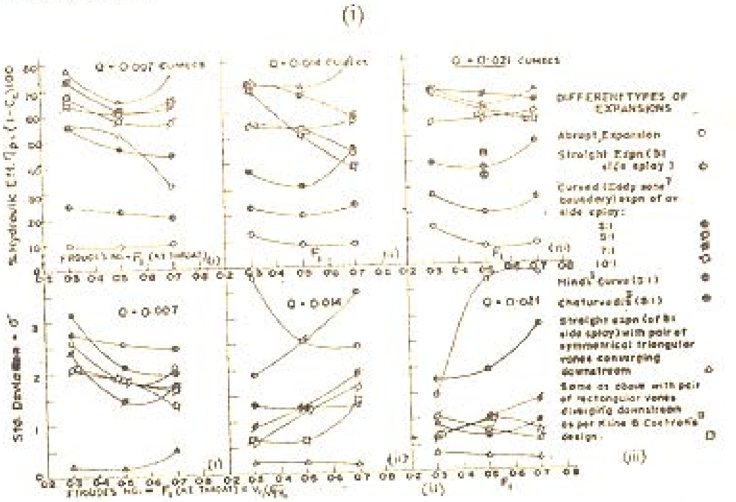
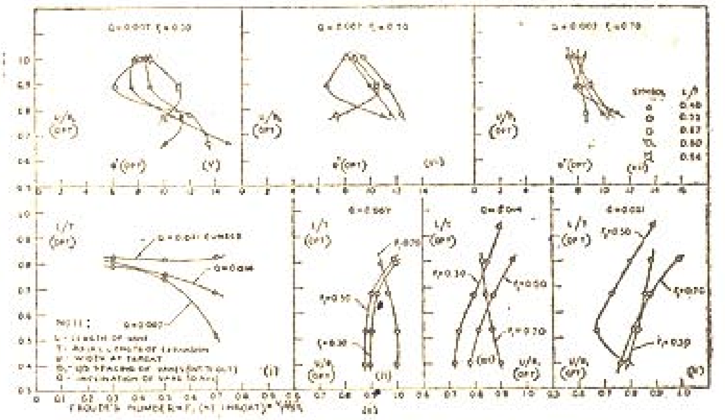


Fig 5 Comparison of hydraulic efficiency and standard deviation for different types of expansions



Design curves of optimum length, spacing and inclination of vanes for maximum hydraulic efficiency

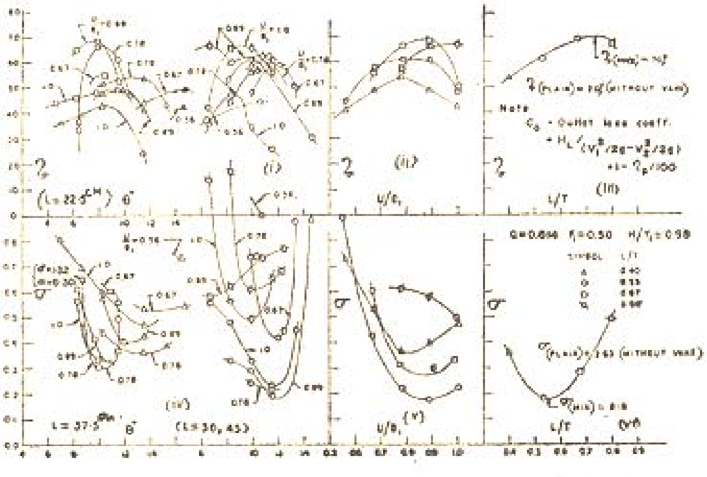


Fig 4 Variation of hydraulic efficiency (η_p) and standard deviation (σ) (with different parameters of vanes)

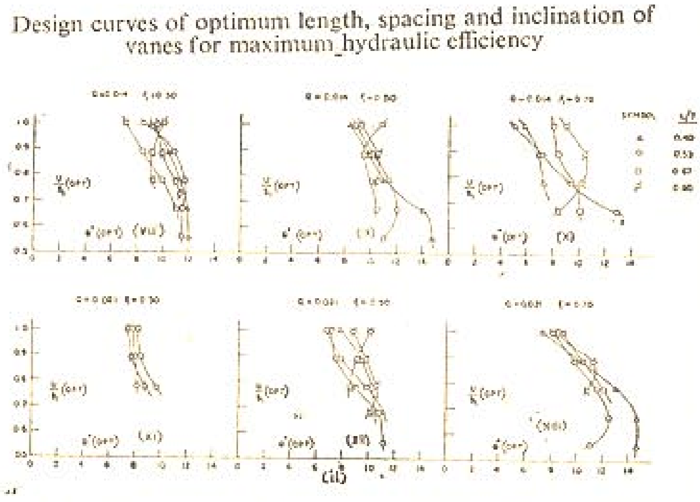
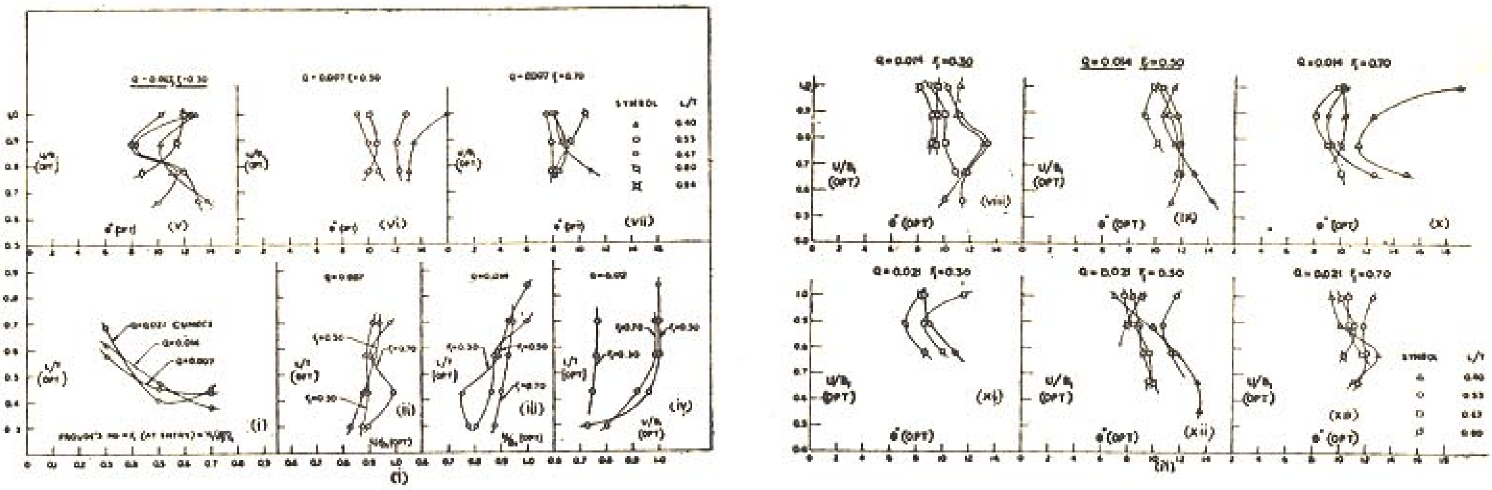


Fig 6 Design curves of optimum length, spacing and inclination of vanes for maximum hydraulic efficiency



(i)

Design curves of optimum length $\left(\frac{L}{T}\right)$ spacing $\left(\frac{U}{B_1}\right)$ and inclination (θ) of vanes for minimum standard deviation of exit-bed shear distribution

(ii)

Design curves of optimum length, spacing and inclination of vanes for minimum standard deviation of exit bed-shear distribution

Fig 7

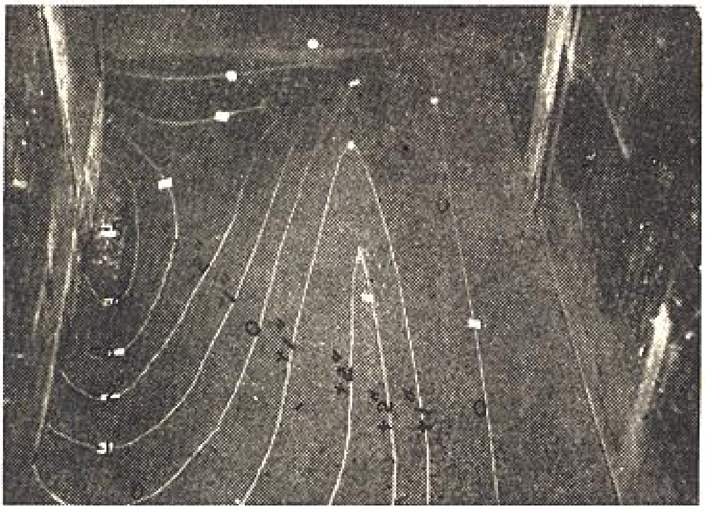


Fig 8 Scour pattern in plain expansion without any vane

Fig 9 Scour completely eliminated with triangular vanes

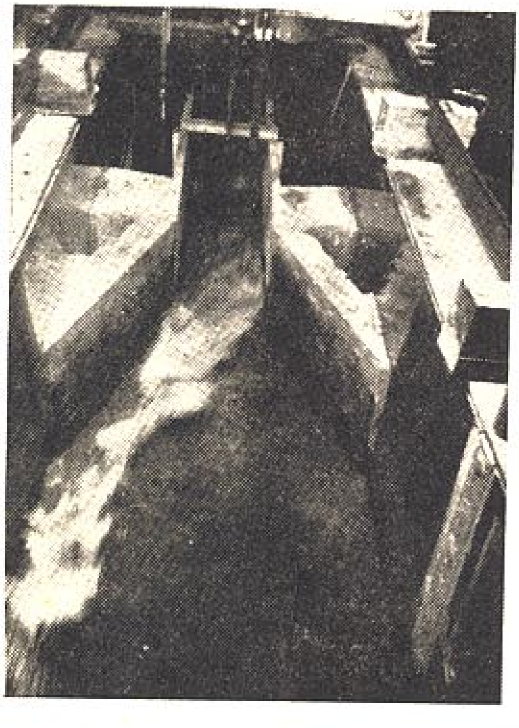


Fig 10 Separation in plain expansion (with any vane)

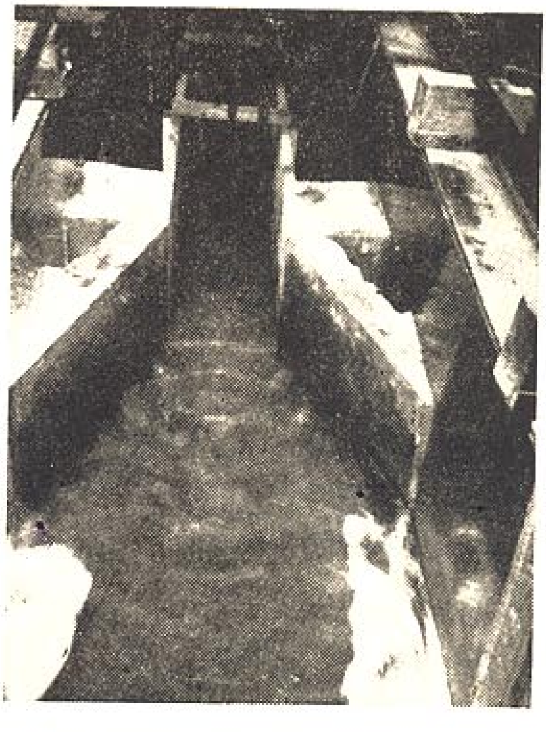


Fig 11 Separation completely avoided with vanes

CONCLUSION

(i) The kinetic energy of water remaining unconverted in the expansion reach causes non-uniformity in velocity distribution in the tail channel.

(ii) The root cause of either loss in head or scour is the separation of boundary layer.

(iii) Providing too long a length or too complicated a shape of an expansion to prevent separation is neither economical nor it secures greater efficiency.

(iv) It is possible to prevent boundary-layer separation and improve performance even in a wide-angle straight expansion by providing suitable appurtenances.

(v) The optimum geometry of the appurtenances to obtain the best performance should be selected carefully ; otherwise, the performance may not be up to the expectation or it may even lead to worse results, as compared to the condition without appurtenances.

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