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Comparison between Various Chute Expansions

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Various types of chute expansion geometries are compared both with the abrupt and the Rouse reversed wall geometries. The first part refers to the transition domain with linearly expanding side walls and additional elements such as the adversely sloping bed or bed deflectors. The second part involves tailwater shock reduction elements with cusp or wedge type local contractions. The results are based on an experimental study combined with a novel representation of flow, by which an immediate performance of chute flow may be achieved. Although most of the elements were tested only in a preliminary approach, the conclusions are such as to favour the standard transition structure. Design guidelines are given at the end of the paper.

INTRODUCTION

Supercritical open channel flow is prone to disturbances. Whenever a flow with parallel streamlines is disturbed, so-called shock waves occur. These waves are stationary for steady flow and may easily be seen in open channel flow due to their free surface pattern. The design of channels with supercritical flow (*ie*, chutes) aims at suppressing or at least reducing the shock waves in order to :

(a) make the flow uniform,

(b) avoid flow concentrations,

(c) safe freeboard,

(d) inhibit spray formation, and

(e) suppress local hydraulic jump formation.

Basic references on shock waves related to hydraulic structures are provided by von Karman[1], Ippen[2], Ippen und Knapp[3], Chow[4] and Hager[5].

Disturbances may include changes of direction, lateral flow, structures in the chute such as baffles, piers or vanes, as well as contractions and expansions. The latter have received only scarce attention. A key paper was presented by Rouse, *et al*[6]. Their approach is dealt with in detail below.

Other sources of interest are the numerical approaches of Sherenkov[7] for the abrupt as well as Herbich and Walsh[8] and Dakshinamoorthy[9] for the gradual expansion using the method of characteristics. Except for Engelund[10], and Molino and Taglialatela[11], no experimental approach was conducted yet. A more detailed review is given by Hager and Mazumder[12]. A state-of-the art on supercritical flows in general is provided by Jayaraman and Sethuraman[13].

Chute expansions occur typically at bottom slope changes from steep to flatter or at chute junctions. Often, expanding flow may develop downstream of spillways controlled by gates under partial operations. Up to the end of piers, the flow is in a prismatic channel, which expands then and gives rise to disturbances. The standing wave pattern is referred to shock waves or just shocks, and different questions arise, such as:

- What is the pattern of shocks,
- What is the height of maximum wave,
- What height of side wall is needed to have no overtopping, and
- What are the means to reduce the shocks.

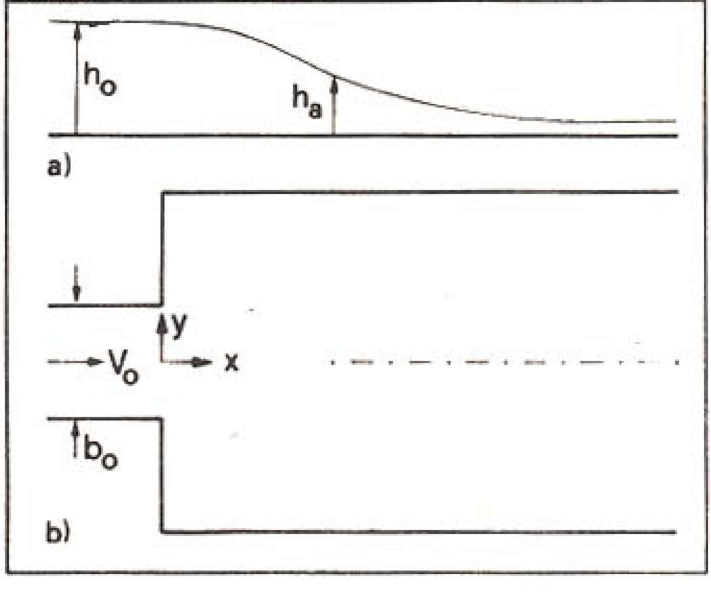
Other questions may relate to the effect of bottom-slope, boundary roughness or channel geometry.

The present paper aims at answering some of the hydraulic questions, which deal mainly with the near-field of the expansion. This is due to the limited length of physical model. Also, the effect of slope and roughness was not studied, and the cross-section was rectangular throughout with an expansion ratio of three. Based on two previous papers [12,14], answers to the following questions will be given :

- What is the optimum transition shape, and
- How can the chute expansion be designed.

After a discussion of previous results, the experimental

FIGURE 1
DEFINITION FOR ABRUPT EXPANSION



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facilities are described, and the various transition geometries are detailed. Then, a number of transition structures are compared, and conclusions are given that respond to the above two questions.

ABRUPT EXPANSION

The abrupt expansion in a horizontal channel corresponds to the simplest expansion geometry. It was analysed in detail by Hager and Mazumder[12] as it is the basis of all other expanding channels. Fig 1 defines the geometry of flow with h, flow depth; b, channel width and V, depth-integrated local velocity; index <<o>> refers to the approach channel, <<a>> to the channel axis, <<w>> to the wall; and x and y are the streamwise and transverse coordinates.

Based on a number of tests in which the 2D-flow surface and velocity field was measured, the axis and wall profiles are found to be significant. Further analysis indicates that similarity occurs provided the coordinate x is transformed to $X = x/(b_o F_o)$. Then, the axial and wall surface profiles may be expressed by the two parameter set $Y = f(X)$ with $Y = h/h_o$ as relative flow depth. The Froude similarity was further found adequate for approach flow depths larger than 48mm and for $F_o \leq 10$. For h_o=24mm, a definite scale effect occurred which was attributed to viscosity. Whereas there is no difference between otherwise equal configurations for h_o=48mm and h_o=96mm in the near field of expansion, viscosity has a definite effect in the far-field of expansion,say $X > 1.5$ to 2. In the present paper, no data is presented which is governed by significant scale effects. Also, all experiments refer to the expansion ratio $\beta = 3$, except tailwater shock control.

For design, both the axial and especially the wall profiles are to be considered. The latter, *ie*, the free surface profile along the wall rises from a value close to $Y_{wm} = 0.1$ at X=0.33 to the maximum $Y_{wM} = 0.81$ at location X =1.33. Indices <<m>> and <<M>> refer to minimum and maximum values, respectively. Analogous results occur for expansion ratios other than $\beta = b_2/b_o = 3$ The axial and wall surface profiles are used in the following to compare the performance of various expansion geometries. The transverse profiles may be shown to be also fully similar.

No similarity was found for the velocity field $\mu = V/V_0$ as a function of X. Depending on both the Froude number F_o and the absolute flow depth h_0, different curves occur. Also, the approach Reynolds number $R_o = V_o h_o / \nu$ with ν as kinematic viscosity does not correspond to a scaling parameter.

ROUSE REVERSED EXPANSION

In order to smoothen the flow in the tailwater chute, Rouse, *et al*[6] introduced the so-called reversed wall expansion. It is a transition structure composed of the so-called modified portion up to the point of tangency and the reversed portion of length L_r. The lengths of modified curve L_p and total expansion $L_t = L_p + L_r$ are[14]

$$\frac{L_p}{b_o F_D} = 0.7\beta \qquad (1)$$

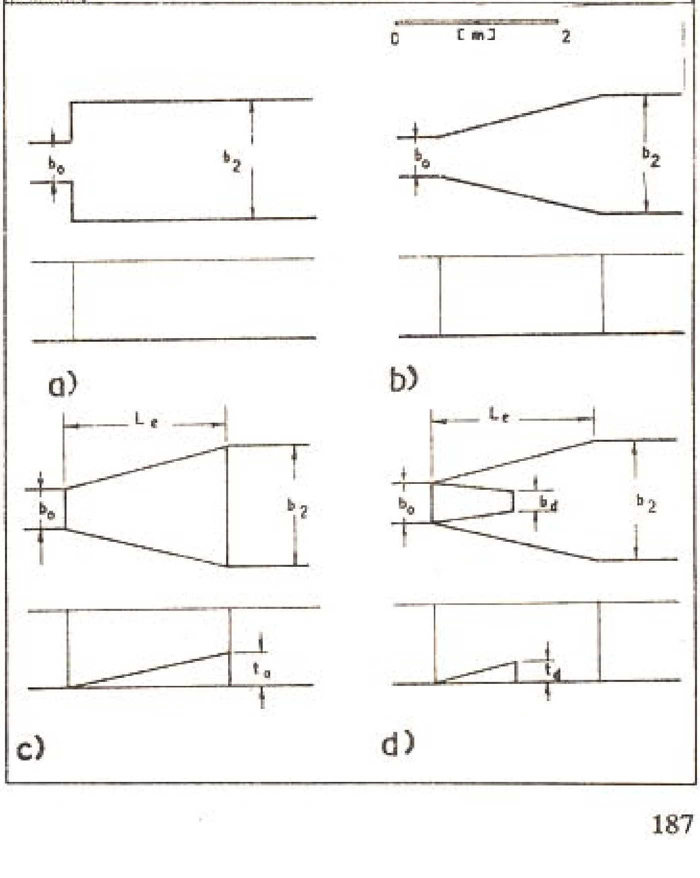
$$\frac{L_t}{b_o F_D} = 1 + 3.25\,(\beta - 1). \qquad (2)$$

The wall geometries of the reversed wall profile may be approximated by curves from the design plot due to Rouse, *et al*[6]. It depends significantly on the design Froude number F_D. The wall profile up to the point of tangency is given by equation (3) below, indicating that the flow with the maximum approach Froude number $F_o = V_o / (gh_o)^{1/2}$ corresponds to the design Froude number F_D.

The design of Rouse, *et al*[6] is based on the cancellation of negative shocks generated from the negatively curved wall geometry by means of positive shocks generated by the positively, *ie*, the reversed curved wall beyond the point of tangency. Allthough this design is efficient in hydraulic terms, it is very costly due to its complicated shape on a considerable length. Thus, experiments were run where the approach Froude number F_o was larger than the design Froude number F_D to check the flow pattern.

When comparing the axial and the wall surface profiles in the abrupt and reversed expansions, the latter follows practically the profiles as generated in an abrupt expansion if $F_o/F_D \geq 3$. For $F_o/F_D = 1$, as recommended by Rouse, *et al*[6], the transition surface is smooth. For F_o / F_D=2 to 2.5, some standing waves occur which may be acceptable, however, as they are small. Note that, with F_o / F_D=2,say, the length of transition may be reduced by 50%. Take, as an example, F_o=5, b_o=2m and $\beta = 3$. According to Rouse, *et al*[6], the transition length L_t=75 m, whereas it may be shortened to 37.5m without substantial loss of performance. Given that the shortening yields still long a transition, further means

FIGURE 2
SCHEMATIC EXPANSION GEOMETRIES IN PLAN VIEW (ABOVE) AND SIDE VIEW (BELOW). (A) ABRUPT, (B) HORIZONTAL GRADUAL, (C) ADVERSELY SLOPING GRADUAL, AND (D) BED DEFLECTOR EXPANSION.



of reducing the length of expansion were sought. The current series of experiments were planned to overcome these shortcomings in the Rouse design and to check whether there are some alternatives. Several expansion geometries are compared with the Rouse reversed curve. As the supercritical expansion is suited to experimental analysis, a model was used where an improved expansion was tested.

EXPERIMENTS

Experiments were conducted in a 1.50 m wide rectangular horizontal channel, with an approach channel 0.50 m wide. The walls were of glass and black PVC, and thus smooth. The inlet was fitted to high velocity flow and issued a compact and smooth jet of height h_o either 48 or 96 mm. Discharges up to 270 l/s and maximum velocities of 6.50 m/s were obtained. The flow depths were measured with a precision point gauge extended by an electric contact probe. For further details on the experimental setup refer to Hager and Mazumder[12].

Apart from the abrupt, the modified and the reversed wall curve expansions, other geometries were tested involving either :

- a gradual linear expansion,
- an adversely sloping bottom,
- a bed – deflector or
- combinations of it.

Further, as the main source of shock was located at the end of transition, a tailwater shock control was tested separately where various parameters were varied. The present study has an exploratory character as means were sought to improve the reversed curve expansion. Therefore, several basic parameters were kept constant such as the expansion ratio $\beta = 3$, the approach flow depth either h_o=48 or 96 mm and the geometric parameters. With one type expansion, the improvement of flow could be compared to the abrupt and the reversed expansion, and dropped if no improvement was found, without recourse to other geometries.

Fig 2 shows the types of expansion geometries analysed, namely the abrupt, the horizontal gradual and the adversely sloping gradual expansions as well as the bed deflectors. The rate of expansion was 1:4.8 throughout; *ie*, the total expansion angle in plan view was 2x11.8°.

The tailwater shock control was always based on the Rouse modified curve designed for F_D=1 in an initial expansion with $\beta = 3$ and final expansion with $\beta_s = 2.25$ and 2.50. In all cases, the channel was horizontal without additional elements such as bed deflectors or vanes. A preliminary test (Run 32) involving a bed deflector in addition revealed poor tailwater flow.

Horizontal, Gradual Expansion

Three experiments were performed in which the approach channel expanded linearly from 0.50 m width to 1.50 m tailwater width within 2.40 m. The free surface and the velocity field were measured at various intervals Δ x.

According to Hager and Mazumder[12], the axial and wall surface profiles yield a good overall representation of flow.

FIGURE 3
TAILWATER SHOCK CONTROL BASED ON MODIFIED EXPANSION (SCHEMATIC). (A) CUSP-TYPE ELEMENT, (B) WEDGE-TYPE ELEMENT, (C) ROUNDED WEDGE AND (D) LINEAR WEDGE WITH BED – DEFLECTOR.

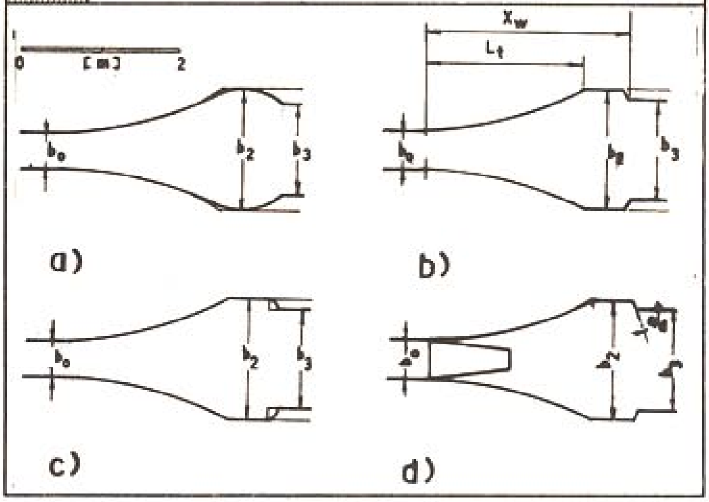
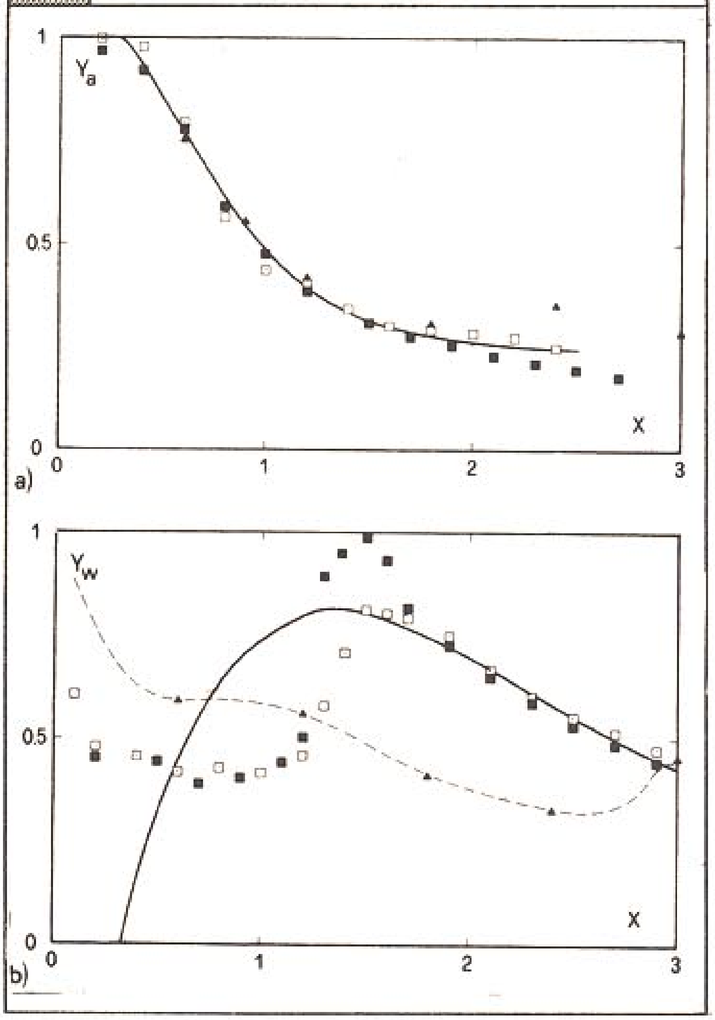


Fig 4 shows $Y_a = h_a/h_o$ and $Y_w = h_w/h_o$ as a function of $X = x/(b_o F_o)$. Herein, h flow depth, Y flow depth relative to the approach flow depth h_o; x, streamwise coordinate; b_o, approach width; and $F_o = V_o/(gh_o)^{1/2}$ is approach Froude number. It is seen from Fig 4(a) that all data $Y_a(X)$ pertaining to the axial surface profile may be plotted by a single curve

FIGURE 4
(A) AXIAL FLOW PROFILE Y_A (X) AND (B) WALL FLOW PROFILE Y_W(X) FOR H_O=48MM AND F_O = (□) 4; h_o = 96MM AND F_O (▲) 2 AND (■) 4. (—) ABRUPT EXPANSION, (- - -) AVERAGE CURVE.



as obtained for the abrupt channel expansion. The only exception occurs for F_o=2 and $X > 2$, where the first shock crosses the axis of channel. The difference between the data for h_o= 48 mm and 96 mm($F_0 = 4$) for $X > 2$ must be attributed to viscosity.

The wall surface profile Y_w (X) shows different trends for variable F_o. Whereas the profile for $F_o = 2$ is steadily decreasing up to X =2.5, the profile for F_o reaches a minimum Y_{wm}=0.4 at X =0.8. Further downstream, the first shock occurs at the wall (X =1.5) with maximum height Y_{wM} =0.81 for h_o=48 mm, and Y_{wM} = 0.99 for h_o = 96 mm. For large $X > 1.8$, the wall profiles follow the profiles obtained for the abrupt expansion, too.

The flow in a gradual expansion thus follows both along the axis and for large X along the wall the profiles of abrupt expansion, provided F_o is sufficiently large. For the abrupt expansion, the location of maximum wall depth is X_M =1.33. If the end of the gradual transition $x_t = L_t$ is larger than $x_M = 1.33 b_o F_o$ a modification of wall profile as compared to the abrupt expansion occurs. If $x_t < x_M$, however, the dead water zone in the expansion corners is practically filled in with wedges, but the flow structures remain essentially as for the abrupt expansion. For $F_o = 2$ as an example, x_M = 1.33 m < x_t = 2.40 m whereas for $F_o = 4$, x_M = 2.66 m> x_t = 2.40 m. For $F_o > F_t$ where $F_t = (1.33 b_o/L_t)^{-1}$ the performance of expansion flow is poorer than in the abrupt expansion, as the wall flow depth is then larger (Fig 4. (b))

FIGURE 5
GRADUAL EXPANSION FOR h_o =48mm, F_o=4. VIEW IN THE DIRECTION OF (A) TAILWATER AND (B), (C) APPROACH CHANNEL.

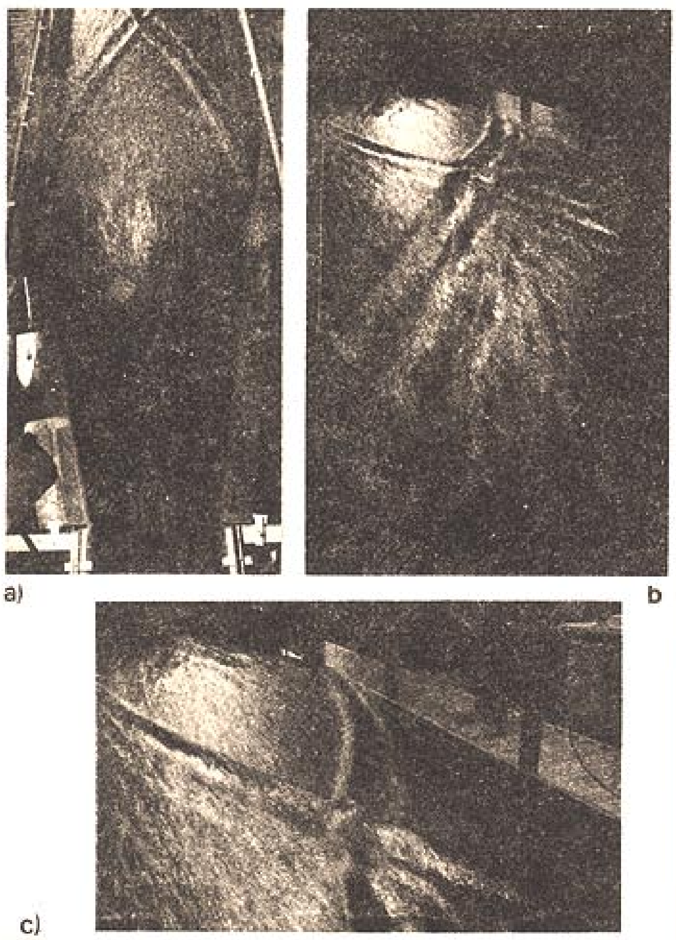


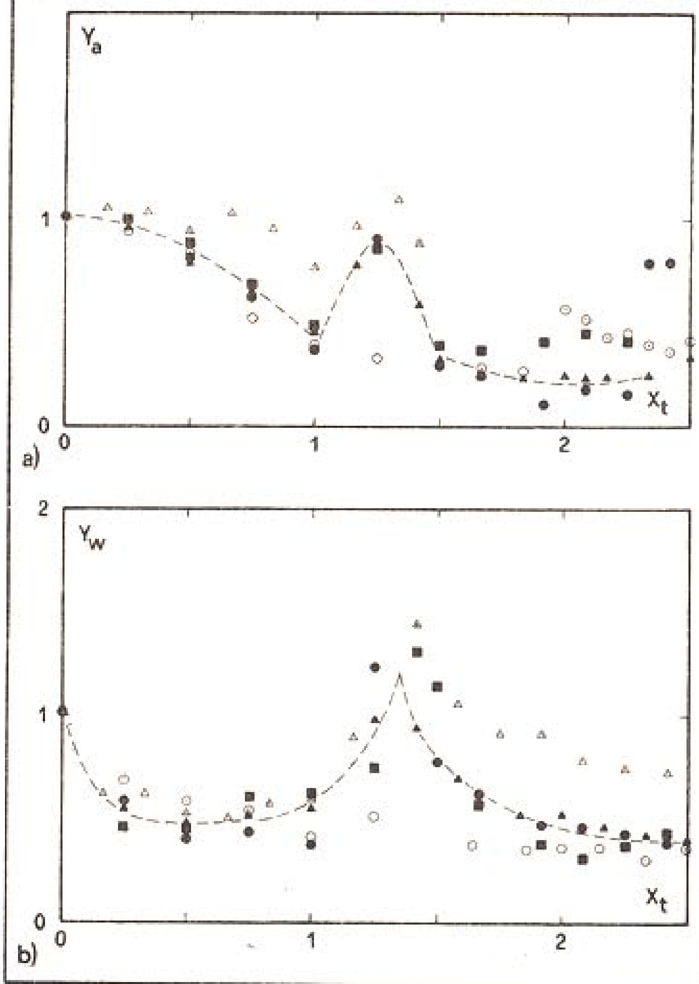
Fig 5 shows photographs of the gradually expanding flow with F_o=4, h_o=48 mm. It is seen that no shocks develop in the expansion domain but that the wall deflection at the expansion end yields a strong primary and a secondary shock, which disturb the tailwater channel considerably. The maximum axial flow depth Y_{aM}=1.06 occurs at x=4.90 m and is larger than the approach flow depth.

For F_o=2, the maximum axial flow depth occurs at x=6.20 m and has a value of even Y_{aM}=1.29. In the abrupt expansion, the corresponding values are 0.73 for $F_o = 4$ and 0.61 for $F_o = 2$. Both values are much reduced and indicate improved flow conditions in the abrupt as compared to the gradual expansion due to better transition from the expansion to the tailwater channel.

Adversely Sloping, Gradual Expansion

The transition length L_t=2.4 m was also used together with three plane adversely sloping elements, of height t_a=70ááand 210 mm (Fig 2 (c)). The adversely sloping element was thought to improve the flow at the transition from expansion and to tailwater channel due to the drop. Fig 6 shows the axial and the wall surface profiles Y_a and Y_w relative to the bottom elevation as a function of X_t=x/L_t. The data for $F_o = 4$ and h_o = 96 mm are shown in full symbols, and reasonable

FIGURE 6
ADVERSELY SLOPING, GRADUAL EXPANSION. (A) AXIAL FLOW PROFILE $Y_A(X_T)$ AND (B) WALL FLOW. PROFILE Y_W (X_T). h_o=96 mm, F_o=4 AND t_A [MM] = (●) 70, (▲) 140, (■) 210. F_O=2 (O) t_A=70 mm; h_o=48 mm, F_O=6, (Δ) t_a - 210 mm



similarity exists. At the end of transition X_t =1, a local minimum occurs, which is followed by a maximum Y_{aM}=0.90 at X_t=1.25. Further downstream an asymptotic surface curve establishes up to the point where the shocks cross the centerline. The data for F_o=2 follow the same trend except for the maximum at X_t=1.25. For F_o=6 a different pattern establishes with essentially constant axial flow depth up to X_t=1.5.

The wall depth profile reveals almost perfect similarity for F_o=4. An absolute maximum of flow depth Y_{wM}=1.3 occurs at X_t=1.33. Further downstream, the wall profile follows the axial profile. For F_o=2, the wall flow depth decreases gradually with X_t, whereas for F_o=6, an even higher maximum occurs than for F_o=4.

As a conclusion adversely sloping bottoms yield no overall flow improvement as compared to the abrupt expansion. The extra cost for the sloping element is not justified, as maximum flow depths higher than the approach flow depth occur. Further, flows in adversely sloping elements are prone to choking, that is subcritical flow may locally establish instead of supercritical flow and submerge the approach channel. This type of flow occurred for h_o=96 mm, F_o=2 and t_a=140 mm as well as for h_o=48 mm, F_o=4 and t_a=210 mm. Further details are described by Hager and Mazumder[15].

Bed Deflectors

A third means to control expansion flow are bed deflectors starting at the expansion section with width equal to the approach width b_o, and extending along the length L_d, with a final height t_d and width b_d=250 mm (Fig 2d). A deflector was thought to expand the flow more to the side zones of the expansion, and reduce concentrations from the center portion. Thus more uniform flow could prevail,at least in the expansion portion. In all experiments, the approach flow depth was h_o=96 mm, and the approach Froude numbers were F_o = 2 and 4.

FIGURE 7
BED DEFLECTOR. (A) AXIAL AND (B) WALL SURFACE PROFILE FOR h_o=96 mm AND F_o=2 (LIGHT SYMBOLS), F_o=4 (DARK SYMBOLS). t_d [MM] = (Δ) 40, (□) 50 AND (o) 60.

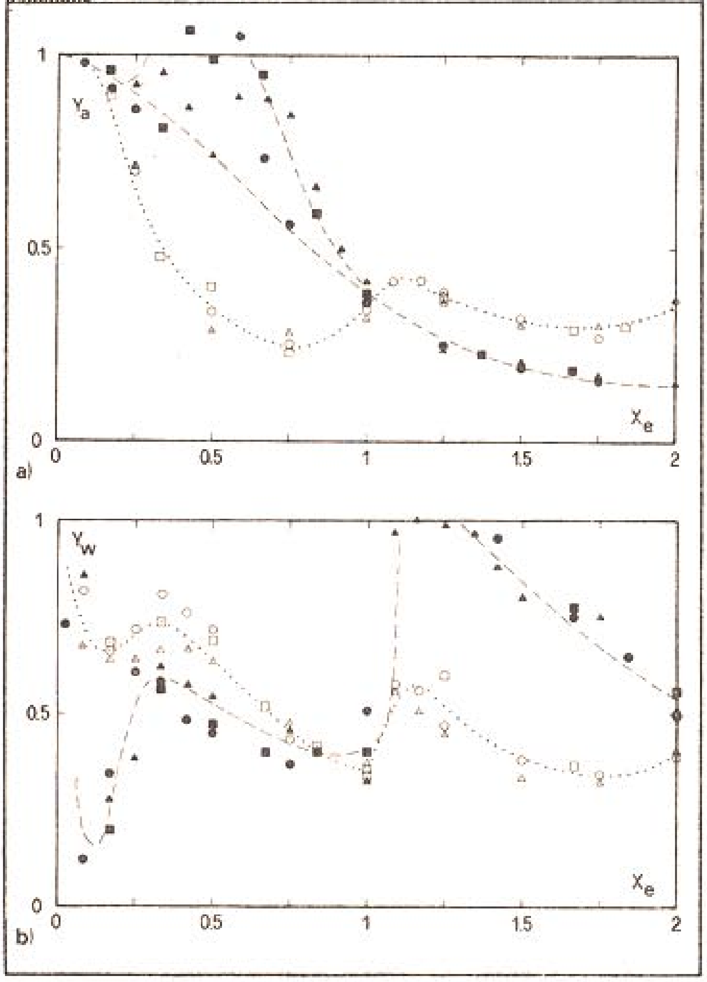
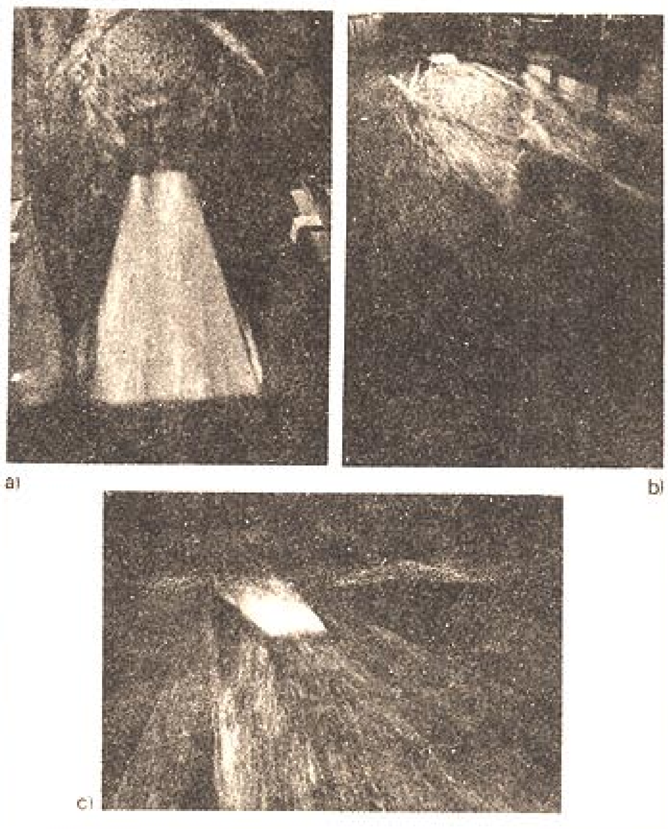


Fig 7 (a) shows the axial free surface profile $Y_a(x_e)$ with $X_e = x/L_e$ and L_e = 2.4 m as length of expansion. It is seen that for various values of L_d and t_d, the data are grouped along average curves for F_o=2 and 4. For F_o=2, a local minimum occurs at X_e≅ 0.75 and a first wave peak is located at X_e≅ 1.15. For X_e> 0.4, the average streamwise flow depth is Y_a≅ 0.35.

Much less uniform axial flow occurs for F_o=4, with a first wave peak at the end of deflector. Depending on the deflector height, those wave heights are up to Y_{aM} = 1.30 for t_d = 60 mm and considerably above the approach flow depth h_o=96 mm, therefore, beyond X_e = 1, all profiles follow a common asymptotic trend.

The wall surface profile has also a general trend depending on F_o alone (Fig 7(b)). An absolute flow minimum occurs close behind the expansion section at X_e≅ 0.15 due to separation, followed by a first maximum at X_e≅ 0.35 due to shock wave reflection at the wall. A second minimum may be

FIGURE 8
BED DEFLECTOR t_d=40MM, F_o=4, h_o=96MM. (A) VIEW FROM APPROACH CHANNEL, (B) AND (C) TAILWATER VIEWS



noted at the end of expansion section $X_e \approx 1$ of height $Y_{wM} \approx 0.40$, followed by the second maximum Y_{wM} at $X_e \approx 1.2$ due to wall deflection at the end of gradual expansion. Whereas the maximum is $Y_{wM} \approx 0.60$ for $F_o = 2$, it becomes $Y_{wM} = 1$ for $t_d = 40$ mm, $Y_{wM} \approx 1.25$ for $t_d = 50$ mm, and $Y_{wM} = 1.42$ for $t_d = 60$ mm and $F_o = 4$. Further downstream, all data collapse on an average curve.

Compared to the abrupt expansion or the Rouse reversed wall curve expansion, deflectors involve much larger surface nonuniformities and thus are not advantageous for transition structures in supercritical flow. Moreover, such elements may dangerously provoke cavitation damage and should not be considered.

Fig 8 shows typical views of bed deflector flow and clearly indicates the aditonal disturbances dueáto the abruptáchang of flow. The deflector is thus ormally unable to deflect he flow sufficienty to theásides and yield a more uniform verall pattern, as may be seen in Fig 8b.

Tailwater Shock Control

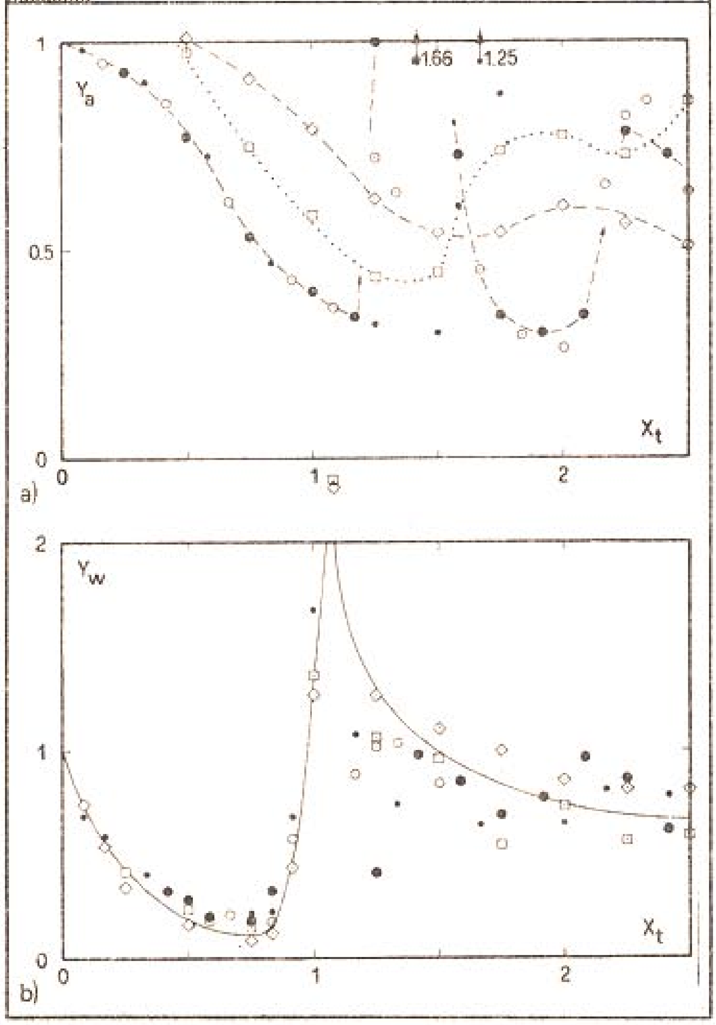
A fourth means to control shocks was investigated, consisting of a so-called modified expansion followed by a short linear contraction. Thus, it was thought, the long reversed Rouse curve portion could be reduced by wave interference, *ie*, the superposition of negative waves on the positive wave pattern resulting from the transition end. The geometry of modified expansion wall[6] $y_b(x)$ is

$$\frac{y_b}{b_o} = \frac{1}{2}\left[1 + \frac{1}{4}\left(\frac{x}{b_o \mathrm{F_D}}\right)^{3/2}\right] \tag{3}$$

Herein, y_b is the boundary coordinate measured from the centerline transversally; x the longitudinal coordinate originating at the expansion section; and $\mathrm{F_D}$ the design Froude number. According to Rouse, *et al*[6], the latter should be set equal to the maximum approach Froude number $\mathrm{F_D}=\mathrm{F_{oM}}$, as discussed previously.

The modified expansion was tested by Mazumder and Hager[14]. They found good performance in the expanding domain but poor characteristics in the tailwater channel due to strong shocks with origin at the transition from expanding to prismatic tailwater channels much in analogy to the gradual expansion (Fig 5). In order to control the tailwater shocks a deflection element of triangular wedge shape was analysed (Fig 3 (b)). Thus, the wall flow depths would possibly be much reduced by wave interference as compared to the modified expansion alone.

FIGURE 9
CUSP TYPE SHOCK CONTROL (A) AXIAL AND (B) WALL FREE SURFACE PROFILE FOR $b_3 / b_o = 2.25$, $x_C=2.70$ m, $\alpha_d=45°$. $F_O=$ (●), 4, (□) 6 AND (◆) 8. (O) $b_3/b_o=2.50$m, $x_w=2.50$, $\alpha_D=75°$. (•) $b_3/b_o = 2.50$, $x_w = 2.50$ m, $\alpha_D = 75°$, $F_o=4$.



The experimental tests involved series with final to approach width $\beta_s = b_3/b_o = 2.25$ and 2.5 as compared to $\beta = b_2/b_o = 3$. The angle of wedge α_D was either 45° or 75° and the location of wedge origin was $x_w = 2.50$ m or 2.70 m. In all experiments the design Froude number of modified wall geometry was $\mathrm{F_D} = 1$, such that the transition length is $L_t = 2.0$ m from Equation (3).

The data in Fig 9 refer to an additional modification of geometry consisting of a cusp shape (Fig 3(a)) in the full expansion to further reduce shocks. The success of such involved geometry, of which the present type was found to be the optimum out of various types tested, is rather limited.

Whereas the axial surface profile is quite uniform for $F_o = 6$ and 8, a large wave maximum $Y_{aM} = 1.66$ occurs for $F_o=4$ at $X_t = x/L_t = 1.4$ with $L_t = 2.4$ m. The data refering to the wall depth profile may be plotted with a single average curve having a minimum $Y_{wm} = 0.1$ at $X_t \approx 0.75$, and a maximum $Y_{wM} = 2.3$ at $X_t \approx 1.1$. Compared to both the abrupt and the Rouse reversed wall expansions, the present geometry performs much poorer and may not generally be recommended. One advantage seems to be the narrow location of maximum wall depth for variable Froude number F_o. More experiments should be conducted, however, to obtain systematic and reliable results.

Two additional experiments were conducted without cusp element, but the modified wall geometry and a wedge element starting at $x_w=2.50$ m with $\alpha_D = 75°$ (Runs 39 and 40). The tailwater expansion ratio was $\beta = 2.50$ and Froude numbers $F_o = 2$ and 4 were tested for $h_o = 96$ mm. The data of the latter experiment is also included in Fig 9 and a perfect agreememt may be noted up to the end of expansion ($X_t = 1$). Further downstream, the maximum axial flow depth

$Y_{aM} = 0.72$ at $X_t = 1.25$ is much reduced. A second maximum $Y_{aM} = 0.86$ occurs at $X_t = 2.33$. Regarding the wall depth profile, the maximum flow depth $Y_{wM} = 2.70$ occurs at $X_t = 1$ and is much larger than the corresponding value with the cusp element. Analogous values were found for $F_o = 2$. In conclusion the tailwater shock controls neither by the cusp element nor with the wedge element are able to improve the flow in the tailwater channel, therefore, in the near field at least.

Still another series of experiments was conducted for $b_3/b_o = 2.50$ with the origin of wedge element at $x_w = 2.50$ m. All approach flow depths were $h_o = 48$ mm, and approach Froude numbers between 2 and 8 were investigated. The data relating to $F_o = 4$ (Run 28) are plotted in Fig 9, and a general agreement with the other two series may again be noted, except for the maximum wave heights $Y_{aM} = 1.25$ at $X_t = 1.66$ and $Y_{wM} = 1.65$ at $X_t = 1$. Compared to the other two runs with $F_o = 4$, the maximum wall depth is now even significantly higher.

CONCLUSIONS

The present study clearly demonstrates, that the chute expansion geometry should be a Rouse reversed wall curve, or an abrupt expansion. The latter configuration involves wave heights which are always below the approach flow depth, whereas a Rouse reversed curve gives an almost smooth transition to the tailwater, provided the design Froude number F_D is at least equal to 40% of the relevant approach Froude number F_o

Based on a detailed experimental research, it was shown that neither the linearly expanding chute or bed deflectors, nor tailwater shock controls are able to improve expanding chute flow.

These elements are, in addition, prone to cavitation damage, and would in any case be restricted to moderate velocity only. Such problems are not encountered with both recommended expansion geometries, except for the abrupt expansion at the expansion section.

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