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階段式魚道에서 隔壁 形狀에 따른 水理學的 特性 및 魚類의 上流移動

Hydraulic Characteristics and Upstream Migration of Fish by the Weir Type in a Pool-Weir Fishway

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Abstract

This study deals with hydraulic characteristics and their effects on upstream migration of fish by the weir type in a pool-weir fishway, and presents an optimal type of weir for an easy upstream migration. Experiment was performed to estimate hydraulic conditions by the weir type and to determine which type was good. The results showed that a rectangular weir with a small rectangular notch installed by a zig-zag type was preferable to a simple weir with no notch or to a trapezoidal weir, since it makes possible for upstream migration even when a water level draws down and moreover, it makes falling flow through a notch which facilitates upstream migration. It was proposed that the notch must be designed that the flow situation may keep the streaming flow so long as the maximum flow velocity does not exceed the critical swiming velocity, i.e., the dimensionless flow rate may exist within the range of 0.27 and 0.41.

요 지

본 연구에서는 階段式魚道의 隔壁 형상에 따른 수리학적 특성과 어류의 상류이동에 미치는 효과를 다루고 있으며, 상류이동이 용이하도록 격벽의 적정 형태를 제시하는 것으로 하였다. 격벽 형상에 따른 수리학적 특성을 조사하고 적정 형태를 결정하기 위해 수리실험을 실시하였다. 실험결과 zig-zag 형태로 설치된 작은 notch를 가진 직사각형 격벽이 notch가 없는 단순 직사각형 격벽이나 사다리꼴 형태의 격벽보다 좋은 것임이 밝혀졌는데, 이는 水位 低下時에도 어류의 상류이동이 가능하고 더우기 상류이동을 용이하게 하는 notch를 통한 落下 흐름을 형성하기 때문인 것으로 판단되었다. Notch는 월류 최대유속이 어류의 유영한계유속을 넘지않는 범위 내에서 表面流를 지속하도록, 즉 無次元流量 값이 0.27과 0.41 범위 내에 들도록 설계하는 것이 바람직한 것으로 나타났다.

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1. Introduction

At a weir and a dam, fishway is installed for upstream migration of fish. In many countries, if a hydraulic structure poses potential problems for the passage of fish, a fishway is required by law (Hirose and Nakamura, 1991). For a fish having strong swimming and jumping ability such ayu, salmon, perch and grey mullet, a pool-weir fishway is installed. The pool-weir fishway consists of successive weirs and pools as shown in Fig. 1. It is called as a fish ladder in some countries (Nakamura and Yotskura, 1987).

A slight different shape of a weir can alter the flow conditions in the fishway and hence can have influence on the upstream migration of fish. If the flow velocity over the weir exceeds the critical velocity for upstream migration, fish cannot or can hardly move against a flow direction. Occurrence of turbulent jet, eddies, and circulating flow prevent fish from moving upstream. So, it is important to determine an optimal type of a weir for fish to migrate upstream easily without consuming time and without being fatigued. Hydraulic experiment on a fishway is very useful for estimating complicated flow phenomenon such as turbulent jets, eddies, and circulation and for determining the optimal type of the weir (Hirose and Nakamura, 1991). The objective of this study is to examine flow conditions and their effects on upstream migration of fish on the existing typical type of the weir in a pool-weir fishway and to provide an optimal shape of the weir for an easy upstream migration of fish through hydraulic experiments.

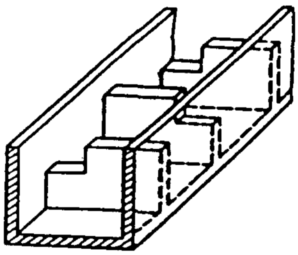


Fig. 1. The Pool-Weir Fishway

2. Experimental Set up and Measurements

The experiments were performed to examine the flow conditions of the fishway. Fig. 2 is the typical fishway model installed in a seadike to the West Sea (Kim, 1993). This model consists of a pool-weir fishway, an attraction channel, and an eel fishway. It is made of transparent acrylic plates, of which the thickness is 30mm, for making visible of flow phenomenon. Its scale is 1/10, the width is 56cm and the length is 452cm. A thick screen was laid at the entrance of a fishway model to reduce a turbulence and to make a flow uniform. The discharge which is controlled by a valve in a feed-back loop could

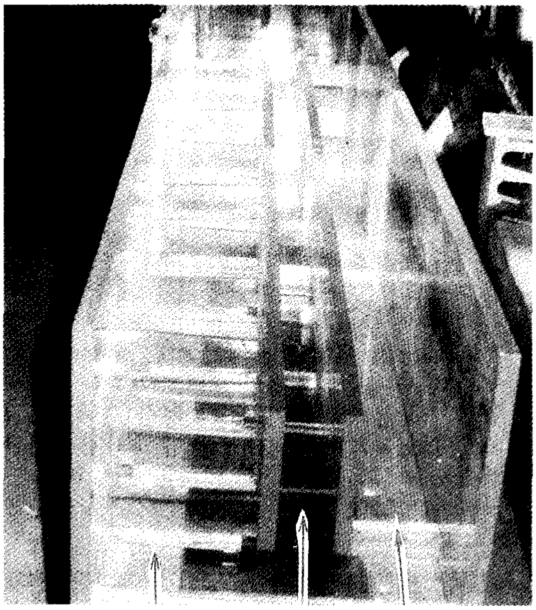


Fig. 2. The Fishway Model (s = 1/10)

be measured with a v-notch at the upstream end. The scope of this study was to the pool-weir fishway. It was designed for upstream migration of fish such as a perch and a grey mullet. Its width is 30cm, the length is 452cm, the distance between weirs is 30cm, and the slope is 1:20. The type of the weir is trapezoidal and its height is 8cm or 9cm at end, which will be shown in Fig. 5. Beneath the weir, the small rectangular orifice, of which the size is 2.5cm ×2.5cm, was made for the purpose of removing deposited bed material in a pool and for upstream migration of an eel. The location of the orifice is reciprocal to an adjacent weir.

Flow velocity was measured by using a two-dimensional acoustic doppler velocity meter. Velocity range is (−)1.0～(+)1.0m/s, respectively. To check a flow pattern, dye injection and a video camera with strong light were used. Tables 1 and 2 show the experimental conditions in the rectangular weir with a notch in a plunging flow and in a streaming flow, respectively. Here, the discharge means one per unit width and the water level means an elevation. Experimental conditions in the trapezoidal weir are shown in some others (Kim and Kim, 1994; Kim, 1993)

Table 1. Experimental Conditions in a Plunging Flow

Run Number	Water Level E.L.(m)	Weir Side			Notch Side			Index
		Flow Depth (m)	Velocity (m/s)	Discharge (m^2/s)	Flow Depth (m)	Velocity (m/s)	Discharge (m^2/s)	
p1	(−)1.688	0.012	0.16	0.002	0.112	0.48	0.054	
p2	(−)1.684	0.016	0.20	0.003	0.116	0.49	0.057	
p3	(−)1.680	0.020	0.22	0.004	0.120	0.55	0.066	
p4	(−)1.678	0.022	0.24	0.005	0.122	0.61	0.074	
p5	(−)1.675	0.025	0.28	0.007	0.125	0.56	0.070	
p6	(−)1.670	0.030	0.29	0.008	0.130	0.69	0.090	
p7	(−)1.668	0.032	0.31	0.010	0.132	0.70	0.092	
p8	(−)1.665	0.035	0.35	0.012	0.135	0.76	0.103	
p9	(−)1.662	0.038	0.33	0.012	0.138	0.66	0.091	
p10	(−)1.660	0.040	0.36	0.014	0.140	0.72	0.101	
p11	(−)1.658	0.042	0.41	0.017	0.142	0.79	0.112	
p12	(−)1.657	0.043	0.40	0.017	0.143	0.73	0.104	
p13	(−)1.655	0.045	0.42	0.019	0.145	0.79	0.115	
p14	(−)1.654	0.046	0.46	0.021	0.146	0.76	0.111	
p15	(−)1.653	0.047	0.45	0.021	0.147	0.74	0.109	
p16	(−)1.653	0.047	0.44	0.021	0.147	0.80	0.118	
p17	(−)1.652	0.048	0.44	0.021	0.148	0.86	0.127	
p18	(−)1.652	0.048	0.45	0.022	0.148	0.85	0.126	

Table 2. Experimental Conditions in a Streaming Flow

Run Number	Water Level E.L.(m)	Weir Side			Notch Side			Index
		Flow Depth (m)	Velocity (m/s)	Discharge (m^2/s)	Flow Depth (m)	Velocity (m/s)	Discharge (m^2/s)	
s1	(−)1.500	0.200	1.10	0.220	0.300	1.22	0.396	
s2	(−)1.500	0.200	1.08	0.210	0.300	1.25	0.375	
s3	(−)1.510	0.190	1.10	0.209	0.290	1.21	0.351	
s4	(−)1.515	0.185	0.98	0.181	0.285	1.18	0.336	
s5	(−)1.525	0.175	0.95	0.166	0.275	1.17	0.322	
s6	(−)1.530	0.170	0.98	0.167	0.270	1.18	0.319	
s7	(−)1.530	0.170	0.97	0.165	0.270	1.14	0.308	
s8	(−)1.535	0.165	0.92	0.140	0.265	1.12	0.297	
s9	(−)1.540	0.160	0.80	0.128	0.260	1.04	0.270	
s10	(−)1.540	0.160	0.82	0.131	0.260	1.02	0.265	
s11	(−)1.545	0.155	0.80	0.124	0.255	1.06	0.270	
s12	(−)1.555	0.145	0.76	0.110	0.245	0.95	0.233	
s13	(−)1.560	0.140	0.75	0.105	0.240	0.94	0.226	
s14	(−)1.565	0.135	0.74	0.100	0.235	0.94	0.221	
s15	(−)1.575	0.125	0.75	0.094	0.225	0.86	0.194	
s16	(−)1.580	0.120	0.72	0.086	0.220	0.84	0.185	
s17	(−)1.585	0.115	0.70	0.081	0.215	0.76	0.163	
s18	(−)1.590	0.110	0.70	0.077	0.210	0.78	0.164	

3. Flow Characteristics and Its Effects on Upstream Migration of Fish in a Trapezoidal Weir

Flow in the pool-weir fishway changes from plunging flow to streaming flow by an increase of discharge (Hirose and Nakamura, 1991). Transition zone exists between these two flows, where two flows occur alternately. According to Katopodis (1987), these two flows are determined by the following dimensionless flow rate equation:

$$\widehat{Q}=\frac{Q}{BSL^{3/2}\sqrt{g}} \tag{1}$$

where $\widehat{Q}$ is a dimensionless flow rate, Q is a flow discharge, B is a width of a fishway, S is a slope of a fishway, L is a length of a pool, and g is a gravitational acceleration. Katopodis (1987) found that transition zone existed roughly at $\widehat{Q} \fallingdotseq 0.25$ through experiments. In this study, transition occurred between 0.20 and 0.27, which was almost the same as his results.

3.1 Flow Characteristics in a Trapezoidal Weir

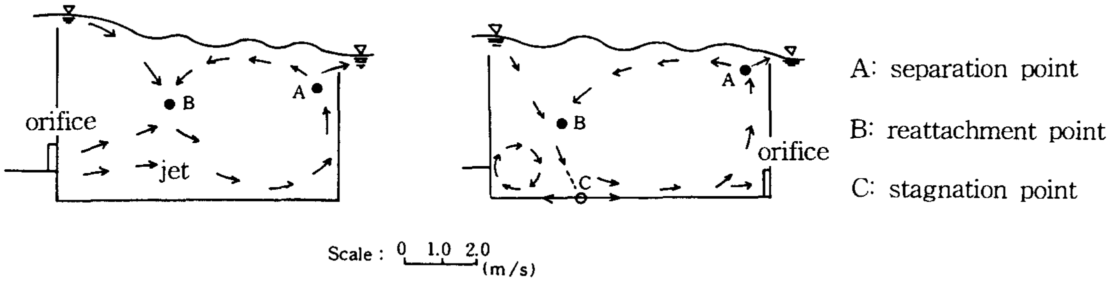
Fig. 3 shows a plunging flow at $\widehat{Q} = 0.15$ in a pool in case the weir type is trapezoidal. In Fig. 3(a), where the rectangular orifice is installed beneath the front weir, a flow passed out of the orifice forms a turbulent jet whose velocity is about 1.4 m/s, which exceeds a critical swimming velocity. Here, the critical swimming velocity means one where a fish can migrate upstream without being pushed out by a flow, which is known to be about 1.2m/s for a perch and 0.5m/s for an eel (Katopodis, 1987; Yu, 1986). It can be seen that the orifice, which originally was made for an upstream migration of an eel, is not effective since there occurs turbulent jet and eddies and their velocity exceeds the critical flow velocity. For the upstream migration of an eel, an eel fishway must be installed. Its structural type and construction method are well studied (Hirose and Nakamura, 1991; Kim, 1993). The flow is separated at a point A and reattached at a point B forming a vertical circulating flow. In Fig. 3(b), where the orifice is not installed beneath the front weir, the vertical circulating flow occurs, but its area is larger than that in Fig. 3(a) since there is no orifice and hence no turbulent jet. There exists smaller circulating flow near the upstream weir whose direction is opposite to a larger one.

Fig. 4 shows the streaming flow at $\widehat{Q} = 0.39$. In Fig. 4(a), where the rectangular orifice is located beneath the front weir, the turbulent jet occurs from the orifice. Its velocity is about 1.8 m/s, which is not good for the upstream migration of fish. Here, the velocity is that transformed into a prototype and fish means a perch or a grey mullet, and so on. A vertically circulating flow also occurs but its direction is opposite to that in Fig. 3(a). In Fig. 4(b), where the orifice is not located beneath the front weir, circulating flow which is larger than that in Fig. 4 (a) occurs covering the whole section of the pool since there occurs no jet. This result is the same as in Fig. 3. The circulating flow is not good for the migration of fish since the fish moves against the flow direction, which means that the fish continues rotation against the circulating flow and feels tired (Kim and Kim, 1994).

Three-dimensional schematic streaming flow at $\widehat{Q} = 0.39$ in Fig. 4 is shown in Fig. 5. Flow velocity and flow pattern were measured by using a two-dimensional acoustic doppler velocity meter, dye injection and a video camera with strong light. Here an arrow means the flow direction and its thickness means a flow quantity. So, the thicker an arrow is, the larger a flow quantity is. Large flow occurs on the lower part of the trapezoidal weir. Its maximun velocity is about 0.9m/s, which does not exceed the critical velocity for a fish. Since the lower part of the successive trapezoidal weir is installed reciprocally to an adjacent one, the large flow forms a S-type. Turbulent jet also occurs from the orifice. Plunging flow or streaming flow occurs over the whole section by the same type, the reason of which seems that the primary flow dominates the flow characteristics.

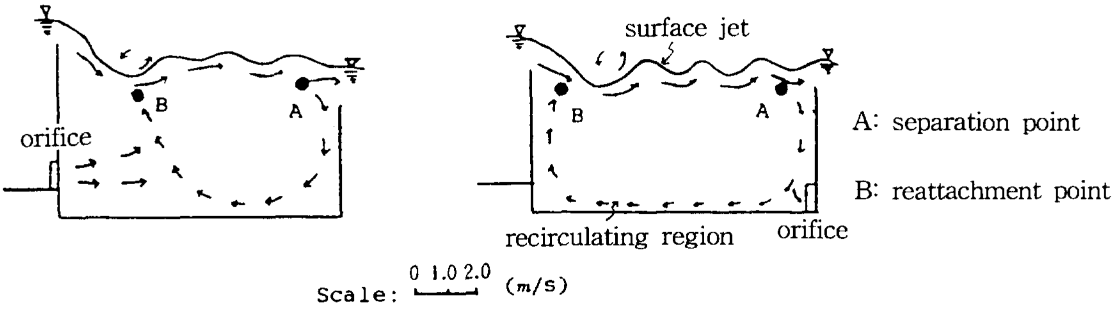
3.2 Upstream Migration of Fish in a Trapezoidal Weir

Fish which moves against a flow tries to raise a head toward a flow direction so as not to be pushed out by a flow, which is called as positive movement (Hirose and Nakamura, 1991). And a fish approaches toward an eddy zone since an oxygen is provided through an air entrainment, but does not move into it. The fish swims over each weir using its burst speed, or in some cases by jumping over them. The fish then rests in the pool for a while before passing over the next weir and so on, till it swims into the up-



(a) Orifice Installed beneath a Front Weir (b) Orifice Not Installed beneath a Front Weir

Fig. 3. Plunging Flow in a Trapezoidal Weir



(a) Orifice Installed beneath a Front Weir (b) Orifice Not Installed beneath a Front Weir

Fig. 4. Streaming Flow in a Trapezoidal Weir

stream region. These were confirmed by experiments and field tests (Katopodis, 1987; Yu, 1986). From these results, we can estimate an upstream migration of fish for given flow conditions in a pool-weir fishway.

Fig. 6 shows a flow situation and the upstream migration of fish in an A and a B section of a pool at $\hat{Q} = 0.39$. Here, an A section is one where the orifice is installed and a B section is the lower part of the weir where the orifice is not installed. A dotted area means an eddy flow zone, an arrow means a flow path, and an arrow with black circle means a jumping location and moving path of fish. An extent of eddy flow becomes large to a horizontal (longitudinal) direction at a B section, since the large flow occurs on the lower part of the weir and the flow velocity becomes large. But it becomes not so large to a vertical direction. While, at an A section, it becomes large to a vertical direction due to a turbulent jet from an orifice.

At an A section in Fig. 6(b), fish tries to move upstream but can not due to a vertically widespread eddy zone and due to an influence of jet from an orifice. So, the fish tries to jump up towards the upstream pool apart from the weir, but falls to the same place and fails. While, at a B section, fish can approach to the weir through below the eddy zone and jump up towards the upstream pool. In Fig. 6(a), thickness of an arrow means the frequency of a jumping. The thicker an arrow is, the more frequently a fish jumps. So, in the trapezoidal weir, fish moves upstream mainly through the lower

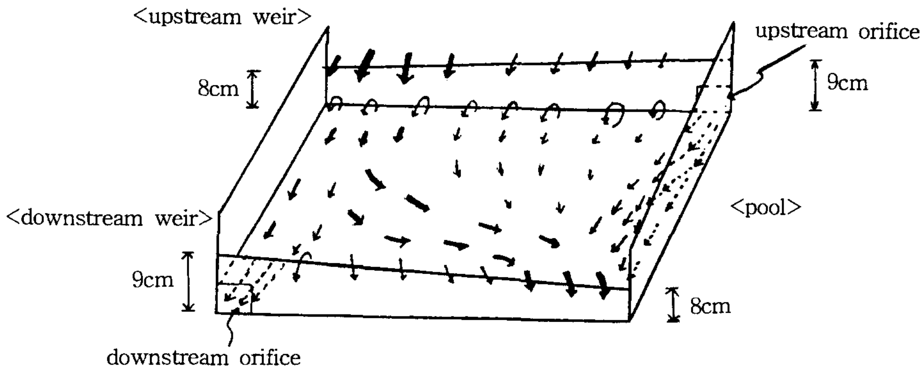
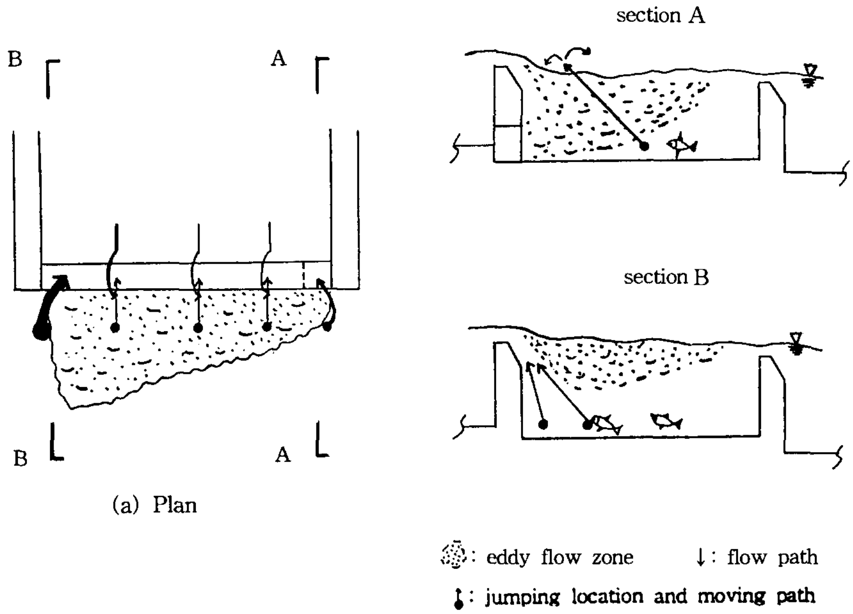


Fig. 5. Three-Dimensional Schematic Streaming Flow in a Trapezoidal Weir



(a) Plan (b) Section

Fig. 6. Flow Situation and an Upstream Migration of Fish in a Trapezoidal Weir

part of the weir with no orifice by a S-type.

The trapezoidal weir is not effective for upstream migration of fish in case a water level draws down, since it gives no appropriate overflow depth for a fish and the rectangular weir is also not effective for the above same reasons (Kim, 1994). The appropriate overflow depth means one through which the fish can jump and move towards the upstream pool safely. If the overflow depth is lower than the appropriate overflow depth, the fish gets hurt during jumping and moving. And if the overflow depth is higher than it, the fish hardly or can not move due to an increase of overflow velocity. For a perch, it is about 10 cm, which is a little larger than the summation of a thickness of a fish body and a fin (Hirose and Nakamura, 1991).

If the rectangular notch is made on the weir, fish can move through the notch utilizing falling flow from it even when the flow depth over the weir is lower than the appropriate overflow depth. So, the rectangular weir with a rectangular notch can be considered.

4. Flow Characteristics and Its Effects on Upstream Migration of Fish in a Rectangular Weir with a Notch

The rectangular weir with a notch can be considered as two types by the location of the notch. It can be made by a straight or a zig-zag type to an adjacent weir, which is shown in Fig. 7. The width of the notch is 10cm, which is almost equal to one-third to that of the weir. And the depth of the notch is 1.0cm. Experimental results showed that both the straight type and the zig-zag type were good for upstream migration of fish on the notch side in case the slope is 1:20. While behind the weir side, the zig-zag type can give a rest pool for fish, whose velocity is about 0.5m/s, but the straight type cannot give a rest pool, since the flow velocity is relatively low (about 0.2m/s) and a fish does not enter this pool. Seiches, which occurs in the zig-zag type and is not good for the upstream migration of fish (Nakamura, 1995), did not occur in this study since the slope of fishway is low. The straight type is known to be preferable to the zig-zag type in case the slope is 1:10 or higher, since the seiches occurs (Nakamura, 1995). Criteria choosing the type for the variation of the slope of fishway will be further studied. In this study, the zig-zag type was chosen for considering the existing slope (1:20).

4.1 Flow Characteristics in a Rectangular Weir with a Notch

Fig. 8 shows the three-dimensional schematic flow characteristics in a plunging flow at $\widehat{Q} = 0.15$. Primary flow occurs through the alternating notch forming a S-type. Its velocity is about 0.7 m/s on the notch and 0.5 m/s in a pool. Secondary horizontal circulating flow occurs due to flow seperation behind the weir side where there is no notch and its velocity is about 0.3 m/s. Fig. 9 is the plan of the plunging flow for Fig. 8. It can be seen that the primary flow of S-type occurs through the notch and the secondary horizontal circulating flow occurs behind the weir. Direction of the circulating flow becomes reciprocal to that in an adjacent pool.

The discharge equation in a plunging flow can be expressed as follows:

$$Q_p = Q_{pw} + Q_{pn} = C_{pw} b_{pw} h_{pw}^{3/2} \sqrt{g} + C_{pn} b_{pn} h_{pn}^{3/2} \sqrt{g} \qquad (2)$$

where, C is a discharge coefficient, b is a width and h is a overflow depth. Subscript pw means the weir side and pn means the notch side in a plunging flow. So, C_{pw} means the discharge coefficient at the weir side and C_{pn} means one at the notch side in a plunging flow, and so on. Q_{pw} and Q_{pn} is a discharge at the weir side and at the notch side, respectively, and Q_p is the total discharge. Discharge coefficient is known to be about 0.61 in case of the simple rectangular weir with no notch (Katopodis, 1987).

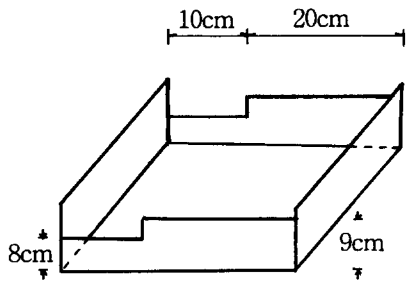
Fig. 10 shows the values of discharge coefficient, C_{pw} and C_{pn} with relative depth, h_{pw}/H and h_{pn}/H, where H is a weir height at the weir side. Values of discharge coefficient are 0.46~0.71 and increases with the increase of relative depth. Their mean value is about 0.57, which is almost the same as Katopodis' (1987) value. Values of the discharge coefficient at the weir side and at the notch side are almost the same at the same water level, the reason of which seems to be that flow velocity becomes large with the increase of a overflow depth. Values of discharge coefficients vary relatively widely and some of their distributions have non-linear type, the reason of which seems that the primary flow and the circulating flow occur simultaneously due to flow seperation, moreover, the position and direction of the circulating flow become reciprocal to that in an adjacent pool and hence the flow becomes unstable.

Figs. 11 and 12 show the flow charateristics in a streaming flow at $\hat{Q}$ = 0.39. Primary flow occurs through the alternating notch forming S-type, which is the same result as that in a plunging flow in Fig. 8. Its maximum velocity is about 1.0 m/s on the notch and 0.7 m/s in the pool, which does not exceed the critical velocity. The horizontal circulating flow, which occurred in a plunging flow, does not occur in a streaming flow. Since the circulating flow is not good for the migration of fish as mentioned in section 3.1, it can be seen that the streaming flow is preferable to the plunging flow as far as the maximum flow velocity does not exceed the critical velocity. Experimental results showed that the critical velocity occurred at $\hat{Q}$ = 0.41. Transition zone between the plunging flow and the streaming flow occurs roughly at $\hat{Q}$ = 0.27. From these results, it can be seen that the notch must be designed that the flow situation may keep the streaming flow so long as the maximum flow velocity does not exceed the critical velocity, i.e., that $\hat{Q}$ may exist within range of 0.27 and 0.41.

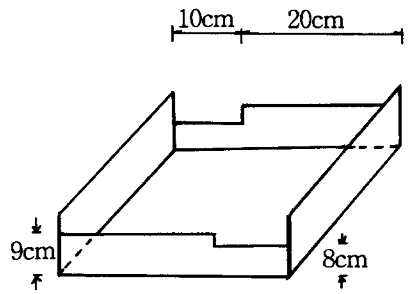
The discharge equation in a streaming flow can be expressed as follows :

$$Q_s = Q_{sw} + Q_{sn} = C_{sw}b_{sw}h_{sw}\sqrt{gSL} + C_{sw}b_{pw}h_{pw}\sqrt{gSL} \qquad (3)$$

Parameters C, b and h were mentioned in Eq. (2). Subscript sw means the weir side and sn means the notch side in a streaming flow. So, C_{sw} means the discharge coefficient at the weir side and C_{sn} means one at the notch side in a streaming flow, and so on. Q_{sw} and Q_{sn} is a discharge in a streaming flow at the weir side and at the notch side, respectively, and Q_s is the total discharge. Discharge coefficient is known to be about 1.50 in the simple rectangular weir with no notch (Katopodis, 1987).



(a) Straight Type



(b) Zig-Zag Type

Fig. 7. Two Types of the Rectangular Weir by the Location of a Notch

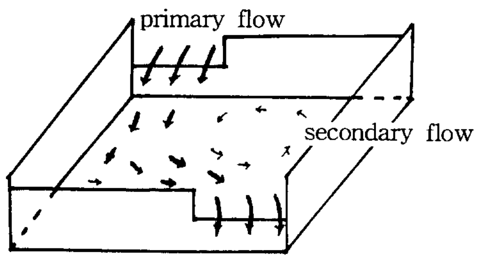


Fig. 8. Three-Dimensional Plunging Flow in a Rectangular Weir

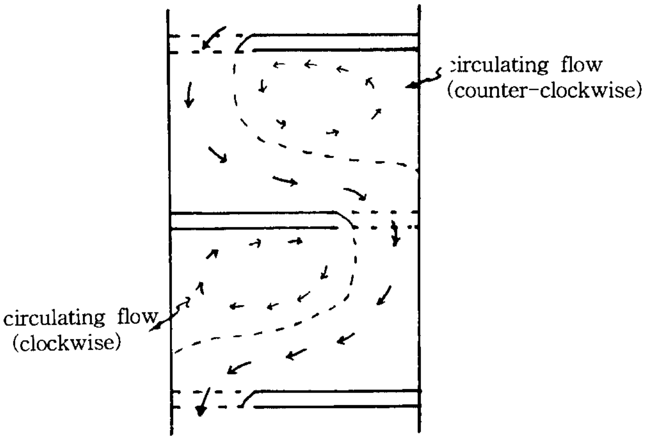


Fig. 9. Plunging Flow in a Rectangular Weir (Plan)

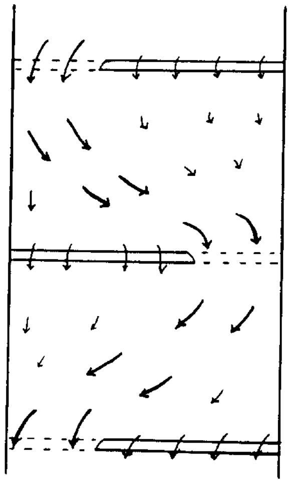


Fig. 12. Streaming Flow in a Rectangular Weir (Plan)

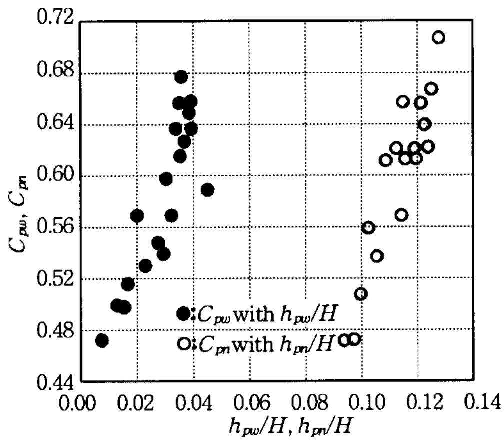


Fig. 10. Values of Discharge Coefficient with Relative Depth (Plunging Flow)

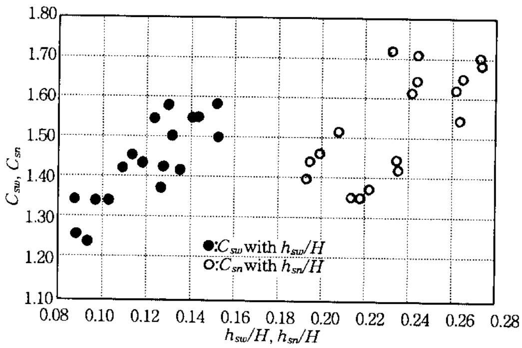


Fig. 13. Values of Discharge Coefficient with Relative Depth (Streaming Flow)

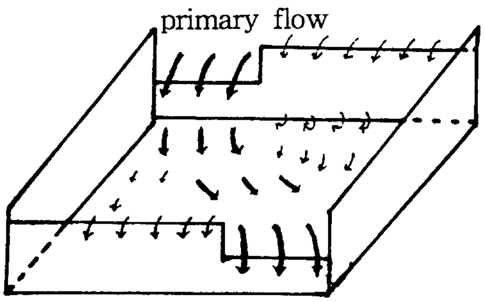
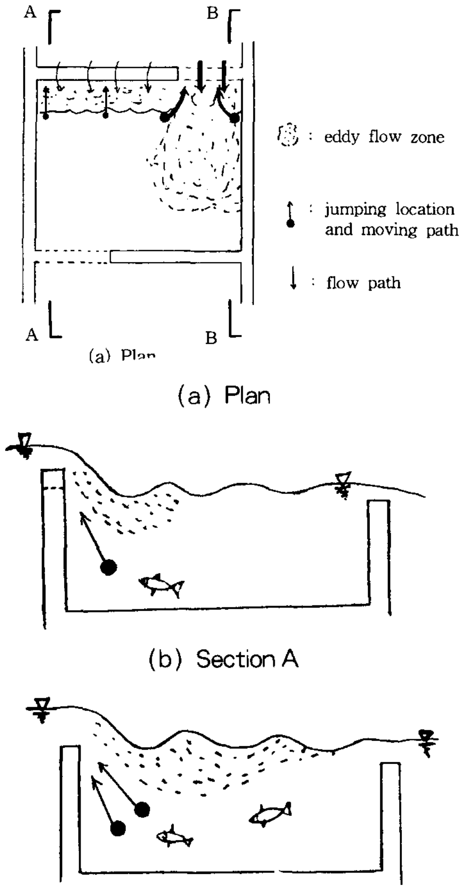


Fig. 11. Three-Dimensional Streaming Flow in a Rectangular Weir

Fig. 13 shows the values of discharge coefficient, C_{sw} and C_{sn} with relative depth, h_{sw}/H and h_{sn}/H. Values of discharge coefficient increase with the increase of relative depth and they are almost the same at the same water level, which is the similar results as in a plunging flow. Mean value is about 1.43, which is almost the same as Katopodis' (1987) value.



(a) Plan

(b) Section A

(c) Section B

Fig. 14. Flow Situation and an Upstream Migration of Fish in a Rectangular Weir

4.2 Upstream Migration of Fish in a Rectangular Weir with a Notch

Fig. 14 shows a flow situation of eddy and an upstream migration of fish in an A and a B section of a pool at $\hat{Q} = 0.39$. The estimation technique of the upstream migration for given flow condition was explained in section 3.2. Here, An arrow means a flow direction and its thickness means a flow quantity. The thicker an arrow is, the larger a flow is. A dotted area means the eddy flow zone and an arrow with black circle means a jumping location and moving path of fish. It can be seen that large flow occurs at the notch side than at the weir side. In an A section, flow velocity is low and the eddy occurs near the weir. However, in a B section, flow velocity is high and the eddy zone becomes large to a horizontal direction compared with that in an A section. But the eddy zone does not extend so large to a vertical direction.

So, the fish moves towards the B section whose velocity is high and approaches near the weir through below the eddy zone. After arriving near the weir, the fish moves to the notch and jumps up to the upstream pool. According to Nakamura (1995), 80 % of the fish jumps to the upstream pool using the notch, and among them, 70 % jumps using the end of the notch. Since the notch makes falling flow which facilitates the upstream migration of fish, the rectangular weir with a rectangular notch can be the optimal type for the upstream migration of fish.

5. Conclusions

Hydraulic characteristics and their effects on the upstream migration of fish by the weir type in a pool-weir fishway were studied by the hydraulic experiments. From these results, following conclusions could be obtained.

(1) The primary flow in a trapezoidal weir forms a S-type and the turbulent jet occurs from the orifice.

(2) The turbulent jet is not good for upstream migration of fish since its velocity exceeds the critical velocity.

(3) The trapezoidal weir is not effective for upstream migration in case a water level draws down since it gives no appropriate overflow depth for a fish.

(4) The rectangular weir with a notch installed by a zig-zag type can give an appropriate overflow depth through the notch even when a water level draws down. Moreover, it gives a free falling flow which facilitates the upstream migration.

(5) The rectangular weir with a notch by a zig-zag type is an optimal type for the upstream migration of fish, where the notch must be designed that the dimensionless flow rate may exist within range of 0.27 and 0.41.

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