Hydraulics of Stepped Spillways and Cascades

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SUMMARY Stepped spillways have become a popular method for handling flood releases. The steps increase significantly the rate of energy dissipation taking place on the spillway face and reduce the size of the required downstream energy dissipation basin. The compatibility of stepped spillways with roller compacted concrete (RCC) and gabion construction techniques results in low additional cost for the spillway. This paper presents a review of recent developments for the design of stepped chutes and cascades, provides a discussion of the effects of air entrainment, and develops new calculation methods that take into account the effects of flow aeration on the flow characteristics and the rate of energy dissipation.

NOTATION

C_{mean}	= depth averaged mean air concentration;
D_H	= hydraulic diameter (m);
d_b	= flow depth at the brink of a step (m);
d_c	= critical flow depth (m);
d_i	= jet thickness (m) at the impact of the nappe with the receiving pool in nappe flow regime;
d_p	= flow depth in the pool beneath the nappe (m);
Fr	= Froude number;
f	= friction factor of non-aerated flow;
f_e	= friction factor for aerated flow;
H	= total head (m);
H_{dam}	= dam crest head above the spillway toe (m);
H_{max}	= maximum head available (m);
H_o	= reservoir head (m) above the spillway crest;
H_{res}	= residual head at the spillway toe (m);
h	= height of steps (m);
k_s	= step dimension normal to the flow : $k_s = h * \cos\alpha$;
k_s'	= surface (skin) roughness height (m);
L_d	= distance (m) from the drop wall to the position of the depth d_1;
L_r	= roller length (m);
Re	= Reynolds number;
V_i	= velocity (m/s) of the falling nappe at the intersection of the nappe and the receiving pool in nappe flow regime;
α	= spillway slope;
ΔH	= head loss (m);
θ	= angle of the impinging jet and the horizontal step;

Subscript

air	= air flow;
c	= critical flow conditions;
w	= water flow;
1	= immediately upstream of the hydraulic jump (fig. 2);
2	= immediately downstream of the hydraulic jump (fig. 2).

1. INTRODUCTION

The world's oldest stepped spillways are probably the Khosr River dam spillways (Iraq). The Khosr River dams were built around B.C. 694 by the Assyrian King Sennacherib, to supply water to the Assyrian capital city Nineveh (near Mosul). Both dams feature a stepped downstream face and were intended to discharge the river over their crests. Much later (between A.D. 100 and 200), the Romans built stepped overflow dams in Syria and Tunisia. After the fall of the Roman empire, Moslem civil engineers gained experience from the Nabateans, the Romans and Sabeans. Stepped spillways built by the Moslems can be found in Iraq and in Spain. After the Reconquest of Spain, Spanish engineers benefited from the Roman and Moslem precedents and designed dams with overflow stepped spillways. In 1791, they built a 50-m high dam with stepped spillway, the Puentes dam, but the dam was washed out in 1802 after a foundation failure.

In all the early dams, stepped spillways were selected to contribute to the stability of the dam, for their simplicity of shape or for a combination of the two. The waters were discharged over the dam crests. The spillway of the New Croton dam (1906) is probably the first stepped chute designed specifically to dissipate flow energy. The steps increase significantly the rate of energy dissipAtion taking place along the spillway face, and reduce the size and the cost of the downstream stilling basin.

Recently the development of new construction materials (e.g. RCC, gabion) has increased the interest for stepped spillways for handling flood releases. The construction of stepped spillway is compatible with the RCC slipforming method and the placing methods of RCC and gabions. Stepped channels can also be used

to increase the discharge capacity. Soviet engineers developed the concept of overflow earth dam. The spillway consists of a revetment of precast concrete blocks laid on a filter and erosion protection layer. The channel bed is very flexible and allows differential settlements : individual blocks do not need to be connected to adjacent blocks. The high degree of safety allows the use of such channels as primary spillways [24].
Stepped cascades are utilised also to enhance the water quality of the polluted canals [13]. Waterfalls can be landscaped as leisure parks and combine flow aeration and aesthetics. Aesthetical applications of stepped cascades can include stepped fountains in cities (e.g in Brisbane, Hong Kong, Taipei).
In this paper, the first part describes the flow regimes on stepped chutes. Then the hydraulic characteristics and energy dissipation performances are reviewed. Later the effects of flow aeration are discussed. It must be noted that this paper presents results obtained for chutes with horizontal steps. ESSERY and HORNER [10], PEYRAS et al. [22] and FRIZELL [11] discussed experimental results obtained with inclined and pooled steps.

FLOW REGIMES AND AIR ENTRAINMENT

The flow over stepped spillways can be divided into two regimes : nappe flow and skimming flow (fig. 1).
In nappe flow regime, the water proceeds in a series of plunges from one step to another. The flow from each step hits the step below as a falling jet, with the energy dissipation occurring by jet breakup in air, jet mixing on the step, with the formation of a fully developed or partial hydraulic jump on the step [25]. For a nappe flow regime the steps need to be relatively large. This situation is not often practical but may apply to relatively flat spillways and streams
In the skimming flow regime, the water flows down the stepped face as a coherent stream, skimming over the steps. The external edges of the steps form a pseudo-bottom over which the flow pass. Beneath this, horizontal axis vortices develop and are maintained through the transmission of shear stress from the water flowing past the edge of the steps. In the early spillway steps, the flow is smooth and no air entrainment occurs. After few steps the flow is characterised by strong air entrainment and vortices at the step toes.
The flow conditions above a stepped chute are characterised by a high level of turbulence and large quantities of air are entrained [5]. In a nappe flow regime, air is entrained at each step by plunging jet at the intersection of the overfalling jet and the receiving waters, and at the toe of the hydraulic jump. With deep pooled steps, most of the air is entrained by plunging jet. For flat steps with shallow waters, most of the air is entrained at the toe of the hydraulic jumps.
On a stepped spillway with skimming flow, the entraining region follows a region where the flow over the spillway is smooth and glassy. Next to the boundary however turbulence is generated and the boundary layer grows until the outer edge of the boundary layer reaches the surface. When the outer edge of the boundary layer reaches the free surface, the turbulence can initiate natural free surface aeration [5,6]. The location of the start of air entrainment is called the point of inception. Downstream of the point of inception, the flow becomes rapidly aerated.
In stepped spillway flows, the amount of entrained air is an important design parameter. Air entrainment increases the bulk of the flow which is a design parameter that determines the height of spillway sidewalls. Also the presence of air within the boundary layer reduces the shear stress between the flow layers, hence the flow resistance and the energy dissipation. Further the presence of air within high-velocity flows may prevent or reduce the damage caused by cavitation. On stepped spillways with skimming flow regime, the reduction of flow velocity and the resulting increase of flow depth reduce also the risks of cavitation as the cavitation index increases.
Recently air entrainment has been recognised for its contribution to the air-water transfer of atmospheric gases such as oxygen and nitrogen. This process must be taken into account for the re-oxygenation of polluted streams and rivers, but also to explain the high fish mortality downstream of large hydraulic structures.

NAPPE FLOW REGIME

Along a spillway, a nappe flow is characterised by a succession of free-fall jets impinging the next step and followed by a fully developed or partially developed hydraulic jump. Stepped spillway with nappe flows can be analysed as a succession of drop structures.
For a horizontal step, the flow conditions near the end of the step change from subcritical to critical at some section a short distance back from the edge. The flow depth at the brink of the step d_b is :

$$d_b = 0.715 * d_c \qquad (1)$$

where d_c is the critical flow depth [27]. Downstream of the brink, the nappe trajectory can be computed using potential flow calculations, complex numerical methods or approximate methods as that developed by MONTES [19]. Application of the continuity and momentum equations to the base of the overfall and to the hydraulic jump leads to the main flow characteristics. RAND [26] assembled several sets of experimental data and developed the following correlations :

$$\frac{d_1}{h} = 0.54 * \left(\frac{d_c}{h}\right)^{1.275} \qquad (2)$$

$$\frac{d_2}{h} = 1.66 * \left(\frac{d_c}{h}\right)^{0.81} \qquad (3)$$

$$\frac{d_p}{h} = \left(\frac{d_c}{h}\right)^{0.66} \qquad (4)$$

$$\frac{L_d}{h} = 4.30 * \left(\frac{d_c}{h}\right)^{0.81} \qquad (5)$$

where d_p is the height of water in the pool behind the overfalling jet, L_d is the distance from the drop wall to the position of the depth d_1 (fig. 2). The flow conditions at the impact of the nappe with the receiving pool can be deduced from the equation of motion. Using equations (1) and (4), the nappe thickness d_i, the nappe velocity V_i and the angle θ of the nappe with the horizontal, at the impact, can be correlated by :

$$\frac{d_i}{d_c} = 0.687 * \left(\frac{d_c}{h}\right)^{0.483} \qquad (6)$$

$$\frac{V_i}{V_c} = 1.455 * \left(\frac{d_c}{h}\right)^{-0.483} \qquad (7)$$

$$\tan\theta = 0.838 * \left(\frac{d_c}{h}\right)^{-0.586} \qquad (8)$$

Downstream of the impact of the nappe (fig. 2), the roller length of a fully-developed hydraulic jump is estimated as [15] :

$$\frac{L_r}{d_1} = 8 * (Fr_1 - 1.5) \qquad (9)$$

where L_r is the length of roller and d_1 and Fr_1 are the depth of flow and the Froude number immediately upstream of the jump (section 1). If the length of the drop L_d plus the length of the roller L_r are smaller than the length of a step l, a fully developed hydraulic jump can take place (fig. 2). Combining equations (5) and (9), a condition for nappe flow regime with fully developed hydraulic jump is deduced : a nappe flow regime with fully-developed hydraulic jump occurs for discharges smaller than a critical value defined as :

$$\left(\frac{d_c}{h}\right)_{char} = 0.0916 * \left(\frac{h}{l}\right)^{-1.276} \qquad (10)$$

Nappe flow situations with fully-developed hydraulic jump occur for $d_c/h < (d_c/h)_{char}$.

Along a stepped spillway, critical flow conditions occur near to the end of each step, and equations (1) to (9) provide the main flow parameters for a nappe flow regime with fully developed hydraulic jump. PEYRAS et al. [22,23] indicated that these equations can be applied also with reasonable accuracy to nappe flows with partially developed jump.

The total head loss along the spillway ΔH equals the difference between the maximum head available H_{max} and the residual head at the bottom of the spillway. Combining the definition of the head loss with the momentum equation applied to the base of the overfall and with the above equations, it yields :

$$\frac{\Delta H}{H_{max}} = 1 - \left(\frac{0.54 * \left(\frac{d_c}{h}\right)^{0.275} + \frac{3.43}{2} * \left(\frac{d_c}{h}\right)^{-0.55}}{\frac{3}{2} + \frac{H_{dam}}{d_c}}\right) \qquad (11a)$$

$$\frac{\Delta H}{H_{max}} = 1 - \left(\frac{0.54 * \left(\frac{d_c}{h}\right)^{0.275} + \frac{3.43}{2} * \left(\frac{d_c}{h}\right)^{-0.55}}{\frac{H_{dam} + H_o}{d_c}}\right) \qquad (11b)$$

where equations (11a) and (11b) apply to un-gated and gated spillways respectively, H_{dam} is the dam crest head above the downstream toe and H_o is the reservoir free-surface elevation above the spillway crest. On figure 3, the energy dissipation (eq. (11a)) is plotted as a function of the relative dam height for various number of steps. The results indicate that the energy dissipation increases with the dam height. Further, for a given dam height, the rate of energy dissipation decreases when the discharge increases.

SKIMMING FLOW REGIME

For small discharges and flat slopes, the water flows as a succession of waterfalls (i.e. nappe flow regime). An increase of discharge or of slope might induce the apparition of skimming flow regime. The author re-analysed experimental data obtained by ESSERY and HORNER [10], DEGOUTTE et al. [8] and BEITZ and LAWLESS [3]. For these data, skimming flow regime occurs for discharges larger than a critical value defined as :

$$\frac{(d_c)_{onset}}{h} = 1.057 - 0.465 * \frac{h}{l} \qquad (12)$$

where h is the step height, l is the step length and $(d_c)_{onset}$ is the characteristic critical depth. It must be noted that equation (12) was deduced for h/l ranging from 0.2 to 1.3. It should not be used outside that range without great care.

In skimming flow regime, horizontal axis vortices develop beneath the pseudo-bottom formed by the external edges of the steps. These vortices are maintained through the transmission of shear stress from the fluid flowing past the edges of the steps. The classical flow resistance calculations must be modified to take into account the shape of the steps. The flow resistance is the sum of the skin resistance and the form resistance of the steps. Dimensional analysis suggests that the friction factor f_e is a function of the surface (skin) roughness height k_s', the Reynolds number, the step roughness height $k_s = h*\cos\alpha$, the spillway slope and the quantity of air entrained :

$$f_e = f_e\left(\frac{k_s'}{D_H} ; Re ; \frac{k_s}{D_H} ; \alpha ; C_{mean}\right) \qquad (13)$$

where C_{mean} is the average air concentration.

The author re-analysed an large number of experimental data. For these model data, a detailed study indicates that the friction factor is independent of the surface roughness k_s' and of the Reynolds number. Assuming that the effects of flow aeration are independent of the step roughness, equation (13) can be rewritten :

$$f_e = f\left(\frac{k_s}{D_H}; \alpha\right) * \left(\frac{f_e}{f}\right)(C_{mean}) \qquad (14)$$

where $f_e/f(C_{mean})$ is the relative drag reduction caused by free-surface aeration [6] and f is the non-aerated friction factor.

Experimental data are presented in figure 4 where the non-aerated friction factor f is plotted as a function of the relative roughness k_s/D_H. For flat chutes (i.e. $\alpha <$ 12 degrees), the data show an increase of the friction factor with the relative roughness that appears to be independent of the channel slope. And equation (14) can be correlated by :

$$\frac{1}{\sqrt{f}} = 1.42 * \text{Ln}\left(\frac{D_H}{k_s}\right) - 1.25 \quad \text{(for flat slopes)} \qquad (15)$$

For steep slopes (i.e. $\alpha > 25$ degrees), the experimental results show little correlation between the flow resistance, the relative roughness and the channel slope. With channel slopes ranging from 50 to 55 degrees, figure 4 indicates values of the friction factor in the range 0.17 to 5 with a mean value of about 1.0. It must be emphasised that these experimental data were analysed neglecting the effects of air entrainment. No information is available on the amount of air entrained during the experiments.

Figure 4 shows a substantial increase of the friction factor when the channel slope increases from around 10 degrees up to about 50 degrees. It is believed that such a difference is caused by different flow patterns in the recirculating cavity beneath the skimming stream. For flat channels, the recirculating vortices do not fill the entire cavity between the edges, and the wake from one edge interferes with the next step. The flow pattern ("wake-step interference" regime) is characterised by the impact of the wake on the next step, a three-dimensional unstable recirculation in the wake and some friction drag on the step downstream of the wake impact. With increasing slopes, the tail of the wake starts interfering with the next wake and the friction drag component disappears. This pattern is called a "wake-wake interference" regime.

For steep slopes, a stable recirculation is observed in the cavities between adjacent steps. The flow resistance is a function of the energy required to maintain the circulation of these large-scale recirculating vortices. As a result, the friction factor results show an apparent lack of correlation with the Reynolds number and relative roughness. A similar result was observed by PERRY et al. [21] who analysed velocity profiles in developing boundary layers in arbitrary pressure gradients.

With strip roughness, ADACHI [1] and KNIGHT and MACDONALD [17] observed a stable recirculation mechanism when the groove height to length ratio of the cavity was larger than 0.4. Other researchers [16,18] studied flows in rectangular cavities with various aspect ratio. and observed stable recirculatory flows for height-length ratio larger than 0.4 to 0.45. For a stepped spillway, the cavity height to length ratio equals : $[\cos\alpha * \sin\alpha]$. A value of 0.4 would correspond to a channel slope $\alpha = 26.6$ degrees. The results of MAULL and EAST [18], ADACHI [1], KISTLER and TAN [16] and KNIGHT and MACDONALD [17] would imply that stable recirculation occurs for slopes larger than 26.6 degrees on a stepped chute. Figure 4 indicates a different flow resistance behaviour for channel slopes larger than 27 degrees, and this is coherent with the findings of these researchers.

Assuming that the flow is uniform at the downstream end of the spillway, the total head loss equals :

$$\frac{\Delta H}{H_{max}} = 1 - \frac{\left(\frac{f_e}{8*\sin\alpha}\right)^{1/3} * \cos\alpha + \frac{1}{2} * \left(\frac{f_e}{8*\sin\alpha}\right)^{-2/3}}{\frac{3}{2} + \frac{H_{dam}}{d_c}} \qquad (16a)$$

$$\frac{\Delta H}{H_{max}} = 1 - \frac{\left(\frac{f_e}{8*\sin\alpha}\right)^{1/3} * \cos\alpha + \frac{1}{2} * \left(\frac{f_e}{8*\sin\alpha}\right)^{-2/3}}{\frac{H_{dam} + H_o}{d_c}} \qquad (16b)$$

where equations (16a) and (16b) apply to un-gated and gated spillways respectively, f_e is deduced from equation (14) and figure 4. Equation (16a) is presented on figure 3 for several channel slopes, assuming $f = 1.0$ and neglecting free-surface aeration. The results are compared also with experimental data.

For a high dam, it is more appropriate to consider the residual head H_{res} than total head loss. At the bottom of the spillway, the residual head H_{res} is :

$$\frac{H_{res}}{d_c} = \left(\frac{f_e}{8*\sin\alpha}\right)^{1/3} * \cos\alpha + \frac{1}{2} * \left(\frac{f_e}{8*\sin\alpha}\right)^{-2/3} \qquad (17)$$

It is worth noting that the aeration of the flow reduces the flow resistance. As a result, the residual energy increases with the amount of entrained air. The relative increase of residual energy caused by the aeration of the flow is :

$$\frac{\Delta(H_{res})}{H_{res}} = \left(\frac{f_e}{f}\right)^{1/3} * \left(\frac{1 + \frac{4}{f} * \tan\alpha * \left(\frac{f}{f_e}\right)}{1 + \frac{4}{f} * \tan\alpha}\right) - 1 \qquad (18)$$

It was shown that the effects of air entrainment on the residual energy become important for slopes larger than 30 degrees on stepped chutes [5]. Indeed the residual energy is strongly underestimated if the effect of air entrainment is neglected.

CONCLUSION

Stepped chutes have become recently a popular method for discharging flood waters. The steps increase significantly the rate of energy dissipation taking place on the spillway face and reduce the size of the required downstream energy dissipation basin. This paper reviews the hydraulic characteristics of stepped chute flows. Two different flow regimes can occur : nappe flow regime for small discharges and flat channel slopes, and skimming flow regime. The hydraulic and energy dissipation characteristics of each flow regime are described. The effects of flow aeration are discussed.

Stepped spillways are very efficient to dissipate a large component of the flow energy. But in skimming flows, the flow aeration may induce a reduction of the energy dissipation efficiency of the spillway.

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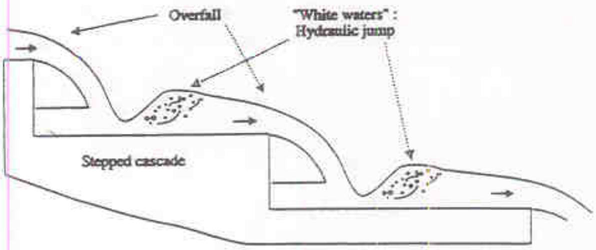
Fig. 1 - Flow above a stepped chute
(a) nappe flow regime
(b) skimming flow regime



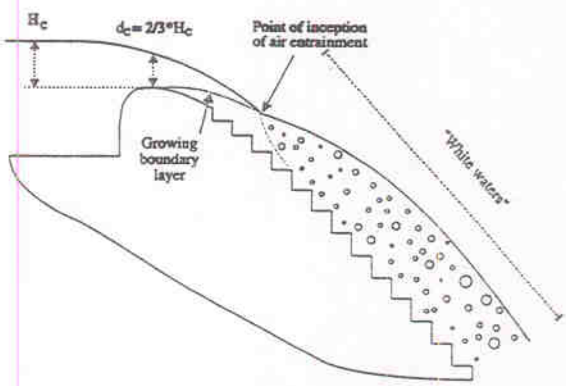
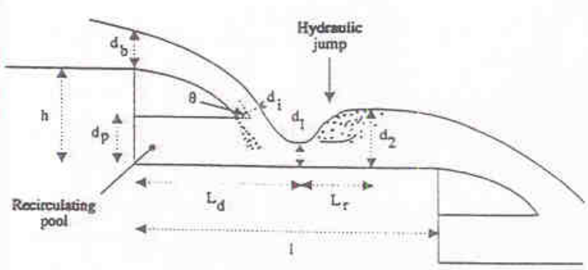
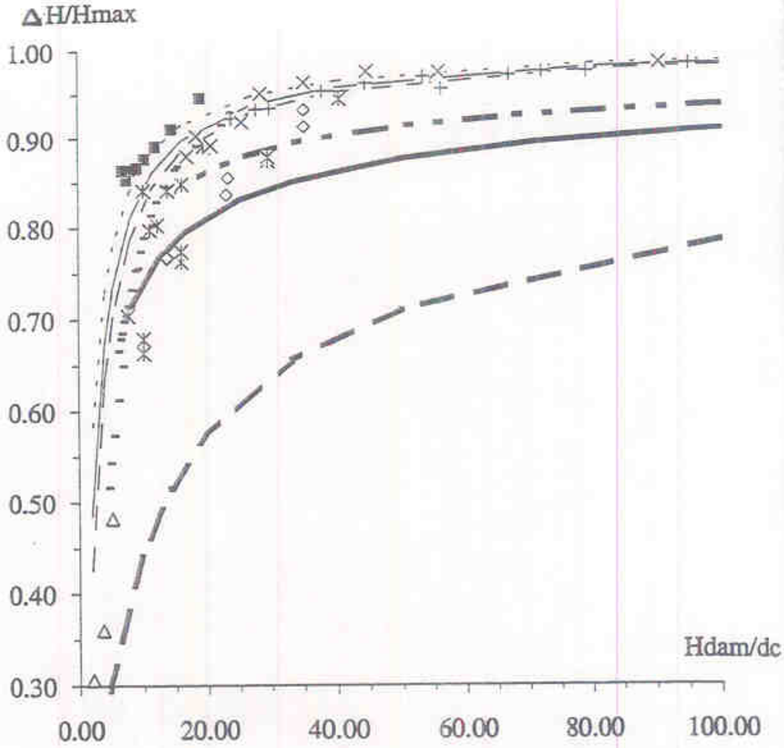


Fig. 2 - Sketch of drop structure





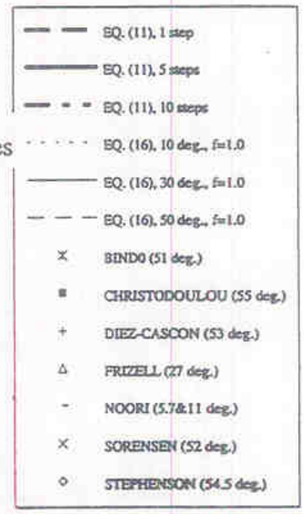


Fig. 3 - Energy dissipation on stepped chutes

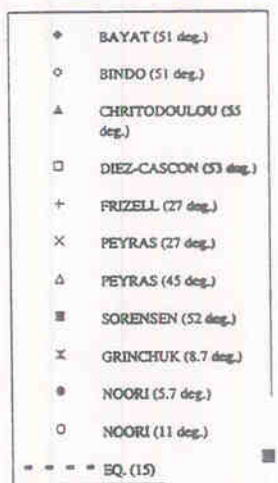
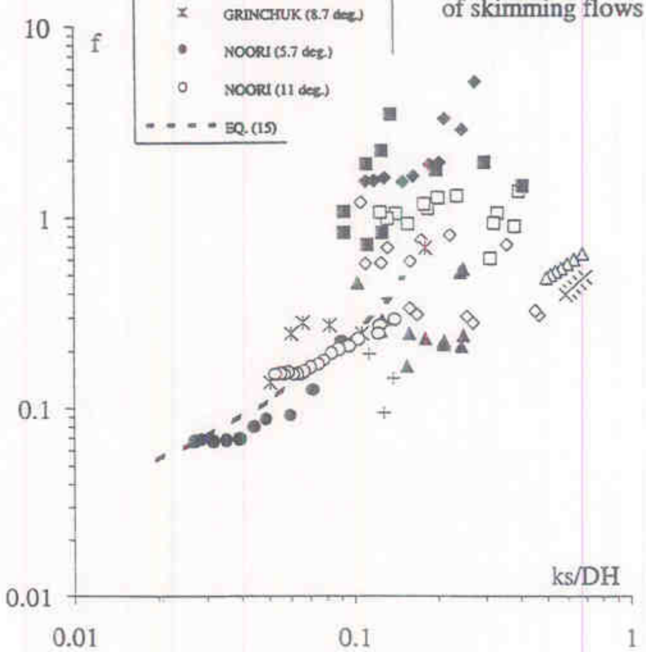


Fig. 4 - Flow resistance
of skimming flows



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