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Hydraulic research at the Swiss Federal Institute of Technology Lausanne (EPFL)

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Summary

Some hydraulic research topics, recently accomplished or currently analysed, are presented. Particular account is made to gated and ungated spillway flow under high heads, and to various types of hydraulic jump energy dissipators. A description of the design cases as appear in stilling basins with positive and negative steps, and with continuous sills, is given.

Résumé: Recherches hydrauliques à l'Ecole polytechnique fédérale de Lausanne (EPFL)

Certains projets de recherche en hydraulique, récemment achevés ou encore en cours d'étude, sont présentés. L'attention est portée sur les écoulements à forte charge sur des déversoirs, contrôlés ou non-contrôlés par des vannes, et sur divers types de dissipateurs d'énergie. On décrit pour ces derniers les cas de dimensionnement en présence de marches positives ou négatives, et de seuils transversaux continus.

Zusammenfassung: Hydraulische Forschung an der Eidgenössischen Technischen Hochschule Lausanne (ETHL)

Es werden einige hydraulische Forschungen vorgestellt, die entweder vor kurzem einen Abschluss fanden oder noch in der Untersuchungsphase sind. Spezielles Gewicht ist dabei auf schützenkontrollierte und freie Überfälle bei grosser Überfallhöhe sowie auf verschiedene Typen von Tosbecken gelegt. Für letztere liegt eine Beschreibung der Dimensionierungsfälle vor, die sich auf Tosbecken mit positiven und negativen Stufen sowie auf durchgehende Querschwellen bezieht.

1. Introduction

The scope of duties dealt with at the Institute of Hydraulic Engineering (ITH) at the Swiss Federal Institute of Technology at Lausanne (EPFL) can be divided into the three following domains:

- teaching of hydraulics, hydrology and hydraulic structures on the graduate and the post-graduate levels,
- research in hydraulics, sediment transport and the hydrodynamics of lakes,
- hydraulic model tests and studies as a public service.

The foundations of the hydraulic laboratory dates back to 1928. Today it disposes of a total lab surface of 1550 m^2 in one of the test halls of the Civil Engineering Department. It is well equipped with modern test facilities. The ITH is led by two ordinary professors, namely Prof. *W. H. Graf*, and Prof. *R. Sinniger*. The model studies are directed under the responsibility of titulary Professor *J. Bruschin* and the hydraulic research related to structures is led by Dr. *W.H. Hager*. The complete team working for the ITH amounts to some twenty persons, including scientific collaborators, PhD students and lab personnel.

Since one of the major fields of analysis is the flow of water over spillways and through outlets, combined with questions relating to the dissipation of energy, several related problems will be exposed in the following. The aim pursued is not to give a detailed insight into the various flow mechanisms, but to outline the complexity of problems, and the lines of attack chosen for their resolution. For the interested reader, further details on the observations executed at the ITH may be consulted in the list of selected references.

2. Spillway flow

Figure 1 shows one of the channels used for research projects; its dimensions are 0.50 m width, 1.20 m (upstream) and 0.70 m (downstream) height, and 15 m length. At the outlet of the front basin, a standard spillway of actually 0.10 m design head H_D and of 0.70 m weir height prevails. Its upstream face is vertical, while the downstream face is sloped 1:1. The maximum discharge amounts to $Q = 400$ *l/s*, for which $H/H_D = 4.5$.

Two major projects are investigated in the upper channel portion: flow characteristics over gated and ungated standard spillways. Particular attention is paid to heads H larger than the design head H_D. This is of certain engineering interest for dams of which the head H is small, say $H < 3$ m. It seems that questions relating to such flows, namely the discharge characteristics, the distribution of bottom pressures along the spillway crest, the free surface profiles, the potential danger for nappe separation, and the cavitational erosion have not yet received a thorough attention. A project relating to these flow configurations is actually under way.

Figure 2 shows a typical plot of the 2-dimensional velocity field near the spillway crest, together with the corresponding photograph for $H/H_D = 3$. Such observations have been collected using a combination of an angle meter and a micro velocity probe [4].

Gated spillways have received scarse attention. Although mostly not relevant for the spillway design, the discharge characteristics of such structures must be known for an appropriate reservoir management. The currently proposed discharge equation according to the "US Corps of Engineers" is based on only few experimental data. Furthermore, from the viewpoint of application, tedious and time-consuming computations are necessary. In order to overcome these defects, gated spillways have been analysed. *Figure 3* shows a serie of typical runs for which the head on the gated spillway H was held constant, but discharge has been varied according to the corresponding gate opening.

The results obtained allow the prediction of discharge as a function of the (quite complicated) geometry and the hydraulic parameters. A typical application might be a project such as the Piedra del Aguila dam (Argentina) of which the model tests have been executed at the ITH (figure 4). Attention has been paid to the approaching flow conditions at partly blocked gates, an anti-vortex system preventing air flow at partly open gates, and the design of aerators along the spillway chute [1]. Detailed model observations at various scales finally led to satisfying results.

3. Energy dissipators

Classical hydraulic jump

A dam must be designed such that a safe and economic operation results for all possible flow conditions. One of the

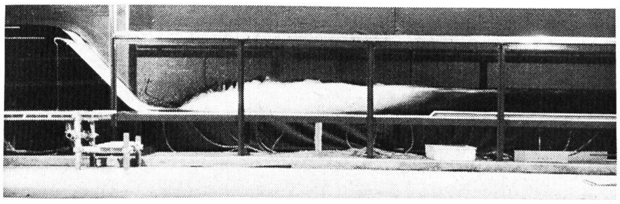
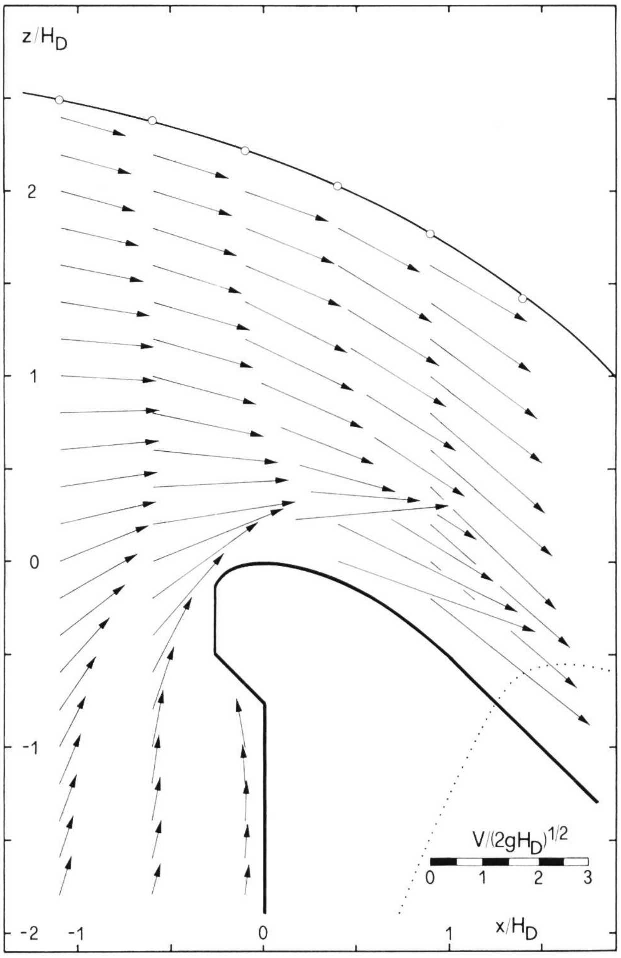


Figure 1. Test channel, containing standard spillway (left) and stilling basin (right).



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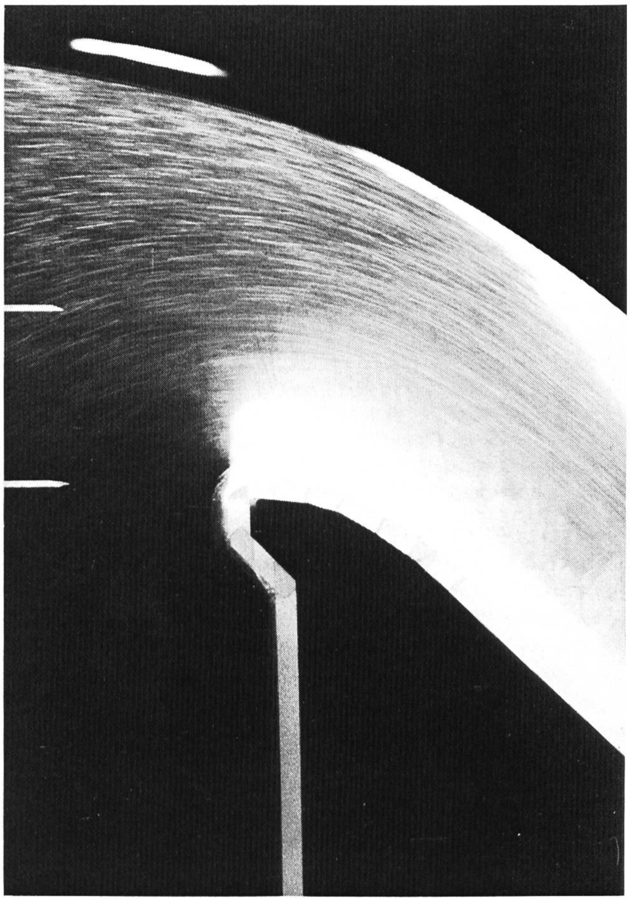
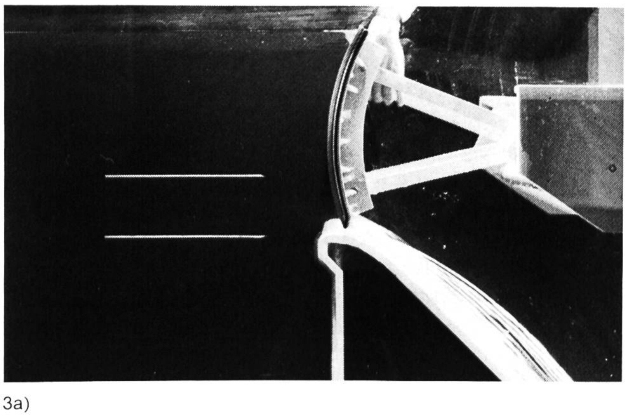


2b)

Figure 2. Velocity field at standard spillway for $H/H_D = 3$. a) according to observations, b) corresponding photograph.

Figure 3. Gated standard spillway flow. H_O = 35.8 cm relative to spillway crest, a) Q = 10 l/s, b) Q = 50 l/s, c) Q = 150 l/s, d) Q 200 l/s (b = 0.50 m).



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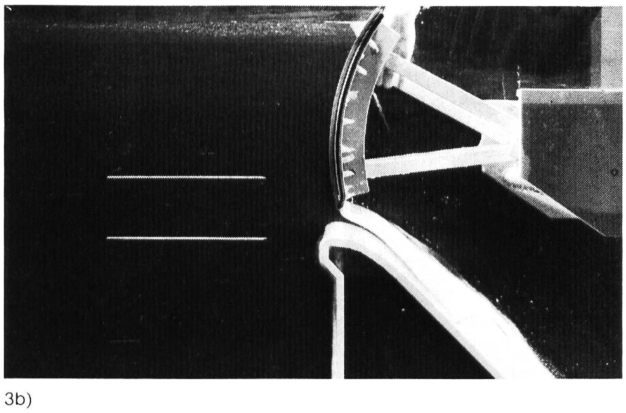

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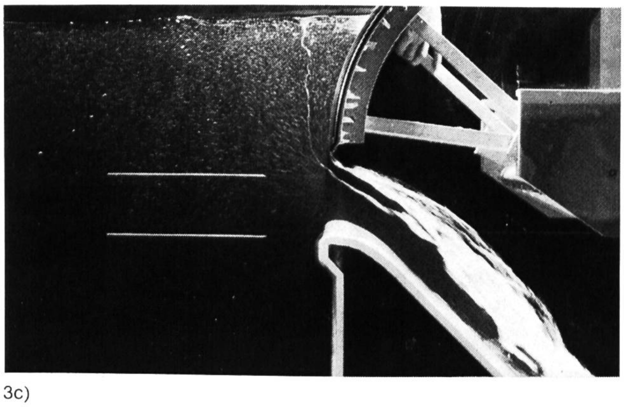

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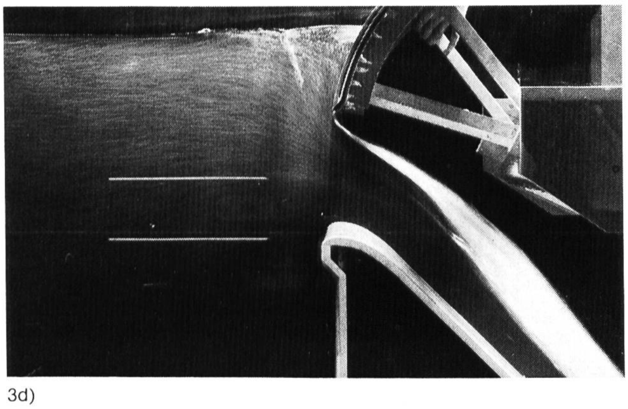

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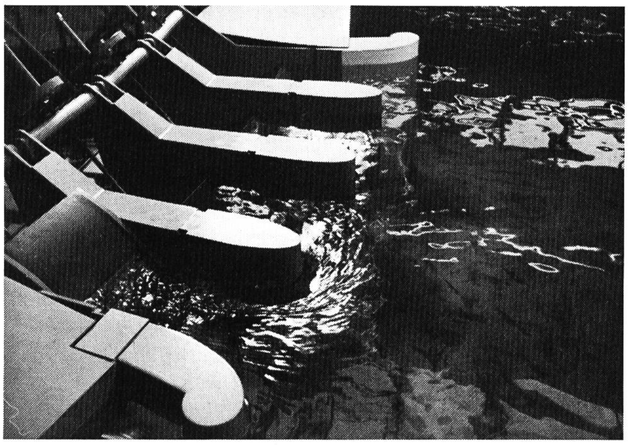
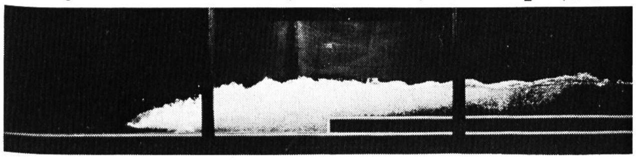


Figure 4. View at Piedra del Aguila spillway model from upstream. The spillway is standard shaped and gated, $Q_{max} = 10000\ m^3/s$ for four bays open.

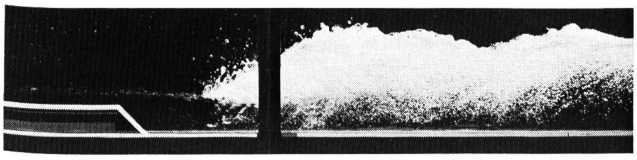
design cases to be considered occurs during flood periods, particularly if the reservoir level is near the spillway crest. Since the intake facilities (such as irrigation channels or headrace tunnels are designed for small discharge compared to the peak flood discharge, the excess discharge must be spilled over the dam and safely be returned to the river. However, the amount of kinetic energy at the dam base is considerable, such that a well-designed transitional area must be prepared in which this energy is dissipated. These structures are referred to as stilling basins; at their downstream end the turbulence character of the flow is so much calmed down that the water can be returned to the river without risk of bed erosion.
Various types of stilling basins have been proposed in the past. Distinction must be made between hydraulic jump basins and plunging jet basins. In hydraulic jump basins the high velocity inflow is directed along a nearly horizontal bottom well protected against the highly erosive potential of the flow. The particular feature of a hydraulic jump is its considerable dissipation of mechanical energy. The efficiency $\eta = \triangle H/H_1$ is approximately [2]

$$\eta = (1 - \sqrt{2}/F_1)^2, \quad F_1 > 2. \tag{1}$$

Herein, H_1 is the approaching energy head, $\triangle H$ the reduction of energy head between the upstream (index 1) and downstream (index 2) sections located at either end of the jump. $F_1 = Q/(gb^2h^3_1)^{1/2}$ is the inflow Froude number of a rectangular prismatic channel, Q discharge, b channel width, g gravitational acceleration and h_1 inflow depth. From Eq. (1) it is seen that η increases with F_1.
Although hydraulic jumps on horizontal channel bottoms are effective in terms of dissipation, they lack of the stability regarding the jump position. This is easily realised when referring to the ratio of the sequent flow depths $Y = h_2/h_1$ [2]



5a



5b

$$Y = \sqrt{2}F_1 - 1/2, \quad F_1 > 2. \tag{2}$$

A slight variation of h_2, say $\triangle h_2$, may only be compensated for by a corresponding adjustment of discharge $\triangle Q = b\sqrt{gh_1}\ \triangle h_2$, thereby accounting for an invariant inflow depth h_1. The flexibility of the classical hydraulic jump thus is poor; a slight modification of one of the parameters h_1, Q, h_2 leads to a blowing out of the jump of the assigned stilling basin area.
An improvement of this configuration can be obtained by providing the area of the hydraulic jump by chicanes inserted on the channel bottom; only by such modifications an effective and safe stilling basin is accomplished. The remainder of this note is confined to the discussion of some flow features encountered in hydraulic jump stilling basins. Particular attention is thereby paid to flow configurations recently examined at the ITH.

Steps

A step in a channel yields a local increase or decrease of the bottom elevation. The first step type is referred to as a positive step, while the second corresponds to a negative step. At both the up- and downstream zones of the step of height s, the channel bottom is assumed nearly horizontal.
Various flow types may establish in stilling basins having a step [3]. For *positive steps* distinction between the A-jump (end of roller at step face), the B-jump (roller at both sides of the step), ventilated step flow and unventilated step flow must be made. These flow types appear consecutively by a gradual decrease of the tailwater level. Regarding a still acceptable energy dissipator, the B-jump corresponds to the lower limit condition. The ratio of the sequent depths than is equal to [2]

$$F_1^2 = \frac{Y\{(Y+S)^2 + S^2 - 1\}}{2\,(Y-1)}. \tag{3}$$

$S = s/h_1$ is the relative height of the step.
Upon letting $\bar{Y} = (h_2+s)/h_1 = Y+S$ the approximation

$$\bar{Y} = \sqrt{2}F_1 - 1/2 - S/4 \tag{4}$$

may be deduced for Eq. (3). The difference $\triangle\bar{Y}$ between Eqs. (2,4) thus becomes

$$\Delta\bar{Y} = S/4 \tag{5}$$

or, in dimensional quantities $\triangle h_2 = s/4$ independent from the inflow Froude number. Consequently, for equal h_1 and F_1, the tailwater may be lowered by $s/4$ if a positive step is positioned into the stilling basin, as compared to the "stilling basin" without step.
The length of the surface roller of a B-jump is approximately

$$L_r \simeq 4.25\,(h_2 + s) \tag{6}$$

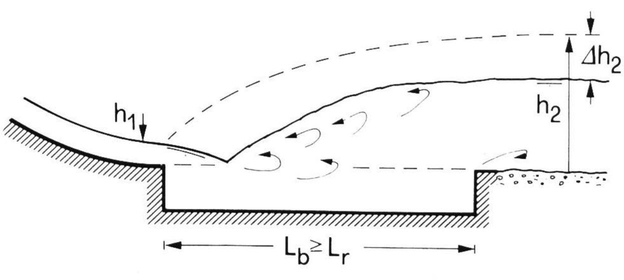
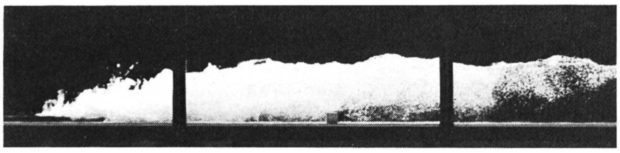


Figure 5, left. Hydraulic jumps at steps, a) B-jump at positive vertical step, $F_1 = 6$; b) minimum B-jump at sloped negative step, $F_1 = 5$.

Figure 6, above. Schematic view of a stilling basin, consisting of a negative upstream, and a positive downstream step.



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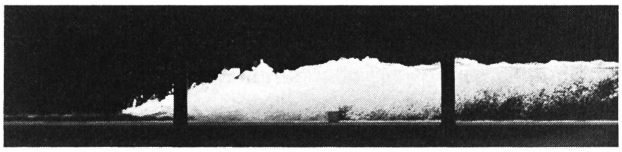

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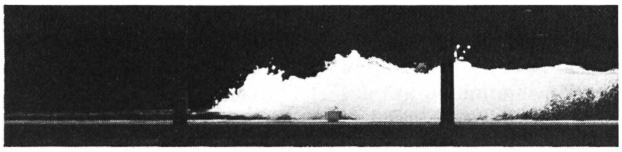

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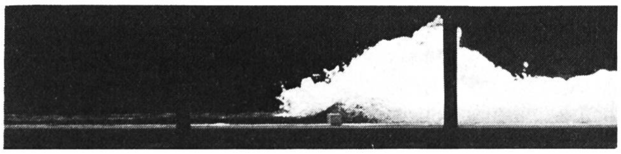


7d)

Figure 7. Typical flow configurations encountered by a transverse sill, a) A-jump, b) B-jump, c) minimum B-jump, d) standing wave. $F_1 = 6.4$.

it extends half up- and half downstream of the step face. *Figure 5a* shows a typical B-jump at a positive vertical step.

Negative steps may lead to a variety of flow types, the most interesting being the minimum B-jump for which the tailwater is adjusted to the lowest possible level still associated with a hydraulic jump in the step vicinity. As outlined by *Hager* and *Bretz* [3], the tailwater level is then equally given by Eq. (2). In other words, if a basin of depth s is designed with a negative step at the upper end and a positive step at the lower end, the downstream level may be lowered by

$$\Delta h_2 = s. \tag{7}$$

The length of the basin L_b should be at least equal to the length of the surface roller L_r [3]

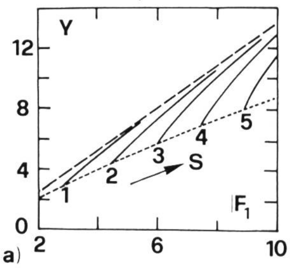
$$L_r = 4.25\, h_2. \tag{8}$$

Figure 6 shows the schematic geometry of the basin, whereas figure 5b shows a photograph of a typical minimum B-jump at a negative step.

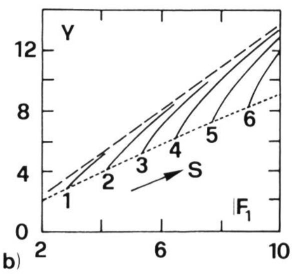
Sills

A continuous sill in a rectangular nearly horizontal channel corresponds to a close succession of a positive and a negative step of equal height s. Yet, the flow features encountered by a sill are quite different than those of steps. Distinction between A-jumps (roller ends above sill), B-jumps and minimum B-jumps, among others, must be made. For the latter the surface roller extends on both sides of the sill, and the tailwater level is lowered to the minimum. Lowering it below this level creates a standing wave downstream of the sill. The resulting jet is lifted quite above the sill and plunges downstream on the channel bottom. As a result, zones of high turbulence and shear are created which considerably may erode it. Therefore, from the point of view of a safe energy dissipator, this type of flow is inacceptable. *Figure 7* shows four types of sill flow, in which the minimum B-jump is considered as the design case.

Figure 8. Sequent depths, $Y = h_2/h_1$ as a function of F_1 and $S = s/h_1$ for continuous, transverse sills. (——) $S = 0$, (...) h_{min}/h_1. a) $K = 0.4$, b) $k = 0.7$ [5].



a)



b)

It should be noted that all flow types shown in *figure 7* are submerged by a certain tailwater, $h_2 > h_c$ as critical depth of flow. *Rand* [5] has conducted detailed model observations on the sequent depths ratio $Y = h_2/h_1$ as a function of the relative sill height $S = s/h_1$ and the inflowing Froude number F_1. Upon fixing the length index of the jump to $K = 0.4$ the plot as shown in *figure 8* results. It is seen that, for a particular F_1, say $F_1 = 8$, the minimum of $Y = 7.2$ occurs for $S = 4.3$. Decreasing S to, say $S = 2$, yields an increase of Y to 10. Finally, for $S = 0$, $Y = 10.8$ results from Eq. (2). The effect of S on Y, and on the relative dissipation of energy η, thus is signifcant.

The length of the stilling basin in front of the sill face should be at least

$$L/h_1 = 4.8\, F_1 - 0.8 \tag{9}$$

whereas its total length L_t has to amount to at least [6]

$$L_t/h_1 = 14(F_1 - 1)\{1 - 0.04(F_1 - 1)\}, \quad F_1 < 10. \tag{10}$$

4. Conclusions

The purpose of this note is to present some hydraulic studies performed recently at the ITH of the EPFL. Particular attention is paid to flows over gated and ungated standard spillways, and to some types of hydraulic jump stilling basins. In both problems, a generalisation of the present state of the art is pursued. On the one hand the geometry of the structure involved is drastically simplified when compared to actual projects whereas the thorough analysis of the flow pattern then becomes possible on the other hand. Such knowledge in turn permits a rather good insight into the main flow features of hydraulic facilities to be realised in the future.

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