VORTICITY IN HYDRAULIC STRUCTURES: MODELLING AND PREVENTING

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Abstract: Free surface vortices at hydropower intakes can significantly reduce turbine efficiency and cause premature mechanical failure; in siphon spillways the vorticity and the air entrainment to the pressure circuit can reduce the spillway discharge capacity. Therefore preventing the occurrence of vortices is very important in the design of water intakes. Due to the complexity of the phenomena, physical models are a valuable help and, apart from the scale effects, vortices observations on physical models can give valuable results that aid in the design of hydraulic structures where vortices might appear.

In this paper, the formation of free surface vortices in two types of submerged hydraulic structures and several solutions to prevent vortices formation are presented. The experimental studies were performed in two scaled physical models which allowed testing several solutions for anti-vortex devices that proved to be generally efficient and can be easily incorporated in the final geometry of water intakes.

Keywords: vorticity, water intakes design, siphon spillways, physical models.

INTRODUCTION

The occurrence of free surface vortices represents a problem in different cases of submerged water intakes, namely at hydropower intakes and at submerged spillways entrances, as for example in siphon spillways. Large free surface vortices can promote the introduction of floating material and entrained air into the intake, which might be harmful for the intake and its subsequent hydraulic circuit.

In particular, free surface vortices in hydropower intakes can significantly reduce turbine performance and cause premature mechanical failure; in siphon spillways the vorticity and air entrainment in the discharge circuit can reduce the spillway discharge capacity and also can cause structural damage on the circuit. Therefore preventing the occurrence of vortices is a priority when designing water intakes.

The water motion tendency when approaching the water intake is unpredictable and strongly dependent on the intake geometry and its correspondent operating rules. Vortices formation is also strongly dependent on the site morphology of the water intakes. Thus, water intakes located at different places may require very distinct anti-vorticity solutions.

The current engineering practice is to develop physical models based on the preliminary design of submerged water intakes and to perform a set of tests with the operation conditions in order to understand if vortices will appear in the tested solution. The results of the physical model study will allow introducing alterations in the preliminary design project that will ascertain that no strong vortices will occur under the expected operating conditions.

The formation of free surface vortices were studied in two types of submerged hydraulic structures: *i)* the spillway intake of Undúrraga Dam (studied at a 1:20 hydraulic scale model), correspondent to a siphon spillway, and *ii)* the water intake of Bemposta repowering scheme (studied at a 1:52.5 hydraulic scale model). Solutions to prevent vortices formation, namely vortex-suppressing devices, such as vertical and horizontal grids were developed. All the tested anti-vortex devices belong to the set of corrective measures to suppress vorticity recommended in Knauss, 1987.

THEORETICAL CONSIDERATIONS

Vortex formation is due to the presence of rotational flow in the fluid mass (Clancy, 1975). Usually, vortices can occur in sites where velocity gradients between two adjacent water layers occur, causing part of the mass fluid to move faster than the other part and resulting in a spiral water motion. According to Durgin and Hecker (1978), there are three fundamental causes to flow vortex formation: *i)* flow direction change; *ii)* velocity gradient and *iii)* obstructions. Generally, vortices appear where transitions from open channel flow to pressure flow exist. Therefore, hydraulic structures with submerged orifices are extremely propitious to the vortices formation. This flow tendency, even though dependent on submergence, is also strongly influenced by added circulation from other rotational sources. Therefore, an asymmetry in the topography surrounding the submerged water intake or in the channel approach geometry, resulting in non-uniform flow-approach conditions or creating motionless water zones, is also propitious to vortices formation.

Hecker (1981) suggested that vortices can be classified according to their strength, presenting the following scale types (Fig. 1): *1)* coherent surface swirl; *2)* surface dimple and coherent surface swirl; *3)* dye core to intake and coherent swirl throughout water column; *4)* vortex pulling floating debris but not air; *5)* vortex pulling air bubbles to intake; and *6)* full air core to intake. A vortice is considered problematic when it draws bubbles or an air core into the inlet (over type 3).

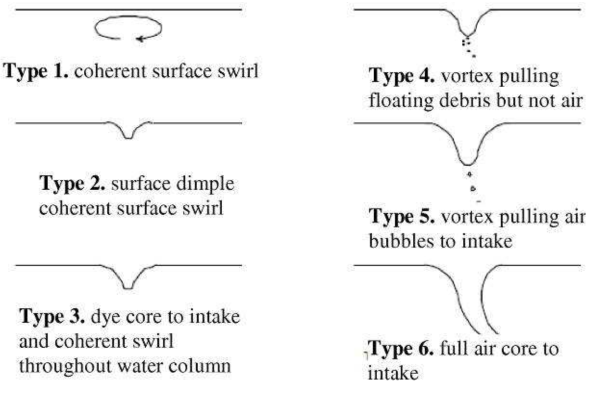

Fig. 1 – Vortices classification according to its intensity (Hecker (1981))

Accordingly to Magalhães and Martins (1981), problems and deficiencies in hydraulic water intakes due to vortices formation include: *i)* head losses increase; *ii)* flow efficiency and water discharge coefficients decrease; *iii)* floating material transport and eventual clogging of entrances or debris concentration in motionless zones; *iv)* debris entrainment into pressure pipes and galleries; and *v)* air entrainment into pressure pipes causing vibration, cavitation and pneumatic phenomena.

The three most common methods used to eliminate vortices are: *1)* improve the “lay-out” of the submerged water entrance; *2)* increase the water entrance submergence and *3)* implement vortex-suppressing devices.

The first and second methods may imply important modifications to the water intake geometry and, therefore, the use of vortex-suppressing devices constitute a current common practice in the final design solution. According to Viseu et al. (2007) flow-straightening devices can be divided into two different types: *i)* devices contributing to eliminate the zones where water is motionless and *ii)* devices to intersect the swirling motion of the flow. The second type (anti-vortex devices) may be classified according to its general appearance - *horizontals beams* or *verticals walls* - or according to its localization - *superficial* or *deep* -. The choice between them is determined by the type of vorticity to eliminate (surface swirl or full air core to intake) as well as by the water level variation in the reservoir. The most currently used devices include*: i)* vertical or horizontal grids; *ii)* the backwall-attached splitters; *iii)* flow deflectors and *iv)* baffle plates (Tullis (1979), Sweeney et al. (1982), Melville et al. (1994) and Bauer et al. (1997)).

PHYSICAL MODELS

Models Scales

A mechanical phenomenon can be studied in scale models where all lengths, times and masses are scaled down λ_L, λ_T and λ_M times, respectively. When constructing a physical scale model, complete similarity between the prototype and its model requires fulfilment of three similarity criteria: *geometric*, *kinematic*, and *dynamic*.

The channel flow in the approach to water intakes is, in average, a stationary non-uniform flow, accordingly the vortices that might appear at water intakes are completely determined by (Yalin 1971): *(a)* the nature of the fluid (μ and ρ); *(b)* the absolute size of the flow (which, for example, can be given by the hydraulic radius corresponding to the cross-section of the intake entrance - R_h); *(c)* the water intake roughness (k); *(d)* the kinematic state of motion (which can be given by the average velocity - U); (e) by the absolute value of the acceleration due to gravity (g);

Any mechanical quantity related to these flow types can be expressed as a function of the last six parameters: $\underline{\Gamma = f_\Gamma\ (\mu, \rho, R_h, k, U, g).}$

The parameters ρ, R_h and U are independent and they can be selected as basic quantities which allow to obtain the dimensionless equivalent to Γ which is $\underline{\Pi_\Gamma = \varphi_\Gamma\ (X_1; X_2; X_3})$; where X_1, X_2 and X_3 are: $X_1 = \rho^1 R_h^{\ 1} U^1 \mu^{-1} \rightarrow \mathbf{X_1 = UR_h/v}$ (*Reynolds number*); $X_2 = \rho^0 R_h^{\ -1} U^0 k^1 \rightarrow \mathbf{X_2 = k/R_h}$ (*relative roughness*) and $X_3 = \rho^0 R_h^{\ -1} U^2 g^{-1} \rightarrow \mathbf{X_3 = U^2/gR_h}$ (*Froude number*).

According to the previous analysis the predominant forces in these flow types are the inertial, gravitational and viscous forces. The physical models of the Undúrraga dam spillways and of Bemposta repowering scheme were built with scales of 1/20 and 1/52.50, respectively.

These scales were achieved so that the *Reynolds number* was sufficiently high in both models to guarantee that the flow regime is turbulent ($Re > 10^4$) and consequently, that the viscous forces effects on the experimental results, namely in the behavior of swirling flow envisaged to occur, can be ignored. For $Re > 10^4$, the predominant forces in these flow types are the inertial ones and, therefore, both physical models were designed according to Froude similarity.

Despite the above, it is well known that physical simulation of surface vortices does not meet Froude criterion meaning that vortices on Froude models are significantly weaker (Gorbachev, 2007). Accordingly, in the vorticity domain, Froude models are against safety (Martins, 1983) and it is expected that the vortices in the models are less developed than in the prototypes. These last facts were taken into consideration in respect to vorticity conclusions in both studies.

Undúrraga dam spillway

Undúrraga dam is located in the Arratia River (Spain) and its main use is the water supply to the metropolitan region of Bilbao city. It is a 36 m high rockfill dam, with a 1.85 hm^3 gross storage capacity. It has a main spillway, and a secondary one was envisaged to increase the dam flood discharge capacity (Fig. 2). This second spillway is formed by four siphons followed by steel conduits with 2.30 m wide and 1.60 m high. The conduits discharge into two open channels, 5.00 m wide, followed by buckets.

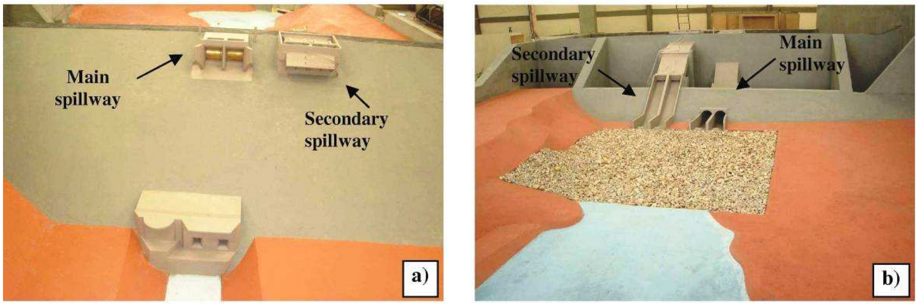

Fig. 2 - Physical model of Undúrraga dam and spillways. a) upstream view, b) downstream view

Water intake of Bemposta repowering scheme

Bemposta dam, built in 1964 on the international course of Douro River, is a curved hollowed gravity dam, with a maximum height of 87 m. The three water intakes of the existent hydraulic circuit, are located on the right bank of the river (Fig. 3 - Left). In 2006 it was decided to repower the Bemposta hydroelectric scheme with a new hydraulic circuit. The water intake of this new hydraulic circuit was envisaged to be also built on the right bank of the river, upstream from the existent intake (Fig. 3 - Right). Bemposta repowering scheme has been operating since November 2011.

Fig. 3 - Bemposta dam. Approach channels and water intakes of the two power stations, old one at left (prototype) and new one for the reinforcement at right (physical model).

EXPERIMENTAL STUDIES

Undúrraga siphon

The hydraulic behaviour of a siphon spillway is complex. According to Khatsuria (2005) it can be divided into three phases, Fig. 4: *1)* weir flow, before the priming of the siphon, where discharge is governed by the normal relationship $Q = K.H^{3/2}$; *2)* air regulated flow, when the rising level seals the entrance and air starts to be entrained and evacuated by the siphon, it is a two-phase flow and the discharge increases for a practically constant water level in the reservoir; *3)* blackwater flow when all the air has been removed and discharge is governed by closed conduit relationship $Q = K.H^{1/2}$.

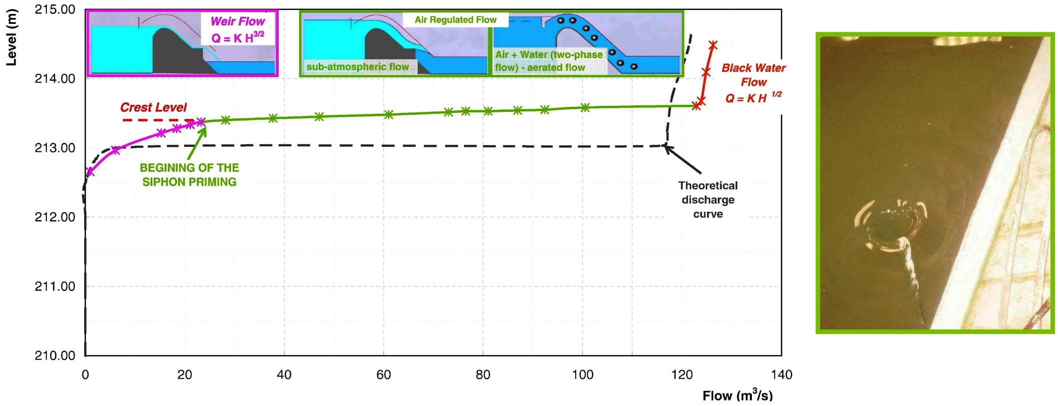

Fig. 4 - Undúrraga dam siphon spillway. Left - discharge curve of the air regulated siphon; Right - Aspect of vortices occurrence during the siphon priming phase.

The Undúrraga siphon spillway studied in physical model was an unusual and non conventional design, particularly due to its atypical implantation circumstances. As a result, an approximation of the theoretical discharge curve of the siphon was obtained by the spillway design under a set of considerations, namely that: *i)* the siphon primes for the flow of 6 m^3/s; *ii)* the losses in the mouth are about 30% of the entrance height and velocity; and that *iii)* the losses at the elbow, exit transition and caused by friction are equivalent to 60% of the exit height and velocity. With these considerations, the theoretical discharge curve for the siphon was obtained by the expression (1) (AGH, 2006):

$$Q = 6.504548\sqrt{19.62(N - 196.866)} \qquad (1)$$

Considering the above, the main reason for the difference between the theoretical and experimental curves presented in Fig. 4 is that the first one was a result of a some simplified considerations, namely in what concerns losses estimations, that, as confirmed by the experimental results, were not verified in practice.

Bemposta water intakes

Two situations of vortices occurrence on the prototype were reproduced in the physical model in order to understand if the physical model was trustable in what concerns the vortices reproducibility, Fig. 5.

Fig. 5 – Vortice near the water intake of the old power circuit. a) physical model of Bemposta dam; b) and c) prototype

Both situations were reproduced reasonably well in the physical model, and quasi permanent and relatively strong vortices of 0.8 to 1.0 m diameter were observed in the experimental tests corresponding to those observed in the dam's site. According to the tests results it was concluded that the vortices observed in physical model give a good idea of the vortices that might occur in the water intake of the repowering scheme (Amaral et *al.*, 2010). In the physical tests it was also observed that the intermittent vortices that appeared near the new water intake were weaker than the vortices that exist in the frequent operation of the existent water intake.

PREVENTING VORTEX FORMATION

Main modifications tested in Undúrraga dam siphon spillway

Three main modifications in the spillway entrance have been tested, Fig. 6. The first one consisted in increasing the inlet length in order to increase the submergence of the water entrance. This modification did not improve the siphon's behaviour and the physical tests showed that vortices still occur at the entrance, essentially when the siphon primes, leading to a substantial increase in water discharge, and consequently, to a fall in the upstream level, which pilots the water surface to approach the inlet ceiling (Fig. 6 – a)). The second modification consisted in a floating horizontal grid formed by horizontal and transversal beans. This floating anti-vortex device, which is cable-stayed to the inlet ceiling, has the advantage of being an economical solution to prevent the vortex formation and is independent from the reservoir water level. Its main disadvantage is the deterioration during long time-period of functioning, i.e., it is a device that could pose some maintenance problems (Fig. 6 – b)). The third device tested consisted in a vertical grid directly constructed in the inlet ceiling. This solution has the advantage of being a fixed device. Physical model tests showed that the vertical and horizontal beans intersect the swirling flow, eliminating the vortices. As a direct consequence, the water flow in the entrance is extremely quiet, even for the higher discharges and lower water levels at the reservoir (Fig. 6 – c)). This was the adopted solution to eliminate vortices in the water entrance of Undúrraga dam spillway (Fig. 6 – d)).

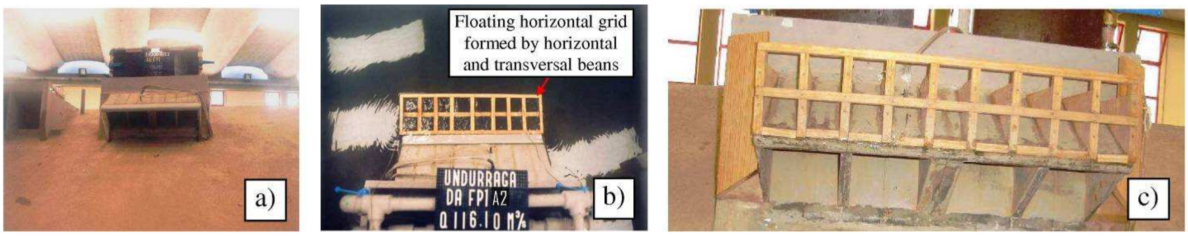

Fig. 6 – Tested devices to prevent vortices at the siphon spillway entrance of Undúrraga dam: a) increased inlet length; b) floating horizontal grid; and c) fixed vertical grid; d) Siphon operation through maximum discharge with the last proposed anti-vortex solution

Alternatives for vortices prevention tested at Bemposta water intakes

Three different alternatives were tested in the physical model to prevent the vortices appearance: *1)* a triangular beam, placed over the entire forehead of the water intake, with a size of 3 x 1.5 x 20 m (height x base width x length); *2)* two small trapezoidal walls, placed on the axis of each water intake bay, both with a size of 5 x 2 x 4.5 x 0.5 m (height x base width x top width x thickness); and *3)* two large trapezoidal walls on the axis of the each water intake bay, both with a size of 7 x 3 x 6.5 x 0.5 m (height x base width x top width x thickness), Fig. 7.

The tests conducted with these three different devices lead to the conclusion that device 1 does reduce the vortices appearance, when the repowering circuit is operating alone, but when both intakes (existent and new) are operating together, the vortex that appears near the new water intake is greater than the one that is formed when no device is installed.

In this case study, it was decided not to recommend the installation of the anti-vortex devices based on the fact that the studied devices did not add enough improvement on the hydraulic conditions of the new intake. Also, an important factor to sustain this decision was the fact that the physical model showed that the vortices occurring near the new intake, were smaller than the existent ones observed, in the physical model and in the prototype, in the old intake, which have not caused deterioration during the fifty years period of operation of the old circuit.

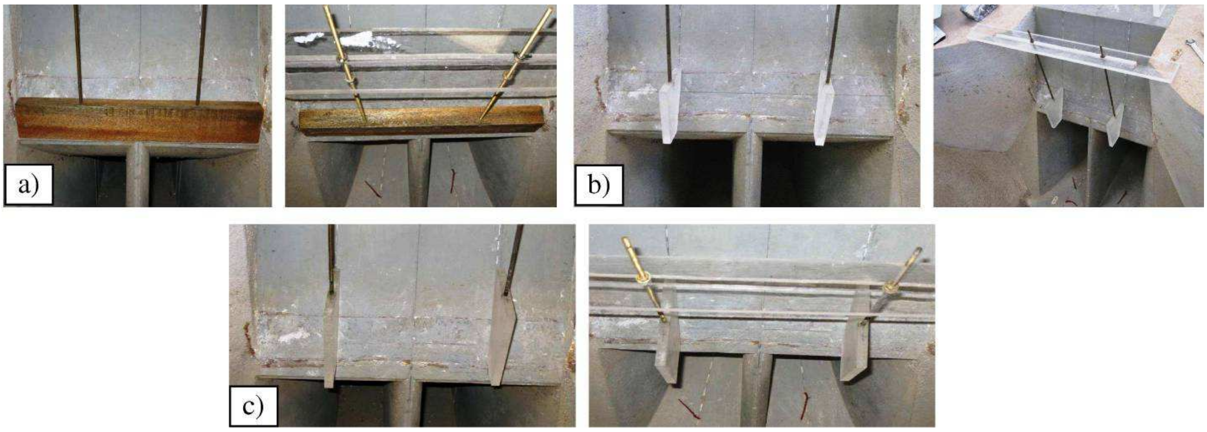

Fig. 7 – Three alternatives to prevent vortices for the new intake of Bemposta dam. a) triangular beam placed over the entire forehead of the water intake; b) two small trapezoidal walls placed on the axis of each water entry of the intake; c) two large trapezoidal walls on the axis of each water entry of the intake

CONCLUSIONS

The occurrence of vortices near submerged water intakes, as is the case of both physical models presented in this paper, is originated by the geometry of the structure and by the surrounding topography. Physical models are very important tools to analyze the characteristics of the vortices, namely, size, intensity, frequency and persistence. Scale effects, which occur essentially for small models, must be carefully assessed. If vortices are deemed to introduce major disadvantages for the operation of the hydraulic structures, anti-vortex devices can be efficiently tested in physical models in order to provide guidelines for the hydraulic structure design and construction.

In this paper, several solutions to prevent vortices formation in two case studies are presented: combined elements materialized by *vertical and horizontal grids* or single elements as *horizontals beams* or *vertical walls*, located in the top water level or deeply, in lower water levels. All these anti-vortex devices, which can be easily incorporated in the final geometry of the water intake, proved to be generally efficient, being recommended in one of the case studies presented.

ACKNOWLEDGMENTS

The authors are grateful to the Consórcio Águas Bilbao - Bizkaia and to EDP - Gestão da Produção de Energia, SA by the support and the agreement to publish the results in the paper.

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