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Experimental Observations on Stilling Basin Design

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Abstract—**The present paper points out that studying three-dimensional effects is fundamental for the identification of technical solutions that will help to reduce scours downstream of a stilling basin. The works analysed by means of a physical model are characterized by a marked asymmetry from both the geometric and the hydraulic point of view; as this asymmetry may give rise to random phenomena of stream flow concentration, it can lead to the anomalous working of the stilling basin as well as deep scours in the mobile river bed. This erosion is reproduced in the model and the experimental study has led to variations in the design of the stilling basin that, through the elimination of concentration and asymmetry in the stream flow, have resulted in a drastic reduction in scours.**

Keywords—stilling basin, local scours, mobile river bed, experimental tests.

I. Introduction

A task that designers inevitably have to undertake is to adapt general design standards to the particular structures being studied. This is not always straightforward as the constraints to which the structure may be subject (effectively making the structure a prototype) may impose boundary conditions that are substantially different from the ones that determined the standards in the first place.

In order to ensure that the standards acquire a general validity, they are often obtained through the use of robust simplifying hypotheses, especially in more complex cases such as turbulent three-dimensional hydrodynamic models. In such cases, the designer may be assisted (at least for structures of greater technical and economic significance) by preliminary studies carried out on a physical scale model before building the prototype. Indeed, when aiming to improve prototype operation, it is not uncommon for studies on models to clarify problems and yield solutions of a more general nature.

Unfortunately, however, such studies are only carried out when far-sighted governing bodies make funding available so that the corresponding structures can be built. As a result, it is generally necessary for engineers to make the most of their knowledge, experience and, at times, imagination in order to solve problems that have not been properly posed. And it is the latter quality that has always made the engineering profession so fascinating but also one laden with responsibility.

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It is, therefore, essential that the engineering world should strive for on-going technical development, but this must be wisely promoted and enhanced by administrative and scientific bodies. Within such a framework, this paper aims to stress some particular aspects and report the results of recent experiences that may help to better contextualise the general criteria to be taken into account in the design of spillways and stilling basins downstream of reservoirs and dams [1, 2].

It is well-known that interest in spillway structures (comprising stilling basins to protect the watercourse from erosion) is mainly focused on their capability to dissipate energy and reduce the potential causes of erosion downstream. In this respect, a major issue lies in the modelling of the watercourse which is generally achieved through the natural, though delicate, equilibrium regimes of actions exerted by the stream on the mobile bed. Artificial reservoirs, like all river barriers affect this regime particularly when high-energy streams are fed into the channel during flow regulation operations.

If this energy leads to dynamic actions that exceed the force required to cause the mobile bed to become detached, then it must be dissipated in order to avoid undesirable scour phenomena. The formation of eddies, turbulence and hydraulic jumps may scour the river bed and may also lead to a collapse of the banks and the destruction of monitoring and control structures along the affected watercourse [3-10].

It is therefore clear that the study proposed in this paper is of some interest and is being developed in specific research activities.

II. Notes on usual design standards

In technical practice, when the flow released into the watercourse downstream of dams or barriers causes considerable scour, the problem is solved with the construction of dissipation structures. A significant example of such works is the stilling basin studied by Nebbia [11, 12] as far back as the 1940s.

These basins are normally fitted with a raised sill at their downstream end and the flows from the outlet works – which have considerable kinetic energy – dissipate most of their energy through the formation of a hydraulic jump: this obviously results in the supercritical upstream flow being slowed down before flowing over the sill and into the downstream reach.

The mathematical models that are normally used when sizing a hydraulic jump stilling basin are generally based on the hypothesis that the hydrodynamic processes are not conditioned by side walls. Therefore the fundamental parameter is the unit flow $q = Q/B$, where Q indicates the discharged flow and B is the width of the stilling basin.

Under this hypothesis, with a fixed width for B the sizing of the basin essentially consists of determining the length L and the height c of the end sill that will determine the hydraulic jump. In order to ensure that the hydraulic jump takes place within the basin, the sill length L must be greater than the length L_R of the hydraulic jump.

The diagram in Figure 1, which has been determined experimentally [13], makes it possible to deduce the values of L_R from the L_R/h_2 ratios, i.e. between the length of the hydraulic jump and the head of the subcritical downstream flow h_2, expressed as a function of the Froude number of the supercritical upstream flow $F_{r1}=V_1/(gh_1)^{1/2}$, where V_1 is the velocity, h_1 is the head and g is the acceleration due to gravity.

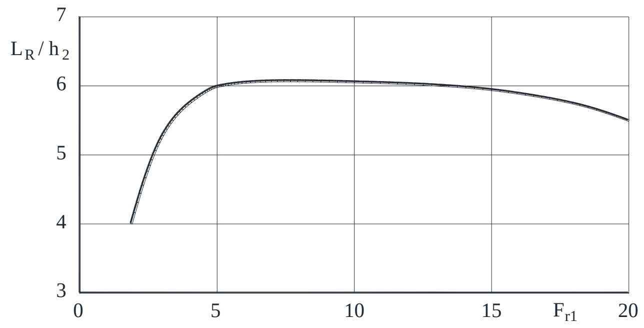

Figure 1. Experimental diagram for calculating L_R .

The height c of the end sill can be determined using the experimental equation (1) by Nebbia [13]:

$$\frac{c}{H_c} = 1 + 0.5\sqrt{\frac{\Delta E}{H_c}} - 0.025\frac{\Delta E}{H_c} - \mathrm{K}\frac{H_3}{H_c} \qquad (1)$$

where H_c is the total critical head (calculated using the flow value q), $\Delta E = E_0 - E_3$ is the difference between the total upstream head (in the reservoir and compared to the chosen reference plane) and the total downstream head (at the downstream face of the sill and compared to the same reference plane), K is a coefficient depending essentially on the geometry of the sill and, finally, H_3 is the total head in the bed immediately downstream of the sill.

In particular, for the coefficient K we have:

- for a sill with a vertical upstream face, K=1 with $c/H_c \geq 0.5$ or $H_3/H_c \approx 1$, otherwise it reaches minimum values up to 0.95;
- for a sill with a 45° sloping upstream face, K $\approx$ 1 with $H_3/H_c \approx 1$ and decreases to 0.85 with H_3/H_c rising up to 1.5.

If the head values drop, these are generally ignored unless they regard the hydraulic jump, and thus the total hydraulic head E_1 of the supercritical upstream flow is set to E_0, while E_3 is set to E_2, i.e. the total hydraulic head of the subcritical flow downstream of the hydraulic jump.

Once the system geometry has been fixed, the values of *H* can be easily determined.

It is worth remembering that if the flow downstream of the basin is subcritical, the E_3 head is determined from the flow characteristics (the reference conditions are generally assumed to be steady flow), if the flow downstream of the basin is supercritical, E_3 can be determined from the critical conditions at the sill.

III. Considerations and preliminary experimental tests

In real life, the boundary conditions are often very different from the hypothesised ideal steady flow conditions on which the mathematical computation model is based. That is why we have chosen to report a laboratory experiment, which highlights how the study of three-dimensional effects is fundamental in identifying technical solutions that will reduce the possibility of scouring downstream of the stilling basin.

In particular, we will point out that making reference to a constant flow along the sill in the stilling basin – like the unit flow q mentioned above – turns out to be a sometimes unacceptable simplification.

The study is based on a test carried out on a physical model (scale 1:50 with respect to the prototype and under Froude's similarity hypothesis) of the outlet works on Farneto del Principe reservoir on the river Esaro (Southern Italy), outlined in Fig. 2.

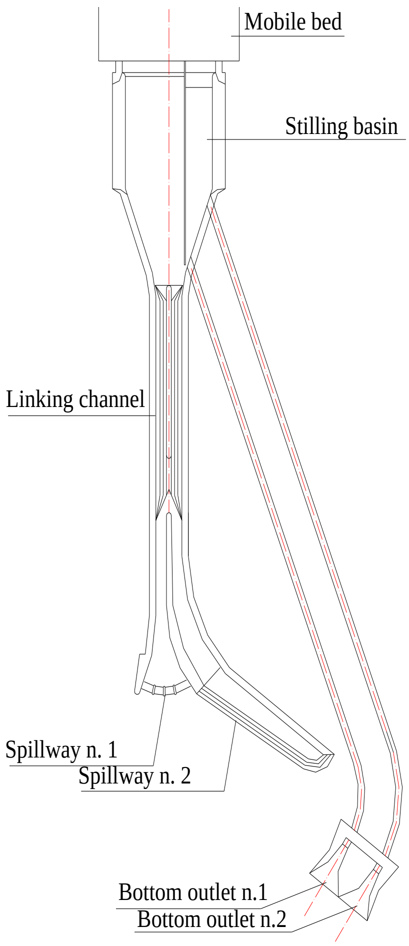

Figure 2. Outlet works analysed by the model.

The prototype of this structure essentially comprises:

- Spillway n.1, with a crest located at an elevation of 136.30 meters above sea level and four apertures measuring 6.10 m each fitted with an automatic flap gate;

- Spillway n.2, with a free crest located at an elevation of 139.70 meters above sea level and measuring 101.00 meters in length, which discharges the water into a variable trapezium-section side channel;
- Two bottom outlets at the base of the outlet works served by two circular pipes with diameter d = 4.95 m , upstream from the sluice gates, and a polycentric section pipe with diameter d = 4.80 m, downstream from the sluice gates;
- A hydraulic jump stilling basin which is lined and has a bottom that is lower than the bed of the downstream reach of the river, into which the flows from the spillways (by means of an open, polycentric-section channel) and the bottom outlets are discharge.

The design specifications call for spillways n.1 and n.2 to discharge a maximum flow Q_1 = 615 m^3/s and Q_2 = 520 m^3/s, respectively, with the reservoir head 141.70 meters above sea level.

The study of this model aims to clarify the overall hydraulic operation of the structure and, above all, the performance of the stilling basin in reducing scour in the downstream reach of the river bed.

Therefore, the erodible river bed downstream of the stilling basin has been reproduced (for separate test batteries) both using sand passed through a 4mm mesh sieve and with small gravel sieved through a 10mm mesh [14].

As is reported below, the conclusive comparison between the tests was carried out with reference to the tests using small gravel: this material greatly simplified both the test procedures and the measurements of scour in the various conditions.

Since experimental tests of this kind can only yield qualitative rather than quantitative indications regarding scour, it was deemed sufficient to identify the technical solution involving less scour by means of a simplified procedure.

Note that the experimental tests on the outflow processes which made it possible to determine the particular scales of flow in the intake works are not described here.

Moreover, only some of the numerous tests regarding stilling basin operation (which required operation of the experimental installation for a few hundred hours) are reported here, namely those that provided conclusive data for inferring results of a more general nature.

Finally, only those tests regarding the simultaneous operation of the two spillways are reported (maximum flow in the model Q_{m1-2} = 64.20 l/s, equivalent to a maximum flow in the prototype Q_{p1-2} = 1135 m^3/s).

Initial experimental tests conducted on the outlet works, as envisaged by the design team, highlighted a geometric and hydraulic asymmetry which concentrated the flows and resulted in the stream forming sometimes on one side and sometimes on the other side of the stilling basin.

Furthermore, the stream had an asymmetric, wave-like motion in the channel between the spillways and the stilling basin. It should be noted that although a hydraulic jump forms in the basin immediately downstream of the side channel, dissipating some of its kinetic energy – in accordance with the theoretical and design hypotheses – unpredictable phenomena of asymmetrical scouring are observed towards the banks of the downstream reach.

The scouring that takes place at the maximum flow rate (discharge from both spillways and equal to Q_{p1-2}=1135m^3/s) reaches considerable values (10 ÷11 cm in model) even in the tests in which the mobile bed is made up of gravel (Fig. 3).

In particular, when the central part of the stream, which has a greater hydraulic head and velocity shifts towards one of the banks, large vertical axis eddies form, affecting the flow over the sill on the basin's downstream edge.

The possibility of this stream randomly shifting to one or the other bank also has an impact on downstream scouring, which may occur in an essentially unpredictable manner on either riverbank.

This phenomenon also makes it difficult to identify the ideal downstream location for river management structures. Fig. 3, referring to the originally designed basin, reports the results both for scour in one of these first experimental tests and for the maximum head reached in the basin (within the same test and compared to a reference elevation 0.00) along both longitudinal alignments (A and B), pointing out the stream's considerable asymmetry.

Bearing in mind that the results yielded by the preliminary tests are unacceptable and that the topographic, environmental and anthropic constraints (of the prototype) mean that the geometry of the outlet works and the stilling basin cannot be radically modified, we sought a solution that would eliminate the highlighted drawbacks through a modest variation in the works' horizontal and vertical alignment scheme.

It was also borne in mind that the tests clearly pointed out how the stream asymmetry makes it difficult to apply mathematical models for sizing, which are based on the hypothesis of a constant flow per width unit q.

IV. Final experimental tests

In view of the preliminary test results, solutions were adopted so that the excessive flow of the stream entering the basin would not only be dissipated by means of a hydraulic jump but also through the action of a series of baffle piers of various shape, size and position.

In particular, we sought out the solution whereby the baffles would both dissipate the supercritical flow and eliminate the stream asymmetry (which would otherwise have a negative effect on the erodible bed of the downstream reach).

Naturally, we also sought the solution that would require the fewest baffles.

Following a series of experimental tests, the stilling basin was modified as indicated in Figure 4. Specifically:

- the horizontal bottom of the basin was raised from 108.60 to 110.10 meters above sea level (prototype measurements);
- the sill bottom was lowered from 113.35 to112.10 meters above sea level;
- baffles were placed in the basin but only in the central area where the stream has greater kinetic energy;
- the bottom of the basin was raised in the two strips on either side of the central area fitted with cube-shaped baffles, 112.10 meters above sea level;
- The side channel from the spillways to the stilling basin was fitted with a central, longitudinal, variable-height element in order to reduce the wave motion and the asymmetry of the stream before it flows into the basin.

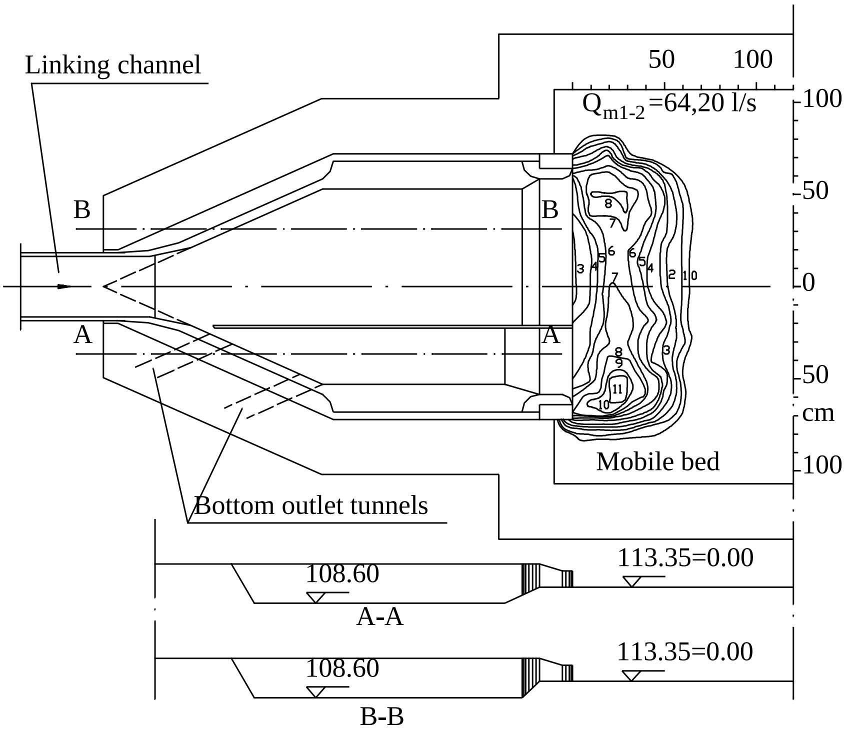

Figure 3. Preliminary test with originally designed basin (Qp1-2 = 1135 m^3/s).

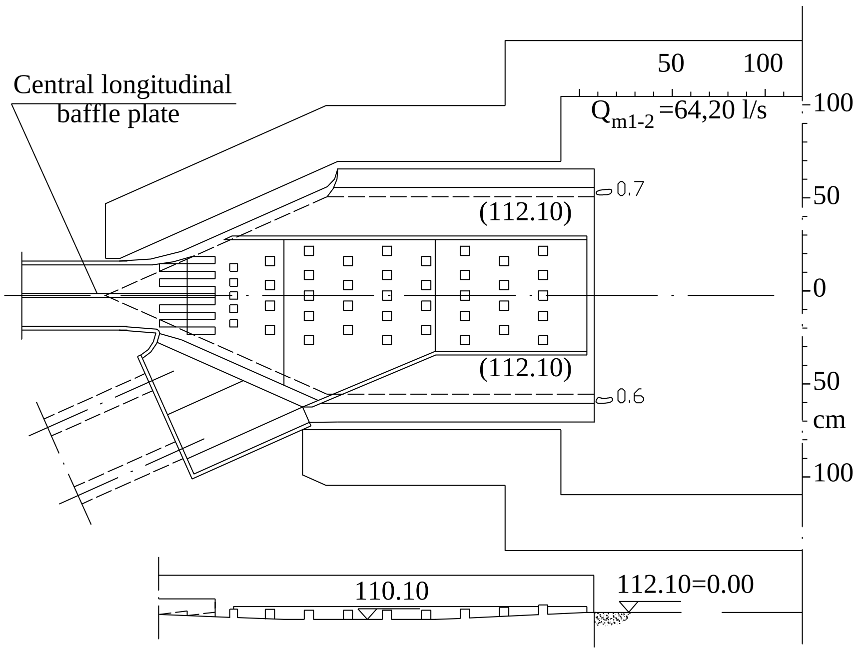

Figure 4. Test with modified basin – Final solution (Qp1-2 = 1135 m^3/s).

The baffles are rows of elements of increasing height offset against one another to prevent excessive rises in the stream flow. In particular, the first two rows of baffles are prism-shaped with a width (in the prototype) of 2.00 m and a triangular longitudinal section measuring 7.50 m along the base and 1.50 m in height at the downstream cathetus; the third-row baffles are cube-shaped and measure 2.00 m on each side; the remaining rows are also cube-shaped but measure 2.50 m on each side.

The basin thus modified, reported in Fig. 4 , succeeds in dissipating the kinetic energy and almost totally eliminates asymmetry, deviation and concentration of the stream giving rise in repeated tests to extremely modest scour, measurable only at maximum flow rate (Qp1-2 = 1135 m^3/s in the prototype). The maximum scour in these operating conditions and using gravel is in model 0.7 cm (Fig. 4).

V. Conclusions

The experimental study reported above highlights how the geometric configuration and the operating procedures of outlet works can seriously restrict application of the mathematical models usually employed for the design and testing of dissipation structures such as hydraulic jump stilling basins.

The structures analysed in the model (although sized using the conventional theoretical hypotheses), reveal a marked horizontal, vertical and hydraulic asymmetry, giving rise to unpredictable instances of deviation and concentration of the stream which may cause deep and equally unpredictable scouring of either side of the erodible bed of the downstream reach.

A model-based study made it possible to reformulate the layout of the stilling basin prototype, achieving a drastic reduction in scour, above all by eliminating deviation and concentration of the stream caused by the above asymmetry.

Despite its specific context and the essentially qualitative results obtained (hence confirming the importance of physical models), this study has yielded some considerations or a general nature.

- The experiments have highlighted that, in the case of asymmetrical (and three-dimensional) streams, by removing the hypothesis for constant flow per width unit q, mathematical models for the design of hydraulic jump stilling basins provide highly approximated results that are unacceptable in practical applications. It would therefore seem appropriate that even the preliminary design phase of outlet works should consider the layout configuration and the geometry of structures, including spillway crests.
- When the asymmetry of the intake structures cannot be eliminated, it needs to be controlled by selecting a suitable shape for the stilling basin: the experimental tests have pointed out that the volume of the stilling basin can even be reduced as long as this eliminates stream deviation and ensures greater efficacy of the required baffles, which can be positioned so as to absorb the greatest kinetic energy in the stream.
- The asymmetry can also be checked by providing the longitudinal section of the basin with an upturned scalene trapezium section, whose longest oblique side acts as the sill.

This better shape respects more fully the geometric conformation of scour in a mobile river bed which, where eddies are present, tends to become more stable.

Moreover, keeping asymmetry in check provides a reasonable certainty in locating any scour phenomena in the erodible downstream reach. This makes it possible to correctly choose and position any river management structures on the banks.

Finally, it should be noted that although the design choice to concentrate all the flows from outlet works in a single dissipation structure may be less expensive, it heightens the danger of asymmetry and accentuates the impact of the stream on the erodible river bed.

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