EXPERIMENTAL STUDY OF DEPTH-DISCHARGE EQUATIONS AND VELOCITY PATTERNS ON VERTICAL SLOT FISHWAYS

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Abstract: Fishways are hydraulic structures that enable fish to go through transverse obstructions to continue their upstream migrations. This paper presents the results of a scale model of a vertical slot fishway. For two different slopes, the performance of two particular designs of vertical slot fishways was studied for a wide range of discharges. Water depths were measured in the almost all the surface of pools. A linear relation between dimensionless discharge and depth of flow, and the same flow patterns for each design were found. With an acoustic Doppler velocimeter (ADV), three-dimensional velocities were measured at several levels in the entire pool to appreciate the structure of the flow. Two different regions in flow patterns were found: a direct flow region characterized for maximum velocities; and a recirculation region, defined by small velocities and horizontal eddies.

INTRODUCTION

Fish populations in rivers are closely dependent on the characteristics of their aquatic habitat, this dependency is more critical in the case of migratory fish. Fish passage structures and in particular vertical slot fishways, try to minimize the negative effects caused by transverse hydraulics constructions. (Larinier *et al*. 1998).

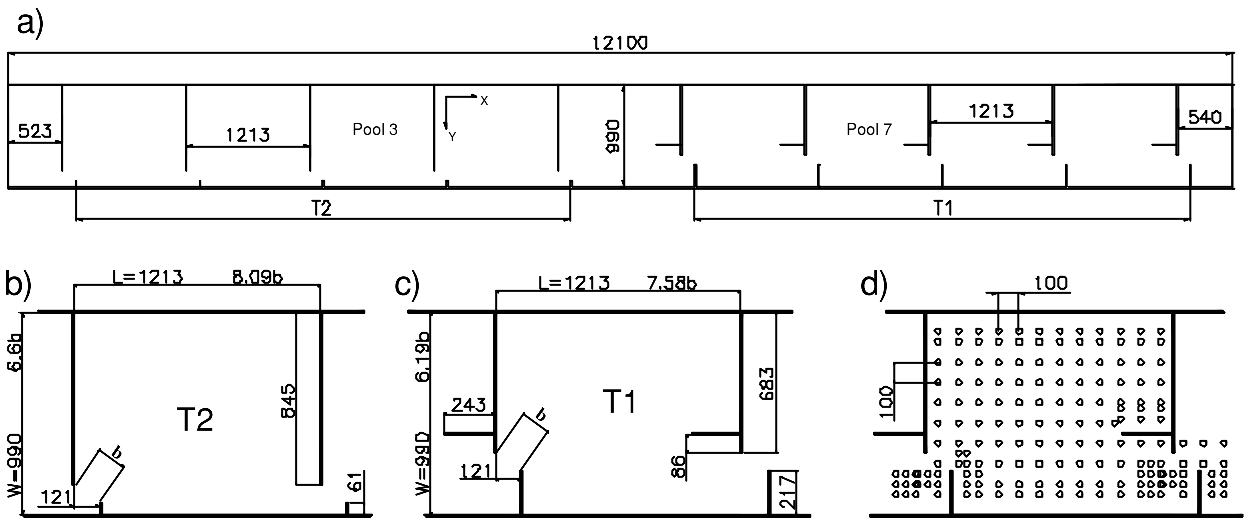

Fig. 1 a) Dimension of the laboratory model of a vertical slot fishway. b y c) Details of T1 and T2 designs. d) Data point mesh in a parallel plane to the bed for T1 design and for a slope of 10,054%.

The earliest vertical slot fishways was developed by Milo C. Bell and it was built at the Hell´s Gate on Fraser River, Canada (Clay, C.H. 1995).Vertical slot fishway consists of a rectangular channel with a sloping bed divided by baffles into a number of pools. Water travels down the channel through vertical slots, passing from one pool to the next one below (Wu *et al.*, 1999) to finally reach the river past the obstacle. The difference in water level between the upper and lower end of the fishway is divided into a number of small falls (Rajaratnam *et al*. 1986).

Table 1. Summary of experimental results

Des.	S_o	Q (m^3/s)	Q^A	Y_o (m)	Y_b (m)	Y_m (m)	Y_{max} (m)	Y_{min} (m)	V_b (m/s)	C_d	E_d (W/m^3)
T1	5,7	0.0159	0.4945	0.125	0.158	0.130	0.175	0.107	0.86	0.73	71.81
T1	5,7	0.0209	0.6529	0.176	0.195	0.179	0.215	0.143	0.85	0.79	67.13
T1	5,7	0.0246	0.7669	0.190	0.230	0.197	0.236	0.167	0.79	0.85	72.99
T1	5,7	0.0341	1.0624	0.253	0.306	0.262	0.313	0.212	0.88	0.80	75.94
T1	5,7	0.0458	1.4277	0.379	0.406	0.386	0.425	0.356	0.84	0.83	68.25
T1	5,7	0.0540	1.6827	0.437	0.476	0.445	0.483	0.400	0.87	0.82	69.74
T1	5,7	0.0641	1.9983	0.488	0.529	0.495	0.540	0.453	0.89	0.85	74.18
T1	5,7	0.0741	2.3104	0.604	0.604	0.608	0.652	0.562	0.88	0.87	69.35
T1	5,7	0.0859	2.6791	0.665	0.697	0.674	0.711	0.628	0.85	0.91	72.97
T1	10.05	0.0348	1.0847	0.155	0.201	0.171	0.253	0.093	1.25	0.86	223.25
T1	10.05	0.0445	1.3879	0.247	0.278	0.262	0.357	0.178	1.20	0.83	179.76
T1	10.05	0.0551	1.7174	0.314	0.371	0.331	0.420	0.242	1.21	0.77	174.88
T1	10.05	0.0643	2.0059	0.366	0.406	0.378	0.469	0.288	1.19	0.83	175.00
T1	10.05	0.0751	2.3425	0.436	0.505	0.452	0.541	0.363	1.25	0.75	171.72
T1	10.05	0.0849	2.6482	0.489	0.553	0.507	0.597	0.429	1.00	0.96	172.94
T1	10.05	0.0945	2.9478	0.526	0.561	0.541	0.634	0.443	1.17	0.90	179.16
T1	10.05	0.1044	3.2554	0.581	0.621	0.596	0.690	0.513	1.05	1.01	179.11
T1	10.05	0.1150	3.5856	0.641	0.681	0.656	0.755	0.556	1.06	1.00	178.79
T2	5,7	0.0160	0.5855	0.102	0.109	0.152	0.061	0.682	0.95	1.05	88.18
T2	5,7	0.0250	0.9153	0.169	0.180	0.225	0.122	1.125	0.93	0.97	83.64
T2	5,7	0.0350	1.2811	0.263	0.274	0.323	0.214	1.750	0.99	0.84	75.23
T2	5,7	0.0453	1.6585	0.350	0.362	0.408	0.298	2.336	1.00	0.81	72.96
T2	5,7	0.0540	1.9772	0.439	0.449	0.497	0.376	2.928	0.97	0.82	69.39
T2	5,7	0.0639	2.3405	0.524	0.531	0.577	0.475	3.495	1.09	0.72	68.82
T2	5,7	0.0741	2.7131	0.606	0.613	0.660	0.552	4.040	0.87	0.92	69.02
T2	5,7	0.0840	3.0785	0.670	0.679	0.732	0.615	4.468	0.96	0.82	70.81
T2	10.05	0.0253	0.9277	0.134	0.138	0.208	0.080	0.892	1.14	0.75	188.43
T2	10.05	0.0352	1.2912	0.206	0.202	0.276	0.132	1.375	1.23	0.79	170.20
T2	10.05	0.0453	1.6601	0.248	0.251	0.329	0.152	1.656	1.32	0.79	181.73
T2	10.05	0.0549	2.0100	0.307	0.311	0.405	0.212	2.048	1.32	0.80	177.95
T2	10.05	0.0645	2.3644	0.371	0.372	0.461	0.275	2.471	1.27	0.85	173.48
T2	10.05	0.0746	2.7325	0.431	0.432	0.515	0.330	2.873	1.31	0.83	172.42
T2	10.05	0.0838	3.0718	0.483	0.480	0.569	0.380	3.222	1.33	0.83	172.81
T2	10.05	0.0954	3.4955	0.536	0.539	0.623	0.437	3.577	1.30	0.85	177.17
T2	10.05	0.1048	3.8398	0.578	0.578	0.657	0.483	3.853	1.30	0.87	180.66
T2	10.05	0.1151	4.2177	0.615	0.612	0.714	0.505	4.100	1.46	0.80	186.50
T2	10.05	0.1248	4.5739	0.650	0.649	0.745	0.536	4.332	1.28	0.91	191.39

A previous experimental research on the hydraulics of vertical slot fishways was considered, this is the research at the University of Alberta (Canada) by Rajaratnam *et al.* (1986, 1992, 1999) where 18 different designs were studied for the following range of slopes S_o=5, 10 and 15%. This paper, trying to continue the research line begun by Wu *et al.* (1999) on the detailed study of the designs recommended as effective by Rajaratnam *et al.* (1992), focus on an experimental hydraulic characterization of a scale model of the other two particular vertical slot fishway designs: the so called design T1 (similar to design 16) and design T2 (similar to design 6). Configurations and dimensions of pools are shown in Fig. 1b and Fig. 1c. An experimental program was planned and a detailed study of depth and velocity fields was conduced, since both of them are the most important parameters on the hydraulic performance of vertical slot fishway.

EXPERIMENTAL ARRANGEMENT

The experimental work was carried out at the CITEEC (Centro de Innovación Tecnolóxica en Edificación e Enxeñería Civil) at the Universidade da Coruña (Spain). The fishway scale model consists of a metallic structure 12 m long with a rectangular section of 1x1 m^2. The fishway scale model is constructed in such a way that it can adopt different slopes. The fishway is divided into eleven pools. The first four pools present a T2 configuration, the following pool is of a transition type and finally the other four pools present a T1 configuration. The flume bed, side walls and the baffles separating the pools were made of transparent plexiglass sheets (1 cm thick) that allows flow observations. Baffles were always vertical, despite of the slope in the fishway model. The experimental measurements took place in pools number 3 and 7 (Fig. 1a).

A cartesian positioner was placed over experimental pools in order to automate the positioning of the measurement instruments. The measurement instruments can be set automatically at any point in the pool (3D mesh). Not simultaneously, two measurement devices were placed on the cartesian positioner: a depth probe and ADV velocimeter. Velocities were measured by means of a Doppler effect velocimeter (MicroAcoustic Doppler Velocimeter SonTek). Water surface height in the pools was measured by means of a conductivity-based depth probe, DHI Wave Gauge Type 202. The DHI Wave Gauge is comprised of two thin parallel stainless steel electrodes.

A summary of experimental measurements is shown in Table 1.

ANALYSIS OF THE EXPERIMENTAL RESULTS

For the representation of the experimental results, the following dimensionless variables were chosen: So, geometric slope of the fishway, Yo/b, relative flow depth at the transverse middle section, Q^A, dimensionless discharge. A new definition (Rajaratnam et al. (1986) Kamula (2001)) for the dimensionless discharge is proposed:

$$Q^A = Q \Big/ \sqrt{g\, b^5} \qquad \textbf{[1]}$$

A summary of the most significant data from the experiments realized are shown in Table 1, where, Y_b is the depth at the slot and Y_m is the average depth in the pool, being Y_{max} and Y_{min} the maximum and minimum depth in the pool respectively. V_b is the velocity at slot, $C_d = Q/(bY_bV_b)$ is a coefficient of discharge which is provided to permit a comparison with the ones shown by Rajaratnam *et al.* (1992) and $E = (rgQS_o)/(LWY_0)$ is the energy dissipation rate in the pool.

DEPTH-DISCHARGE EQUATION

Following the indications by Rajaratnam *et al.* (1986), a simple analysis was realized to find the flow equations which establish the relationship between the discharge and the depth:

$$Q^A = a\left(\frac{Y_0}{b}\right)^l \qquad \textbf{[2]}$$

where $Q^A = Q/\sqrt{g\,b^5}$ is the dimensionless discharge in the fishway model, Y_o/b is the relative flow depth, and α, λ are coefficients relating the dimensionless discharge and the relative flow depth. The experimental results: relative depth Y_o/b versus the nondimensional discharge can be seen in Fig. 2, and the corresponding flow equations are shown in Table 2. The values of the α are proportional to the slope. A higher value for the proportionality factor (steepest line) means that for the same discharge the depth reached is lower and therefore the velocity profiles should increase, which means a higher efficiency in conveyance.

Table 2. Flow equations, relationship between dimensionless discharge and relative depths. In parentheses, correlation coefficent (r^2).

Design	So	Q^A	Y_{min}/b	Y_b/b	Y_{max}/b	Y_m/b
T1	5,7%	0.631Yo/b (0.9946)	0.9739Yo/b-0.1409 (0.9986)	0.9758Yo/b+0.2512 (0.9944)	0.9993Yo/b+0.3018 (0.9992)	1.015Yo/b (0.9998)
	10.054%	0.8888Yo/b (0.9889)	0.9742Yo/b - 0.3822 (0.9979)	1.0008Yo/b+0.2918 (0.9933)	1.021Yo/b+0.6133 (0.9996)	1.033Yo/b (0.9987)
T2	5,7%	0.6867Yo/b (0.9903)	0.9789Yo/b-0.2871 (0.9994)	1.031Yo/b+0.0407 (0.9983)	1.0065Yo/b+0.3583 (0.9997)	1.0183Yo/b (0.9994)
	10,054%	0.9988Yo/b (0.9903)	0.9196Yo/b-0.4069 (0.9965)	0.9949Yo/b+0.2826 (0.9949)	1.0323Yo/b+0.4811 (0.9982)	1.0002Yo/b (0.9997)

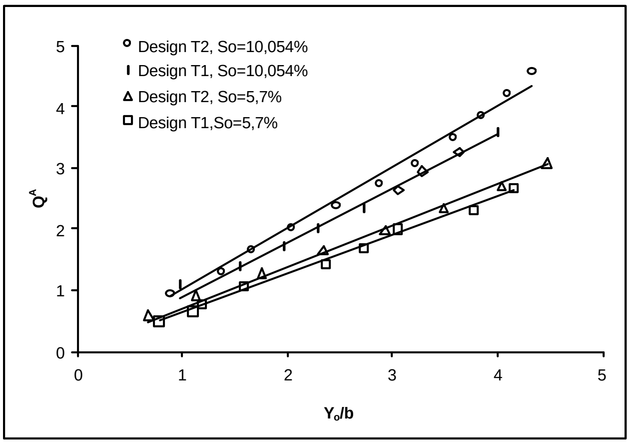

Fig. 2 Dimensionless relationship a) Q^A against Y_o/b.

DEPTH DISTRIBUITON

The average depth at the middle transverse section has been chosen to verify the performance of the design, but it is also important to know the values of other characteristic depths as Y_{max}, Y_b, Y_m and Y_{min}. Each of them inform us of a particular feature of the fishway: wall design criteria (Y_{max}), the limitations that depth can suppose to fish passage (Y_{min}) and also to know the depth at critical sections (Y_b).

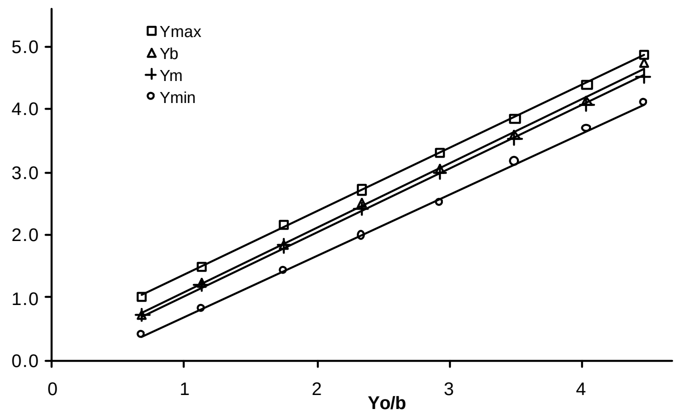

Fig. 3 Relationship between characteristic depths, in T2 design for S_0=5,7%.

A linear relationship has been found between each of the different characteristic depths and the relative flow depth at the middle transverse section Y_o/b,

$$Y/b = \alpha'\left(Y_0/b\right) + \beta' \qquad [\ 3\ ]$$

where Y stands for any of the characteristic depths, α´,β´ are coefficients which depend on the related characteristic depths, on the slope and on the configuration of the baffles (Table 2).

In Fig. 3, the experimental results for the different characteristic depths versus Y_o/b can be seen as well as the corresponding equations (straight lines graphs).

WATER SURFACE

Typical level contours can be observed in Fig. 4, for the four experimental situations studied and for a single discharge of 0.065 m^3/s. There is always a region of large depths just upstream of the slot and also at the region downstream of the pool, nearest to the larger baffles. Just at the slot itself there is a sharp drop in the depth and in going down the slot, following the jet direction, there is a region of minimum depths as a consequence of such decay. Depth patterns are quite independent of flow rates.

Since the configurations patterns of the water surface are independent of discharges, the performance of the vertical slot fishway remains stable with variations in flow rates. This stability is one of the most important characteristic concerning the application of vertical slot fishway.

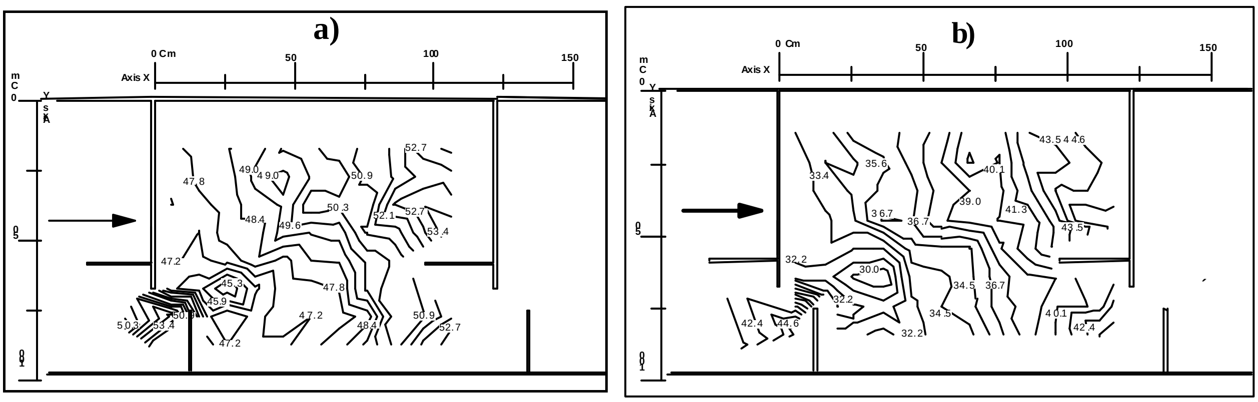

Fig. 4. Contour lines of water free surface (data model), for a discharge Q=0.065 m^3. a) Design T1, S_o=5,7%. b) Design T1, S_o=10,054%.

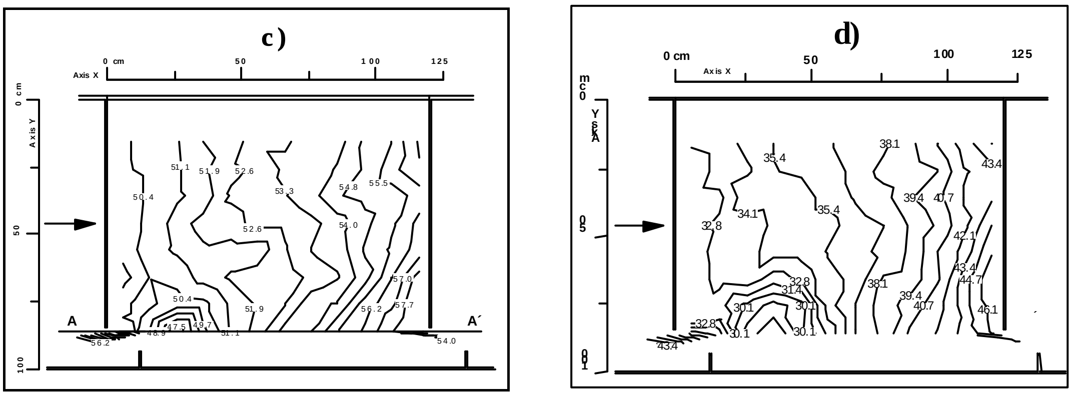

Fig. 4. Contour lines of water free surface (data model), for a discharge Q=0.065 m^3 c) Design T2, S_o=5,7%. d) Design T2, S_o=10,054%.

FLOW PATTERNS

The velocity fields taken in planes parallel to the bed are shown in Fig. 5, where horizontal components (V_x and V_y) of the velocity vectors can be seen. A reference vector is included in order to make the comprehension of the figures more intuitive.

It can be observed in a general way how two different kinds of regions are formed: one that will be called direct flow region, where the flow circulates in a curved trajectory at high speed from one slot to the next slot downstream; and the others that will be called recirculation regions, which are characterized by smaller velocities, flow in the reversed direction and by the existence of vertical axis eddies. Two recirculation regions of a different size and separated by the direct flow region, are shown in the flow patterns; the larger one, close to the long baffles and the smaller one by the short baffles.

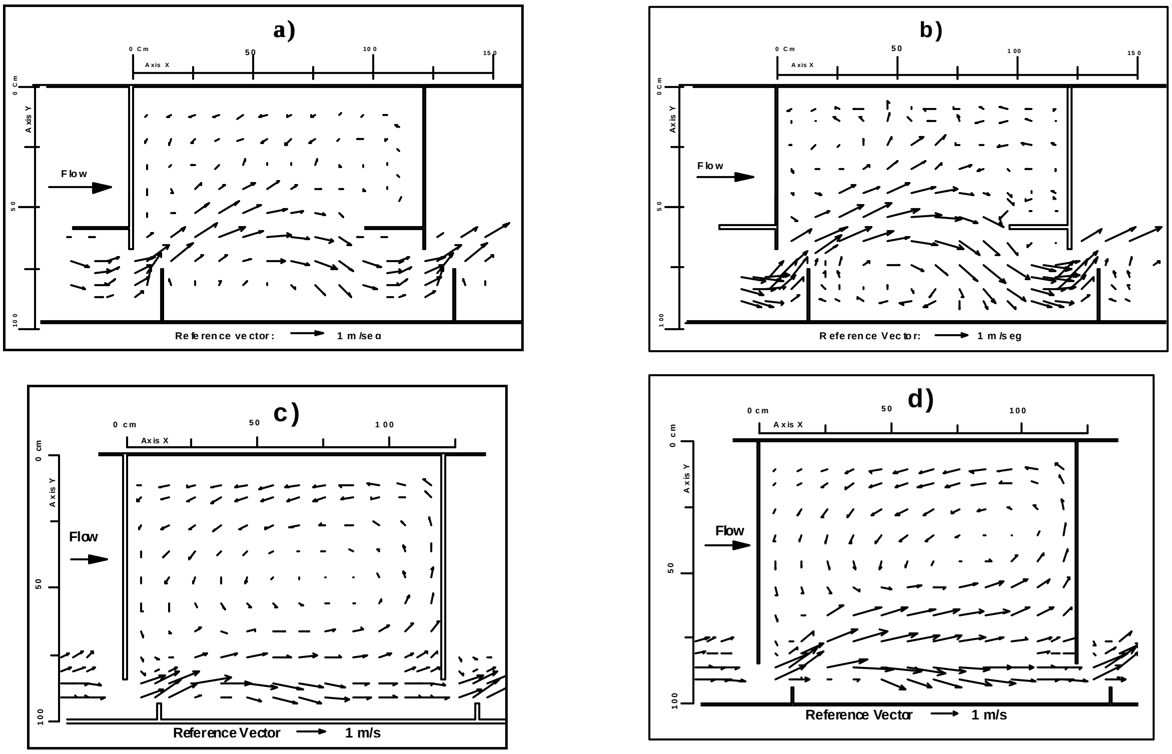

Fig. 5 Horizontal velocity fields, V_x-V_y in planes parallel to the bed for several experimental situations: a) Design T1, S=5,7%, Q=85 l/s, h=35 cm; b) Design T1, S=10,054%, Q=105 l/s, h=5 cm; c) Design T2, S=5,7%, Q=54 l/s, h=25 cm; d) Design T2, S=10,054%, Q=75 l/s, h=25 cm

Flow is basically bidimensional in both designs, independently of slope and discharge; in other words, Z-direction flow velocity is minimal by comparison with flow velocity in the X and Y directions. Furthermore, flow velocity shows little variation with depth. Flow patterns are more stable in response to variations in discharge and slope in baffle design T2 than in baffle design T1 (Fig.5).

a) **b)** **c)**

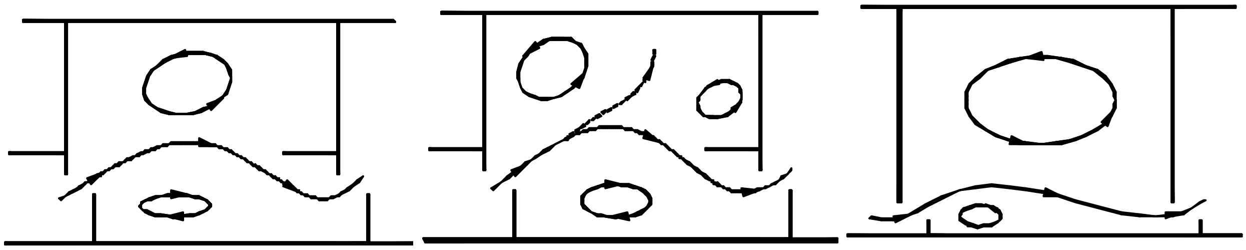

Fig. 3 Flow patterns in pools: a) Design T1, S_o=5,7%; and S_o=10.054% with Q^A<2.75. b) Design T1, S_o=10.054% with Q^A>2.75. c) Design T2.

CONCLUSIONS.

For their usual slopes, the performance of two particular vertical slot fishway designs has been studied for a wide range of discharges. A linear relationship has been found between the dimensionless discharge and the average depth at the middle transverse section, as well as some linear trends among the different characteristic water depths. Hydraulic behaviour patterns have been found for both types. In those patterns, two clear regions were distinguished: the recirculation regions characterized by small velocities, horizontal eddies and reversed flows; and the direct flow region characterized by bidimensionality and maximum velocities.

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