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Pool-and-Chute Fishways

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Abstract.—The pool-and-chute fishway is an economical means of providing fish passage over constructed barriers. Pool-and-chute fishways resemble pool-and-weir fishways at low flows and become baffled chutes at moderate to high flows. The economy of the concept is achieved by exceeding the usual criteria of fishway pool volume based on energy dissipation in each pool. The size and complexity of the structure are thus reduced. Design guidelines covering appropriate application and geometry ensure hydraulic conditions that allow fish passage. Cost comparisons based on actual and estimated construction costs of pool-and-chute and other styles of fishways verify the economic benefit of the concept.

The success of a fishway depends on the range of flows through which it operates successfully, on attraction of fish to the fishway, and on adequate maintenance to keep the fishway operating as intended. A critical element of success of a fishway is its ability to attract and pass fish during periods of high stream flows.

Traditional styles of instream fishways often have limited success at high flows if they lack auxiliary water and flow control systems, which entail substantially greater capital and operating costs. Auxiliary water systems may consist of a water intake, control gate, and diffuser pool to introduce additional water to the entrance pool of the fishway. The additional water enhances the attraction of fish to the entrance. The water supply and diffuser require fine-mesh trash racks. Fishway flow control may consist of orifices with flow depletion or supplementation systems. Mechanical devices such as water surface sensors, automatic flow control gates, tilting or telescoping weirs, and related electronic control systems are often required.

It is assumed during design, sometimes erroneously, that adequate maintenance will be provided. Maintenance demands are often underestimated during design; a fishway owner's commitment to operation and maintenance is obviously influenced by future economic considerations. A design that minimizes operation and maintenance demands is highly desirable.

A hybrid fishway, termed a pool and chute, that includes some advantages of both pool-and-weir fishways and roughened chutes has been designed and constructed. The pool-and-chute fishway is essentially a pool-and-weir fishway with V-shaped weirs that may include ports near the floor. Figure 1 shows plan and elevation views of a pool-and-chute fishway. During low and normal flows, the fishway operates as a pool-and-weir fishway with orifices. At high flows, a high-velocity streaming flow passes down the center of the fishway while a plunging flow is maintained near the sidewalls, providing a zone for fish passage.

Currently Used Fishway Styles and Design Standards

An understanding of currently used fishway styles and their relevant design standards is a basis for design of the pool-and-chute fishway. For the purpose of this discussion, fishways can be divided into three categories: pool fishways with some combination of vertical slots, orifices, and overflow weirs; roughened chutes; and lifts. Lifts include locks, brails, and hoppers. They are rarely used except for fish collection and are not discussed further here.

Fishways are generally designed to operate within design criteria for a specific range of design flows. These design criteria include adequate attraction of fish to the fishway entrance, limited water surface difference between adjacent fishway pools, adequate volume and appropriate geometry to dissipate energy and allow fish to rest in pools, plunging weir flows, minimum water depth, and maximum water velocity within the fishway.

Design Flow

The upper design flow of a fishway is the maximum flow at which the design criteria for fish passage are not exceeded. It is recognized that fish passage during extreme high and low flows is not practical (Bates and Powers 1988). The construction and operating costs of providing passage at all flows is prohibitive, in most cases, due to volume within each pool and a proper pool geometry to dissipate the energy of the flow entering it.

Three criteria that are typically and specifically applied to the design of pool-and-weir fishways and that determine their size, geometry, and flow range are (1) maximum hydraulic drop between pools; (2) minimum length of pool to maintain plunging-flow regime over each weir; and (3) adequate volume in pools to dissipate the energy of the flow entering the pool.

The maximum allowable drop between pools depends on the leaping or swimming ability of the fish intended to be passed and normally ranges from 0.5 to 1.0 ft. The other criteria are discussed below.

Hydraulics of pool-type fishways.—Normal flow circulation in a pool-and-weir fishway is termed plunging regime. Plunging flow is defined as the regime in which the direction of flow on the surface of the pool is upstream. This circulation is set up by the flow from the nappe of the upstream weir plunging to the fishway floor, moving downstream along the floor, and rolling back toward the upstream weir along the surface of the pool. Streaming flow occurs at higher flows than the plunging regime. A surface jet flows over the crests of the weirs and skims over the water surface of the pools; the water accelerates over the weirs without circulating through the pool. Shear forces from the streaming jet cause a circulation in the pool opposite to that in the plunging regime. Rajaratnam et al. (1988) provided a good description of these flow regimes.

Model studies have been performed to determine the characteristics of plunging and streaming flows and the transition between regimes (Rajaratnam et al. 1988; F. Andrew, International Pacific Salmon Fisheries Commission, unpublished). Hydraulic instability occurs in the transition between the upper range of plunging flow and the lower range of streaming flow.

Both the shape of the weir crest and the presence and design of orifices within the weir significantly affect the hydraulics of the downstream pool. They are effective in extending the flow range through which the plunging-flow condition is present and can therefore be used to extend the design flow of the pool-style fishway. Weir shapes similar to an ogee crest are most effective in producing plunging-flow conditions. Studies at the Fisheries-Engineering Research Laboratory at Bonneville Dam (Thompson and Gauley 1965) showed a qualitative improvement in flow conditions in the pool and more rapid fish passage with weirs similar to ogee crests. Model studies for the International Pacific Fisheries Commission (Andrew, no date) identified stable flow ranges as a function of weir-crests shape and orifice configuration.

The flow ranges are based on visual observations of a 1:6 scale model and were recorded for prototype scale. The upper flow limit of plunging-flow conditions in an 8-ft-long pool was increased by 33% (3.9 to 5.2 ft^3/s per foot of weir length) by rounding the weir crest and adding a 6- by 12-in port at the floor. The addition of the ports also eliminated the unstable transition from plunging to streaming flow ranges by lowering the lower limit of streaming flow from 6.1 $ft^3/s \cdot ft$ (square crest, no ports) to 5.2 $ft^3/s \cdot ft$ (round crest, with ports). The upper flow limit of plunging-flow conditions in a 10-ft-long pool was increased by 10% (4.0 to 4.4 $ft^3/s \cdot ft$) by rounding the crest. These findings are close to the dimensionless results presented by Rajaratnam et al. (1988) for normal fishway pool lengths.

Fish passage at high flows is often limited by excess turbulence in pools of the fishway. Excess turbulence eliminates both the steady circulation pattern required to guide fish upstream and the resting or holding areas for fish. Turbulence and aerated water also reduce the thrust a fish can develop to accelerate and move against flowing water. Total energy entering a pool is equal to the product of the head (potential head plus velocity head) between the pool and the next upstream pool, the specific weight of the fluid, and the rate of flow. The efficiency of dissipation of that energy in a pool is a function of the effective volume of the pool. The geometry of the pool determines how much of the actual volume is effective in energy dissipation. A standard used in the Pacific Northwest was described by Bell (1986); the maximum suggested energy dissipation in a fishway pool is 4 foot-pounds per second per cubic foot of pool volume. For water, the volume formula is simplified to

$$V \geq 16 \times Q \times h;$$

V is the effective pool volume in cubic feet, Q is the fishway flow in ft^3/s, and h is the total head of the flow entering the fishway in feet. The energy dissipation criterion was originally intended for application to vertical slot fishways, but it has proven effective in the design of weir-and-pool fishways. Application of this standard limits the flow allowed through a fishway or dictates the volume of fishway pools required. Maximum flow and energy between them. This is an idealization of the actual flow condition only for the purpose of design; there certainly is flow and energy interchange across that plane. The chute segment is analyzed at high stream flow only to calculate the total flow. It is treated as a roughened chute according to the definition of roughness given by the Chezy equation (Chow 1959). In at least one design, the normal energy dissipation volume requirement was reduced in the center segment by 50% (U.S. Army Corps of Engineers 1988).

The baffle segments are not relevant to the low-flow fishway hydraulics because all the flow is concentrated in the center of the fishway. At high flow they are analyzed as a pool-and-weir fishway; thus two design standards are applied. Pool volume in the baffle segments must satisfy the criterion of energy dissipation volume described above, and the distance between pools must be such that plunging flow is maintained.

Observations

Model study.—A physical scale model was constructed to determine the best geometric configuration for fish passage and to test the simplified design concept described above. The model was tested at the McAllister Creek Hatchery near Olympia, Washington. The testing was begun with a model of the Town fishway at a 1:10 scale and a slope of 4.9%. The results described in this section relate to the prototype scale of Town Dam fishway. The model was also tested at slopes of 11.1% (which closely corresponds to a 1:5 model of the Rainbow Creek fishway described in the next section) and at 16.7%.

A range of flows and several weir geometries were tested both with and without ports. Fish passage evaluation was based on visual observation of level of turbulence in the outer-third segments of the fishway and in the uninterrupted circulation patterns intended to guide fish to the next pool. Fish passage ratings were expressed as one of five categories in a range from poor to excellent. Flow circulation patterns were mapped on a horizontal grid at 2 and 4 ft above the floor of the prototype.

The flow at which the circulation in the center segment changed from plunging to streaming was recorded with increasing flow and the reverse with decreasing flow. Water surfaces were recorded in order to determine the Chezy roughness coefficient of the fishway with streaming flow. Velocities of the jet entering the tailwater of the fishway were recorded at 2.0 ft below the water surface at 0, 20, 40, and 60 ft downstream of the fishway.

Streaming flow existed separate from and parallel to the passage corridor. At high flows it spread laterally, only on the surface, over the plunging circulation that persisted within the pools. Passage conditions existed at the passage corridor, where plunging flow was maintained. The passage corridor was consistently about 3 ft wide over each baffle. Flow through the ports was stable and consistent.

Good passage conditions were observed in the 4.9, 11.1, and 16.7% models at flows up to 450, 468, and 136 ft^3/s, respectively, by modifying the cross-sectional shape of the weirs. The weir heights were increased with increasing flow to achieve good passage conditions. The interior weirs (other than two exit weirs) had final heights of 3.3, 5.8, and 6.7 ft, respectively, for the three slopes tested. Additional improvements could likely be made to the 4.9% model to further increase the flow at which good passage conditions exist. The deterioration of passage conditions at the upper limit of "good" passage was due to increased upwelling on the upstream side of the baffles and excessive or unstable standing waves just upstream of the weirs. Standing waves existed in most situations upstream of the weirs at the upper limit of what was considered "good" passage but did not influence the passage corridor.

Specific model study observations are described below with suggested design standards.

Rainbow Creek Fishway.—Rainbow Creek fishway was constructed in 1983 by the U.S. Forest Service. The fishway is 12 ft wide, and pools are 6 ft long with a drop of 0.75 ft/weir for an overall slope of 11.1%. The high design flow of 85 ft^3/s is expected to be exceeded 10% of the time during November through January. At that flow, 76 ft^3/s is intended to pass through the horizontal weir segment and 4.5 ft^3/s through each of the baffle segments. The volume intended for energy dissipation in the outer thirds of each of the pools was 75 ft^3, which is 50% greater than the standard volume criterion described above.

The fishway has been observed through a range of stream flows. On March 26, 1988, a flow of 88 ft^3/s, nearly equal to the design flow of 85 ft^3/s, was measured through the fishway. I observed the fishway at that flow and considered it passable, but at the upper limit of its passage range. The water surface was 0.35 ft higher than the point where the baffles meet the fishway side walls and additional shear forces of the rough channel boundary.

A second possible limitation is bed-load deposition in the pools of the fishway. Deposition and filling of the pool areas along the walls of the fishway decrease the volume and therefore decrease the high design flow.

Sediment accumulation may be a greater limitation in a pool-and-chute fishway than it would be for other fishway styles. Because of the higher design flow of the pool-and-chute fishway, the flow at which it is scoured clean is likely greater than in a pool-and-weir fishway and is therefore less likely to occur. Large debris may block orifices. Denil fishways are essentially self-cleaning of bedload material. Several cubic yards of gravel and cobble were dumped into a Denil fishway at a 17% slope to evaluate its ability to pass bed material (D. Cagle, Washington Department of Fisheries, unpublished). All but a small portion of material smaller than 4 in passed through the fishway; about half of the 4–6-in rock passed through the fishway. Floating debris, however, can effectively block passage through Denil-style fishways.

Suggested Design Standards

Based on the model studies and observations of existing pool-and-chute fishways, the following design criteria for weirs and baffles are suggested. Dimensions are given in a prototype scale comparable with the Town Dam fishway. These suggested design standards have not been entirely field-verified.

The length, slope, and crest shape of the baffle and the length of the weir determine the fishway flow capacity and high design flow for passage. The width of horizontal weir will determine the allowable quantity of flow passing through the fishway; there is not expected to be a hydraulic or fish passage limitation on the width or flow through the center segment. The width is only limited by cost. The minimum horizontal crest length is based on the flow required at high flow to attract fish for fishways built within a dam crest.

The length of the baffle segments, together with the lateral slope of the baffles, depends on the expected range of forebay water surfaces. The lateral slope of the baffles controls the width of the passage corridor over the weir and establishes the high design flow. The steeper the baffle slope, the narrower the passage corridor but the higher the high design flow. The 1:3 slopes studied provided a passage corridor that was consistently about 3 ft wide; that slope ratio is recommended.

In designing for high flows, the change from static head at the upstream two weirs to velocity head in the interior weirs must be accounted for. The two upstream weirs (exit weirs) should be modified by lowering the upper weir crests to elevations below the grade extended from the downstream weir crests. Unless the exit weirs are modified, additional drop over the upper weirs greatly diminishes the passage rating of the fishway. The number of weirs modified and their modified elevations depend on the slot velocity within the fishway at the high design flow. The greater the difference between the forebay approach velocity and the streaming flow velocity in the fishway, the farther the exit weirs should be lowered. The upstream weir should be lowered an amount equivalent to the gain in velocity head from the forebay to the third weir; the second weir is lowered half as much as a transition.

Figure 1 shows weir elevations of the Town Dam fishway based on model study results. Figure 4 shows water surface profiles at 304 ft^3/s through the model fishway with all weirs 4.2 ft high and with the height of the exit (most upstream) and second weirs modified to 2.5 and 3.3 ft, respectively.

The cross sections of the weir crests can be square in the weir segment to minimize complications of concrete forming. The downstream edge of the crest of the baffle segments should be rounded or truncated to optimize plunging-flow conditions.

Minimum depth is controlled by the elevation of the weirs and should be at least twice the height of ports to prevent the port flow from boiling to the surface. Though not studied, it is expected that a minimum depth must also be provided to maintain plunging flows.

The spacing of weirs was not specifically studied in the model test. The spacing is derived from the desired slope of the fishway and the maximum drop per weir. Close spacing will maintain streaming flow, maximize roughness, and maximize slope of the fishway. At the lower limit of spacing, the design approaches that similar to a Denil fishway. A minimum spacing of 6 ft is suggested to allow adequate resting area within the pools.

Hydraulic Analysis

The depth and velocity, and therefore capacity, of flow within the chute segment during high flows can be determined with the Chezy equation. Fig-

TABLE 1.—Cost comparison of three fishway styles normalized to total head, fishway entrance flow, and 1988 construction cost.

Location	Fishway rise (ft)	Fishway design flow (ft^3/s)	River design flow (ft^3/s)	Cost (US$): Total construction	Cost (US$): Unit construction	Cost (US$): Annual maintenance
Vertical slot with auxiliary water						
Town Dam	3.9	104	4,000	337,000	864	5,800
Sunnyside Dam	6.5	104	12,000	322,147	476	7,800
Gibbons Creek	12.0	30	70	222,860	619	
Pool and weir with flow control						
Gibbons Creek	12.0	15	70	166,700	892	
Pool and chute						
Carpenter Creek	8.0	40	40	41,300	129	a
Rainbow Creek	8.0	85	85	25,350	36	a
Town Dam	3.9	354	4,000	214,000	155	700
Gibbons Creek	12.0	70	70	90,700	108	

[a]No maintenance required in last 5 years.

able within and downstream of the fishway. Slopes exceeding the tested slope of 11.1% should not be attempted without further evaluation.

Design flow.—Maximum design flow is based on width of the weir segment. Allowable flow depth over the baffles should be based on maintaining a plunging-flow regime. The estimate of the upper limit of plunging flow described by Rajaratnam et al. (1988) is a function of weir spacing; that estimate agreed well with the results of this study.

Ports.—Ports do not affect the streaming portion of the fishway. They provide an alternative passage route and should be included any time the low design flow is greater than their combined capacity. Ports also help keep the outer portions of the pool clean from sediment.

Ports should be located as close to the side walls and floor as possible and at least 4 ft laterally from the end of the weir to ensure that turbulence from the weir does not disrupt their operation. Sizing of ports depends on size of fish and amount and size of debris expected at the site; 1.5-ft-square ports or larger are recommended for salmon.

Further Studies

It is suggested that further model and prototype studies be conducted to verify detail design standards and to test effects of sediment deposition. Pool widths and geometric details should be further studied to optimize these details for fish passage.

It is also suggested that a standard be developed to quantify acceptable levels of turbulence in fishway pools of all styles. Pressure fluctuations might be recorded for this purpose. The rapidity and magnitude of pressure fluctuations in a fishway pool may be good indicators of turbulence, and a limit could be determined at which fish passage or guidance is hindered.

Cost Comparisons

Costs of fishway construction currently vary from about US$2,500 per vertical foot for a small, simple pool-and-weir built with force-account labor to as high as $50,000 per vertical foot for a vertical slot ladder with flow control, multiple entrances, auxiliary water supply, and flood and debris protection and constructed under federal contract.

Table 1 shows construction costs for three styles of fishways. An effort was made to normalize the costs for this comparison. Final costs are presented as "unit construction costs," which are total construction cost per foot of rise of the fishway per ft^3/s of design flow at the fishway entrance. Calculating relative costs on the basis of total head and total entrance flow accounts for differences in scale of each fishway and of the river for which each is designed.

Construction costs in Table 1 are presented as 1988 construction costs updated with the Engineering News Record construction cost index. The Town Dam vertical slot fishway cost is from a preliminary design and cost estimate by the U.S. Bureau of Reclamation; the pool-and-chute option was selected for construction.

Flow control at the Gibbons Creek fishway consisted of an orifice control section. Sunnyside,