CHAPTER 8

FISH PASSAGE THROUGH CULVERTS, ROCK WEIRS AND ESTUARINE OBSTRUCTIONS

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1. FISH PASSAGE THROUGH CULVERTS

1.1 Problems posed by migration of fish through culverts

In terms of both lower construction and maintenance costs, culverts of many types (circular, elliptical, ovoid, boxed, pipe, arch and bottomless-arch) are an attractive alternative to traditional bridges for the provision of road and motorway crossings of watercourses.

Substituting such structures for the natural river channel modifies the local flow characteristics, substrate composition and lighting conditions.

They may constitute serious obstructions to fish migration with excessive water velocity (up to 3-4 m/s), insufficient water depth, elevated outlets (*i.e.* the downstream invert becoming perched above the existing stream-bed), and accumulation of debris being the most frequent causes of impediment for migratory fish.

Where culvert gradients are significant, the acceleration of flow at the inlet of the structure can be intense. As a result of the low rugosity values typical of culverts the water velocity accelerates rapidly, often significantly (the flow may even become torrential), and then remains almost constant throughout the structure. This uniformity of the velocity precludes the existence of resting areas for the fish, which must then pass through the entire structure at one stretch. During low flow periods, the flow can become very shallow, and the water depth may become insufficient to allow the fish to swim effectively.

Frequently fish passage is obstructed at the downstream end of the structure when the culvert becomes perched. Sometimes this drop is intentional but most frequently it is the result of a poor or improper installation, which has not taken existing bed levels into account. Where no preventative measures have been taken (armouring the streambed, installing low-head concrete or rock weirs) it may also result from the erosion of the river bed downstream of the culvert.

More rarely, incorrect positioning of the upstream end of the culvert (upstream invert level too low) may result in the creation of a steep, and impassable section of river channel immediately upstream of the structure.

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1.2 Guidelines for the design and installation of passable culverts

1.2.1 Requirements for fish passage

As soon as the installation of a culvert causes any modification to the hydraulic conditions of the stream it must be ensured that it does not constitute an obstruction to fish passage.

Whether a culvert can be passed or not depends on the swimming ability (in terms of swimming speed and endurance) of the species that are likely to require passage, and on the hydraulic conditions found in the culvert during their migration period.

The swimming ability of a fish is generally represented by empirical curves showing the distance which fish of a given species and length can travel, in a flow with a given velocity.

With the aid of this information, hydraulic criteria (maximum flow velocity not to be exceeded taking account of the length of the culvert, and minimum water depth sufficient for the fish to swim) which allow the passage of fish may be determined and used when designing the culvert.

The following conditions must be satisfied:

- The “reference fish” (species and size) must be the one with the lowest swimming ability likely to require passage at the culvert;

- The flow conditions taken account of should be those encountered during the migratory period.

The hydrological regime for the stream during the migratory period must be determined, in the same way as for any other fish passage facility.

When the daily flow duration curves are available, the culvert should remain passable between low flow (Q_{90}-Q_{95}) and a flow that is only exceeded for 5-10% of the time (Q_5-Q_{10}).

In the absence of this data, which is most often the case on minor streams, the culvert should be passable at flows of up to approximately twice the mean annual daily flow.

In addition to a maximum velocity which may not be exceeded, a minimum depth of water must be maintained in the culvert to allow the largest fish to pass during low water periods, *i.e.* a minimum of around 0.15 m for trout and 0.30 m for salmon and sea trout.

1.2.2 Design and installation criteria for a passable culvert

The shape of the culvert determines the hydraulic parameters, such as water depth and velocity, which will influence the passage of the fish. Culverts with a wide span (box culverts, arched culverts, bottomless arch) allow the cross section of the flow to be kept relatively similar to that of the natural stream. The velocity is therefore likely to be less critical in this type of culvert than in a circular one, constructed with material of the same rugosity. Furthermore, if the cross section and installation conditions of the culvert (moderate gradient, installation below the natural gradient of the stream) allow it, sediment load (gravel, pebbles...) can be deposited on the bed, increasing the roughness and thus helping to reduce the water velocity. However, circular and elliptical culverts are preferable if a minimum depth is to be ensured during low stream discharge periods.

In France, culverts are generally designed to accommodate peak stream flows based on 100-year-flood return periods for motorways, and on between 25 and 100-year return periods for roads. The water velocity in the culvert is calculated (by the Manning-Strickler formula) for specified maximum flow during the migratory period, taking the characteristics of the culvert into account (dimensions, shape of the cross-section, rugosity and slope).

In determining if the size and type of culvert are acceptable for the passage of fish the criteria required for passage of the “reference fish”are used. If the criteria for fish passage cannot be met by the use of a conventional culvert then other solutions should be considered:

- Experience suggests that the best solution is either a bottomless arch, or else a culvert with dimensions sufficient to maintain a width and cross-section of the flow comparable to that of the stream. Both would be filled with material that was equivalent in size to that of the initial bed, thus ensuring that the hydraulic characteristics of the stream remain mostly unaltered through the culvert. The culvert must be installed with the same average slope as the initial stream, and the invert must be installed below the bed of the stream both at the upstream and the downstream ends. This helps in large part to recreate the bed of the natural stream inside the culvert (KATOPODIS, 1984). The dimensions of the materials that compose the bed layer must be sufficient to remain stable during floods. Designing a culvert to be passable by fish generally means that it has to be over-sized in comparison with the strict hydraulic need.

- In the case of a moderate length culvert and natural channel slopes, the culvert can be installed horizontally. The invert must be installed below the channel bed and the width of the culvert must be equal or greater than the natural channel width. As in the precedent case, this naturally recreates a stable bed in the culvert. A reasonable upper limit of this option would be at sites where the product of the channel slope and the culvert length does not exceed 20% of the culvert diameter or rise (BATES, 1999).

- The velocity in the culvert can also be reduced to an adequate level by adjusting the size or the slope of the culvert. This solution usually results, as in the previous case, in the culvert being over-sized. However, the culvert should not be designed at a slope that is much less than that of the watercourse except in the case of short culvert on moderate slope sites. The latter could lead either to the perching of the culvert outlet (creating a drop), or else to scouring of the bed upstream (creation of a steep section), both of which would have a detrimental effect on the passage of the fish.

- Another solution that can be used to control velocity and water depth in a culvert to enable fish to pass is to install baffles, artificial roughness (large rocks anchored to the bottom, more or less regularly positioned on the bottom of the structure), or even a traditional fishway.

In order to guarantee a minimum depth at all times, particularly during low flow periods, the bottom of the culvert must be placed around 30 cm lower than the natural bed of the stream (Figure 1), (WATTS, 1974; DRYDEN and STEIN, 1975; DANE, 1983).

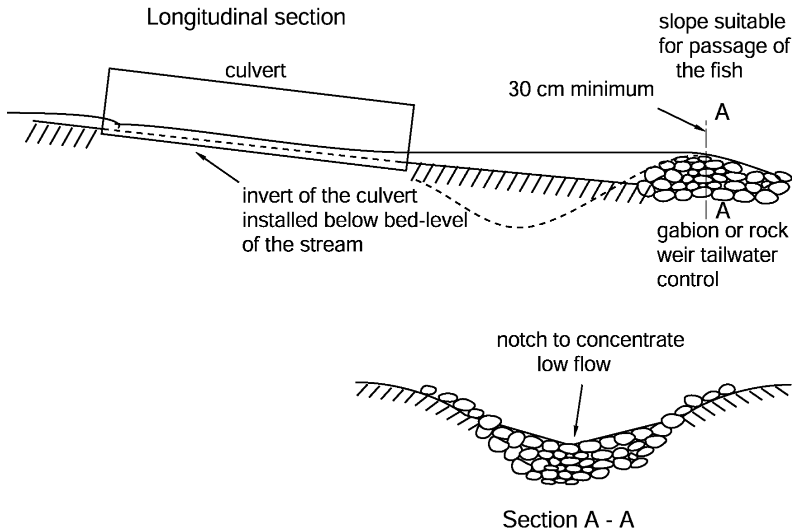

Figure 1: View showing the installation of a culvert with a low rock weir positioned downstream to control the tailwater.

Downstream of the culvert both bank protection and an outlet pool must be provided. These structures are required to:

- Provide a rest zone for the fish before it passes through the culvert;

- Ensure both a minimum water depth in the downstream section of the culvert (entrance for the fish) and to attenuate any drop or acceleration at the entrance;

- Control erosion downstream of the culvert by dissipating residual energy from the water outflow, thus preventing any lowering of the tail-water level.

The pool must have sufficient volume to ensure correct dissipation of the energy without excessive turbulence or aeration for the fish. It may be made of concrete, however it is better to armour it with rip-rap, which is a more flexible solution in that it can adapt to any future minor changes in the bed.

It is advisable to install a control structure at the downstream end of the pool designed to maintain the water level at least 30 cm above the bottom at the outlet of the culvert, to prevent acceleration of the flow and development of a significant drop during high flows. In certain cases, either as a preventive measure or else to correct a fall that is too high at the downstream end, it may be desirable or even necessary to construct several pre-barrages below the culvert. Their number will depend on the slope and topography of the site. The total drop will be divided into several small drops that the fish can pass. The structure will behave like a fish pass to which traditional design criteria will apply, in particular the head difference between weirs should not exceed 0.25-0.30 m.

All the pre-barrages must have notches to concentrate flow thus enabling fish to pass during low flow periods.

1.3 Culvert baffles

Experience gained in North America shows that in the case of new culverts the best solution is to maintain conditions within the structure which are as close as possible to the original stream (gradient, bed material, cross-section and wetted perimeter). The installation of baffles is likely to cause serious maintenance problems, and also to greatly reduce the maximum discharge that the structure can accommodate (ENGEL, 1974; DANE, 1983). However, the retrofitting of baffles is often the only measure that can be used for existing culverts where no provision was made originally for fish passage. On the other hand, when the gradient of any new culvert becomes significant, the installation of artificial roughness or baffles often becomes necessary. The baffles also serve both to limit the velocity in the culvert and to protect the floor of the culvert during large flood events.

The most commonly used types of baffle that are both efficient and simple to install are described below.

1.3.1 Horizontal baffles with notches or slots (Figure 2)

A series of weirs are installed across the entire width of the culvert to ensure both a sufficient depth of water during low flow periods and an acceptable velocity during periods of high flow. Notches in the centre or side (square, rectangular or triangular), or vertical slots going completely to the bottom, are calibrated for the low flow discharge and to facilitate passage of the fish across a broad range of flow (RAJARATNAM and KATOPODIS, 1989, 1990).

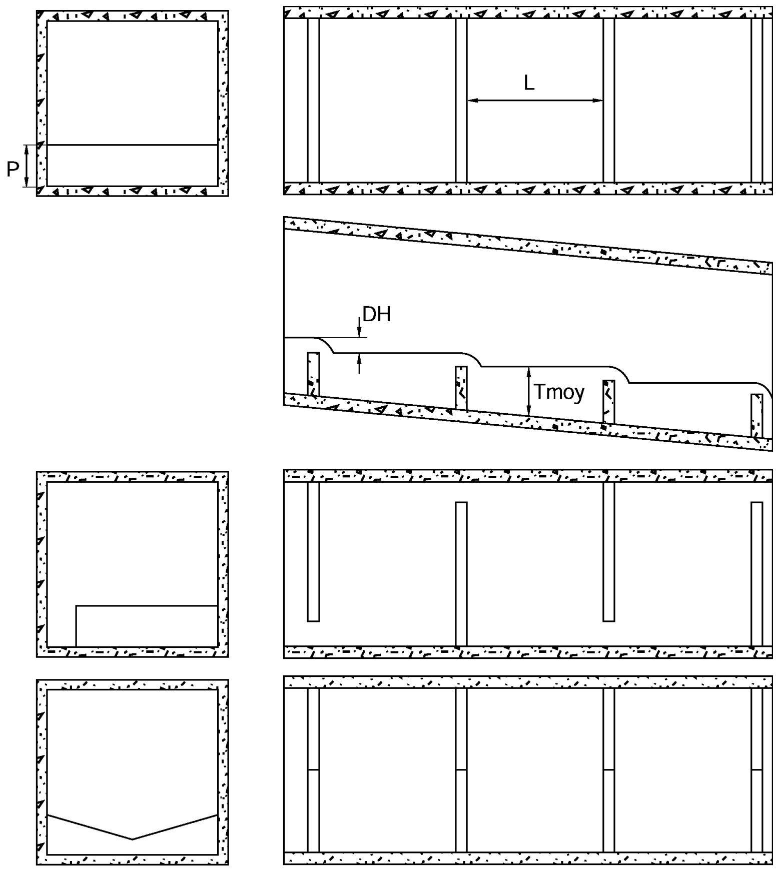

Figure 2: Rectangular, triangular and slotted weir baffle systems.

This type of fish passage facility is similar to a traditional pool pass. It may be designed using the same criteria, particularly with respect to the minimum heads on the weirs, which will depend on the migratory species concerned. The following specific precautions must be taken:

- The height of the walls should be such that the criteria regarding the minimum water depths (Tmin) (15 cm for trout and 30 cm for salmon) are always observed, particularly in the shallowest zone which is generally situated immediately downstream of the weirs.

- The depth of the water at the bottom of each drop should be at least 2-2.5 times the head difference between the pools to enable the fish to pass.

- The spacing between the weirs must be sufficient. If the weirs are too close together recirculation zones form between the baffles as soon as the flow increases, the flow then becomes streaming and the energy is not dissipated. A “quasi-smooth flow” (KNIGHT and MCDONALD, 1979) is then formed, with very high velocities.

- The volumetric dissipated power in each cell must remain at an acceptable level (see criteria used for pool fishways).

These requirements lead to the height of weirs (p) generally varying between 0.15 m and 0.40 m and to weir spacings (L) such that the value (S x L/p) lies between 0.20 and 0.30 *i.e.* (LARINIER and CHORDA, 1995):

$$0.20 \leq (S \times L/p) \leq 0.30$$

where S is the slope of the structure.

1.3.2 Triangular-crested baffles (Figure 2)

Compared to the above solutions, weirs with a triangular crest have the advantage of creating more heterogeneous flow conditions. Fish can choose the zones through which they prefer to pass, depending on the prevailing conditions at any particular discharge. The gradients of the sides of the triangle are around 1/5 and 1/7. During low flow periods, the discharge will only fill the bottom of the triangle. If under these conditions, the upstream head (minimum head Hmin) above the point of the triangle vertex is insufficient to enable the fish to pass, the flow should be concentrated in a rectangular notch, as in the case of horizontal crests. Design criteria identical to those used for horizontal baffles can be used to determine their spacing and height.

1.3.3 “Offset” baffles (Figure 3)

This configuration of baffles has been widely used in Canada and the USA (MCINLEY and WEBB, 1966; ENGEL, 1974; RAJARATNAM *et al.*, 1988) where it has been adapted for all types of culvert. The main disadvantage of these baffles, although they are more efficient hydraulically than the aforementioned baffles, is that they are more difficult and costly to install. This is because of their complexity and the narrow spacing, which means that large numbers of them are required.

Figure 3 shows the geometric characteristics of this system. The dimensions and spacing are shown in a dimensionless form as a function of the width of the channel.

Model tests (LARINIER and CHORDA, 1995) have shown that the spacing of the baffles can be increased in order to reduce their number, especially in the case of culverts with a moderate slope. The spacing (L) can be varied according to the height (p) of the baffles and the slope (S) of the culvert as follows:

$$0.25 \leq S \times L/p \leq 0.35$$

The weirs have a minimum height of 0.20-0.30 m. At low flows this device acts as a small vertical slot fish pass, whilst at larger flows the orientation of the side wall creates helical currents and the culvert acts as a super-active baffle fishway fishway.

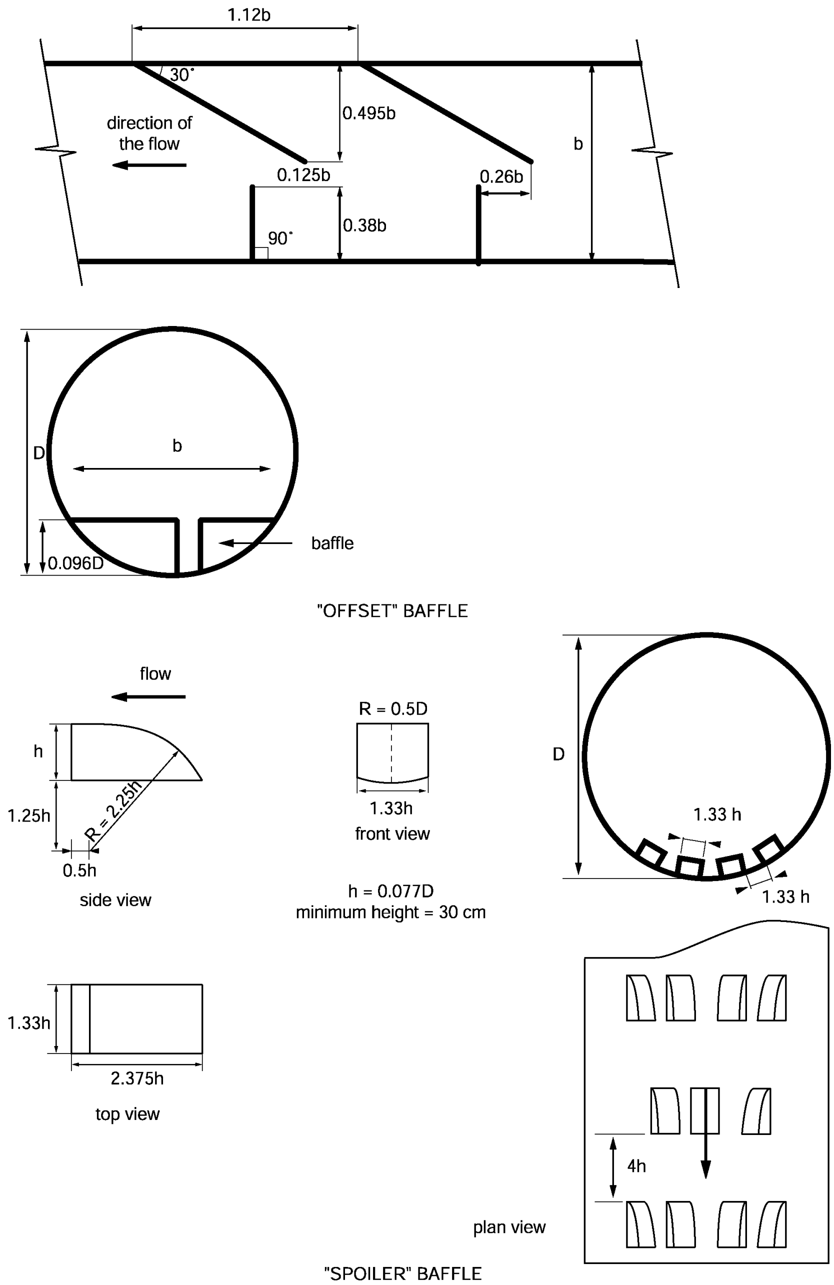

Figure 3: Offset and spoiler baffle design dimensions.

1.3.4 "Spoiler" baffles (Figure 3)

This system of baffles, studied on hydraulic models for circular culverts (ENGEL, 1974; KATOPODIS *et al.*, 1978), consists of a series of streamlined blocks, regularly spaced and placed in staggered rows. The shape of these baffles has been carefully designed in order to minimise their impact on the hydraulics of the culvert, as well as the risk of blockage by debris, whilst ensuring that the fish has sufficient rest areas in the separation zones. The recommended minimum height of the "spoilers" is 0.3 metres.

It should be verified that the water velocity between the "spoilers" remains compatible with the swimming speeds of the species concerned, as the distance to be travelled in these jets is around 2.5 times the height of the "spoilers". By integrating the results obtained by ENGEL (1974), KATOPODIS (1978) gives the velocity of the flow as a function of the gradient, and in dimensionless form in the following formula:

$$V/(gRh)^{0.5} = 7.97\ S^{0.539}$$

where Rh is the hydraulic radius of the culvert (cross-sectional area/wetted perimeter) which is not fitted with baffles, and S is the slope of the culvert.

Although the system has been tested on circular culverts, it can also be adapted to suit elliptical or arched culverts, by adding additional blocks at the side. ENGEL (1974) proposes a formula for calculating the number of blocks required across the width:

$$N = 1/2\ (1 + 7B/H)$$

where H is the height and B the width of the culvert.

The major disadvantage of this type of baffle system is the large number of blocks, since the lateral gap between two blocks is only equal to their width. It is also not clear whether they create a sufficient depth of water at low flow to enable fish to pass, particularly in the case of relatively wide elliptical culverts.

The main advantage of the "spoilers" over the other types of baffle is that they offer less resistance to the flow, and the culverts are therefore less subject to silting and blockage by drifting debris.

1.3.5 Effect of baffles on the flow

All the devices mentioned above have been used for gradients of culvert from less than 0.5% to 5%. Their use on steeper gradients must be considered very carefully.

They all significantly increase the depth of water in the culvert for any given discharge. This effect increases as the ratio of the depth of water to the height of the baffles increases.

The effect of the baffles on the discharge capacity of the culvert is related to their equivalent "rugosity", which itself depends on the ratios L/p and h/p (ratio of their spacing and of the depth of water to the height.

For a ratio between the depth of water and the diameter of the culvert (h/D) of between 0.5 and 1, the "offset" baffle (height p/D equal to 0.10) reduces the flow by 55% to 45% respectively (RAJARATNAM *et al.*, 1988).

The Strickler coefficient K, for a box culvert with a gradient between 1% and 5%, with horizontal or offset baffles, a weir height (p) of 0.30m, and with ratios of L/p (ratio of baffle spacing to baffle height) of between 5 and 20, varies from 15 to 21. This means that the installation of baffles in a culvert drastically reduces its capacity (LARINIER and CHORDA, 1995).

2. FISH PASSAGE THROUGH ROCK WEIRS

In France between the years 1965-1975 an increased demand for construction materials generated a drastic increase in gravel mining in alluvial streams. This excessive exploitation, which was often carried out under the pretext of "maintenance" of the river, caused enormous impacts on the natural equilibrium of stream channels. Effects included the lowering of the level of the watercourses, channel degradation, bank erosion, destruction of bank protection structures, exposure of structure foundations and lowering of water tables.

Large numbers of rock weirs have been installed in order to stabilise the resulting incising channels. The height of these stabilisation structures has varied from less than 1.50 m to more than 8 m.

These weirs usually constitute obstructions which are difficult to pass, or even totally impassable, for migratory fish. They are often at right angles to the banks and, since in most cases the crest is horizontal, the flow conditions (velocities and water depths) are uniform across the entire width of the weir. At average or high river discharges, the velocity becomes too high to allow the fish to pass. At low discharges the water trickles through the rocks and the lack of any water depth usually make it either difficult or impossible for large fish to pass, even in low structures.

Different solutions have been planned to make such obstructions passable. On the Gave de Pau, some weirs have been equipped with floor-baffle fishways, also used by canoes or kayaks. However, this type of fish passage facility has proved to be only partly effective in resolving the problem satisfactorily. They are not sufficiently attractive to the migrating fish, because their discharge and their width are very limited compared to the discharge of the river and the overall width of the structure. They are neither sufficiently flexible to take account of the wide range of species in the watercourse (salmonids, but also cyprinids), nor the large variations in upstream water level.

A better solution consists of installing vertical slot, or deep side notch and submerged orifice fishways, designed for large flows (greater than 1 m^3/s). They are more suitable both for the range of species present and the fluctuations in water levels. However, it should be noted that gravel deposits can create serious problems in this type of pass, causing reduced efficiency and increased maintenance costs.

Another solution consists of low rock weirs constructed near to one or both of the banks, forming pre-barrages which break up the drop to be passed.

On the Adour and Gave de Pau, several natural bypass channels with large flows have been installed with some success (Toulouzette, Meillon, Baudreix weirs). The very low gradient required (2% to maximum 5%) makes them very long, and this has prevented their widespread use. Their intake, depending on their location, can be affected by frequent gravel deposits after floods, which can disturb their supply and make a regular maintenance necessary. Nevertheless, this solution should be used wherever possible to make existing weirs passable to fish.

The best solution (apart from the obvious one of not building any new weirs) would be to make the weirs easily passable by design. Care should be taken to minimise their height, and to try to adopt a form that can facilitate fish passage. Tests have been carried out on hydraulic models (LARINIER *et al.*, 1995) to try to establish some criteria, and following this some experimental weirs have been built on the Adour and Gave de Pau rivers.

The principles are:

- To constrain the height of the weirs (to 1.0 m to 1.20 m maximum).

- To maintain heterogeneous conditions in terms of water velocity, water depth and unit discharge across the width of the structure. This is achieved by using a slightly triangular profile (20 cm to 80 cm variation in crest elevation across the width of the weir, depending on the variation of upstream water level during the migration period). During low river discharges flow is concentrated in the central, lower section (thus offering acceptable water depths for the larger fish), whereas with high flows there are still acceptable conditions for the fish at the sides of the weir.

- To restrain the velocity of the flow by limiting the gradient of the downstream face of the weir to 10%-12%, or else to construct "steps" in the structure so that the installation acts as a series of pre-barrages (Figure 4).

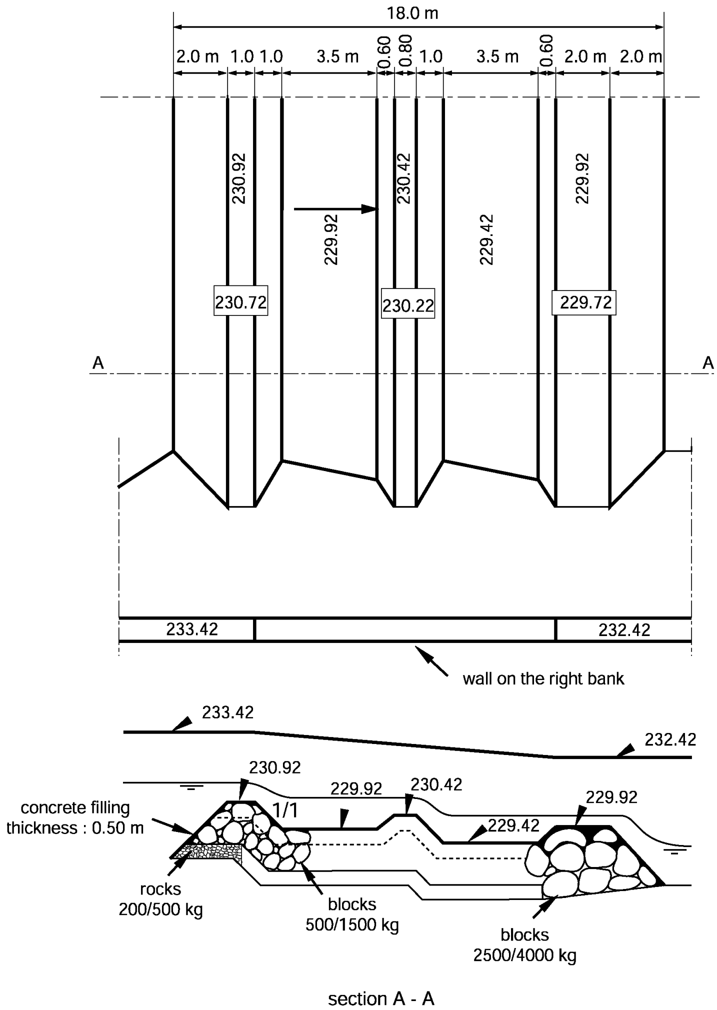

Figure 4: Stepped lined rock structure on the Adour River.

These solutions will result in higher construction costs for the weirs. On the other hand, at least as far as the better swimming species (*i.e.* salmonids) are concerned, they will eliminate the need to build more classical, concrete fish passage facilities. The latter are both difficult to integrate into the structure of a rock weir and, more often than not, will generate maintenance problems.

3. FISH PASSAGE AT COASTAL AND ESTUARINE OBSTRUCTIONS

Some installations obstruct migration more due to their function than to their height. This is the case with tidal sluices or estuarine dams intended to limit tidal incursion in the lower section of estuaries. This may be in order to provide a means of protecting agricultural land from flooding, to create freshwater reservoirs upstream of the structure for either recreational purposes or industrial or human water supply, or to create conditions for the development of docks. In this type of obstruction the fluvial discharge towards the sea is only allowed to occur at low tide. Once the incoming tide level exceeds a predetermined level the sluices or gates close. The level on the seaward side can then rise several metres above that on the river-side.

Two particular factors complicate the problems for fish migration and both must be taken into account:

- The levels from one side of the obstacle to the other vary greatly. The downstream level depends on the state of the tide, while the upstream level varies as a result of the storage of freshwater. The size of the fluctuations of the water level downstream depends on the amplitude of the tides (tidal coefficient) and the distance between the dam and the sea.

- The structure can prevent the movement of salt water upstream. Instead of benefiting from a gradual gradient in salinity, which is favourable for a progressive adaptation to the change in the environment, fish often find themselves confronted by a very sudden change. The biological effects (stress, mortality) and the behavioural effects (delaying or obstructing migration) of this are still poorly understood or unknown.

Since the end of the 19th century numerous coastal rivers in the Seine Maritime area have seen their estuaries disappear as a result of the culverting of their outlets to the sea, which was done to enable land development. They pass through a covered channel, which is generally fitted with a tidal flap gate intended to prevent flooding of the former estuary zone at high tide (EUZENAT and FOURNEL, 1983). These flap gates are generally constructed of one or more thick wooden panels hinged at the top of the culvert outfall. They allow the river to drain in its normal direction and prevent tides from backing water into the river channel.

These installations generally constitute a major obstruction to migration of salmonids, with increased velocities in the culverts, local acceleration at the sluices at low tide, and total closure of the sluices at high tide all preventing the fish from passing upstream.

Several solutions can be envisaged for specific installations. The water velocities in the culverts can be reduced by installing either deflectors, or else baffles on the floor. Passage at the sluices can also be improved by opening an orifice in the flap-gate, or by modifying the design of the sluices. The gate can be rotated and hinged on the side but at an angle less than 90° so that the weight of the gate will help close it.

Tests on models have shown that the behaviour of the sluices (duration and degree of opening) is very sensitive to their weight, the position of their centre of gravity, the return torque, etc. (I.M.F.T., 1988a, 1988b). The passage of the fish can be greatly facilitated by replacing existing sluice gates with lighter ones, and also in some cases by replacing one or more of the flap gates with a gate with hinged sections. This enables a wider gap to be provided for the fish to pass. The gates can also be actuated by floats, which can be adjusted so that they automatically open or close the gates predetermined tide levels.

Recently, a barrage was constructed on the river Bresle, in Le Tréport harbour, comprising a navigation lock, and a discharge installation including a sluice gate and fish passage facility. No matter what the level of the tide may be the fish can reach the entrance to the pass thanks to a series of three pre-barrages, which guarantee a minimum water level at the foot of the installation. The upstream river level is maintained at the level of 7.5m (reference 0.00 = minimum tide level), while the downstream, *i.e.* sea, level varies between 4.20 m and 10.00 m, depending on the tide. The fish passage facility consists of, from downstream to upstream (Figure 5):

- A lower entrance, fitted with a controlled sluice, and operating between the sea levels of 4.20 m and 6.50 m.

- Two flights of a chevron type baffle fish pass (16% gradient) leading the fish to an elevation of 6.75 m.

- An upper entrance, fitted with a control sluice, and working for sea levels over 6.50 m.

- A section of lateral deep notch-type pool pass allowing the fish to pass upstream.

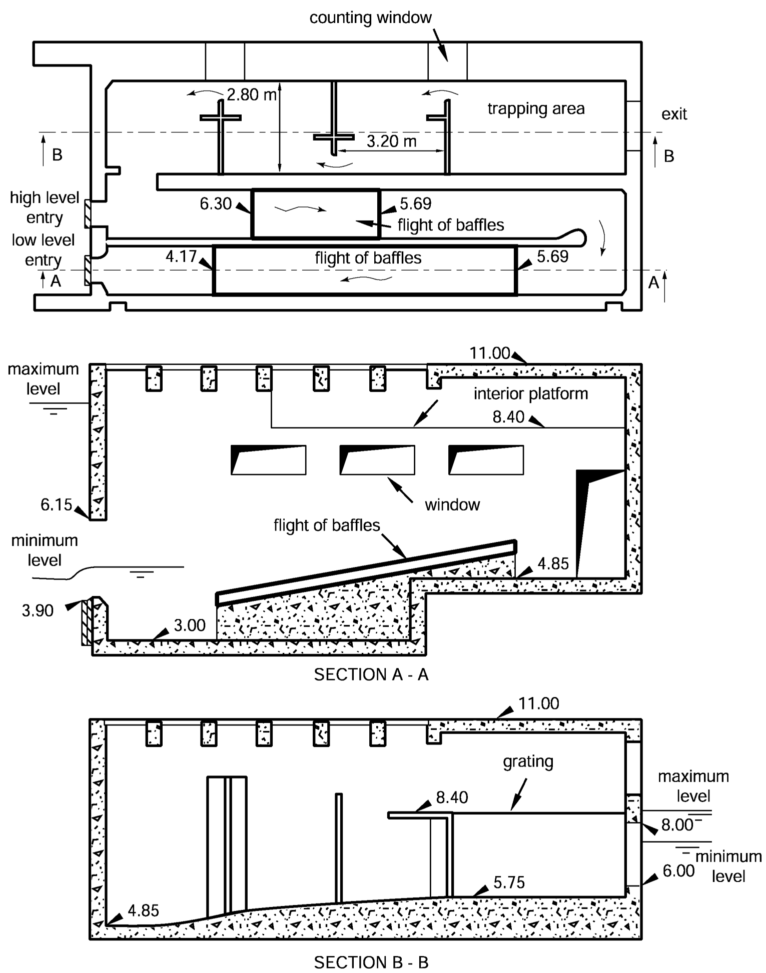

Figure 5: Views showing the estuarine fishway on the Bresle River.

As soon as the water level on the sea side reaches 6.50 m, the lower entrance closes and the upper one opens, allowing the fish to pass directly into the pool pass.

The facility also functions in the reverse direction from the sea towards the river as a submerged orifice pass, enabling fish to move upstream, provided that the level of the tide remains less than 9.50 m (EUZENAT and LARINIER, 1990; I.M.F.T., 1990)

After several years of operation, no significant detrimental effect of the construction of the barrage facility on the fish population has been detected by the fish monitoring station situated several kilometres upstream.

BIBLIOGRAPHY

BATES, 1999. Fish passage design at road culverts. Washington Department of Fish and Wildlife, Habitat and Land Program, Environmental Engineering Division Rep., 50 p.

DANE B.G., 1983. A review and resolution of fish passage problems at culverts sites in British Columbia. Fisheries and Marine Serv., Vancouver, Rep. 810, 126 p.

DRYDEN R.L., STEIN J.M., 1975. Guidelines for the protection of the fish resources of the Northwest territories during highway construction and operation. Fisheries and Marine Serv., Tech. Rep. Series CEN/T-75-1, 32 p.

ENGEL P., 1974. Fish facilities for culverts of the McKenzie highway. Nat. Wat. Res. Inst., Burlington, Ontario, 33 p.

EUZENAT, G., FOURNEL, F., 1983. *Etude préliminaire des conditions hydrauliques du passage mer/rivière des salmonidés migrateurs en Seine-Maritime. Problèmes du busage estuarien* (Preliminary study of the hydraulic conditions of the passage of migratory salmonids from sea to river in Seine-Maritime. Problems of estuary culverts). Conseil Supérieur de la Pêche Rep., 8 p.

EUZENAT, G.; LARINIER, M; 1990. *Port de Pêche du Tréport, barrage-écluse. Dispositif de franchissement par les poissons migrateurs* (Le Tréport fish harbour dam lock. Fish passage facility for migratory fish). Conseil Supérieur de la Pêche Rep., 65 p.

I.M.F.T., 1988a. *Etude sur modèle réduit de l'écoulement dans les exutoires des rivières côtières de Seine-Maritime. Cas de l'Arques* (Study on a model of the flow in the outlets of the coastal rivers in Seine Maritime. The Arques case.). Rep. 436.2, 21 p.

I.M.F.T., 1988b. *Etude sur modèle réduit de l'écoulement dans les exutoires des rivières côtières de Seine-Maritime. Ouvrage de rejet en mer. Rivière La Durdent* (Study on a model of the flow in the fish outlets of the coastal rivers of the Seine Maritime. Sea gate. La Durdent River). Rep. 436.3, 38 p.

I.M.F.T., 1990. *Port du Tréport. Etude sur modèles réduits d'une passe à poissons de l'évacuateur de crues du chenal de restitution* (Le Tréport harbour. Study on models of a fish passage facility at the spillway of the control channel). Rep. 452.1, 65 p.

KATOPODIS C., 1984. Drainage design considerations for fish passage. Proc. of 3rd Annual Western Provincial Conf. Rationalization of Water and Soil Research and Management. Manitoba Water Resources Branch: 347-376.

KATOPODIS C., ROBINSON P.R., SUTHERLAND B.G., 1978. A study of model and prototype culvert baffling for fish passage. Fisheries and Marine Serv., Tech. Rep. 828, 78 p.

KNIGHT D.W., MCDONALD J.A., 1979. Hydraulic resistance of artificial strip roughness. J. Hydr. Div., 105 (HY6): 675-690.

LARINIER M., CHORDA J., 1995. *Prise en compte de la migration du poisson lors de la conception des ouvrages de rétablissement des écoulements naturels dans les aménagements routiers ou autoroutiers* (Fish passage design at road and motorways crossings). GHAAPPE Rep. 95.01, 11 p.

LARINIER M., CHORDA J., FERLIN O., 1995. *Le franchissement des seuils en enrochements par les poissons migrateurs. Etude expérimentale* (Rock weirs for migratory fish passage. Experimental study). GHAAPPE/HYDRE Rep. 95.05, 25 p.

MCKINLEY W.R., WEBB R.D., 1966. A proposed correction of migratory fish problems at box culverts. Fish. Res. Pap., 1(4)*:* 33-45.

RAJARATNAM N., KATOPODIS C., 1989. Hydraulics of culvert fishways II*:* slotted-weir culvert fishways. Can. J. Civ. Eng., 16 (3)*:* 375-383.

RAJARATNAM N., KATOPODIS C., 1990. Hydraulics of culvert fishways III*:* weir baffle culvert fishways. Can. J. Civ. Eng., 17 (4)*:* 558-568.

RAJARATNAM N., KATOPODIS C., LODEWYK S., 1988. Hydraulics of offset baffle culvert fishways. Can. J. Civ. Eng., 15 (6)*:* 1043-1051.

SAYRE W.W., ALBERTSON M.L., 1961. Roughness spacing in rigid open channels. J. Hydr. Div., 87 (HY3)*:* 121-150.

WATTS F.J., 1974. Design of culvert fishways. Dept. Civ. Eng., Univ. of Idaho, USA, 62 p.

Photo 1: View from the downstream opening of a culvert illustrating the problems facing migrating fish: perching, high velocity and insufficient water depth in the culvert.

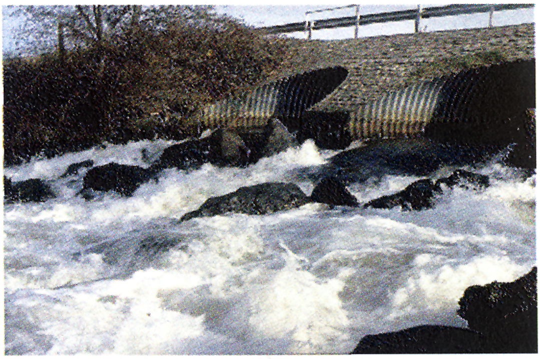

Photo 2: View from downstream illustrating the problems facing migrating fish : high velocities and turbulence.

Photo 3: View from the downstream opening of a culvert illustrating the problems facing migrating fish: perching and high velocity.

Photo 4 : "Offset" baffles.

Photo 5: Rectangular baffles in an arched culvert.

Photo 6: Chevron baffles in an arched culvert.

Photo 7: the natural cross-section of the stream has be maintained in this motorway crossing.

Photo 8: Rock weirs can be an impassable barrier during low flow.

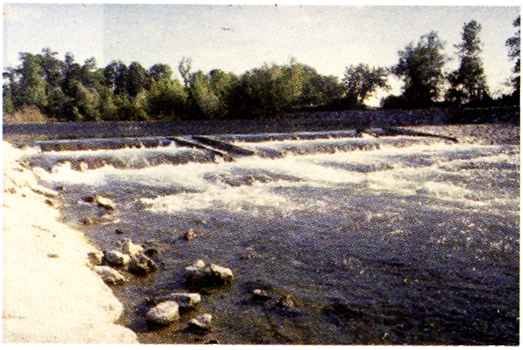

Photo 9: Stepped lined rock structure on the Adour river (Pyrénées).

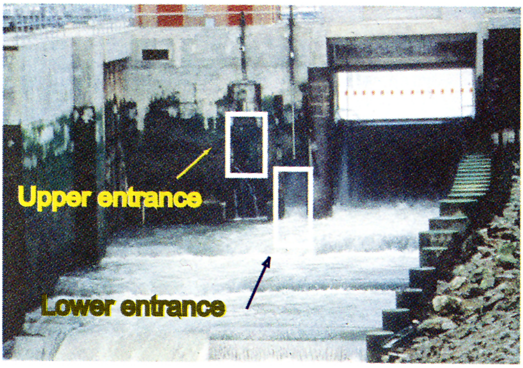

Photo 12: General view of the estuary dam at Le Tréport showing the pre-barrages, which allow the fish to reach the low level entrance to the pass at low tide. The discharge sluice is on the right.

Photo 10: Rock ramp with intentional low gradient passable by fish.

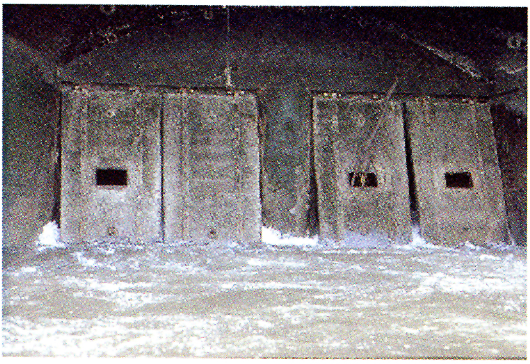

Photo 11: Tidal sluices on the river Arques at Dieppe (Nornandy).