AN EFFICIENCIES' COMPARISON CONCERNING THE ENERGY LOSSES BETWEEN INCLINED SUBMERGED AND FREE WATER OUTFLOWS DOWNSTREAM OF A HYDROPOWER PLANT

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SYNOPSIS

The viability, effectiveness and performance of any hydropower plant depend not only from the hydroelectric machines' but even from the efficiency of the water outflow works, such as channels driving the water out, stilling basins, several appurtenances, etc. In such water outflows the mechanical energy losses are of great interest especially when the outflow conditions are varying. When the energy losses are large enough they are produced by rather violent hydraulic phenomena such as free hydraulic jumps. However, sometimes this jump becomes more calm, when for example, it becomes submerged and the energy losses are smaller.

It is in the engineer's selection what he will choose. Any violent water outflow (through a free jump) may damage the plant (or dam or reservoir or barrage foundations) although it gives larger energy losses. On the contrary, when the outflow conditions are non violent-as in the case of submerged water flow-the energy losses are smaller, but the downstream area of a power plant is safer.

In this experimental study the mechanical energy losses for both categories of water outflows are measured and given in dimensionless terms.

The results of this investigation refer to the fact that in dimensionless terms (relative energy loss vs a suitable Froude number), for the same Froude number, the free jump losses are much higher than the submerged jump losses. The submerged jump is not an effective means to dissipate excessive mechanical flow energy in comparison to the free jump, although it consists a calm flow and presents some external similarities with the free jump.

INTRODUCTION

The steady-turbulent water flow under a sluice gate-like structure (wall) and subsequent hydraulic jump (when formed under suitable conditions) belong to some of the most important hydraulic phenomena which are appearing in practice within open water channels. Sometimes the hydraulic jump is free and some other times is submerged, depending on the ensuing flow conditions, i.e. on the free or obstructed downstream channel flow. In the last case an obstacle such as a solid body (for example another sluice gate or a weir) is raising the water level just after the sluice gate and the entire flow becomes submerged. The higher part of any hydraulic jump-under appropriate conditions – is permanently remaining at its place although the flow under it is steadily developing along the open channel.

Fig. 1 schematically shows the general flow case where the outflow rectangular channel is inclined (angle φ) to the horizon – with a slope $J_0 = \sin\varphi$ – and includes a suitable wall (perpendicular or not to the channel floor) which has the same width as the channel, and a lower aperture α. The water discharge per unit width is q, the most important depths are p_1, p_2, for the submerged jump and d_1, d_2, for the free jump. Both jumps are schematically presented in Fig. 1 and show the difference of the two states of flow. The submerged jump has an inclined length L and the free jump a corresponding length L_d.For the submerged jump the control volume is included between cross

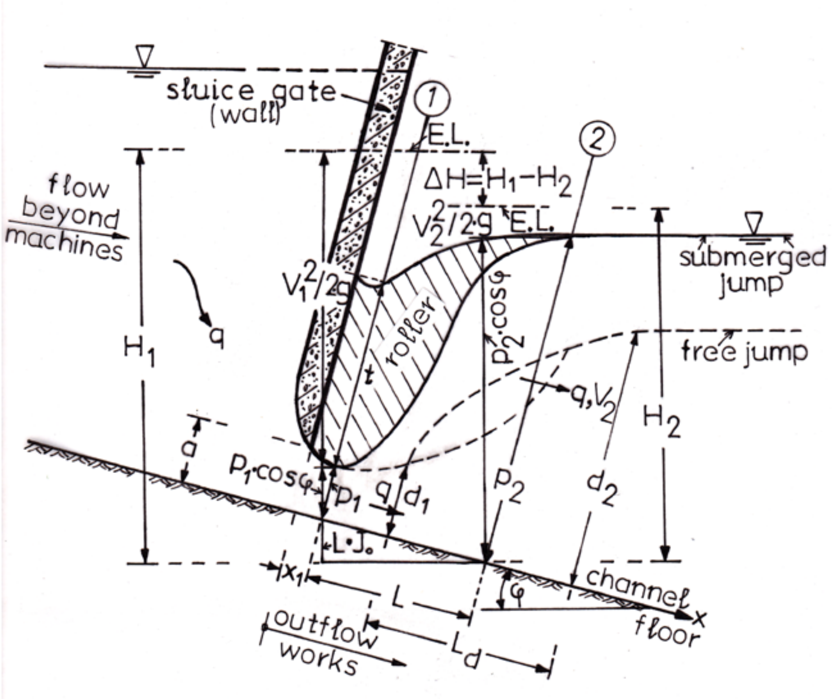

Fig. 1 Submerged and free jump geometry.

sections 1 and 2 where the local pressures are assumed to be hydrostatic. Cross section 1 is considered as coinciding with the contracted cross section of the free jump – at a distance x_1. The submerged jump has a mean water free surface profile starting from the outer face of the sluice gate, followed by a local fall along x_1, and then it turns (along L) towards the downstream horizontal. Beyond x_1, the lower limit of the submerged jump has a complicated form also ending at p_2 depth, while between the upper free surface and the lower limit a roller is created with its recirculating flow. The discharge q goes across p_1 and p_2 , while at cross section 1 the roller's water is increasing the pressure on depth p_1 and the entire pressure distribution (column $t+p_1$) is considered as hydrostatic, with a resultant force along the flow direction (x) $0.5 \cdot \gamma \cdot (t + p_1)^2 \cdot \cos\varphi$, where γ=specific water weight.

The one dimensional continuity equation is $q = p_1 \cdot V_1 = p_2 \cdot V_2$, while the momentum equation along x (with negligible tractive force on the channel boundaries) is,

$$0.5 \cdot \gamma[(t+p_1)^2 - p_2^2] \cdot \cos\varphi + W \cdot J_o = \rho \cdot q^2 \cdot [(1/p_2) - (1 - p_1)] \quad (1)$$

The above equation has been solved in the past by Demetriou. 2006 – [6], for the theoretical ratio $\lambda_t = p_2/p_1$, after experimental determination of the water weight W among sluice gate, channel floor, cross section 2 and free surface. This theoretical ratio has also been successfully compared to corresponding (experimentally determined) ratio λ_e.

Fig. 1 also illustrates the mechanical energy (per unit water weight) H_1 at section 1(depth p_1) and H_2 at section 2 (depth p_2), while $\Delta H = H_1 - H_2$ is the local loss of energy between conjugate depths p_1 and p_2 which is due both to tractive stresses (for $\varphi > 0^0$) and internal friction. The present paper is dealing with H_1, H_2 and ΔH, and the comparison of them with corresponding quantities of free jump, both in inclined rectangular channels. The most important parameters are $\lambda = p_2/p_1$, L/p_2 (experimentally determined) and the Froude numbers Fp_1 (section 1) and Fp_2 (section 2), generally with

$$Fp = q/g^{1/2} \cdot (\text{corresponding depth})^{3/2} \quad (2)$$

where $Fp_1 > 1$ and $Fp_2 < 1. Fp_2 = q/g^{1/2} \cdot p_2^{3/2}$ was mainly used here, while all Reynolds numbers had large enough values (turbulent flows).

For the hydraulic jump the conjugate depths d_1 and d_2 (and their ratio $\delta=d_2/d_1$), the length L_d/d_2 and Froude number $Fd_2 = q/g^{1/2} \cdot d_2^{3/2} = Fd_1 \cdot (d_1/d_2)^{3/2}$ are used, while any comparison with the submerged jump is meant with $Fp_2=Fd_2=Fr_2$. The points which appear on the following figures came out as results of energy computations, based on the above experimental data-and in combination with one dimensional energy expressions.

PREVIOUS EXPERIMENTAL RESULTS

For the submerged hydraulic jump within inclined rectangular channels, Demetriou et. al, 2005, [3], and 2006, [4], [5], [6], have presented the following experimental equations:

a) For the jump length (with φ in degrees and $Fp_2=Fr_2$),

$$L' = \frac{L}{p_2} \cdot \frac{\cos\varphi}{(2.7 \cdot \varphi + 30.8) \cdot Fr_2} = (-2.9053 + 0.0069 \cdot \varphi - 0.0018 \cdot \varphi^2) \cdot Fr_2 + (-0.03 \cdot \varphi + 1.125) \tag{3}$$

The above length L is the distance between the sluice gate and cross section 2, while the distance x_1 (between sluice gate and cross section 1) was measured as $x_1 \cong 1.7 \cdot \alpha$. Since x_1 is rather small - in comparison with L, it is reasonable to consider the distance 1-2 as approximately equal to L.

b) For the conjugate depth's ratio (with φ in degrees),

$$\left.\begin{aligned} &\lambda = p_2/p_1 = 1 - \{[(L')^2 - 1]/B_1\} \quad \text{where,} \\ &B_1 = [1.776 + 0.022 \cdot \varphi + 0.224 \cdot e^{-\varphi}] \cdot Fr_2^{(1.840 - 0.105 \cdot \varphi^{0.5} + 0.16 \cdot e^{-\varphi})}. \end{aligned}\right\} \tag{4}$$

The above equations are used here for $\varphi = 3^o$-6^o-9^o-12^o-15^o, $0.08 \le Fr_2 \le 0.15$ for $\varphi = 9^o$ and smaller Fr_2 ranges for other angles φ.

a) For the free hydraulic jump, Demetriou,2005, [2], has experimentally given the following equations:

For the jump length (with φ in degrees and $Fd_1=Fr_1$),

$$L_d/d_2 = [7.69 - 0.094 \cdot Fr_1 - (6.27/Fr_1)] \cdot \cos\varphi^{\,(3.35 \cdot J_0^{-1.3} - 2)} \tag{5}$$

b) For the conjugate depths' ratio, the following equation was verified,

$$\delta = d_2/d_1 = 0.5 \cdot [(1 + 8 \cdot Fr_1^2)^{1/2} - 1] \cdot e^{3.5 \cdot J_0} \tag{6}$$

The above equations hold for $0^0 \le \varphi \le 16^0$, $2 \le Fr_1 \le 19$ for $\varphi=0^o$,and smaller Fr_1 (≥2) ranges for other angles φ. Eq.(6) gives exactly the same δ vs Fr_1 lines as Chow's, 1959-[1],graphical straight lines

RESULTS. ANALYSIS AND DISCUSSION

For the submerged jump the mechanical energy H_1 is (Fig.1), $H_1 = L \cdot J_o + p_1 \cdot \cos\varphi + (q^2/p_1^2 \cdot 2 \cdot g)$, or, with the use of Fr_2 (=Fp_2), $\lambda=p_2/p_1$, and after division by p_1,

$$H_1/p_1 = \lambda \cdot (L/p_2) \cdot J_o + \cos\varphi + 0.5 \cdot \lambda^3 \cdot Fr_2^2 \tag{7}$$

Also, $H_2 = p_2 \cdot \cos\varphi + (q^2/p_2^2 \cdot 2 \cdot g)$, or

$$H_2/p_1 = \lambda \cdot [\cos\varphi + 0.5 \cdot Fr_2^2] \tag{8}$$

The local loss of mechanical energy between p_1 and p_2 is

$$\Delta H/p_1 = (H_1/p_1) - (H_2/p_1) = \lambda \cdot (L/p_2) \cdot J_0 + (\lambda - 1) \cdot \cos\varphi + 0.5 \cdot Fr_2^2 \cdot \lambda \cdot (\lambda^2 - 1) \tag{9}$$

or, in terms of $\Delta H/H_1$,

$$\Delta H/H_1=(\Delta H/p_1)/(H_1/p_1) \tag{10}$$

Corresponding energies and loss of energies for the non submerged (=free) jump are given by similar equations, although-instead of p_1,p_2, λ, L and Fp_2(=Fr_2) -corresponding quantities d_1,d_2, $\delta=d_2/d_1$, L_d and Fd_2(=Fr_2) are used, while any comparison is meant for the same Froude number.

For the submerged jump Fig. 2 presents H_2/p_1 vs Fr_2 for $\varphi=3^0$, where the pertinent line is a descending curve. H_2/p_1 is decreasing with Fr_2, for example from 7.2 (at Fr_2=0.14) to 6.3 (at Fr_2 =0.20), i.e. the percentage decrease is $(7.2-6.3)\cdot 100/7.2 \cong 12^{0}/_{0}$.

The same trends present H_2/p_1 vs Fr_2 for $\varphi=6^o$-9^o-12^o-15^o in Figs. 3, 4, 5, while the general level of H_2/p_1 is rising from $\varphi=3^o$ to $\varphi=15^o$.

Fig. 6 presents all previous curves (submerged jumps – solid lines) and all the corresponding H_2/d_1 vs Fr_2 (free- jumps – dashed lines).Both families of descending lines are very systematic: For Fr_2= const.H_2/p_1 for submerged jumps are increasing with angle φ, while to H_2/d_1=const. correspond larger Fr_2 values when φ is increasing. It is also clear that H_2/d_1 are generally larger than H_2/p_1 for any pair of lines with the same angle φ, i.e. the dimensionless energy at cross section 1 for submerged jump, is lower than the dimensionless energy at corresponding cross section for free jump (at d_1 depth) – in the present field of measurements. As a simple example for $\varphi=9^o$ and Fr=0.10 $H_2/p_1 \cong 8.6$ for submerged jump, while $H/d_1 \cong 14.5$ for free jump, i.e. there is a percentage energy increase of $(14.5-8.6)\cdot 100/8.6 \cong 68\,\%$. However, although the present measurements had a rather narrow Fr_2 range it may be predicted that any pair of corresponding lines for the same angle φ – do not meet between them but they are incompatible curves.

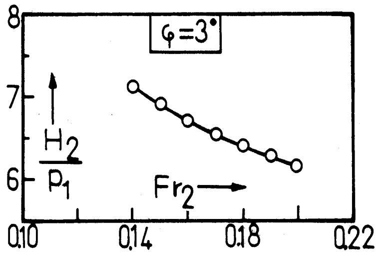

Figure. 2. H_2/p_1 vs Fr_2 for $\varphi=3^o$.

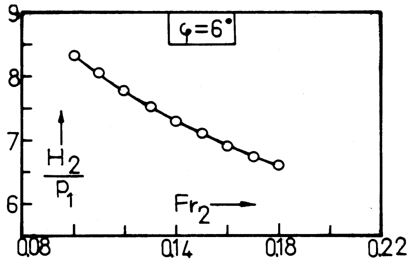

Figure 3. H_2/p_1 vs Fr_2 for $\varphi=6^o$.

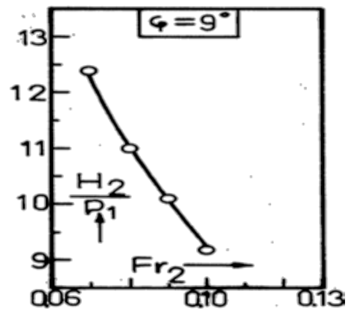

Figure 4. H_2/p_1 vs Fr_2 for $\varphi=9^o$.

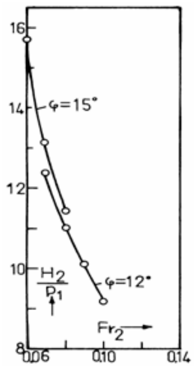

Figure 5. H_2/p_1 vs Fr_2 for $\varphi=12^o$ and $\varphi=15^o$.

Fig. 7 shows the dimensionless energy loss $\Delta H/H_1$ vs Fr_2 at angle $\varphi=3^o$ for submerged jumps. When Fr_2 is increasing $\Delta H/H_1$ are sharply increasing: As an example for $Fr_2=0.18$ $\Delta H/H_1$ is 0.062, while for $Fr_2=0.20$ $\Delta H/H_1$ becomes 0.136, i.e. there is a percentage increase of energy loss of $(0.136-0.062)\cdot 100/0.062 \cong 120$ %, while the difference in Fr_2 is only 10%.

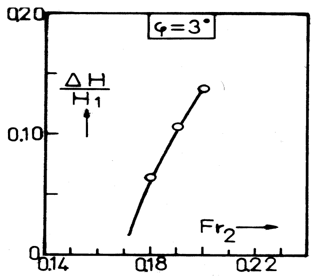

Figure 7. $\Delta H/H_1$ vs Fr_2 for $\varphi=3^o$.

Next Figs 8,9 and 10, present $\Delta H/H_1$ vs Fr_2 for $\varphi = 6^o$-9^o-12^o-15^o, which also show the same trends as in Fig. 7, but the general level of the dimensionless energy is strongly increasing with angle φ.

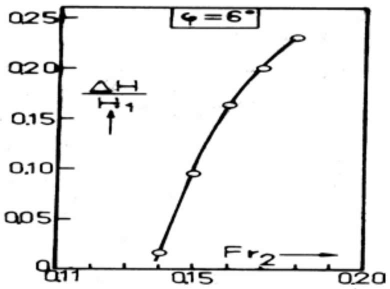

Figure 8. $\Delta H/H_1$ vs Fr_2 for $\varphi=6^o$.

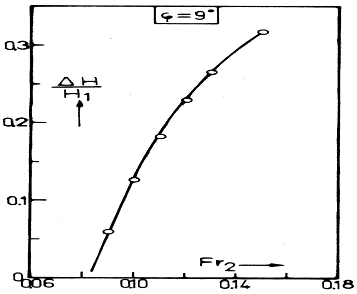

Figure 9. $\Delta H/H_1$ vs Fr_2 for $\varphi=9^o$.

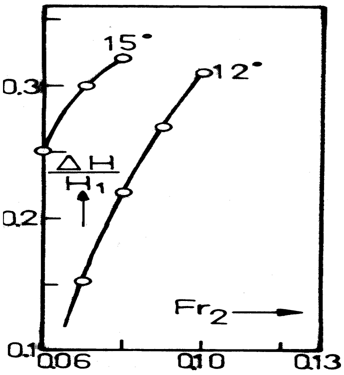

Figure 10. $\Delta H/H_1$ vs Fr_2 for $\varphi=12^o$ and 15^o.

Furthermore Fig. 11 presents all previous $\Delta H/H_1$ vs Fr_2 curves (solid lines) for submerged jumps and (dashed lines) for free jumps. Both families of lines are very systematic. For Fr_2=const. $\Delta H/H_1$ for submerged jumps are largely increasing when angle φ is increasing. For example for submerged jumps and $Fr_2=0.10$ $\Delta H/H_1 \cong 0.125\,(\varphi = 9^o)$, while for same Fr_2 $\Delta H/H_1 \cong 0.31(\varphi = 12^o)$, i.e. there is a percentage energy loss increase of $(0.31-0.125)\cdot 100/0.125 = 148$ % - when angle φ is increasing with a much smaller rate (~33%).

Finally, the most important result in Fig. 11 comes from a comparison between $\Delta H/H_1$ for submerged jumps - solid lines- and for free jumps – dashed lines – for the same Fr_2 and angle φ: $\Delta H/H_1$ for any pair at φ=const. is considerably smaller for submerged jumps than for corresponding free jumps – in the present field of measurements. As a simple example for $\varphi=9^o$ and $Fr_2=0.13$ $\Delta H/H_1 \cong 0.265$ for submerged jump, while $\Delta H/H_1 \cong 0.41$ for free jump, i.e. there is a percentage energy loss increase in free jump of $(0.41-0.265)\cdot 100/0.265 \cong 55\,\%$. This fact looks quite reasonable since the flow nature of submerged jump is rather calm, while the free jump is much more violent: The submerged jump is not an effective means to dissipate excessive mechanical flow energy in comparison to free jump, although it presents some external similarities with the free jump.

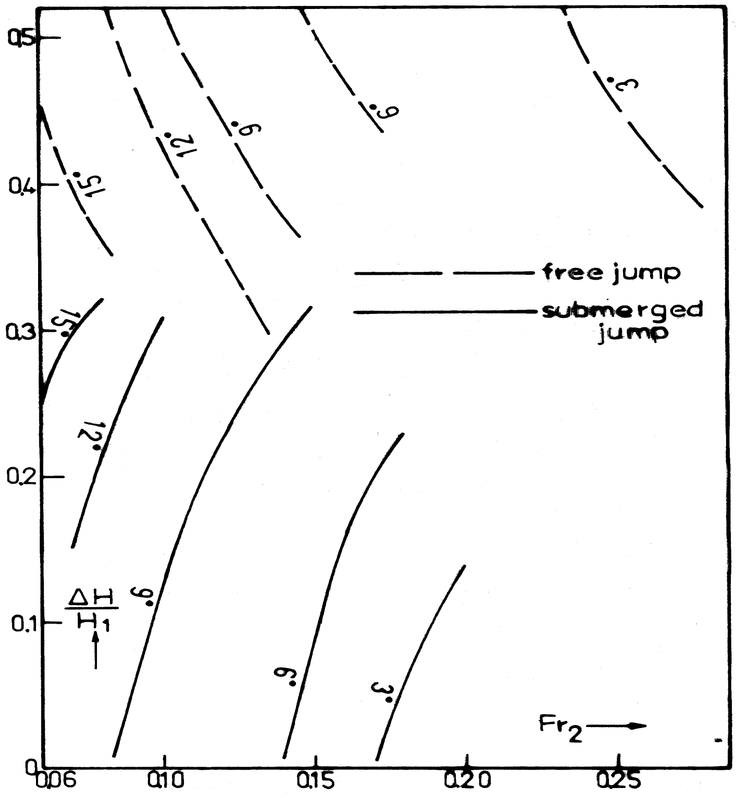

Figure 11. $\Delta H/H_1$ for submerged and free jumps, $3^o \le \varphi \le 15^o$.

CONCLUSIONS

This experimental study concerns the efficiency of the water outflow works from any hydropower plant, especially the flow mechanical energy losses under varying conditions of free or submerged inclined hydraulic jumps, where all the results are given in dimensionless terms. The main conclusions are: 1) All the results are functions of the outflow channel's inclination angle (φ) and suitable dimensionless Froude numbers. 2) The relative mechanical energy losses are in general larger for the violent free hydraulic jump than for the calm hydraulic jump. 3) For the submerged hydraulic jump, at any constant Froude number value, the energy losses are increasing with angle φ. 4) For the free hydraulic jump, at any constant Froude number, the energy losses are increasing when angle φ is decreasing. 5) The submerged jump is not an effective means to dissipate the excessive mechanical energy flow, but it consists a calm flow. 6) The free jump is much more an effective means to dissipate the excessive mechanical flow energy, but it consists a violent flow phenomenon. 7) The hydraulic engineer has to choose between the above two flow phenomena downstream a hydropower plant, in order to secure the outflow conditions. 8) The authors believe that the results of the present investigation contribute to the entire hydrosystem efficiency, the improvement of the system management and its maintenance.

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