Flow choking in an expanding bucket

By W. H. Hager* and S. K. Mazumder**

The authors review the literature on flow choking in different channel geometries. Then, the mechanism of the choking process is described by a typical example: for a channel with an adversely sloping bottom and linearly diverging boundaries. The choking is shown to occur progressively, involving a number of well defined stages of flow.

Flow choking in different channel geometries

Choking of flow is associated with supercritical open channel flow. According to Henderson[1], a choke corresponds to the limit condition when both sub- or supercritical flow may occur downstream of a local bed elevation. Henderson's discussion covers the concept of one-dimensional (1D) flow, and situations such as local bed elevations and local width constrictions. Other situations are local variations of discharge or bed roughness.

Choking characteristics may be important to consider when designing a channel for supercritical flow, as this flow pattern may break down and considerably modify the flow features near a hydraulic jump. Taking as an example a ski jump, to which normally only supercritical flow is associated: when the approach flow is too weak, the supercritical flow may not persist right up to the take-off section. The latter then acts as a control section, analogous to a weir, and the approach flow is subcritical with a hydraulic jump slightly upstream from the bucket. If this feature is overlooked, and no account is taken of the falling jet (as well as of the trajectory ejected far away from the ski jump), dangerous scour downstream of the bucket may occur for small discharges[2].

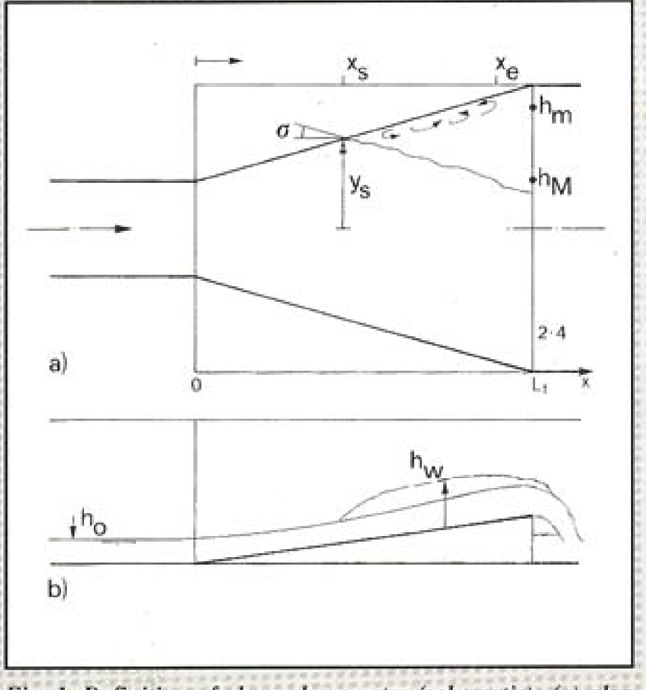

Fig. 1. Definition of channel geometry (schematic): (a) plan view; and, (b) side view.

Other examples where submergence of flow may occur instead of supercritical flow are described by Kozeny[3] in relation to a local bed jump. Kozeny points to the instability of the flow pattern: a hydraulic jump may be washed out by simply increasing the discharge, but may be re-established by decreasing the flow by only a small amount. Abecasis and Quintela[4] found a hysteresis effect on local bed humps. A large number of experiments relating to baffle sills were presented by Tamura[5] and various features of choking flow were described, yet without a generalized result. Karki[6] provided further details for transitional flow at sills.

Allen[7] considered choking at a bottom hump and a domain of flow close to critical flow where steady flow is impossible. Hager and co-authors[8] investigated choking at aerated sills and found that the limit sill height s/h_0 increases with the approach Froude number F_0. Also, the mechanism of flow breakdown was mentioned and documented by photographs.

Further 1D flow models for choking were presented by Austria[9] and Lawrence[10]. The effect of sill geometry on the choking flow depth was recently analysed by Kansoh[11].

Although similar in terms of flow features, but different from a 2D point of view, choking in a contracted channel has been analysed much less. A 1D approach by Sturm[12] was extended in the discussion by Hager and Bretz. An alternative approach was presented by Heggen[13], who investigated the limiting contraction angle in relation to the approach Froude number and the choking of the flow.

The purpose of this article is to describe the choking process for a somewhat more complex channel geometry, consisting of an adversely sloping bottom and linearly diverging boundaries. It is clearly shown that choking occurs progressively and cannot be described by a 1D approach.

Description of flow

The channel in which the experiments were conducted was rectangular in cross-section and had a horizontal PVC bottom. The approach portion was 0.5 m wide and the channel began to widen linearly at location $x = 0$. The angle of divergence was 11.8°, such that there was a transition length $L_t = 2.4$ m to the 1.5 m-wide tailwater channel.

A 3.33° adversely sloping wedge-type element was positioned in the transition domain, so that the channel in the transition had an increasing width and bed level at the same time (Fig. 1). The transition resembled an expanding bucket, as there was an abrupt drop at $x = 2.4$ m to the original channel bottom.

For discharges above the limit discharge Q_{L1} (in the present case $Q_{L1} = 72$ l/s) the flow was perfectly symmetrical; no separation of flow occurred and the flow was supercritical everywhere (Fig. 2a). A slight separation along the side walls was caused by the abrupt change in flow direction at the expansion section. At $Q = Q_{L1}$ separation of flow occurred on either of the two sides, starting at the drop section and extending along the side wall upstream (Fig. 3a). Fig. 2b refers to $Q = 68$ l/s and the asymmetry of the flow to the right can clearly be seen. An oblique hydraulic jump extended over the last third of the channel portion.

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Fig. 4a is a photograph of this flow configuration. Note the incipient separation at the left channel side, whereas the separation has fully developed at the right channel side. The profile at the drop section rises strongly from the centre portion (undisturbed flow) to the maximum of a standing wave h_M; it then decreases almost linearly to the minimum disturbed flow depth h_m at the right-hand side wall.

A second characteristic flow pattern was reached when the two cross-waves met at the drop section (Fig. 3b). Both Fig. 2c and Fig. 4b still indicate considerable asymmetry of flow. At $Q = Q_{L2} = 64$ l/s, the two fronts just met, whereas at a slightly smaller discharge of $Q = Q_{L3} = 62$ l/s, the height of the flow depth $h = h_c$ at the crest section was at a maximum. The flow in the centre channel portion was still supercritical, however (Fig. 3b).

Once the two cross-waves had met in the central channel portion, a further decrease of discharge led to a rapid upstream movement of the cross-wave fronts, as schematically shown in Fig. 3c. Figs. 2d and 4c relate to $Q = 61$ l/s and still indicate supercritical axial flow beyond the meeting point of the fronts. Fig. 2e shows what happened for $Q = 60$ l/s, an only slightly reduced discharge. This pattern corresponded to the limit of supercritical flow. Decreasing the discharge to $Q = Q_{L4} = 59$ l/s led to the breakdown of the supercritical flow structure. Both wedges of disturbed flow then moved upstream to the approach channel, and the oblique fronts broke to form one single front across the channel (Figs. 2f and 3d). Thus, a usual hydraulic jump was established, and the flow beyond the front was subcritical. The flow was now controlled by the drop section and the expanding domain was submerged (Fig. 4d). The choking of flow was thus not related to a unique discharge, but to various distinct patterns of flow, as is also shown in Fig. 5.

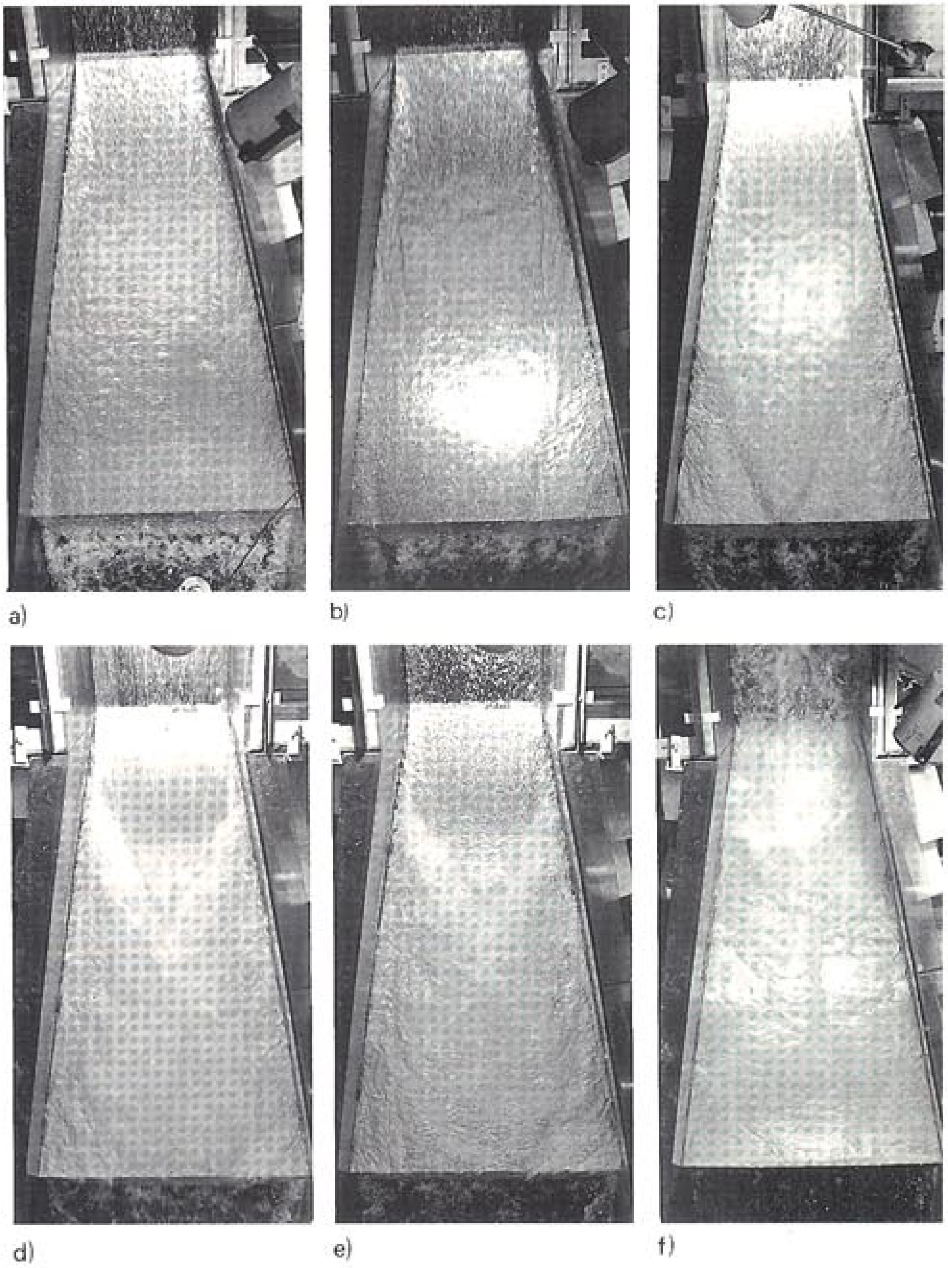

Fig. 2. Plan view at various stages of flow choking.

Observations

The mechanism of choking flow is quite difficult to determine, as two- and three-dimensional flow features dominate both primary and secondary currents. Also, the configurations where choking may occur are widespread. The present geometry may serve as an example from which some additional information may be taken.

During the observations, typical measurements were recorded. These included the position of separation x_s, its extent y_s at the drop section, the position of the downstream separation end x_e, the minimum and maximum flow depths h_m and h_M at the drop section (Fig. 1), and the crest coordinates (x_c, h_c) for the meeting point of the cross-waves (Fig. 3c).

It was found that the angle σ between the cross-wave and the channel axis remained constant at $\sigma = 25° \pm 2°$ for all discharges $61 \leq Q \leq 71$ l/s. The approach Froude number to the cross-wave was thus almost constant at various stages of flow. Also, the position of the separation end x_e was practically stationary, and was located at $x/h_0 \equiv 4$ upstream from the drop section, where h_0 is the approach flow depth. Both the minimum and maximum flow depths at the drop

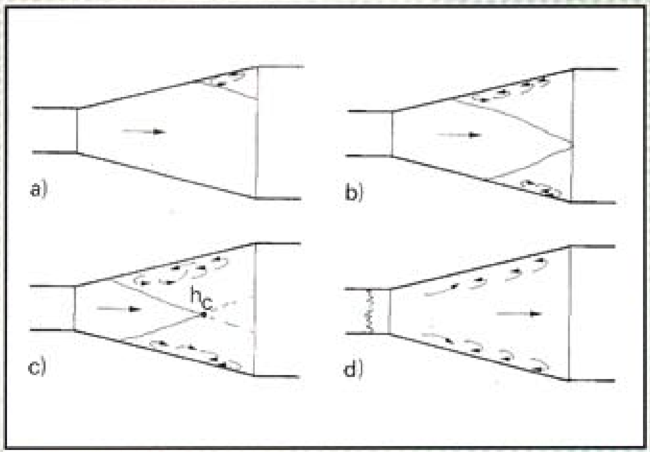

Fig.3. Schematic flow patterns at various stages of choking in the adversely sloping, gradually expanding channel.

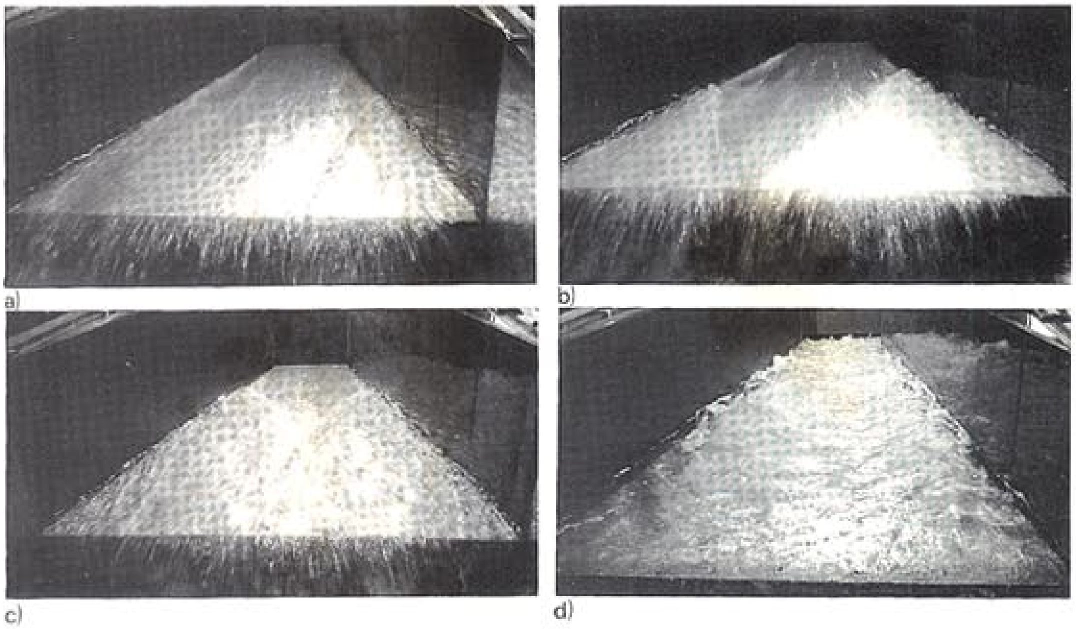

Fig. 4. Choking of flow, front views.

section were also constant, with $h_m/h_0 = 0.5$ and $h_M/h_0 = 1$ up to the point where flow of type 2 started (Fig. 3b). The maximum height in the separation zone increased with decreasing discharge up to the point where the breakdown occurred (Fig. 3c), from $h_w/h_0 = 1$ to $h_w/h_0 = 1.5$. The same was true for the maximum crest flow depth which increased from $h_c/h_0 = 2$ (Fig. 3b) to $h_c/h_0 = 3$ (Fig. 3c).

Conclusions

Based on these experiments in a linearly expanding and adversely sloping rectangular channel, the features of flow choking can be seen to be much more complex than commonly acknowledged in the hydraulic approach. Four stages of choking have been introduced and described by photographs. Some preliminary observations regarding the main dimensions of flow have also been given. □

Acknowledgements

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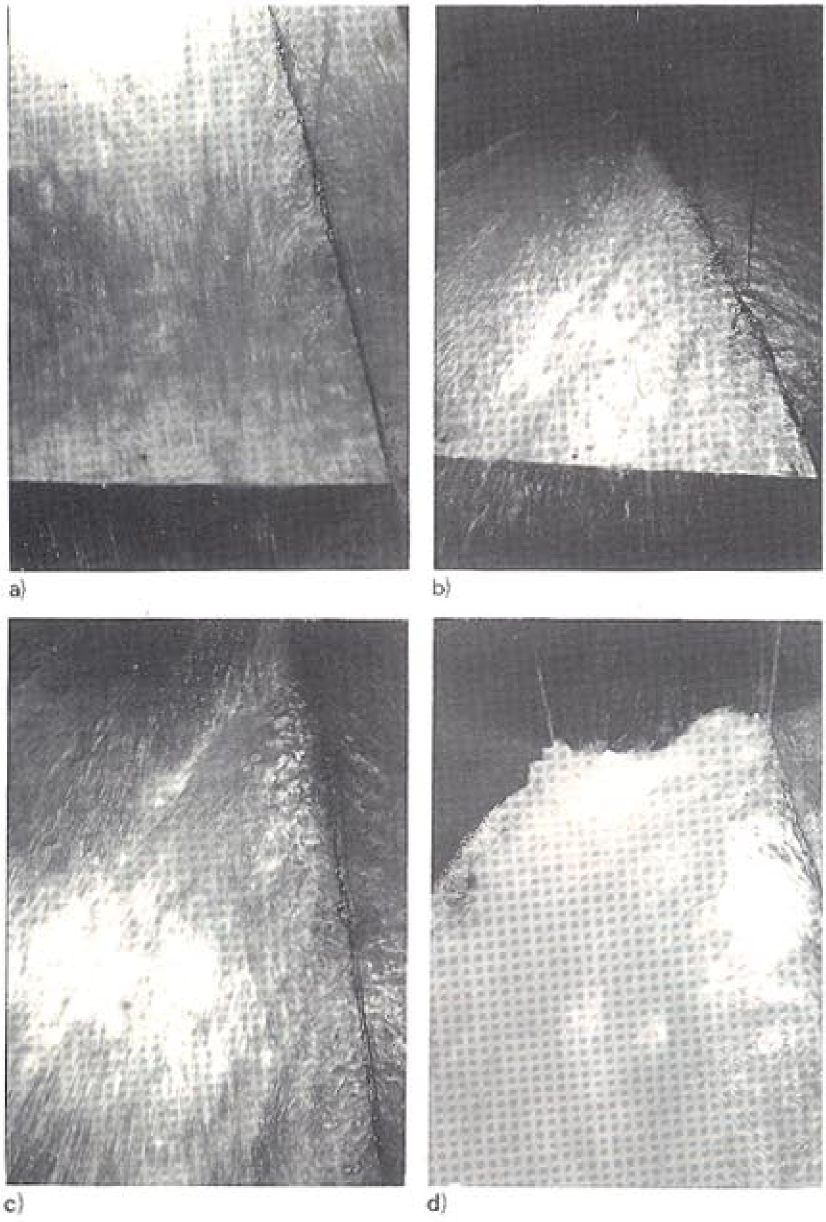

Fig. 5. Choking of flow, details: (a) incipient choking, (b) established choking, (c) symmetrical choking and (d) definite choking.