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An Experimental Study on the Effect of Vortex Breakers on Discharge Coefficient for the Shaft Spillways with Sharp Edge and Wide Edge

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ABSTRACT: Shaft spillways are used where there is not adequate space to build other types of spillways to convey flood water from reservoirs downslope dams because shaft spillways are placed on upslope dams and inside dam reservoirs. This spillway has three parts: crest, shaft and tunnel. Shaft can be built vertically. In the earth embankment dams it is better not to build on the body of dam. Here morning glory spillway is very useful. The major problem with these spillways is the strong spiral vortices in the inlet which will reduce the efficiency of tank discharge system. In this paper, the physical model was constructed and the effect of vortex breaker plate on the power of spiral vortex and the efficiency of flow system was studied. Once the data were analysed, the conclusion was that a 20% increase in spillway discharge coefficient was experienced via using blade-vortex breaker and the increase in spillway discharge coefficient with sharp edge was more than a wide-edged.

Keywords: Vortex, Shaft Spillway, Vortex Breaker Plate, Hydraulic Model.

INTRODUCTION

These instructions give you the guidelines to prepare when there is not adequate space to construct spillways to discharge floodwater from reservoirs dams, especially when dam sites are narrow and abutments are very steep, use of shaft spillway is a suitable option because these spillways are placed on upslope dams and inside dam reservoirs. In general, a shaft spillway consists of an inlet funnel, conical transition shaft, bend, outlet tunnel and a stilling basin (Figure 1).

This spillway is used in the following cases: earth dams where concrete spillway on the dam is not recommended. Apart from the dam and in the reservoir, using these spillways will result in a lower risk of scour and the saturation of the downstream of the dam. They are also used in narrow valleys where it is difficult to build other spillways. The main advantage of this type of spillways is a slight increase in water level upstream. Another advantage is automation and its good performance without mechanical equipment. These spillways, compared with the overflow spillways with the same head and length, have lower discharge coefficient because it has a circular shape, leading to the compression of the flow lines and the energy loss. On the other hand, in other types such as overflow spillways, as the flow deepens, the discharge rate increases. But in a shaft spillway, discharge is reduced when the depth of flow rises. Vortex flows are the product of a change in the flow direction, viscosity and surface tension. This flow may be the source of some problems for structures and hydraulic machines including a negative impact on the discharge coefficient of spillway (especially shaft spillways) the negative impacts of two-phase system (especially for pumps and turbines), vibrations in structures, turbulence in the flow, and the creation of unsteady flow.

An effective method for controlling the vortex, vortex breaker plates are installed on the crest. In this paper, the effect of the number of vortex breaker plates on discharge coefficient of the shaft spillway was studied based on a hydraulic model.

The discharge in shaft spillways is expressed as follows:

$$Q = C_d . LH^{1.5} \quad (1)$$

$$L = 2\pi R \quad (2)$$

Where Q is the discharge passing through the shaft spillway, C_d the discharge coefficient of the shaft spillway, L the length of the spillway crest, H the height of water over the spillway, and R the radius of the spillway crest (USBR, 1987).

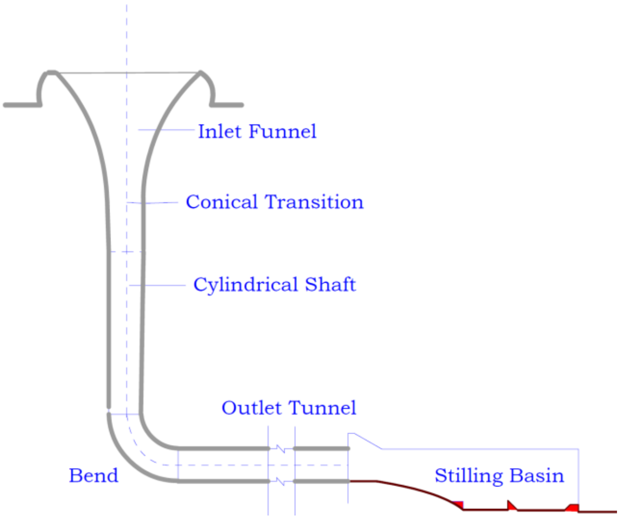

Figure 1. Definition sketch of shaft spillway

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Rankin (1958) divided whirlpool into two parts: the central part, relatively small, has a high viscosity and is like a rigid whirling object and the other part which has a lower viscosity turns around the pressurized whirlpool. In the central part, the fluid in the whirlpool turns in such a way that tangential speed changes linearly with the radius. Fattor and Bacchiega (2003) concluded that in shaft spillway, when they are submerged, the discharge intensity will be 1.34 times that of free flow and if the water conveying tunnel is not aerated, there will be turbulent flow at the spillway. Bagheri et al. (2010) investigated the effect of polyhedral spillway crests on the discharge intensity of the flow passing through the spillways and on the discharge coefficient of shaft spillways, by constructing physical hydraulic models of shaft spillways and through carrying out 180 different experiments on these spillways. They showed that using polyhedral spillway crests caused an increase in discharge passing through the shaft spillway and also increased the discharge coefficient of the spillway. The greatest increase was obtained when trihedral spillway crests were used.

MATERIAL AND METHODS

Vortex formation in a squeeze tube is a fully 3D problem that should be considered along with simplifying assumptions of motion equations. In this study, the vortex which is created in the entry of shaft spillway is affected by the following parameters:

$$H = f(d, Q, \Gamma, \nu, \sigma, \rho, g) \quad (3)$$

Where H is the upstream water elevation of spillway (deep submergence), d pipe diameter, Q discharge, Γ the vortex parameter, equal to $2\pi r V_\theta$, V_θ tangential velocity of the radial distance, r the distance from the axis of the shaft spillway, υ kinematic viscosity, σ surface tension, ρ density, g acceleration of gravity using the relationship given by Buckingham and assuming variables such as Q, d, ρ, as repeated variables, the equation is as following:

$$\frac{H}{d} = f_1\left(\frac{\Gamma d}{Q}, \frac{\nu d}{Q}, \frac{d^5 g}{Q^2}, \frac{\sigma d^3}{\rho Q^2},\right) \quad (4)$$

By replacing $Q = (\frac{\pi d^2}{4})(V)$, v is the average velocity of flow, in shaft spillway given:

$$\frac{H}{d} = f_2\left(\frac{\Gamma d}{Q}, \frac{\nu}{Vd}, \frac{dg}{V^2}, \frac{\sigma}{\rho V^2 d}\right) \quad (5)$$

In equation 3, value $\frac{\Gamma d}{Q}$ is equal to the rotation number (N_Γ). $\frac{\nu}{Vd}$ Is equal to the inverse Reynold`s number (R_e^{-1}), $\frac{dg}{V^2}$ is equal to the inverse square of the Froud number (F_r^{-2}), $\frac{H}{d}$ is the submergence number, and $\frac{\sigma}{\rho V^2 d}$ is equal to inverse Weber number W_e^{-1}. As a result, the following dimensionless parameters have an influence on vortex in shaft spillways:

$$\frac{H}{d} = f_2(N_\Gamma, R_e^{-1}, f_r^{-2}, w_e^{-1}) \quad (6)$$

According to the conditions proposed by Dagget and Keulegan (1974) and Jain et al. (1978), the effect of Reynolds and Weber numbers on the vortex may be negligible. Given the following equation, the discharge coefficient of vertical intakes and the square root of submergence number are reversely related.

$$C_d = \frac{4Q}{\pi d^2 \sqrt{2gH}} = \frac{4Q}{\pi d^{2.5} \sqrt{2g\frac{H}{d}}} \quad (7)$$

As mentioned above, the vortex in shaft spillways is affected by the following factors:

Structural geometry, flow parameters and fluid properties. Zomorredian (2004) stated that an increase in the circulation number helps reduce spillway discharge coefficient in a shaft spillway, and a decrease in the Froude number lessens the impact of the circulation number on spillway discharge coefficient. Therefore, the factors that reduce the tangential velocity of approach zone increase shaft spillway discharge coefficient. As such, the vortex breaker plates may be utilised as one of the main factors to reduce the tangential velocity and increase the efficiency of shaft spillways.

For this reason, the physical model which was constructed and tested in the laboratory is shown in Figure 2.

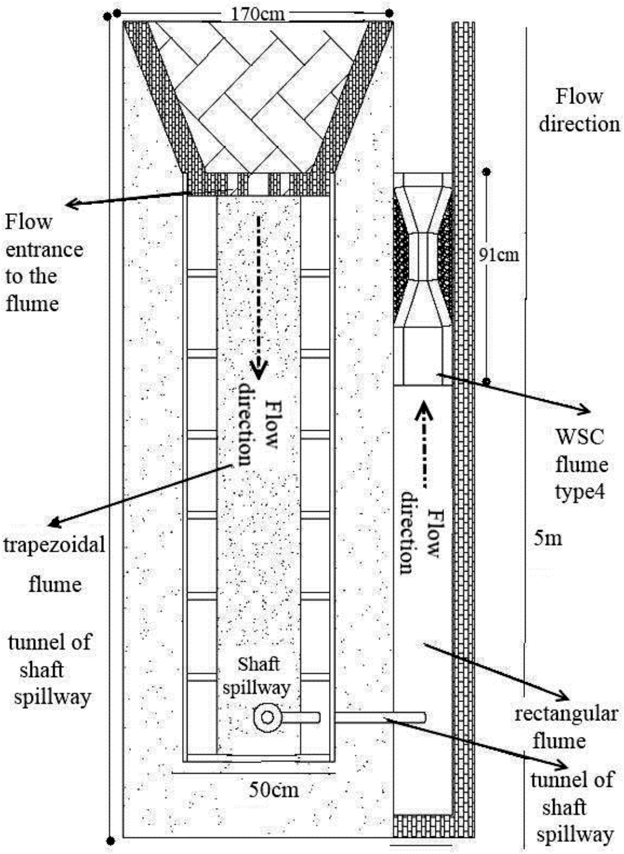

Figure 2. General view of the physical hydraulic model used in the laboratory

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The laboratory consists of a main tank with a capacity of 2000 liters which supplied the water required in conducting the experiments. The tank water will be transferred, through a floating pump with a 120 horsepower electric motor, to the main tower which is about 4 meters high. The water is conveyed by two pipes, from the tower into the entrance of the model that includes a trapezoid-shaped flume with steel frame work. It has glass walls and concrete floors. The side walls of the flume are made of eight- millimeter glass. The main flume is 50 cm wide, 61 cm high and has a wall with a 3:2 slope. The flume is 373 cm long and its slope is zero. In the downstream main flume a slider valve was installed to control the water level. Laboratory model of shaft spillway is placed into the flume. The distance between the spillway and the end of the flume is 30 cm. once the water goes out through the tunnel; it enters into a channel of 5-meter length. Discharge of flow channel is measured by a WSC flume 4^{th} type. The values of water level at the beginning of WSC are read by a gauge and then calculated using the calibration curve and discharge - gauge equation of flume. The flume is located at a distance of 134 cm from the end of the channel. Shaft spillway model with the following specifications was made. Spillway crest body is made of pottery, tunnel is made of glass, with a length of 51 cm, inner diameter6 cm, and two different types of crest diameters were used. The bend is made of two PVC pipes of 45 degrees and the joints are filled with glue so that the inner surface becomes as smooth as possible. The spillway tunnel is at a higher elevation than the channel floor; therefore, the tunnel will not be submerged. Vortex breaker plates are made of plastics with a thickness of 4 mm.

To examine the effect of the number of the vortex breaker plates on the shaft spillway discharge coefficient, 48 different tests were conducted. The first stage of the tests without installing vortex breaker plates was performed with 12 different submergence depths. In the next stage, a group of vortex breakers was mounted on a shaft spillway crest. After the model was prepared, in each test, the main valve was slowly open and water was slowly put into the model. After the water enters the tank, by a slide valve, and pezometers, water level in the outlet of reservoir is placed at the desired level. To avoid any error, caution must be taken so that the elevation remains constant until the end of the experiment. This is the time when the experiment begins. By the main valve, water flow slowly increases.

Then, the conditions remain constant for some time. The height of water on weir was read, by a depth gauge located on the top of the spillway (on a rail). Then, the output value of the shaft spillway tunnel, entering the water channel, is measured by the WSC flume. Water depth in the WSC flume is recorded, and by the relevant chart, the discharge was calculated. Once read, the input flow is slightly raised, and the previous steps are repeated. Several times during each test, the discharge of model, and the water level on top of the spillway was controlled not to be changed. Details of the various options for physical model tests show in Table 1.

Table 1. Details of the various options for physical model tests

Experiments	**Type of spillway**	**Spillway diameter (cm)**	**Number of vortex breaker**
A1	Sharp edge	9.56	-
A2	Sharp edge	9.56	3
A3	Sharp edge	9.56	6
B1	Wide edge	14.2	-
B2	Wide edge	14.2	3
B3	Wide edge	14.2	6

RESULTS AND DISCUSSION

The data clearly indicate the samples on which vortex breakers were installed with no specific head had a lower discharge coefficient. The experiments show that the distribution of data is generally higher in the samples on which no vortex breaker was mounted. Here some obstacle is developed against the tangential flow resulting in a slower tangential velocity. Therefore, it helps the flow move directly toward the shaft spillway throat and thereby a higher discharge. In case of any vortex, a tangential velocity will be also formed so the resulting velocity will make the flow go astray and have a longer distance to travel. Given the loss equation, it appears that the longer distance for the flow, the greater loss. Thus it can be concluded that the presence of vortices, the flow path resulting in the loss of more than a case, the vortex is not present.

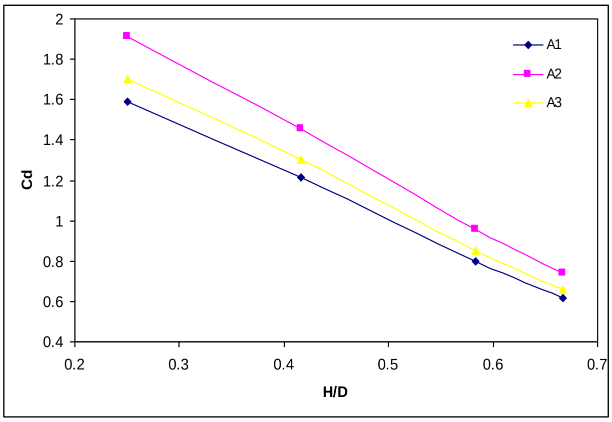

Figure 3. Changes in discharge coefficient in relation to depth of submergence in shaft spillway with sharp edge

As in Figures 3 and 4 for the corresponding relative depths, the increase in shaft spillway discharge coefficient is highly affected if vortex breaker blades are to be used. Due to the compressed flow lines, these blades shift from a spiral into a straight direction and into the shaft spillway and thus a greater discharge coefficient. As in figure 3, when the number of the blades in the sharp-edge spillways increases from 3 to 6, the discharge coefficient will drop but in wide-edge spillway (Fig. 3) an increase will take place in that coefficient. as such, in spillway with sharp edge installation of 3 blades and 6 blades for those with wide edge, a 20 percent increase will be experience in the spillway discharge coefficient because of the larger length of the wide-edge spillway $(L = 44.6cm)$

compared with the that of the sharp edge ($L = 30.1cm$). As in figure 5, the discharge coefficient of sharp-edge spillway is greater than that of the wide edge. Also as the thickness of shaft spillway crest increases, the discharge coefficient is more largely affected by the number of vortex breakers. With respect to figures 2 and 3, on the whole, using vortex breaker blades is likely to increase the efficiency of discharge coefficient of shaft spillway by 20%.

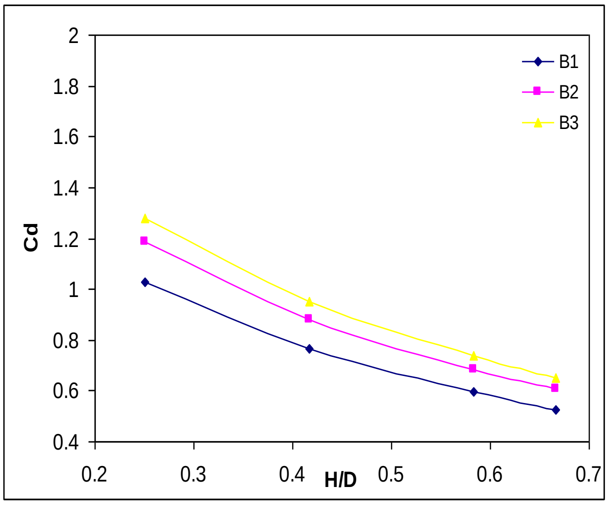

Figure 4. Changes in discharge coefficient in relation to depth of submergence in shaft spillway with wide edge

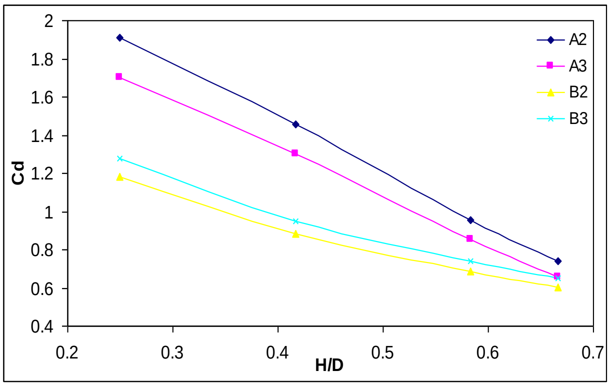

Figure 5. Changes in discharge coefficient in relation to depth of submergence in shaft spillway with sharp and wide edge

CONCLUSION

The use of blade-vortex breaker to a large extent controls the flow turbulence at the inlet spillway. Therefore, a 10 – 20-percent increase in the efficiency of the discharge coefficient, depending on the type of the weir (sharp or wide edges) and the number of vortex breakers, were observed. The discharge coefficient of the shaft spillway with sharp edge was more than that of a wide edge.

By increasing the number of vortex breakers from 3 to 6, due to the resulting decrease in the effective length of spillway, the discharge coefficient of shaft spillway with sharp edge drops. But in all cases, the flow rate is higher than the case where the vortex breakers are not used.

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