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Discussion

Tailwater level effects on flow conditions at an abrupt drop

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Discussers:
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The Authors experimentally investigated hydraulic conditions for the transition from supercritical to subcritical flow at an abrupt drop.

In this discussion, the comparison of the flow conditions at an abrupt drop between channel widths of $B = 40$ and 80 cm (Photo 1) reveals that the Authors' experimental results with channel widths of $B = 30$ and 40 cm include the effect of the channel width on the hydraulic conditions for the formation of various flow conditions. Also, it is emphasized that the flow condition at an abrupt drop can be predicted on the basis of the results of Ohtsu and Yasuda (1991, 1992) in which the effect of the channel width is negligible.

Photo 1 Comparison of flow conditions between $B = 80$ cm (forward) and 40 cm (backward) channel widths.

Reference section of supercritical flow depth on step

In the Authors' experiments, a brink depth at the downstream end of the step has been used as a reference section of the supercritical flow depth on the step. The brink depth is affected by the curvature of streamline of the main flow passing over the drop, and it is not adequate as a reference section on the step. Also, the supercritical depth in the momentum equation (3) is defined as the section where the pressure is hydrostatic, and the effect of the curvature of streamline is negligible at the upstream section of the control volume. In the experiment of Ohtsu and Yasuda (1991, 1992), the upstream section was defined as a first section where the pressure becomes hydrostatic ($3.5\,h_1$ upstream from the downstream end of the step; h_1 is the supercritical depth at the reference section).

Definition of flow conditions

The Authors have described the flow conditions of A-jump, wave flow, maximum plunging condition, and limited jump. A comparison between the Authors' results and the predicted results by Ohtsu and Yasuda (1991) for different types of flow conditions has been presented in Fig. 4. But, the Authors' definition of each flow condition might differ from that of Ohtsu and Yasuda (1991).

Ohtsu and Yasuda (1991) have defined A-jump, maximum wave, maximum plunging condition, and limited jump as follows:

A-jump (Photo 2) is defined as a jump with a surface roller, most of which is formed on the step. In A-jump, the streamline of the main flow passing over the step is always upward.

By lowing the tail water elevation from A-jump, at a certain stage, maximum wave (Photo 3) is formed, which is defined as a non-breaking wave flow at the central part of the channel. If the effect of the channel width on the formation of the wave type flow is negligible as in the case of $B = 80$ cm, the shape of a large single wave is two-dimensional except for the flow near the sidewalls (Photo 3).

Photo 2 Flow condition of A-jump ($F_1 = 6$, $s/h_1 = 3$, $B = 80$ cm).

Photo 3 Flow condition of maximum wave ($F_1 = 6$, $s/h_1 = 3$, $B = 80$ cm).

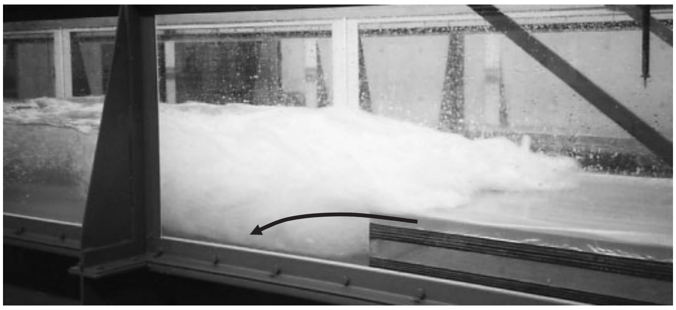


Photo 4 Flow condition of maximum plunging condition defined by Ohtsu and Yasuda ($F_1 = 6$, $s/h_1 = 3$, $B = 80$ cm).

Maximum plunging condition is defined as a jump that has a surface roller (Photo 4) immediately before the transition from a plunging flow to a wave type flow by raising tailwater elevation. As shown in Photo 4, the streamline of the main flow passing over the step is always downward and the toe of the jump is on the step. When the effect of the channel width on the jump formation is negligible, the toe location on the step is very near the drop.

In accordance with the Authors' experimental results shown in Table 1, the Authors' definition of the maximum plunging condition might correspond to the plunging flow for which the toe of the surface roller is located at the downstream end of the step (Photo 5).

Limited jump is defined as a lower limit of the formation of the plunging flow. In addition, the effect of the tailwater direction on the formation of each flow condition is negligible under the range of $F_1 \geq 3$ and the low drop regime ($0.5-1.5 \leq s/h_1 \leq 8.0-9.0$) (Ohtsu and Yasuda, 1991).

Photo 5 Plunging condition, which toe of surface roller is located at downstream end of step ($F_1 = 6$, $s/h_1 = 3$, $B = 40$ cm).

Effect of channel width on hydraulic conditions for formation of each flow condition

Comparison of each flow condition for channel widths between $B = 40$ and 80 cm has been made under given Froude number F_1 and relative step height s/h_1. Photos 2–8 show an example of each flow condition for $F_1 = 6$ and $s/h_1 = 3$, in which the values of h_1, s, and V_1 are constant.

In the case of maximum wave for $B = 40$ cm, as shown by Photo 6, the main flow passing over the drop concentrates at the central part of the channel, and the shape of a large single wave becomes three-dimensional. While, for a wide channel as in the case of $B = 80$ cm, a two-dimensional wave is formed except for the flow near the sidewall (Photo 3). The wave height and the bottom length of a large single eddy for $B = 40$ cm are 1.1 times larger than those for $B = 80$ cm. For the value of the relative downstream depth y_t/h_1 required to form the maximum wave, there is no difference between channel widths of $B = 40$ and 80 cm.

In the case of the maximum plunging condition defined by Ohtsu and Yasuda (1991), as shown by Photo 7, the toe location of the surface roller on the step for $B = 40$ cm is more upstream than that for $B = 80$ cm (Photo 4). For the case of $B = 40$ cm, when the maximum plunging condition is formed, the downstream depth is 1.1 times larger than that for $B = 80$ cm.

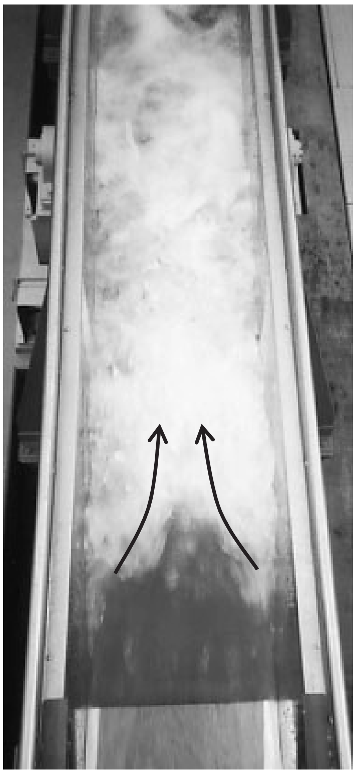
If the flow conditions are compared for channel widths between $B = 40$ and 80 cm under the same downstream depth, as shown by Photos 7 and 8, a wave type flow is formed in the case of $B = 80$ cm. However, for $B = 40$ cm, a maximum plunging condition is formed.

Accordingly, in the case of $B = 40$ cm, the effect of the channel width on the formation of each flow condition is shown, and the flow condition is apt to be three-dimensional. The Authors' results include the effect of channel width, and it is difficult to propose general information for hydraulic-design guidelines by using the Authors' results.

Prediction for formation of each flow condition at an abrupt drop

The experimental results of Ohtsu and Yasuda (1991, 1992) were obtained under a wide range of relative drop heights s/h_1($0.5 \leq s/h_1 \leq 20$), Froude numbers F_1 ($1.0 \leq F_1 \leq 7$), and relative downstream depths y_t/h_1. Also, the hydraulic condition required

(a) Sideview



(b) Plan view

Photo 6 Flow condition of maximum wave for $B = 40$ cm ($F_1 = 6$ and $s/h_1 = 3$).

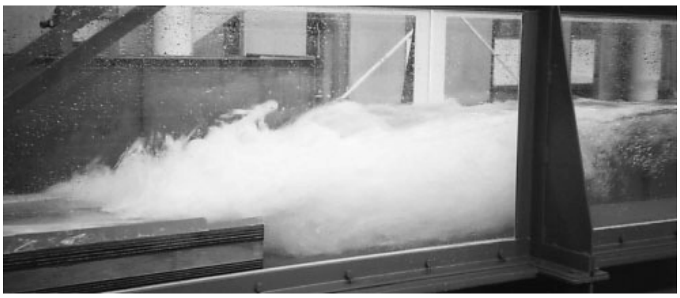


Photo 7 Flow condition of maximum plunging condition defined by Ohtsu and Yasuda ($F_1 = 6, s/h_1 = 3, y_t/h_1 = 9.74, B = 40$ cm).

to form each flow condition (i.e. A-jump, maximum wave, maximum plunging condition, and limited jump) has been formulated by using the momentum equation (3) and the experimental equation for k based on the measurements of the pressure acting on the vertical face of the drop. Thus, prediction curves have been shown. Further, the effect of the channel width on the formation

Photo 8 Flow condition of wave type flow ($F_1 = 6, s/h_1 = 3, y_t/h_1 = 9.74, B = 80$ cm).

of each flow condition is negligible for the experimental results of $B = 80$ cm, and the results of Ohtsu and Yasuda (1991, 1992) agree with the results obtained by many researches (e.g. Hager and Kawagoshi, 1990; Pagriala, 1992; Armenio *et al.*, 2000).

Figure 18 shows an example of a design chart for predictions for each flow condition. As shown in Fig. 18, the flow regime of a plunging flow having a surface roller, in which the streamline of the main flow passing over the drop is always downward, has

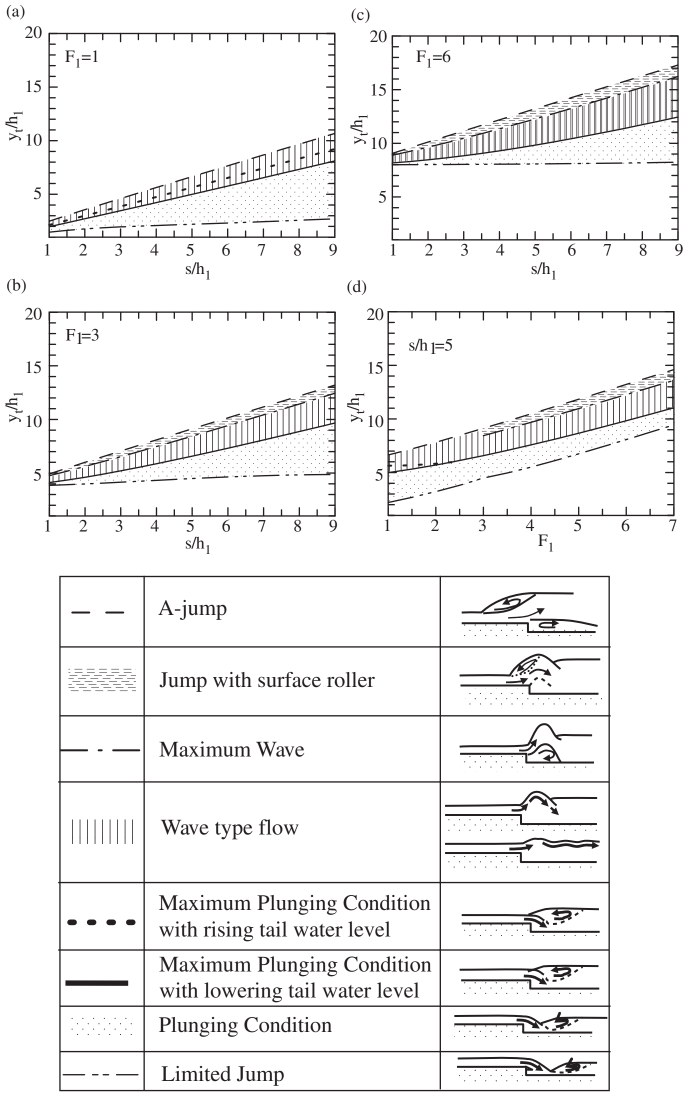


Figure 18 Example of hydraulic design chart of each flow condition at an abrupt drop.

been determined by using the prediction curves of both maximum plunging condition and limited jump. Also, if the downstream depth is less than the predicted depth for the formation of limited jump, the jump location is not stabilized for the change of the tailwater level.

The flow regime of wave-type flow not having a surface roller has been determined by using the prediction curves of both maximum wave and maximum plunging condition.

In the flow region between those of the prediction curves of A-jump and maximum wave, there has been formed a stabilized jump in which the streamline of the main flow passing over the drop is always upward.

On the basis of the results of Ohtsu and Yasuda (1991, 1992), it is possible to predict the flow conditions in accordance with the relative downstream depth y_t/h_1 under given values of the supercritical Froude number F_1 and the relative step height s/h_1.

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Reply by the Authors

The Authors appreciate the interest of the Discussers and think that the investigation presented by Ohtsu and Yasuda (1991) is a fundamental contribution to the analysis of hydraulic jumps at an abrupt drop. The Authors' paper (Mossa *et al.*, 2003) represents a sort of continuation, presenting design charts of valuable interest for the hydraulic engineering practice, and new insights into the oscillating phenomena, supported by 211 experimental runs, whose results are also confirmed in literature. In fact, the Authors' Fig. 4 shows good agreement between their experimental results and the Discussers' theoretical results, with an average error, defined as

$$\frac{|F_{1\,\mathrm{exp}} - F_{1\mathrm{theor}}|}{F_{1\mathrm{theor}}},$$

equal to 10.17%. This value is very reasonable, taking into account both the experimental errors and the approximations in the Discussers' theory.

Regarding the well known definition of the jump types, the writers used the following table:

(1) A-jump (Fig. 1, [1a] and [1b]);
(2) Wave jump (Fig. 1, [2a] and [2b]);
(3) Wave train (Fig. 1, [3a] and [3b]);
(4) B-jump (or plunging conditions) and its maximum condition, that is, the maximum plunging condition (Fig. 1, [4a] and [4b]); and
(5) Limited jump with the minimum B-jump condition (Fig. 1, [5a] and [5b]).

From an engineering perspective, the Authors think that it is possible to group plunging conditions with its maximum, because the latter represents a limit situation of the former, and limited jump with minimum B-jump condition for the same reason. Furthermore, the Authors grouped also wave jumps with wave trains to obtain more readable flow charts. These charts were subdivided in the following area:

(1) A-jump (the short legend in the chart is *A-Jump*);
(2) Wave jump and wave trains (the short legend in the chart is *Wave*);
(3) B-jump and its maximum condition (the short legend in the chart is *Max plung. Cond*);

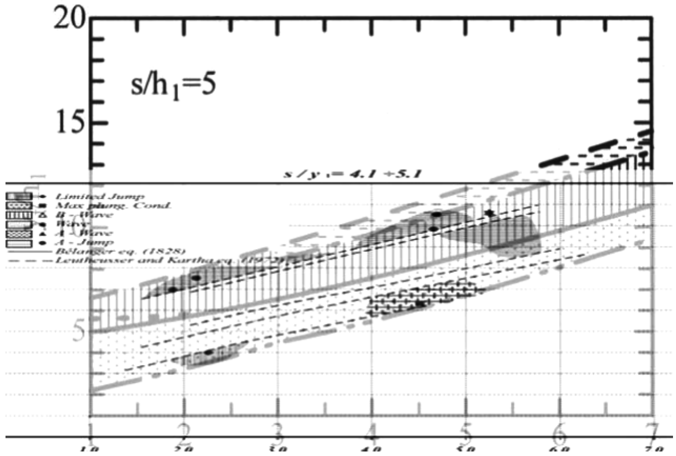

Figure 19a Overlapping of the flow charts of Figs 11 and 18(d).

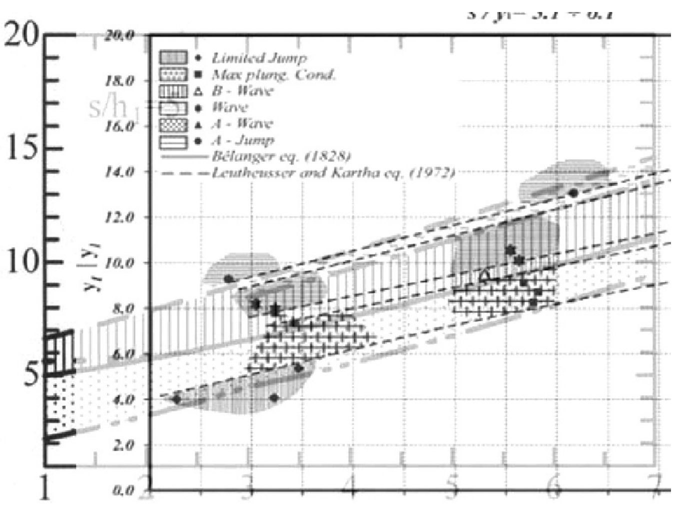

Figure 19b Overlapping of the flow charts of Figs 12 and 18(d).

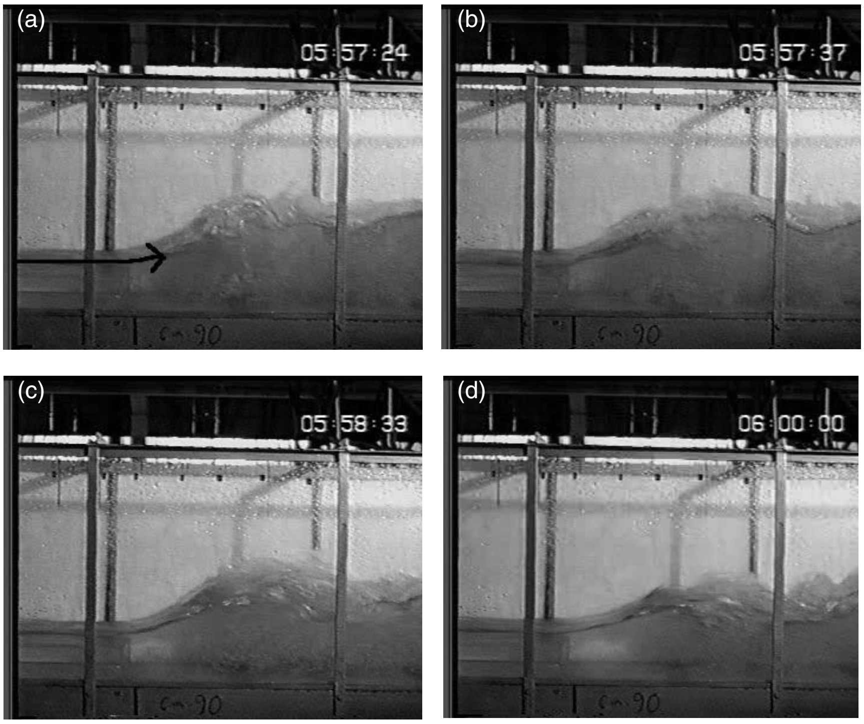

Figure 20 Typical wave jumps.

with, in addition, the intermediate flow types, characterized by oscillating phenomena:

(4) Oscillations between A-jump and Wave jump (the short legend in the chart is *A-Wave*);
(5) Oscillations between B jump and Wave jump (the short legend in the chart is *B-Wave*).

The Authors think that the difference between maximum plunging conditions with lowering level and with rising level is of a certain importance. However, as shown in Fig. 18(d) of the Discussers, the difference between the two flow conditions are evident only with an upstream Froude number F_1 less than 2, which was not investigated by the authors (Mossa *et al*., 2003). Altogether Fig. 19(a,b) shows an appreciable overlapping of the flow charts of the Discussers (Fig. 18d) and of the writers (Figs 11 and 12, respectively).

In fact, the previous figures show a surprisingly fair agreement, considering that the Authors' charts of Figs 11 and 12 present all the experimental tests with $s/y_1 = 4.1$–5.1 and $s/y_1 = 5.1$–6.1, respectively, while the Discussers' chart is valid only for $s/y_1 = 5$ (i.e. for the extreme value of s/y_1 of Figs 11 and 12; for this reason the comparison of both Figs 11–18d and Figs 12–18d is shown). Figure 19(a,b) shows that the Authors' experimental points are in the correct jump regions proposed by the Discusser, with the exception of very few points (for the reason explained above). Furthermore, Figs 7 and 8 show also a fair agreement between the experimental results of the Authors and the regime charts of Moore and Morgan (1959).

The problem of the three-dimensional flow effects is considered to be fundamental by the Authors, who agree with the Discussers on the importance of further experimental investigations. For example, Fig. 20(a–d) shows that in the case analysed by the Authors (and also by Moore and Morgan, 1959), the inflow height is almost equal along the whole final part of the step (in Fig. 20a the drop and the flow pattern have been highlighted). This situation is different from that of the Discussers, as shown by their photos.

Moore and Morgan (1959) used a channel width equal to 33 cm, Rajaratnam and Ortiz (1977) used a channel width equal to 41 cm, Kawagoshi and Hager (1990) carried out experiments in a channel width equal to 50 cm, while Hager and Bretz (1986) used a channel width equal to 50 cm. Yet the Authors agree with the Discussers on the importance of the channel width regarding possible 3D flow effects, especially in very large channels.

Even if the 3D effects of flows passing over drops depend essentially on the aspect ratio B/s, where B is the channel width and s the step height, the importance of the channel width is particularly evident also for flows below abrupt expansions (mainly studied in literature; see, e.g. Noseda, 1964; Ohtsu *et al.*, 1999). As written, also in the aforementioned cases, the 3D effects are particularly evident especially in very large channels. Furthermore, the past experience with abrupt expansion (Noseda, 1964; Ohtsu *et al.*, 1999) or with abrupt expansion and drop (Ferreri and Nasello, 2002) provides valuable insight on 3D effects of flows downstream abrupt drops.

On this point, Noseda (1964) presented an interesting and worthwhile study, perhaps not as well known as it deserves. Noseda carried out his experiments in a 9.40 m long channel with different widths, ranging between 0.90 and 2.70 m. Noseda observed that "for some configurations a peculiar cyclic phenomenon was observed, where the position of the hydraulic jump and the characteristics of the downstream subcritical current

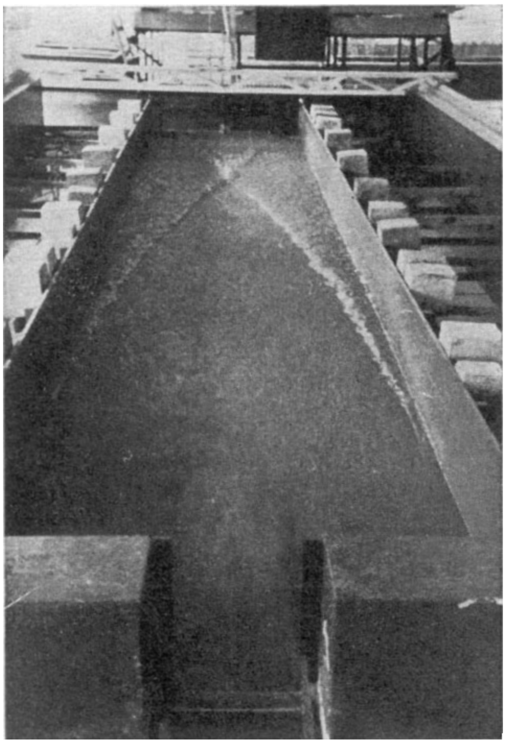

Figure 21a Symmetrical flow condition (by Noseda, 1964).

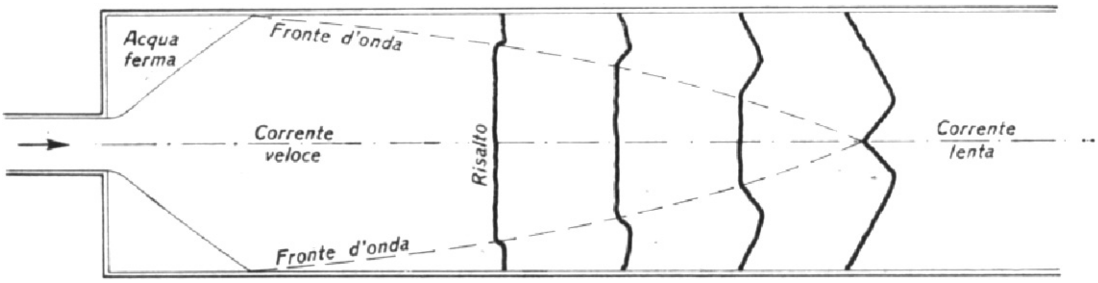

Figure 21b Sketch of the symmetrical flow condition (by Noseda, 1964).

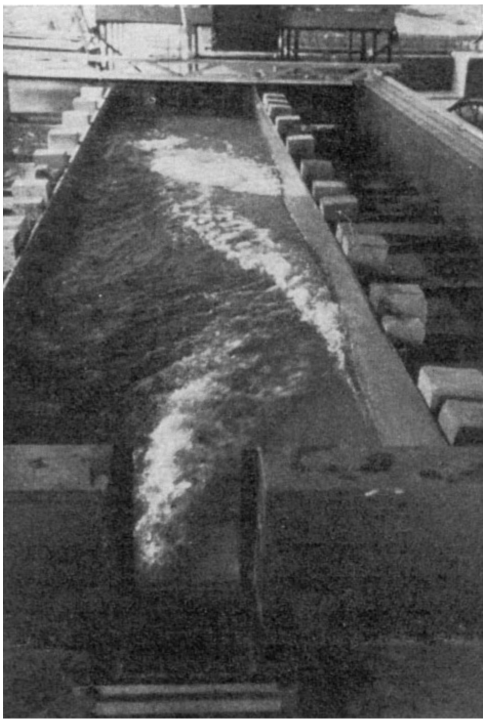

Figure 22a Asymmetrical flow condition (by Noseda, 1964).

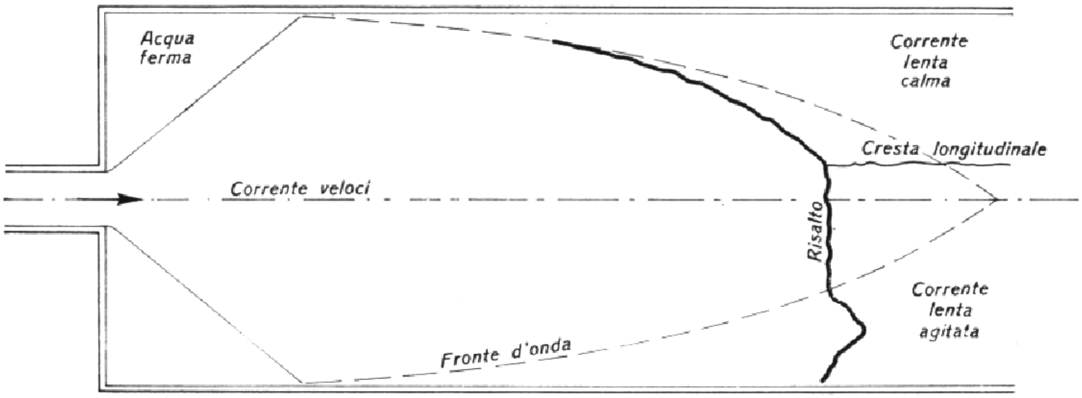

Figure 22b Sketch of the asymmetrical flow condition (by Noseda, 1964).

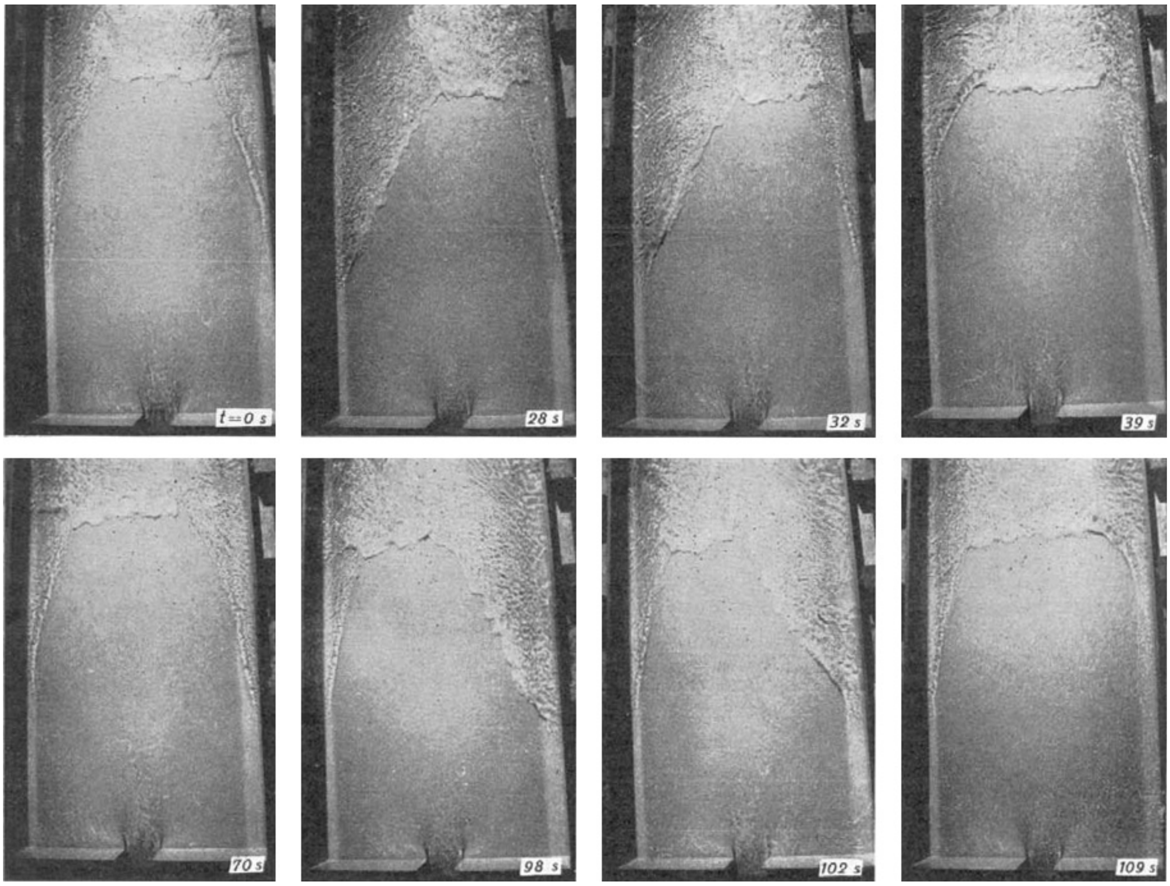

Figure 23a Cyclic flow in the case of asymmetrical flow condition with time expressed in seconds (by Noseda, 1964).

are subjected to very clear periodic variations". Figure 21(a,b) shows the abrupt expansion and transition from supercritical to subcritical flow and the typical formation of the hydraulic jump, where *acqua ferma* = stagnant water (i.e. the whirling pool zone, see also Ferreri and Nasello, 2002), *corrente veloce* = supercritical current, *corrente lenta* = subcritical current, *risalto* = jump, *fronte d'onda* = wave front. The figures show also the lines which, on the average, divide the supercritical flow from the subcritical flow.

Noseda observed that, by increasing the downstream flow depth, "instability conditions of the hydraulic jump, with abrupt variations of the fluid flow aforementioned were observed". For channel widths between 0.90 and 1.90 m, he observed a "breaking" of the hydraulic jump, described as the deviation of the subcritical flow towards the stagnant water region of Fig. 21(b). This phenomenon was present on only one of the channel's lateral walls at a time, without distinction, and is shown in Fig. 22(a,b), where *cresta longitudinale* = longitudinal crest, *corrente lenta calma* = still subcritical flow, and *corrente lenta agitata* = rough subcritical flow. The consequent flow asymmetry was constant with time. For channel widths between 1.90 and 2.40 m (i.e. between 6.3 and 8 times the widths of the inflow supercritical current), the flow behaviour was completely different. Noseda observed the flow type shown in Fig. 21(b) only for low downstream tailwater depths. When the downstream gate position was raised in order to increase the flow depth, the subcritical current and the line dividing supercritical flow from subcritical flow were asymmetrical, as shown in Fig. 22(b).

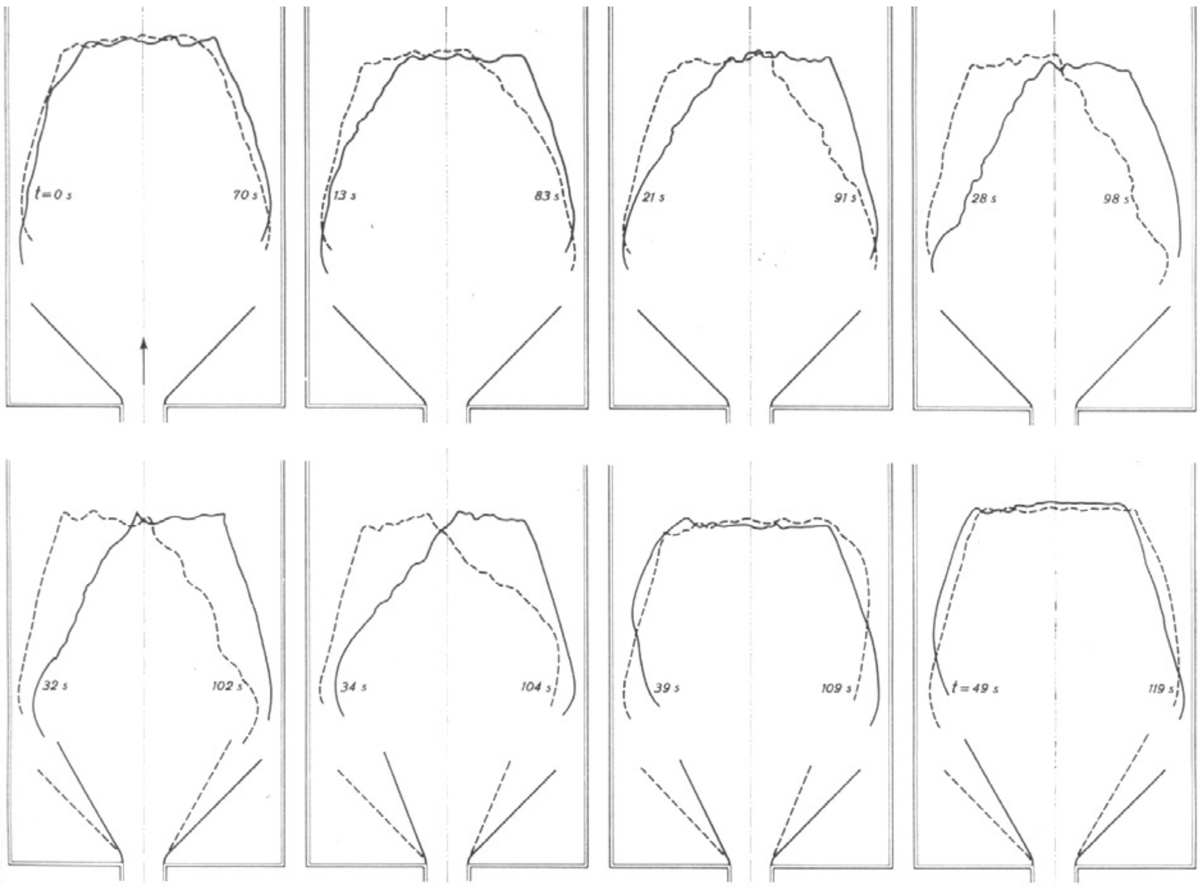

Figure 23b Sketch of the cyclic flow in the case of asymmetrical flow condition with time expressed in seconds (by Noseda, 1964).

Furthermore, for some runs characterized by the aforementioned asymmetry, Noseda observed oscillating variations of the line dividing the supercritical flow from the subcritical flow. Figure 23(a,b) shows this cyclic phenomenon with time.

The study of Noseda (1964), briefly described above, shows the macroscopic flow behaviours because of 3D effects due to the channel width, highlighting their importance in very large channels. Even if the above-mentioned study of Noseda (1964) and that of Ohtsu *et al.* (1999) emphasize the macroscopic 3D effects due to abrupt expansions of the channel, it is important to underline that 3D effects of three dimensional flows passing over an abrupt drop are mainly caused by the drop itself. In this case, the formation process of 3D effects is quite different, but equally macroscopic in very large channels. For this reason, further studies of 3D effects of jumps with abrupt drops in very large channels are definitely necessary, aimed at a better understanding of the flow behaviour, also from a quantitative point of view.

In conclusion, the Authors are in agreement with the Discussers. They think that it is essential to know the channel width effects on the flow characteristics quantitatively, and to develop further cooperation and experimental research, including utilizing new, large-sized facilities. It is fundamental to gain new insights into three-dimensional flow effects in large channels, acknowledging that past studies may provide additional relevant information.

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