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Analysis and Application of Hydraulic Jump with Downstream Abruptly Expanded Channel Flow

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Abstract- Analytical-statistical solutions of the characteristics in hydraulic jump, including submerged situation with the sluice gate effects of downstream non-slope and without the sluice gate effect of downstream sloping expanded rectangular channel of 3D flow, or called 2DV with 2DH flows, such as primary velocity profile for fixed bed and the kinetic energy loss coefficient are derived respectively. Then, the comparisons of the analytical solutions are made with the experimental results. Good trends and agreements are obtained, while the applicability of the analytical results are also presented and discussed.

Index Terms- **Turbulence; hydrodynamics; hydraulic jump; submerged hydraulic jump; Abruptly expanded channel flow; primary velocity; kinetic energy loss coefficient;**

I. INTRODUCTION

In nature and human interference, the channel geometries vary both in the lateral direction and in the depth one, or said 3-D. while due to the lack of sufficient data to be used to calibrate this 3-D model, the flow situation may be simplified to 2DV or 2DH flows with the assumption of quite uniformity in the width or depth direction. The idea of plan turbulent wall jets, which possessed very strong turbulence, is chosen to describe and solve the 2-D hydraulic jump flows. The primary velocity profile along the depth direction strongly dominate the turbulent phenomena, such as turbulent shear stress with the expression of turbulent eddy viscosity, turbulent kinetic energy, and the energy dissipation rate of a hydraulic jump in a horizontal channel downstream a sluice gate were solved analytically [Luo (2013), IJEIT; 2015 JET]. While the direct result of turbulence generates at the boarders of a free or submerged case inlet jet, the fluid within the jet undergoes both lateral diffusion and deceleration, and at the same time, fluid from the surrounding region is brought into motion in more explicit terms. The difference in velocity between a jet and the region into which it is discharged gives rise to a pronounced degree of instability, and the latter steadily decaying through viscous shear forming energy dissipation rate. The new velocity profile was re-derived, and then the analytical turbulent shear stress, turbulent kinetic energy, and energy dissipation rate profiles were shown respectively for this abruptly expanded channel flow [Luo (2013), AJCE]. The hydraulic jump within a lateral expansion is found to be of interest of the Hydraulic Engineers. These types of jumps may be expected at downstream of hydraulic structures where the incoming supercritical flow occupies a smaller width and leading to a wider tail water.

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The most important application of the hydraulic jump is in the dissipation of energy below sluices, weirs, gates, etc. so that objectionable scour in the downstream channel is prevented. The classical jump is formed in the regular rectangular channel in horizontal floor. In practice, the classical jump is being used for the design of regular type of stilling basin. But when the tail water depth is inadequate to give a classical jump in a channel of constant width even with the aid of appurtenances and if it is not possible to depress the basin floor because of difficulties in excavation, then a lateral expansion remains the only possibility for guaranteeing the required dissipation of energy (Herbrand 1973). In such basins, there are mainly two problems faced by the field engineers who monitor the design performance. One is the determination of sequent depth and the other is the estimation of energy loss (Agarwal 2001). Hydraulic jumps in expanding channels have received considerable attention, although only limited information on successful energy dissipation are available (Nettleton and McCorquodale 1989). Notable efforts have been made by Rajaratnum and Subramanya (1968), Herbrand (1973), Hager (1985), and Bremen and Hager (1993, 1994). After making several investigations, Herbrand (1973), Hager (1985), Chow (1959) and, Bremen and Hager (1994) separately developed equations for sequent depth ratio of abrupt expansion. If this jump occurs in a sloping condition the analysis of the phenomenon becomes very complex due to the inclusion of so many parameters related to sudden expansion and channel slope. The sequent depth ratio of a hydraulic jump in an abrupt expansion of a sloping channel is considered in this present study. The results of the developed prediction equation for computing sequent depth ratio in an expanding channel with sloping channel of downstream will be derived analytically and comparing to the well-known Belanger equation for classical jump with modification of Froude number.

II. ANALYTICAL SOLUTIONS OF PRIMARY VELOCITY PROFILE FOR HYDRAULIC JUMP FLOWS OF FIXED BED

As mentioned above, the wall jet proposed is used to derive the primary velocity and turbulent shear stress profiles, which are then used to express the turbulent eddy viscosity. The 2-DV continuity equation and equation of motion are used to derive the secondary velocity and turbulent kinetic energy. Finally, the 2-D k-ε two-equation model is used to obtain the energy dissipation rate.

The idea of plane turbulent wall jets is used to solve analytical solution of velocity profile for hydraulic jump

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flow [Luo (2013), IJEIT; 2015 JET]. The primary velocity profiles are obtained by using 2-D continuity equation and equation of motion in primary flow direction with neglecting wall friction items and assuming the vertical velocity smaller after comparing with the primary one. The definition of each symbol is shown in Figures.1 and 2.

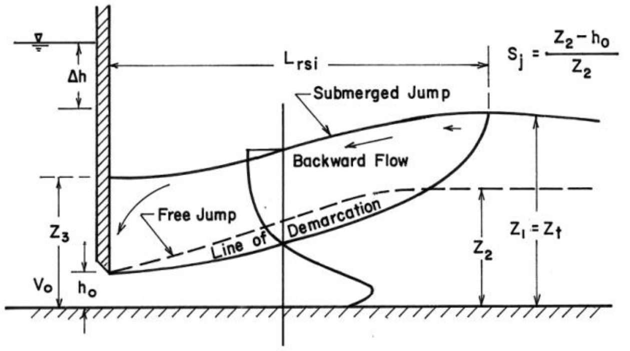

Fig 1: Submerged hydraulic jump (from N. Rajaratnam, 1965)

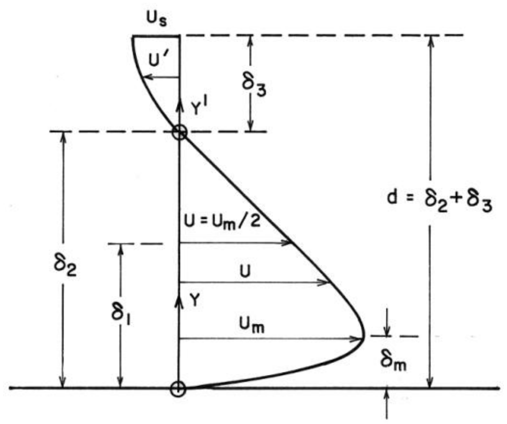

Fig 2: Submerged hydraulic jump （from N. Rajaratnam, 1965 ）

(a) Forward flows

$$\frac{U}{U_{max}} = \exp\left[-0.905(\eta - 0.125)^2\right] \qquad \text{.......................... (1).}$$

$$\frac{U_{max}}{V_0} = 5.395\left(\frac{x'}{h_0} + 11.2\right)^{-0.555} \qquad \text{............................ ... (2).}$$

$$\frac{\delta}{h_0} = 0.0678\left(\frac{x'}{h_0} + 11.2\right) \qquad \text{...(3).}$$

$$x = x_0 + x'$$

$$x_0 = \left(\frac{h_0}{2}\right)\cot\theta$$

$$\theta = 1.94^{o} \qquad \text{..(4).}$$

Where η =dimensionless boundary layer displacement=z/Δ; 2.0$\leqq \eta \leqq$2.5. The distance, x, the location to be analysed, includes the distance from the virtual origin x_0, which is the length for translating the flow from developing to fully developed flow case and generally is neglected for calculating velocity values but it is included for concerning calculation of the length of submerged hydraulic jumps. And there is a core angle, 3.8°, and the opening of the sluice gate is h_0. V_0 is the inflow velocity. The inflow Reynold number (R_e) is less than 50,000 when $F_{ro} \leqq 1.0$, while $F_{ro} > 2.0$, $R_e >$ 500,000.

(b) Backward flows

$$\frac{U'}{U_s} = f(\eta') = -1.122(\eta')^2 + 2.098\eta' \qquad \text{..................(5).}$$

$$\frac{U_s}{V_0} = -0.27\sin(\pi\alpha) \qquad \text{..(6).}$$

with η'=z'/δ3, and δ3= h–2.5δ, the velocity distribution in the backward flow is in Figure. 3, here, Us is the surface velocity of adverse flow. And the analytical velocity profile in vertical direction is about 0.04 V_0, quite small (Luo, 1993).

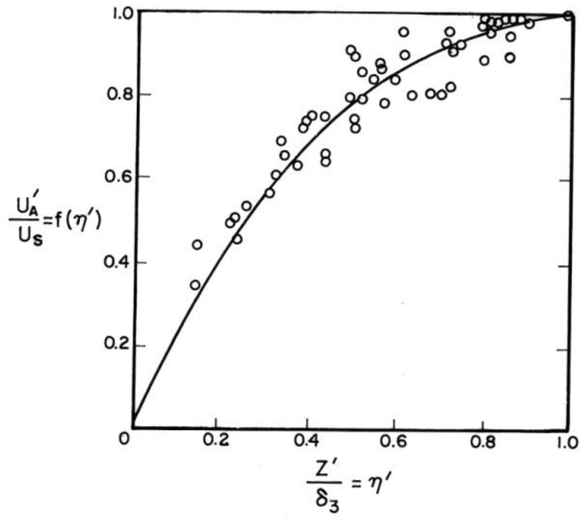

Fig 3: Velocity distribution in the backward Flow (from N. Rajaratnam, 1965）

III. ANALYTICAL SOLUTIONS OF PRIMARY VELOCITY PROFILE FOR NON-SLOPE ABRUPTLY EXPANDED CHANNEL FLOW

In view of the Newtonian principle of motion between action and reaction, moreover, it is realized that deceleration of the fluid in the jet can occur only through simultaneously acceleration of the surrounding fluid, so that the total rate of flow passion through successive sections of the jet actually increases with distance from the outlet. In this case, $\beta = 90^{\circ}$, the circulating flow situation happens from the entrance until certain distance downstream [Luo (2013), AJCE]. Within the circulation region, convective term, diffusion term, bottom stress, and the dispersion term in 2-D modelling exist due to the reason for the depth-integrated method from 3-D flow equation. The new velocity profile must be re-derived (Fig. 4).

The approximate characteristics of the corresponding mean flow pattern are expressed based on the assumptions that; (1) the pressure is hydrostatically distributed through the flow; (2) the diffusion process is dynamically similar under all conditions; (3) the longitudinal component of

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velocity within the diffusion region varies according to the normal probability function at each cross section

$$\frac{U}{U_{max}} = \text{Exp}\left[-\frac{y^2}{2\sigma^2}\right] \ldots\ldots(7)$$

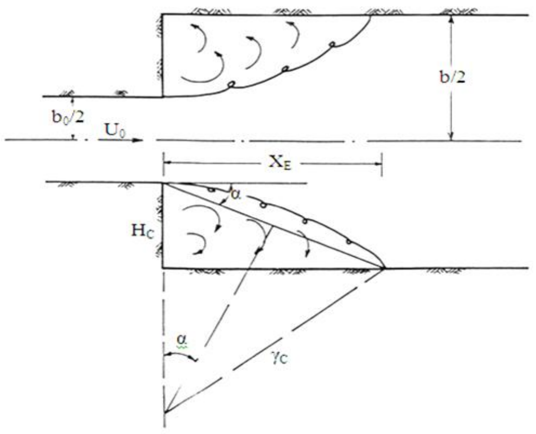

Fig. 4. The Definition of Non- slope Abruptly Expanded Flow

Based on the condition of dynamic similarity simultaneously σ/x= constant=C is required that at all cross-section, regardless of the efflux velocity. It hints the angle of jet diffusion must be constant.

$$\ell_n\left(\frac{U}{U_0}\right) = -42.3\left(0.096 + \frac{y-\frac{b_0}{2}}{x}\right)^2 \ldots\ldots(8)$$

and

$$\ell_n\left(\frac{U}{U_0}\right)\left[\sqrt{\frac{x}{b_0}}\right] = 0.83 - 4.24\left(\frac{y^2}{x^2}\right) \ldots\ldots(9)$$

Where Eq.(8) is for the zone of flow establishment, x≦x0, and Eq. (9) is for the zone of established flow, x≧x0, and ideally x0 = 5.2 b0, of course, it can be varied. Problems of major concern related to the efficiency and safety of sudden enlargement energy dissipation are the loss coefficient, cavitation potential and pressure fluctuation for a certain type of in-line sudden enlargement dissipater, even for a series of sudden enlargement which has been researched by (Zhang, 1989).

$$\Delta H = \frac{(U_0 - U)^2}{2g} = \left(1 - \frac{A_0}{A}\right)^2 \frac{U_0^2}{2g} = k_L\left(\frac{U_0^2}{2g}\right) \ldots\ldots(10)$$

$$k_L = \frac{E_0 - E}{\left(\frac{U_0^2}{2g}\right)} = \left(1 - \frac{A_0}{A}\right)^2 \ldots\ldots(11)$$

$$\bar{U} = \left(\frac{4U_0}{b}\right)\left(\sqrt{xb_0}\right)\left[\text{erf}\left(\frac{1.03b_0}{x}\right) - \frac{1}{2}\right] \ldots\ldots(12)$$

IV. ANALYTICAL SOLUTIONS OF PRIMARY VELOCITY PROFILE FOR HYDRAULIC JUMP FLOWS OF NON-SLOPE ABRUPTLY EXPANDED CHANNEL FLOW

It was shown in the previous section that the jump can be drowned repelled) if the tail-water depth is large (or smaller) than the required conjugate depth. In practice one should, in general, anticipate a situation when the tail-water depth is not is not equal to the required conjugate depth at all discharges. The jump can then form close to the structure, be drowned or be repelled downstream at different discharges. Ideally the jump should form close to the structure and certain appurtenances or artifices are used to control the location of the jump, i.e. to force the jump to occur at a desired location. The jump is then known as a forced jump. The devices used for this purpose may be baffle blocks and sills or a depression or rise in the floor level. The case of an abrupt drop is discussed first and is followed by a discussion of the case of the abrupt rise and baffle blocks. Figure 5 shows an abrupt expansion from a width b to B. The momentum equations of this situation are listed as following based on the Figure 5 for both (a) free jump and (b) submerged jump:

$$P_1 + P_3 - P_2 = \rho Q(U_2 - U_1) \ldots\ldots(13)$$

$$\frac{\rho g h_1^2}{2} b + \frac{\rho g h_1^2}{2}(B - b) - \frac{\rho g h_2^2}{2} B = \rho Q\left(\frac{Q}{Bh_2} - \frac{Q}{bh_1}\right) \quad (14)$$

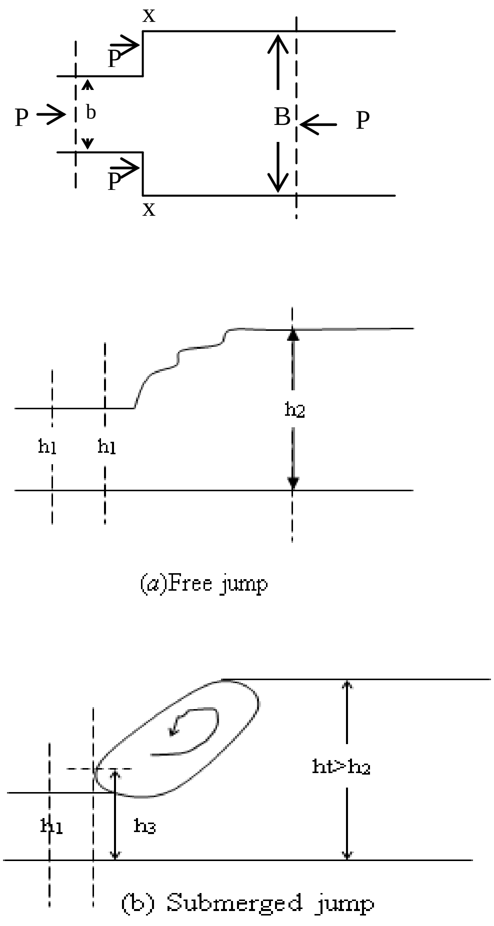

Fig. 5 Hydraulic jump at an abrupt expansion.

Eq. (18) can be simplified to:

$$(h_1^2 - h_2^2) = 2\left(\frac{U_1^2 b^2 h_1^2}{gB^2 h_2} - \frac{U_1^2 b^2 h_1^2}{gbh_1 B}\right) \ldots\ldots(15)$$

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$$\left(\frac{h_2^2}{h_1^2}-1\right)=2\left(-F_1^2\frac{b^2}{B^2}\frac{h_1}{h_2}+F_1^2\frac{b}{B}\right) \quad\text{................}(16)$$

Defining h_2/h_1 as η_B and b/B as β. And U_1 (as U_0 also) is the mean velocity at the entrance while U_2 is the one within the zone of hydraulic jump. The above two equation can be rewritten as:

$$\eta_B^2-1=2F_1^2(\beta-\beta^2/\eta_B)$$

$$\eta_B^3-\eta_B(1+F_1^2\beta)+2F_1^2\beta^2=0 \quad\text{.....}(17)$$

The solution of Eq. (20) can be obtained by shown in graphical form or by trial and error in Froude number clearly be seen that the conjugate depth is smaller or equal when there is an expansion as R-jump. The empirical satisfactorily predicts the conjugate depth in an expanding channel and may be used as an alternative to h_{2b}, the conjugate depth corresponding to the given values of U_1 and h_1 in a prismatic channel of width b at the entrance.

The jump is repelled down from section XX if the tail-water depth is smaller than or equal to the conjugate depth given by Fig.5(a) (R-jump). If the tail-water depth is larger than the above value, the toe of the jump will move up the channel of smaller width. Such movement is prevented in case of a sluice gate located at XX; a submerged jump as shown in Fig. 5(b), as the S-jump, will result in such a case. The depth h3 can then be obtained from the momentum equation as follows:

$$\frac{\rho g h_3^2}{2}B-\frac{\rho g h_t^2}{2}B=\rho Q\left(\frac{Q}{Bh_t}-\frac{Q}{bh_1}\right) \quad\text{...}(18)$$

$$h_3^2=h_t^2-\frac{2Q^2}{gB}\left(\frac{Bh_t-bh_t}{Bbhh_t}\right)$$

$$\frac{h_3}{h_t}=\sqrt{1-2F_t^2\left(\frac{1}{\beta}\frac{h_t}{h_1}-1\right)} \quad\text{..................}(19)$$

In which F_t is the Froude number in the downstream channel. and h_2 can be substituted from Eq. (16) or Eq. (17) as h_t in Eq. (22).

V. APPLICATION AND DISCUSSION

For the abruptly expanded flow situation and based on the 2D continuity equation as Eq. (20), we can have the lateral velocity profile as Eq. (21) which will gives some variations on both discharge and momentum on width direction mainly within the zone of flow establishment and certain region of established flow.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad\text{...}(20)$$

$$\lim_{n\to\infty}\left(\frac{V}{U_0}\right)\sqrt{\frac{x}{b_0}}=-0.155 \quad\text{.............................}(21)$$

If we assume that:

$U_2(x,y,z)= U(x,z)U(x,y)$................................(22)

Where U2 is the velocity profile of the zone for hydraulic jump and abruptly expanded flow combination. U(x,z) is expressed as Eqs. (1), (2), (5) and (6) with V0 as U1 the entrance or called approached velocity of upstream while U(x,y) as Eq.(8) or Eq.(9) with U0 as U1 and b0 as b, and b as B in fig.4 in order to consist with the definitions from Eq. (13) to Eq. (19).

From the continuity equation, we can have:

$U_1h_1b \geqq U_2h_2B$....................................(23)

It is because of the mass transfer on the lateral direction within the hydraulic jump with abruptly expanded situation, 3D case.

From Eq. (26), we rewrite it as:

$(h_2/h_1) \leqq (U_1/U_2)(b/B)$......................................(24)

and it has the similar form as Eq.(17). By substituting Eq. (24) to Eqs. (15), (16), and (17), and plotting the new results in Fig. 6, we can see the new results (by dotting) are close to the solid lines, which are based on 1D flow. The slight differences, especially for smaller b/B ratio, is due to the effective lateral flow function of abruptly expanded channel. The smaller the b/B ratio is, the less the h2/h1 for a given upstream flow Froude number and it means that the more turbulent energy is needed to be dissipated, or says, the length of hydraulic jump roller must be large enough.

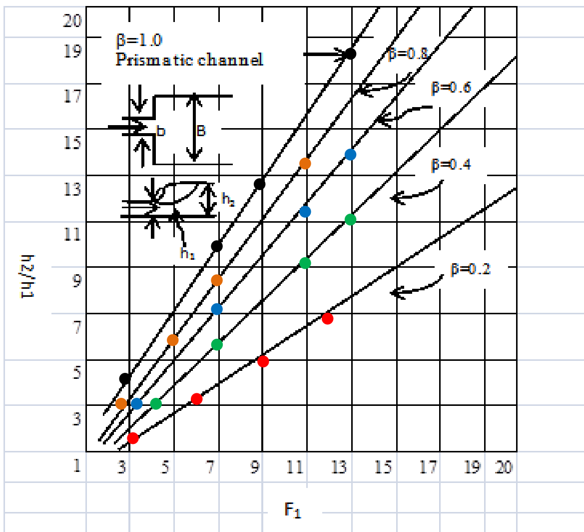

Fig. 6. Conjugate depth relation for an abrupt expansion.

For the case of constant width hydraulic jump flow, the length of the hydraulic jump roller, Lj, will be function of the depth and the Froude number of upstream flow, h1 and F1, for R-jump, while the function of Froude number of upstream flow, F1, with the conjugate water depth, h2. In the view of abruptly expanded channel flow, the channel width difference between b and B, says (B-b), will be the governing factor for determining the length of R-jump with abruptly expanded flow, while the best hydraulic section of the downstream, or says the minimum wetted perimeter for a

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given discharge, and for rectangular channel section for S-jump, and the value is r0 = B/2. From this point of r0, it could be seen that b/B ratio could not be too small, or says, B will not be too large. For R-jump of abruptly expanded channel flow:

$L_j/(B-b) = f(F_1) = a_1(F_1 - a_2)^{c_1}$ …………………(25)

For S-jump of abruptly expanded channel flow:

$L_j/r_0 = f(F_1) = a_3(F_1 - a_4)^{c_2}$ ………………………(26)

By combining the results from N. Rajaratnam and K. Subramanya, (1968) and Luo (1993), the values of a_i and c_i for

Eqs. (25) and (26) are:

a_1= 1.508, a_2= 1.5, and c_1=0.595 ………..…..(27)

With correlation coefficient equals 0.97.

a_3= 2.285, a_4= 1.0, and c_2=0.672 …………… (28)

With correlation coefficient equals 0.95.

Just we mentioned before the width of B is limited, if we need to have a more effective energy dissipation, do we need to have a sloping abruptly expanded channel for the hydraulic jump zone, and they can be solved by:

$\rho QU_1+P_1+W\sin\varphi=\rho QU_2+P_2$………………..(29)

With

$U_1h_1b \geqq U_2By\cos\varphi$ and $y=h_2\cos\varphi$……..(30)

Where $P_1=b\rho g{h_1}^3/3$

$P_2=\rho g{h_2}^3 B\cos\varphi/3$

$W=\rho g{h_1}^3(B-b)/2$

φ is the bed slope in the zone of flow on abruptly expanded hydraulic jump, and slope=tanφ≒sinφ.

In Fig. 7 and Fig. 8, we can have the one-dimension analytical results (the solid lines) and the two-dimension analytical ones with Eq. (22).They show the very similar results just with a little smaller results from 2-D due to the effects of lateral flows.

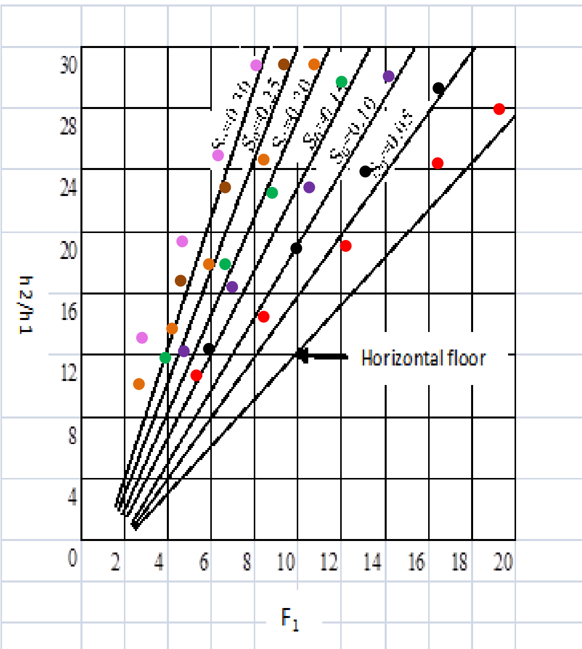

Fig. 7. Conjugate depth relation for jump on sloping floors

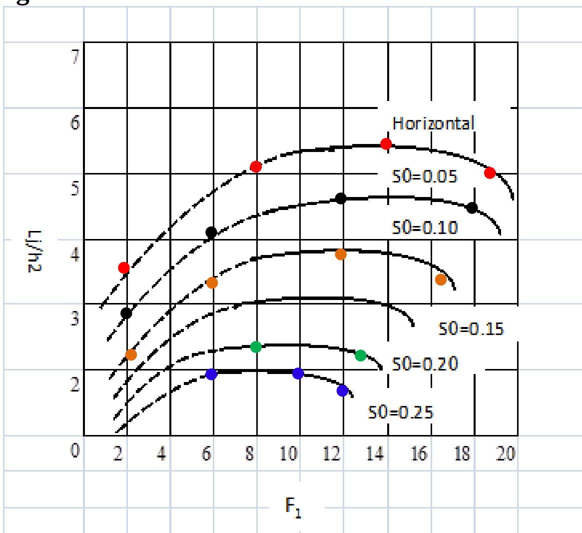

Fig. 8. Length of hydraulic jump on sloping floors

VI. CONCLUSION

The abruptly expanded channel flow has a very obviously function on energy dissipation for hydraulic jump rollers. The smaller the ratio of b/B, the stronger the lateral dispersion effects and the smaller the ratio of h_2/h_1, but the length of the hydraulic jump becomes larger for the energy dissipation due to the entrance of eddy momentum back from the lateral direction for R-jump. For the design of economy consideration and the best cross-section view point of submerged hydraulic jump, called S-Jump, the depth of tail-water will be an important control factor.

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