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Mazumder, S.K. & Darde, P.N.

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INSTABILITY OF FLOW DOWNSTREAM OF HYDRAULIC STRUCTURES:

S.K. MAZUMDER, Professor of Civil Engineering
Delhi College of Engineering, Delhi, INDIA.
and
P.N.DARDE
Manager, National Hydro-Electric Power Corpn.
Dulhasti Hydro-Electric Project, Kishtwar
Doda District, Jammu & Kashmir, India.

ABSTRACT

Residual Kinetic energy of flow is defined as the difference in energy to be dissipated and that actually dissipated. Higher is the residual Kinetic energy, greater is the non-uniformity and instability of flow downstream. Analytical & experimental study of flow through an expanding passage indicated that substantial amount of residual Kinetic energy left downstream when the floor of the expansion was level, resulting in highly non-uniform and unstable flow. It was possible to eliminate the residual Kinetic energy by Providing reverse slope to floor of the expansion. When the floor of the expansion was sloped with optimum angle of inclination determined theoretically, the flow downstream was found to be uniform and stable. It is concluded, therefore, that the instability of flow arises due to residual Kinetic energy of flow.

KEYWORDS: Residual K.E., Expansion, Instability.

1. INTRODUCTION

A number of hydraulic structures such as barrages, bridges, embankments, groyens etc. are constructed in alluvial flood Plain of river to meet various objectives like storage and diversion of flow, communication, flood control, river training etc. In most of such constructions, original flood plain of the river is constricted. Fig. 1(B) shows the plan view of Kosi barrage in India. There is a lateral constriction of flood plain of 6,900 m width to 1150 m, width of Kosi barrage. Apart from lateral constriction, there is constriction of flow in the vertical plain also (Fig.1A). Owing to these constrictions, there is an afflux (3.60 m in Kosi barrage), resulting in rise of total energy line (TEL) upstream with respect to the normal TEL downstream prior to the construction.

For structures like dams and barrages, there is provision for dissipation of energy. No such provision exists in case of bridges, embankments, groyens etc. No energy dissipating structure can be designed for 100% dissipation of energy (ΔE in Fig.1A) under all conditions of flow. As such some residual (K.E.) of flow ($\Delta E - \Delta E'$) , as shown in Fig. 1A, leave all such hydraulic structures downstream. The excess (or residual) K.E. of flow can be contained in a given flow with a given depth only through non-uniform distribution of velocity.

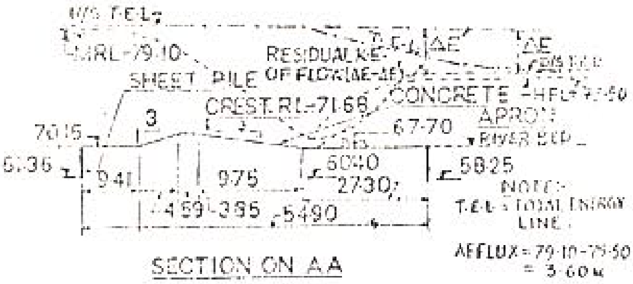

FIG. 1A SHOWING SECTION OF KOSI BARRAGE

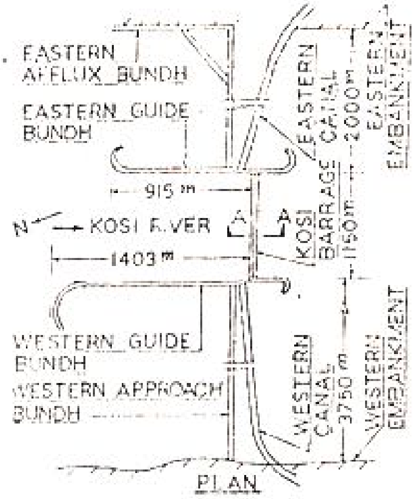

FIG. 1.B SHOWING PLAN OF KOSI RIVER BARRAGE

K.E. correction factor (also known as Corioli's coeff.) defined by eq.1 below is a measure of distortion and non-uniformity of flow

$$\alpha_2 = \frac{1}{A_2 V_2^3} \int_{A_2} u^3 dA \qquad (1)$$

where, α_2 is the K.E. correction factor downstream, A_2 & V_2 are the downstream cross sectional area and mean velocity of flow respectively, u is the local velocity of flow through an elementary area dA on A_2-Plane.

Instability of flow may occur when α_2 is very high, indicating that substantial amount of residual K.E. is transported downstream. For normal and uniform flow $\alpha_2 \doteqdot 1.0$. Since the normal K.E. of flow $(V_2^2/2g)$ in sub-critical flow is extremely small in most of the rivers flowing in alluvial flood plains, even a small amount of residual K.E. may cause large amount of distortion of flow resulting in high value of α_2. Relation between efficiency of an energy dissipator $\eta\ (= \Delta E'/\Delta E)$ and α_2 is plotted in Fig.2. It is seen that even 2% of residual K.E. ($\eta = 98\%$) results in α_2- value ranging between 4 to 14 depending on flow condition.

FIG. 2 VARIATION OF EFFICIENCY (η) WITH K.E. ENERGY CORRECTION FACTOR (α_2)

Non uniformity of flow associated with instability is the root cause of erosion, meandering and even change of river course downstream of hydraulic structures, constructed in alluvial flood plains. Such phenomena are reported to have occured downstream of barrages like Kosi, Gandak & Farakka etc. in India.

One of the Principal objectives of the Paper is to investigate the Problem of instability of flow downstream of hydraulic structures.

2. REVIEW OF EARLIER WORKS

Sherenkov (1967) attributed instability of flow due to sudden expansion resulting in formation of eddies. From the momentum, energy & continuity Principles, he developed the following criteria for instability of flow. The flow will be unstable if

$$-\frac{dQ_c}{ds} < \frac{V_c}{\alpha_b}\left[\lambda_g \chi_c + \sum_{j=1,2} \lambda_{Kj} h_{cj}\right] \tag{2}$$

where, λ_g is the coefficient of eddy viscosity, λ_K is the coeff. of molecular viscosity, α_b is the Boussinesq's coefficient, χ_c is the perimeter of the channel in the region of central live stream, V_c is the mean velocity of flow and Q_c is the rate of flow of the live Central stream at any distance S from the entry to the expansion. Indices $j = 1$ & 2 refer to eddy flow on the left & right sides of the Central stream respectively. $-dQ_c/ds$ gives the rate of flow exchange from the live stream to the eddies in the rear half of the eddies. For any given flow (V_c) , Eq.2 states that the instability of flow is governed by the following Parameters:

(a) Rate of flow exchange $-\frac{dQ_c}{ds}$; higher is the exchange rate, greater is the instability.

(b) Non-Uniformity of flow (α_b); higher the non-uniformity , greater will be α_b and more will be the instability.

(c) Resistance offered by turbulent shear λ_g and viscous shear λ_K ; higher the values of λ_g & λ_K, more stable will be the flow.

Kline (1959) and Smith & Layne (1979) studied development of stall (separating flow in eddy) in 2-D diffusers. The important Parameters which govern the different flow regimes & stability are:

(a) Length of diffuser wall (L) and the width (w) at entry to the diffuser; higher the value of L/W, more unstable is the flow.

(b) Total angle of the diffuser (2Θ); greater the 2Θ - value more unstable is the flow.

(c) Turbulence level of the incoming approach flow; higher the initial turbulence level, more stable will be the flow.

3. INVESTIGATION BY THE AUTHORS (1984)

3.1 Flow Characteristics In Expansion With Level Bed ($\beta = 0$).

3.1.1 Momentum & energy principles in expansion with level bed.

Assuming linear variation of water surface in an expansive passage (Fig.3) the axial component of side wall reactions $2R_{SX}$ may be expressed as

$$2R_{SX} = \frac{\gamma_w L_a}{3}\left[Y_1^2 + Y_2^2 + Y_1 Y_2\right] \tag{3}$$

where , γ_ω is the unit wt. of water; various other symbols used are explained in Fig.3. Entering the above expression in momentem equation, theoretical relation between the depth ratio $(y' = Y_2/Y_1)$ is given by

$$F_b^2 = y'r\left(2 - 2y'^2 r + y'r + r - y' - y'^2\right)/6(1-y'r) \tag{4}$$

where, F_b is the Froude's number of flow at entry to the expansion, r is the constriction ratio $(r = B/b)$.

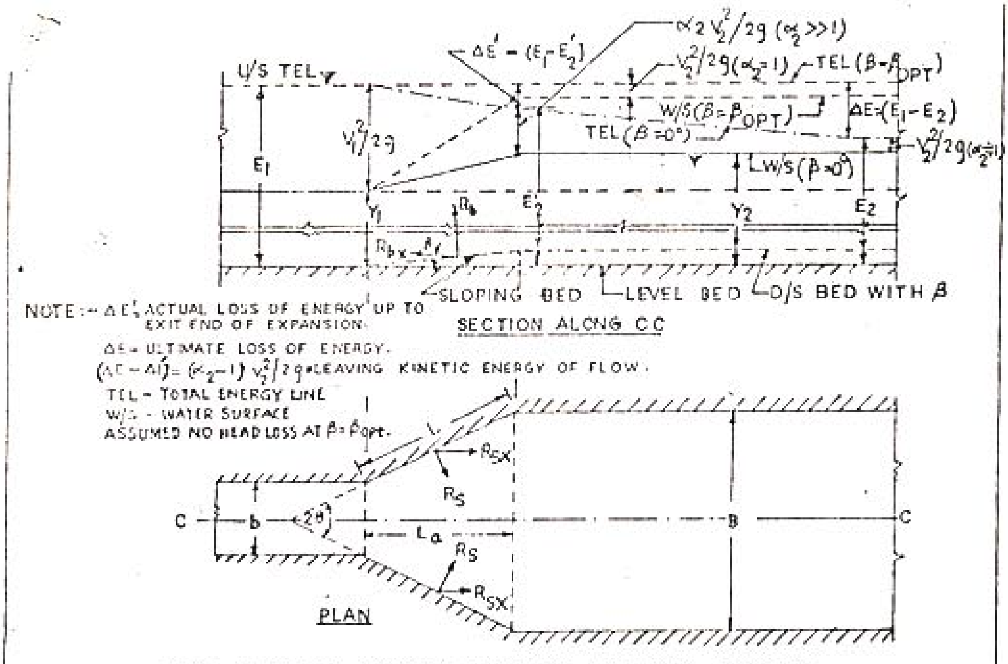

FIG 3 PLAN AND SECTIONAL VIEW OF EXPANSIVE PASSAGE

Theoretical loss of energy (ΔE) to satisfy the momentum & energy Principles may be expressed as

$$\Delta E/Y_1 = (1 - y') - \frac{(1 + y'r)(2 - 2y'^2 r + y'r + r - y' - y'^2)}{12 y'r} \qquad (5)$$

Solid lines in Fig.4 give the variation of $\Delta E/Y_1$ with Fb as obtained from eq.4 and eq.5. It may be seen that $\Delta E/Y_1$ increase with Fb & r (i.e. 2θ for a given value of b). Residual Kinetic energy of flow, $(\Delta E - \Delta E')/Y_1$, arises when the actual loss of energy $\Delta E'/Y_1$ due to production of turbulence lags behind $\Delta E/Y_1$ required in a level bed.

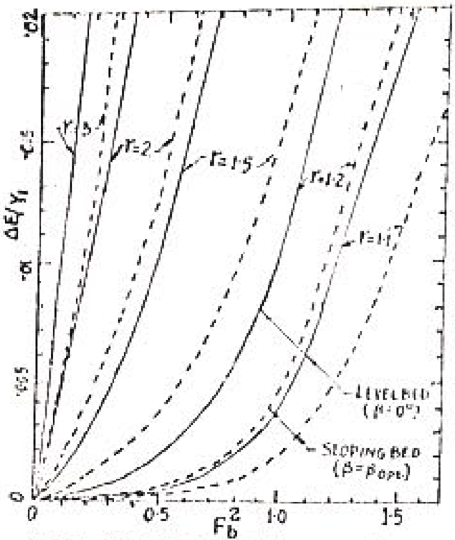

FIG. 4 - VARIATION OF $\Delta E/Y_1$ WITH F_b

3.1.2 Experimental results:

Authors studied the flow characteristics in the expansion with level bed $(\beta = 0°)$ as shown in Fig.3. It was observed that the flow remained unstable upto a certain angle $(2\theta \doteq 20°)$ of the expansion. With further increase in 2θ, the flow became unstable resulting in non uniformity of velocity distribution, separa-

-tion and eddies illustrated in Figs. 5 & 6. α_2 Values were computed from the measured distribution of velocity in each case and are given in line (iii) of table-I. It may be seen that with increase in 2θ, values of α_2 increased rapidly - indicating thereby transport of substantial amount of residual K.E. downstream. Non-dimensional values of residual K.E. of flow, $(\Delta E - \Delta E')/Y_1$, obtained experimentally are given in line (v) of Table-I.

Fig.5 separation and formation of eddy on the left side, $2\theta = 29^0$, $\beta = 0^0$

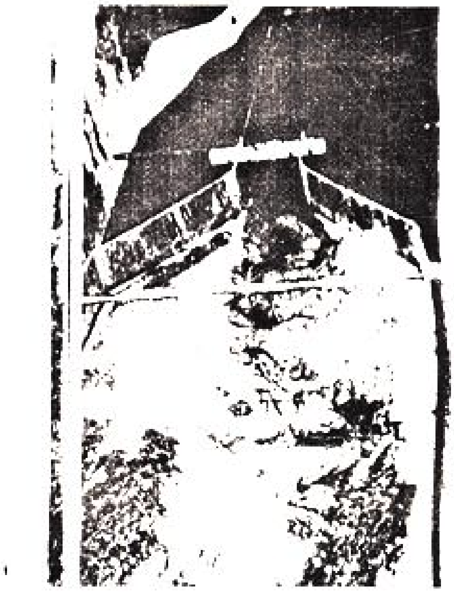

Fig.6 Separation with eddies on either side and Central unstable Jet flow, $2\theta = 62^o$, $\beta = 0^o$

3.2 FLOW Characteristics In Expansion With Inclined Bed.

3.2.1 Optimum angle of Inclination ($\beta_{opt.}$)

Fundamental difference between flow characteristic in a passage having parallel side walls (with stable flow) and that in an expansive passage having diverging side-walls (with unstable flow) lies in the fact that the axial component (R_{sx}) of side wall reaction in the later, does not exist in the former. It was contemplated, therefore, that the flow in an expansion may be stabilised by providing reverse slope to the floor of the expansion such that the axial force (R_{bx} in Fig.3) acting backward exactly balanced the axial force ($2R_{sx}$) acting in the forward direction. It may be shown that the value of R_{bx} is given by

$$R_{bx} = \frac{\gamma_w L_a \tan\beta}{6}\left(bY_2 + BY_1 + 2BY_2 + 2bY_1\right) \qquad (6)$$

Equating $2R_{sx}$ from Eq.3 with R_{bx} in Eq.6, it can be proved that the optimum angle ($\beta_{opt.}$) of inclination of the floor to achieve stable flow is given by

$$\tan\beta_{opt.} = \frac{2Y_1}{b}\tan\theta\,\frac{1+y'^2+y'}{2+2y'r+y'+r} \qquad (7)$$

values of $\beta_{opt.}$ (obtained from Eq.7) corresponding to different values of 2θ are given in Line (ii) and Line (i) of table-I respectively.

3.2.2 Momentum and energy principles in expansion having reverse floor slope

Since the axial components of forces from side walls and bed are exactly balanced, the momentum and the energy equations may be expressed as

$$F_b^2 = \frac{1}{2}\left(\frac{1-y'^2 r}{1-y'r}\cdot y'r\right) \tag{8}$$

$$\frac{\Delta E}{Y_1} = (1-y') - \frac{(1+y'r)(1-y'^2 r)}{4y'r}\cdot\frac{\Delta h}{Y_1} \tag{9}$$

where $\Delta h = L_a \tan \beta_{opt.}$. Theoretical values of $\Delta E/Y_1$, as obtained from Eq.8 and Eq.9 are given by dotted lines in Fig.4. For any given F_b and r values, the energy loss required ($\Delta E/Y_1$) in an expansion with reverse slope ($\beta = \beta_{opt.}$) is much less than that required in the expansion with level bed ($\beta = 0$). If the actual head loss due to Production of turbulence balances the required theoretical loss of energy in expansion with reverse bed slope, there will be negligible amount of residual K.E. resulting in uniform and stable flow downstream.

3.2.3. Experimental results

Experiments were conducted in expansion provided with reverse bed slope as stated under 3.2.1. Separation was completely eliminated and the flow downstream was found to be uniform and stable as shown in Fig. 7 & 8.

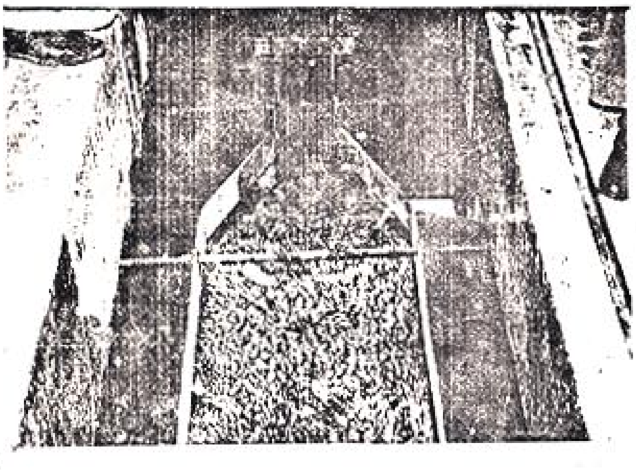

Fig.7 separation free uniform & stable flow , $2\theta=29^\circ$, $\beta_{opt.}=6.3^\circ$

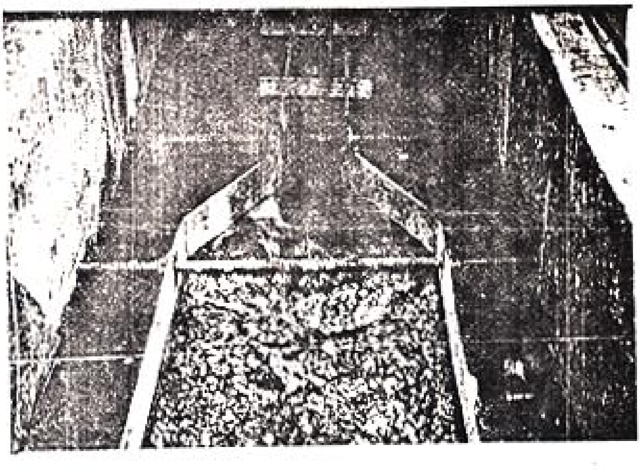

Fig.8 Separation free uniform & stable flow, $2\theta = 62^\circ$, $\beta_{opt.}=9.9^\circ$

α_2-values computed from measured distribution of velocity are given in line (iv) and the residual K.E.of flow in line (vi) of table-1.

4. CONCLUSIONS

Flow downstream of expansion with level bed is non-uniform. Higher is the angle of expansion (2θ), greater is the non-uniformity and instability of flow due to higher magnitudes of residual K.E. of flow moving downstream. provision of optimum reverse bed slope (β_{opt}) remarmably improved the flow conditions downstream. The flow was almost uniform and stable right from the exist end of expansion, irrespective of the total angle of divergence (2θ). The residual K.E. of flow was negligible in all the cases. It is,therefore , concluded from the above results that the non-uniformity and instability of flow arises due to residual K.E.of flow moving downstream of hydraulic structures.

TABLE-I

(i) Total angle of expansion (2θ)	22°	29°	52°	62°
(ii) Bed slope (β_{opt}) for equality of axial reactions from bed & side walls (from eq. 7)	5.1°	6.3°	8.8°	9.9°
(iii) α_2 (with level bed)	1.65	3.00	4.87	6.40
(iv) α_2 (with sloping bed)	1.12	1.14	1.18	1.17
(v) Residual K.E. of flow (Level bed) i.e. $(\Delta E - \Delta E')/Y_1$ for $\beta = 0^\circ$	0.0187	0.0420	0.0435	0.0460
(vi) Residual K.E. of flow (sloping bed) i.e. $(\Delta E - \Delta E')/Y_1$ for $\beta = \beta_{opt.}$ in (ii)	0.0070	0.0070	0.0070	0.0053
(vii) Residual K.E. ratio between level and sloping bed (v/vi)	2.67	6.00	6.21	8.67

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