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Effects of modifications on the hydraulics of Denil fishways

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From the biological point of view, fishways are structures that enable fish to continue their migration past obstructions. In terms of hydraulics, fishways are energy dissipating structures. One of the most effective fishways in energy dissipation is a Denil fishway. This paper presents the most important results of the studies on Denil fishways carried out at the Hydraulics and Water Resources Engineering Laboratory at the University of Oulu. The studies were focused on Denil fishways with wide relative baffle width ($B/b = 2$). Dimensionless discharges for Denil fishways with $B/b = 2$ are higher for the same water depth than for the standard Denil reflecting higher water velocities in the cross section. The dimensionless discharge curves for the standard Denil and for designs with different baffle angles are quite close to each other. The experiments show, however, clear trends in using different baffle angles to the bed.

Introduction

Biologically speaking, fishways are special structures built in connection with weirs and other obstructions to enable fish to continue their migration. Hydraulically speaking, fishways are energy dissipating structures. One of the most effective fishway types in energy dissipation is the Denil fishway. It consists of a channel containing symmetrical closely spaced baffles (or fins, or vanes) on the side wall and the floor. The baffles conduct a part of the energy of the main flow to the walls and to the bottom of the channel. This arrangement provides considerable energy dissipation and establishes low velocity flow in the central zone of the fishway.

Denil fishway was first conceived by G. Denil in 1908. The intricacy of the original design led to the development of simpler versions of this fishway. In England, the Committee on Fishpasses gave general design criteria for plain Denil fishways already in 1942. Nowadays, this design is considered as the standard Denil, and in many studies on Denil fishways, the results obtained are compared to the hydraulics of the standard design. The most advanced studies have been carried out at the University of Alberta, Canada, where the studies on Denil fishways started in the

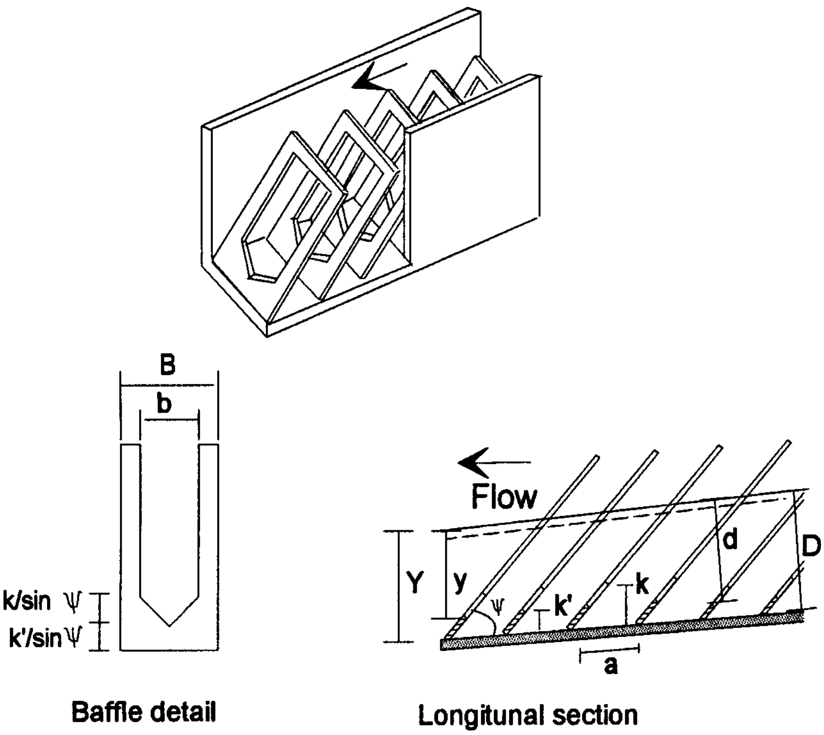

Fig. 1. A schematic representation of a plain Denil fishway with definitions for dimensions. For standard design, B = 0.56 m, b = 0.36 m, a = 0.25 m, $k = k'$ = 0.13 m and ψ = 45°.

early 1980s. Special interest has been paid on the hydraulics of the standard Denil fishway, and the hydraulic characteristics of modified structures have been compared to those of the standard structure (Katopodis and Rajaratnam 1983, Rajaratnam *et al.* 1987, Katopodis *et al.* 1997).

This paper is based on the experimental studies on the hydraulics of Denil fishways carried out at the Hydraulics and Water Resources Engineering Laboratory of the University of Oulu. Dimensional analysis is based on experiments and the results are compared to the hydraulic characteristics of Denil fishways defined at the University of Alberta.

Standard design of plain Denil fishway and the main characteristics of the flow

The standard design of a Denil fishway consists of a rectangular channel with a total width B of 0.56 m and a clear central width b of 0.36 m (Fig. 1). It has a set of baffles inclined at an angle ψ = 45° (against the flow) with the perpendicular height k' (to the crest of V) equal to 0.13 m. The water depths in a Denil may vary even equal to 5 times b (or 1.8 m). Slopes of the flumes are as high as 33%, but most commonly 20% or less (Katopodis *et al.* 1997). The dimensions of the standard Denil fishway can also be expressed as relations between total width B, clear opening b, baffle spacing a, and height k' as B:b:a:k' = 1.5:1.00:0.69:0.36.

The flow in a Denil fishway consists of two interacting parts, namely, of the main stream in the central portion of the channel and of a series of systematic lateral streams, each one corresponding to a side pocket created by baffles. There is a very extensive mixing between the predominantly undirectional main stream and the lateral streams. The baffles direct the water of the main stream into the side pockets where large circulation patterns are set up; subsequently, the water is redirected to strike and to counteract the main stream. The flow is very turbulent and air entrainment is considerable throughout the flow. The main stream is characterized by symmetry, strong surface undulations, and sizable, systematic, and periodic water level fluctuations. The lateral streams are symmetric, homologous and isodynamic when compared to one another. The interaction between the main stream and the lateral ones provides the

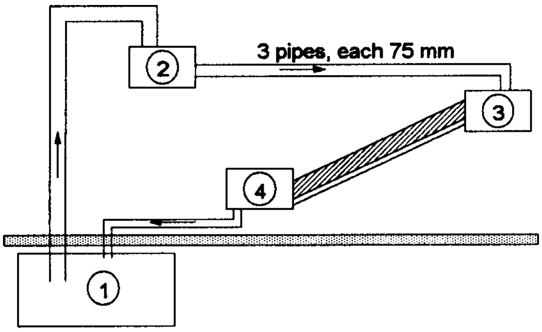

Fig. 2. Study arrangements and water circulation: (1) collection tank, (2) equalizing flume, (3) head tank, and (4) tail tank.

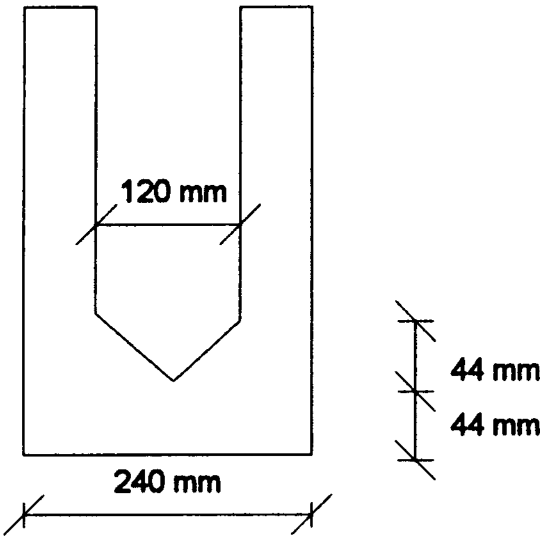

Fig. 3. The dimensions of the baffles in the model.

main mechanism for transferring mass and momentum, and producing considerable turbulence and energy loss. In the Denil fishway, the water mass on the surface is fast moving and reasonably smooth. The water level in the side pockets is lower than in the main stream. Spiral motion forms in the side pockets around an axis parallel to the vanes (Katopodis and Rajaratnam 1983).

Experimental arrangements and accomplishment of the research

Laboratory and field studies on the hydraulics of Denil fishways have been carried out at the University of Oulu, Finland, since 1993. All the studies have been conducted for practical purposes in close connection to the design process of the Isohaara fishway at the Kemijoki, a river in northern Finland. This project has largely defined the relative dimensions of the model and directed the studies. When possible, the hydraulic function of scale models has been compared to that of prototypes.

The basic experimental arrangements are shown in Fig. 2. Water was pumped from the collection tank into the equalizing flume and conducted from there through the head tank with a well-designed inlet into the model and through the tail tank back into the collection tank. A simple tilting arrangement was used to set the model on any desired slope. Discharge was controlled by valves. The walls of the flume were made of polycarbonate plates and the baffles of plywood.

Discharges were determined by volumetric measurements and confirmed afterwards with a magnetic flow meter. Water depths and velocities were measured at the centerline of the flume in the middle of the baffles perpendicular to the bottom. The water depths were measured from the bottom of the flume by using a ruler. For dimensional analysis, the mean depths were transformed into depths from V. Time-averaged velocities were measured parallel to the flow by using a current meter with a propeller of 8 mm surrounded by an external ring of 11 mm in diameter. Discharges, water depths, and water velocities were measured several times to minimize the effects of fluctuations and mean values were used in analysis.

Flume and baffle dimensions were the same in all the experiments with $B/b = 2$, $a/b = 1.17$, and $\psi = 45°$ (Fig. 3). The ratio $B/b = 2$ was chosen for the experiments because it has been used as a default parameter in the Isohaara fishway. The studies were made with different slopes and discharges. Because of the poor pump capacity, only small values of relative water depths could be reached.

First, the main characteristics of the flow in Denil fishways with $B/b = 2$ were determined. Velocity distribution along one baffle was measured in order to find out where in the reduced cross section the maximum velocities locate (Fig. 4). After that, several modifications were studied to solve the problems in existing fishways. The ef-

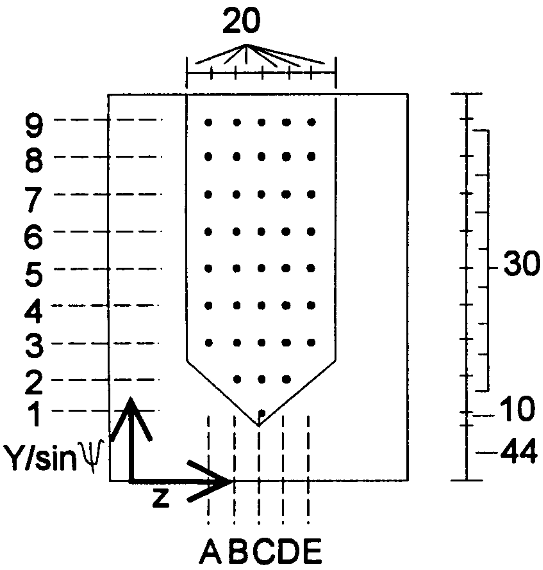

Fig. 4. Measuring points in the baffle opening (dimensions along the baffles, in millimeters).

fect of baffle spacing was studied because the baffle spacing used has been larger than in the standard Denil fishway. Also, the baffle angles in many existing fishways have been noticed to deviate from the designed 45 degrees, ranging from 40 to 50 degrees. While no references were found on the hydraulics of other than the 45-degree baffle angle, the effect of different baffle angles to the bottom also needed to be studied. Degrees of 40, 45 and 50 were chosen for closer studies.

For all the experiments, water depths and velocity distribution were measured in the region of fully developed flow and in addition in the uppermost region for the experiments on baffle angle and baffle spacing. Rajaratnam and Katopodis (1984) point out that the velocity distribution in the central plane of a standard Denil is fully developed after a short distance from the water inlet. This is due to considerable resistance caused by the baffles which brings about an extremely turbulent flow as the water enters the fishway from the head tank.

Analyses and comparison

In fishways, basically the same structure in different scale is suitable for different sites and purposes. If geometric symmetry between structures exists, the structures operate under the same hydraulic laws. In such cases, dimensionless parameters are useful. With dimensionless parameters, structures of different scale can easily be compared. Dimensionless parameter is the dimensionless relation of factors that affect in dynamically similar systems. In fishways, dimensionless parameters are valid for different slopes and discharges, and actual discharges and water depths can be calculated by substituting the fishway dimensions in equations for dimensionless parameters.

Denil fishways have been studied intensively at the University of Alberta, Canada. The studies have included both the standard Denil fishways and Denil fishways with modified baffle spacings, modified ratios of free opening to channel width and different heights of the upper part of the bottom baffle. Hydraulic function of modified Denil fishways has been compared to that of the standard Denil fishway. The results obtained on Denil fishways with varying geometry have been gathered by Katopodis *et al.* (1997).

Rajaratnam and Katopodis (1984) introduced a dimensionless discharge Q_* for standard Denil fishways to be used for a wide range of discharges and slopes. The relation between Q_* and Q is

$$Q_* = \frac{Q}{\sqrt{gS_o b^5}} \quad (1)$$

where Q_* = dimensionless discharge, Q = discharge in fishway, g = acceleration due to gravity, S_o = bed slope of fishway, and b = free opening.

Similarly, dimensionless velocity u_* can be defined as

$$u_* = \frac{u}{\sqrt{gS_o b}} \quad (2)$$

where u is time-averaged longitudinal velocity.

For dimensional analysis, a velocity scale u'_m for Denil fishways is defined as the velocity u at a relative depth y/d = 0.75, where y is normal water depth from the V notch and d is the depth of flow perpendicular to the bottom (Katopodis 1983). It is used for determining dimensionless velocity scales and normalized velocity profiles. Normalized velocity profiles describe the velocity distribution in the centerline of the fully developed flow. Dimensionless discharges can be transformed into fishway discharges and dimensionless velocity scales into velocities at the depth of $y/d = 0.75$.

Dimensionless discharge curve, dimensionless velocity scale and normalized velocity profile for standard Denil fishway

For the standard Denil fishways with the relation B/b equal to 1.56, an equation for dimensionless discharge Q_* is introduced as

$$Q_* = 0.94*(d/b)^{2.0} \tag{3}$$

where d/b is normalized water depth (Katopodis and Rajaratnam 1984). Katopodis *et al.* (1997) suggested that Eq. 2 can be applied for Denils with varying geometry within the limits of $1.5 < r_a < 2.4$, $0.78 < r_B < 2.34$, $0.55 < r_k < 1.90$ and for $d/b < 2.5$, $0.78 < r_a < 1.27$, where

$$r_a = \frac{\left(\frac{a}{b}\right)}{\left(\frac{a}{b}\right)_s},\ r_B = \frac{\left(\frac{B}{b}\right)}{\left(\frac{B}{b}\right)_s},\ r_k = \frac{\left(\frac{K}{b}\right)}{\left(\frac{K}{b}\right)_s},$$

with the suffix s denoting the respective value in standard design of Denil fishway.

Dimensionless velocity scale u_* for standard Denil fishway can be described by equation

$$u_* = 0.76(Q_*)^{0.61} \tag{4}$$

Normalized velocity profiles for standard Denil fishways for different dimensionless depth ranges d/b can be described with Eqs. 5, 6 and 7 (Katopodis *et al.* 1997):

$$\frac{u}{u_m'} = 0.55 + 1.4\left(\frac{y}{d}\right)^4, \tag{5}$$

for d/b from 0.7 to 1.1

$$\frac{u}{u_m'} = 0.35 + 1.6\left(\frac{y}{d}\right)^3, \tag{6}$$

for d/b from 1.1. to 2

$$\frac{u}{u_m'} = 1.50 + 1.3\left(1 - \frac{y}{d}\right)^{0.7}, \tag{7}$$

for d/b from 2 to 5.3.

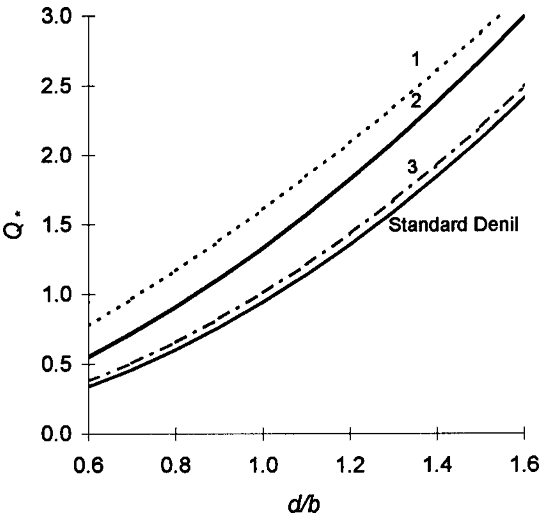

Fig. 5. Dimensionless discharge curves for *B*/*b* = 2 with different ratios of *a* to *b.*

Dimensionless discharge curves, dimensionless velocity scales and normalized velocity profiles for Denil fishways with *b*/*b* of 2.0 and different ratios of *a*/*b*

The most important parameter that affects the dimensionless discharge and velocity curves for Denil fishways is baffle spacing (Katopodis *et al.* 1997). As the baffle spacing increases in Denil fishways, the lateral streams become less effective in slowing down the main stream. In the studies at the University of Oulu, the values describing the deviation from standard Denil were $r_a = 0.82$ or $r_a = 1.63$, $r_B = 0.89$, $r_k = 1$ and $1 < d/b < 2.5$ for all discharges

These values fall within the range where Eq. 3 is valid. Thus it should be applicable to all the studied designs when analyzing the results. Plotting all the curves for dimensionless discharge in the same graph, it can be seen that they are almost parallel to each other (Fig. 5). The difference in the curve created at the University of Oulu could be explained by the narrower range of depth ratio d/b. The curves indicate that at the same relative depth d/b, dimensionless discharge is higher for other than the standard design (Fig. 5 and Table 1). This means that for the same discharge, velocities in the same cross section are higher, as can be seen from the curves of normalized velocities (Fig. 6 and Table 2).

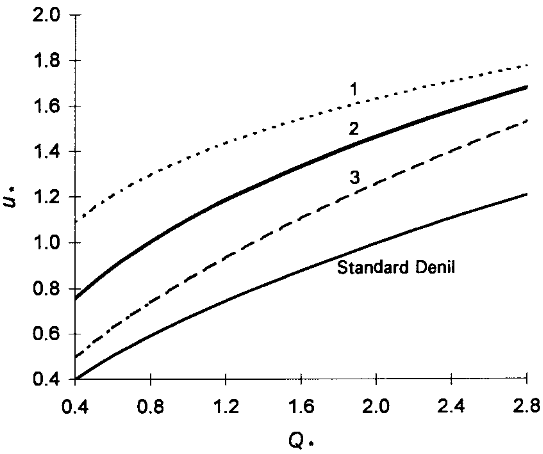

Fig. 6. Dimensionless velocity curves for *B*/*b* = 2 with different ratios of *a* to *b*.

Katopodis *et al.* 1997 stated that increasing *B*/*b* from 1.56 to 2.0 does not affect the normalized velocity profiles to any noticeable extent. Thus, most likely, Eq. 6 should describe the normalized velocity profile for all the studied designs, if nothing else affects them. On the other hand, velocity profiles for designs with $r_a > 1.5$ depart from that of the standard Denil (Katopodis *et al.* 1997). Normalized velocity profiles for experiments with baffle angles 40° and 45° are plotted in Fig. 7 with the delineator of Eq. 6. There seems to be only a slight difference when compared to the delineator for the standard Denil. The few values that deviate from the main trend are values for small dimensionless discharge Q_* (less than 1.5). Most likely, the differences in normalized velocity profiles are due to larger baffle spacing and excessive baffles should bring the normalized velocity profile closer to that for the standard Denil.

Table 1. Curve definitions for Fig. 5.

Curve	*a*/*b*	Q_*	Defined at
1	2.58	$1.61(d/b)^{1.43}$	University of Alberta
2	1.17	$1.32(d/b)^{1.74}$	University of Oulu
3	0.91	$1.35(d/b)^{1.57}$	University of Oulu
Standard Denil	0.72	$0.94(d/b)^{2.00}$	University of Alberta

Table 2. Curve definitions for Fig. 6.

Curve	*a*/*b*	u_*	Defined at
1	2.58	$1.37(Q_*)^{0.25}$	University of Alberta
2	1.17	$1.10(Q_*)^{0.41}$	University of Oulu
3	0.91	$0.84(Q_*)^{0.58}$	University of Oulu
Standard Denil	0.72	$0.76(Q_*)^{0.61}$	University of Alberta

Velocity distribution in the cross section of fully developed flow

Velocity distribution in the Denil flume was measured along one baffle. Results are plotted by vertical and horizontal measuring axes (Figs. 8 and 9). The highest velocities in the cross section of a Denil fishway are not located in the centerline but on the sides. The location of the highest velocities can be explained by the formation of vortices in the side pockets: water flows from the main stream with accelerating speed into the side pockets where the water level is lower than in the main stream.

The velocities are not distributed symmetrically to the mid-axis C–C. This is especially true for lower values of *d*/*b* (less than 1.3) and for steeper slopes. This is probably due to the nonuniform flow in the fishway.

Denil fishways with different baffle angles

The effect of baffle angle to the bottom was studied by using 40-, 45- and 50-degree angles. Simultaneously, the effect of baffle spacing was studied by dividing the uppermost spacings in half. The excessive baffles were removed one by one starting from the lowest one. Water velocity, water depth and discharge measurements were made after every change in the structure. Different structures were named according to the baffle angle and the number of divided spacings (Table 3).

Dimensionless discharge curves for Denil fishways with different baffle angles

With equal water depths, the dimensionless discharges for Design 450 with *B*/*b* = 2.0 were al-

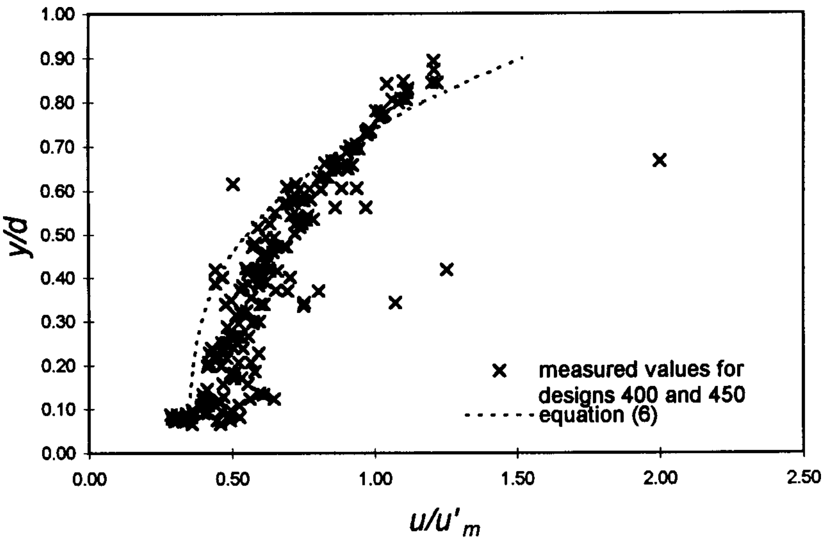

Fig. 7. Measured dimensionless velocities for experiments with baffle angles 40° and 45° and the delineator of Eq. 6 for normalized velocity profile for the standard Denil.

most the same as for the standard Denil (Fig. 10). For Design 500, with equal water depth, the discharges were slightly lower than for the standard Denil although the difference can be regarded as negligible. For Design 400, the measured discharges for equal water depths with all discharges and slopes were higher than for the standard Denil. In other words, with the same discharge, the mean velocities in the centerline are lower for Designs 500 and 450 than for Design 400.

The dimensionless discharge curves for the standard Denil and for designs with different baffle angle do not differ very much. A clear trend, however, can be noticed for Design 400.

Normalized velocity profiles for Denil fishways with different baffle angles

Normalized velocity profiles were built for all the designs and the curves were compared to that for the standard Denil (Fig. 11). As stated earlier, it was found that for Designs 400 and 450, the normalized velocity profiles are of the same form as for the standard Denil, only the normalized velocities are slightly greater. For Designs 450 and 400, equation

$$\frac{u}{u'_m} = 0.45 + 1.6\left(\frac{y}{d}\right)^3 \quad (8)$$

can be applied.

Normalized velocity profile for Design 500 could better be described by equation

$$\frac{u}{u'_m} = 1.30 + 1.1\left(1 - \frac{y}{d}\right)^{3.1} \quad (9)$$

It can be noticed that the velocity distribution for Design 500 was vertically more even at the centerline than for the other designs.

Table 3. Names and description of the designs and design series.

Design Series	Design	Baffle angle	Number of uppermost spacings divided
40		40°	free
	400	40°	none
	401	40°	one
	402	40°	two
	403	40°	three
45		45°	free
	450	45°	none
	451	45°	one
	452	45°	two
	453	45°	three
50		50°	free
	500	50°	none
	501	50°	one
	502	50°	two
	503	50°	three

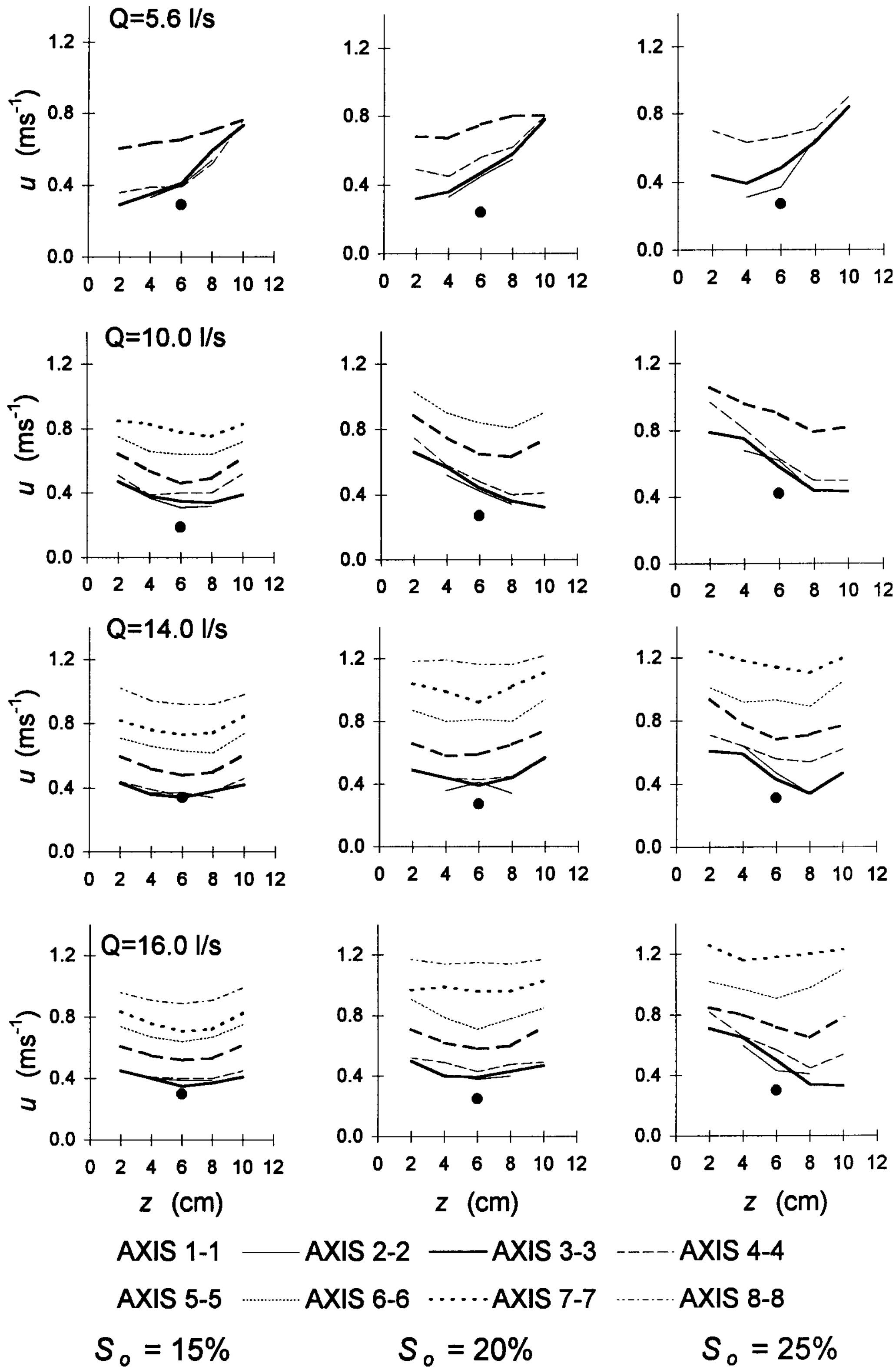

Fig. 8. Velocity distribution at the vertical axes, *Y* and *D* are measured from the fishway bottom.

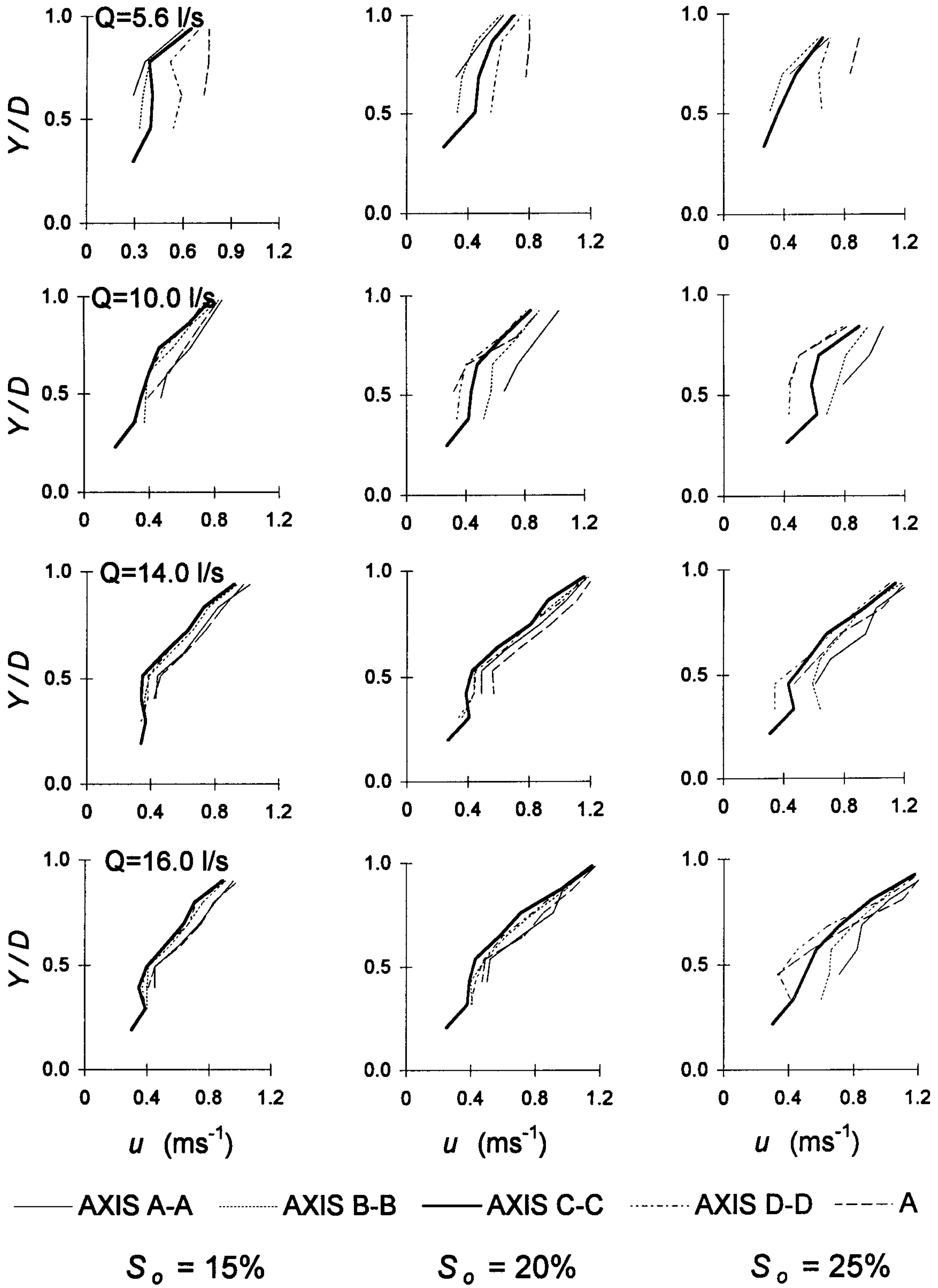

Fig. 9. Velocity distribution at the horizontal axes, coordinate *z* indicates the distance from the left edge of the baffle opening, looking downstream.

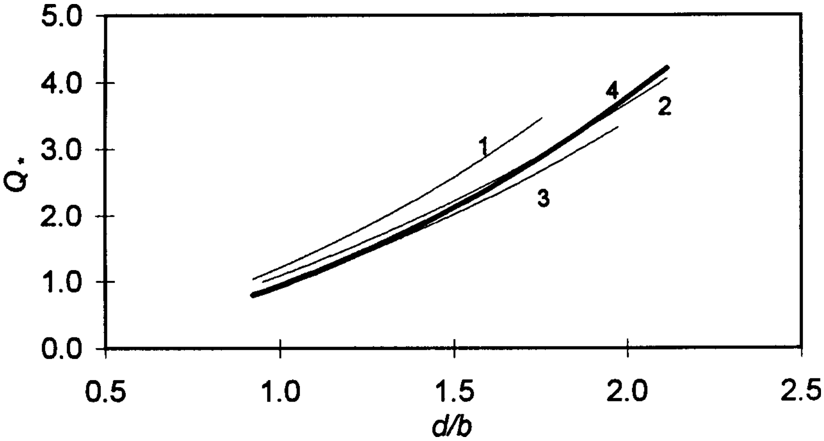

Fig. 10. Dimensionless discharge curves for (1) design 400, (2) design 450, (3) design 500, and (4) standard Denil fishway.

The effect of excessive baffles

In Denil fishways with B/b = 2, flow development is not as fast and energy dissipation not as effective as in Denil fishways with B/b less than 2. In addition, in Denil fishways with B/b = 2, velocity distribution in the centerline is greatly affected by the discharge. The velocity distribution for low discharges deviates from that of the standard Denil which worsens the operation of the fishway. For the studies, it was assumed that excessive baffles in the uppermost region of the fishway would improve its hydraulic function.

The nature of the velocity field in the upper part of the Denil fishway with B/b = 2 and baffle angles of 40°, 45° and 50° were studied by measuring the vertical distribution and the magnitude of the velocity u (time-averaged) in the direction of the centerline of the fishway. Measurements were made in the uppermost region of the fishway in several cross sections in the middle of the baffles and in several depths.

Dividing the uppermost baffle spacings increases the flow friction for Designs 400 and 450 which can be seen as higher water depths at the same discharges (Fig. 12a and b). For Design Series 50, there is practically no noticeable difference (Fig. 12c). For all the designs, the effect is clearer with higher discharges. For practical purposes, this means that adding excessive baffles is advantageous with higher discharges for designs with baffle angle less than 45° because this increases the water depths in the fishway. The studied discharges were, however, reasonably low.

Excessive baffles in the uppermost spacings decreased the scatter in the normalized velocity profiles for all the designs, in exception with the smallest dimensionless discharges (Fig. 11). For Design Series 40, excessive baffles brought the normalized velocity profile closer to that of the standard Denil.

Dividing the uppermost baffle spacings increases the flow friction in the uppermost region of the Denil fishway, thus accelerating the flow development. This results to higher water depths in the fishway (Fig. 12). Velocity distribution in the centerline of the fishway approaches that of the standard Denil fishway (Fig. 11).

Conclusions

The highest velocities in the cross section of Denil fishways are not located in the centerline but on the sides. The velocities are not distributed symmetrically to the mid-axis because of the non-uniform flow in the fishway. This is especially true for lower values of d/b (less than 1.3) and for steeper slopes.

The curves for dimensionless discharge for the studied designs and for the standard Denil were noticed to be almost parallel to each other. Energy dissipation in Denil fishways with B/b = 2 is not as effective and flow development is not as fast as in Denil fishways with B/b less than 2. Dimensionless discharges for equal water depth are

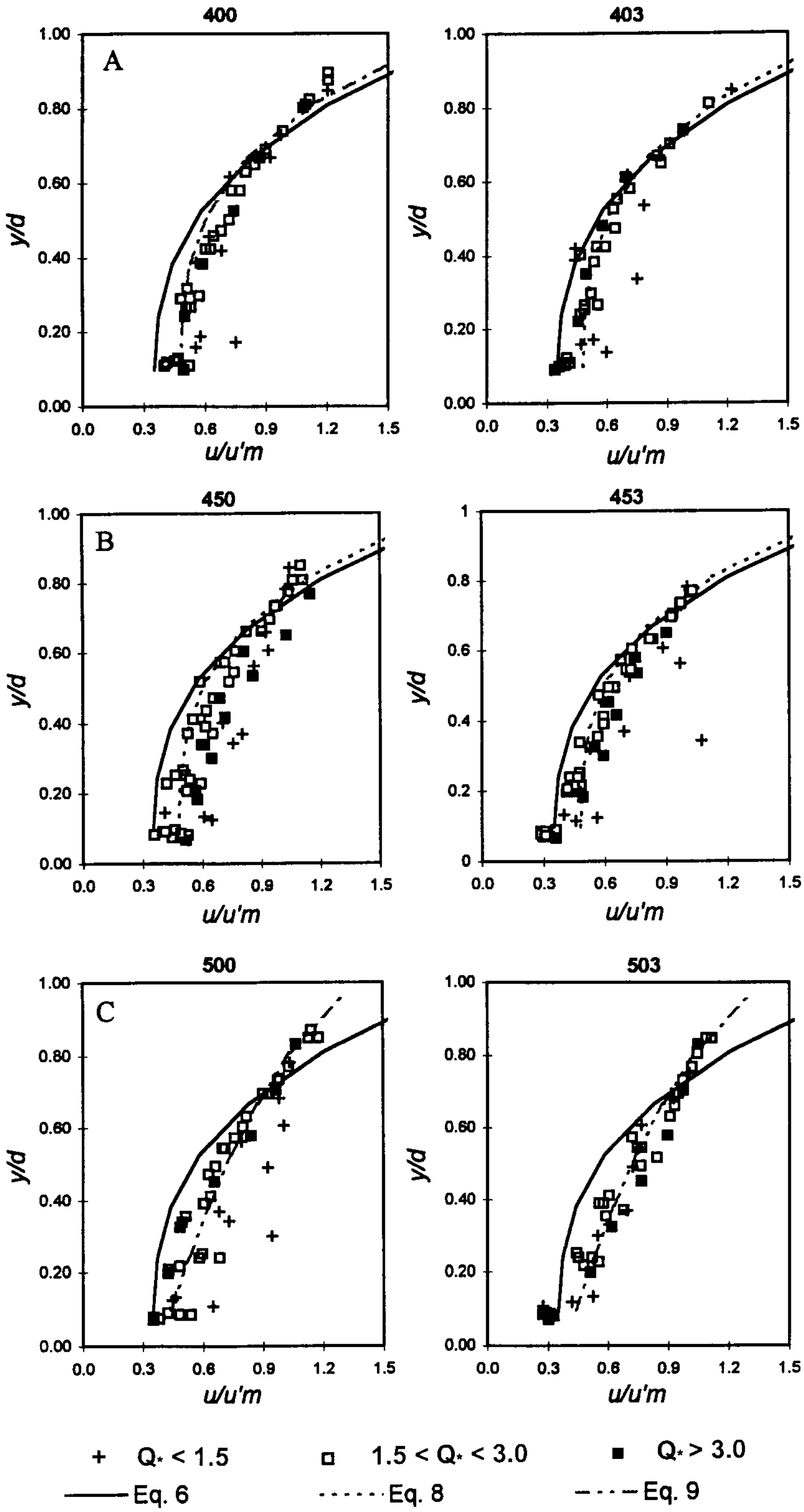

Fig. 11. Normalized velocity profiles for Designs (A) 400 and 403, (B) 450 and 453, (C) 500 and 503.

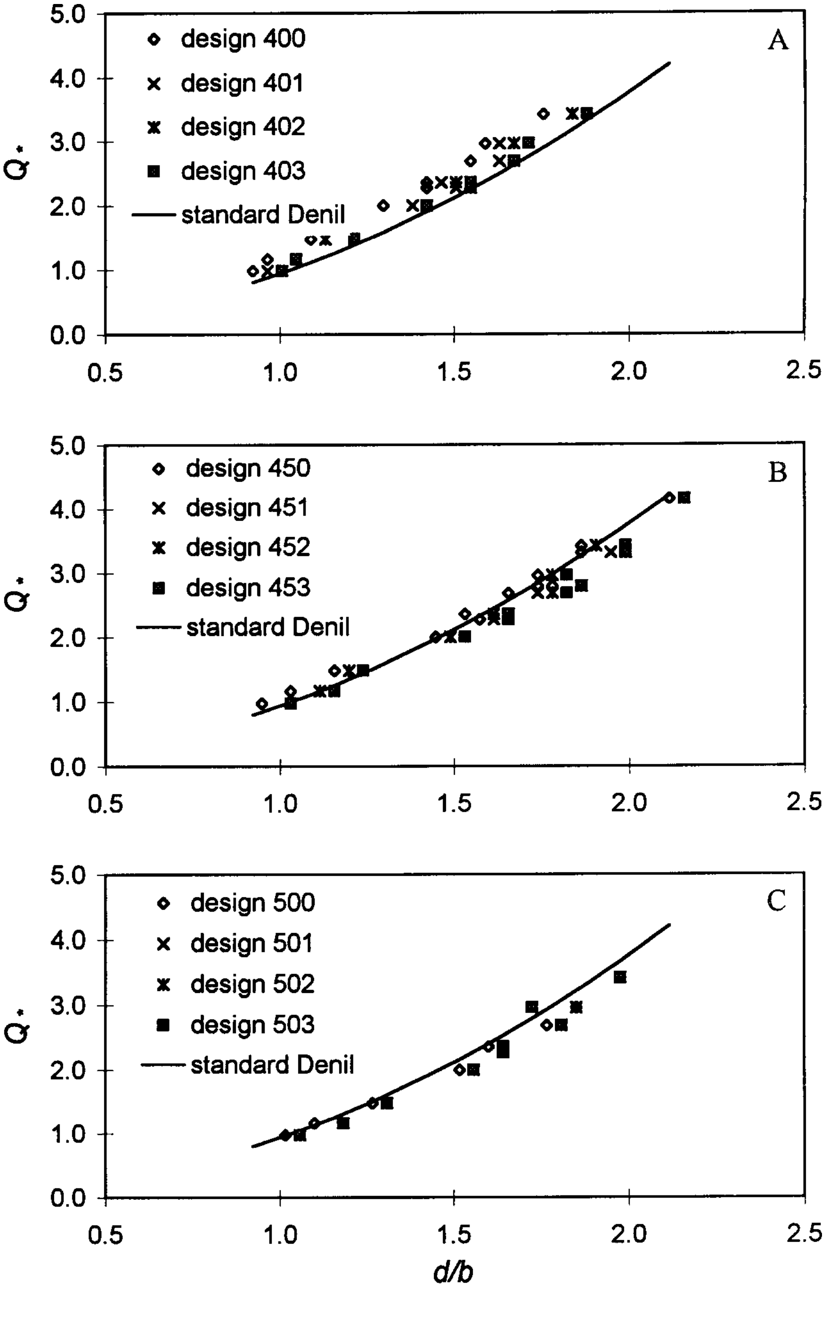

Fig. 12. Dimensionless discharge curve for a standard Denil fishway and measured dimensionless values for different designs with a different number of excessive baffles, (A) Design Series 40 (B) Design Series 45, (C) Design Series 50.

higher for Denil fishways with $B/b = 2$ than for the standard Denil reflecting higher water velocities in the cross section. There is only a slight difference in normalized velocity profiles when compared to the delineator of normalized velocity profiles for the standard Denil. Differences in normalized velocity profiles are most likely due to larger baffle spacing. In Denil fishways with $B/b = 2$, velocity distribution in the centerline is greatly affected by the discharge. For lower discharges with d/b less than 1.3, velocity distribution deviates from that of the standard Denil.

The dimensionless discharge curves for the standard Denil and for designs with different baffle angles are quite close to each other. Only for the designs with baffle angle of 40° to the bottom, the discharges are higher with the same relative water depth *d*/*b*. Normalized velocity profiles for designs with baffle angles of 40° and 45° differed only slightly when compared to that of the standard Denil. The few values that deviate from the main trend are the values for small dimensionless discharge Q_* (less than 1.5). The velocity distribution for designs with baffle angle of 50° is vertically more even at the centerline than for other designs.

Flow friction increases in the uppermost region of Denil fishways with *B*/*b* = 2 and flow development accelerates by dividing the uppermost baffle spacings. This results to higher water depths in the fishway and velocity distribution in the centerline of the fishway approaches that of the standard Denil fishway. For designs with baffle angle of 40°, the effect of excessive baffles was clear in all the discharges and for designs with baffle angle of 45° with higher discharges. For designs with baffle angle of 50°, excessive baffles had no noticeable effect.

The uppermost part of the Denil fishway is the most difficult for fish because there is always a region of higher velocities. The shorter the region is the easier the exit from the Denil flume is for fish. In Denil fishways with low relative depth *d*/*b* (less than about one), the flow has a low velocity region of significant thickness (Rajaratnam *et al.* 1987). Thus, for higher discharges, excessive baffles seem to be advantageous because they accelerate flow development in the upper part of the fishway. Even one excessive baffle may be enough. The studied discharges were, however, reasonably low and increasing the water depth over a certain limit (*d*/*b* more than about 3) might worsen the conditions for fish passage (Rajaratnam *et al.* 1987).

Clear trends were noticed in the dimensionless discharge curves and in normalized velocity profiles for designs with different baffle angles to the bottom when compared to those for the standard Denil. Thus, new experiments with a larger range of baffle angles and with wider discharge variety should be carried out.

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