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CONTENTS

COVER: Placng RCC near the top of the Saluda Dam

Vortex study at orifice spillways of Karun III dam

S R Khodashenas[1], R Roshan[2], H Sarkardeh[2] and H Md Azamathulla[3]

The effects of vortex formation on the performance of orifice spillways using two physical models (sectional and comprehensive) of the Karun III dam in Iran, have been studied and presented in this paper. The sectional model was designed with one orifice and a scale of 1:33.33, and the scale of the comprehensive model was selected as 1:80. Experiments on the sectional model showed that in relative submerged depth (S/D) = 5.6 a weak vortex (Class C) was formed. By decreasing S/D to 3.7, a strong (Class A) vortex was formed. At S/D = 2.4 vortices again became weaker until they were eliminated when S/D = 1.2. Also, where S/D = 3.7, a stable vortex was formed whilst in other S/D's all observed vortices were unstable. The experiments also show that in presenting vortices with different classes, the discharge coefficient of the orifice spillway was decreased. The experimental results on the comprehensive model of the Karun III dam with four orifice spillways showed that operating them together has a positive effect on reducing vortex strength.

Keywords: Vortex, orifice spillway, discharge coefficient, Karun III dam, physical model.

1. INTRODUCTION

The formation of vortices at intakes is expected at lower reservoir levels. Intake submerged depth, geometry and layout, as well as the number of intakes, could all affect their strength. Formation of these vortices may cause a number of problems, e.g. entrainment of floating particles, and air entrainment into the intakes [10]. Based on research by Sarkardeh *et al* [15], vortices are divided into three classes. Class C vortices are observed as a weak rotation of flow at the water surface, and in addition a drop may also be observed in the water surface. In Class B vortices, the rotation of flow is extended down to the intake itself and, in a stronger position, dragging of debris and trash into the intake is expected. In Class A vortices, air bubbles are entrained from the water surface and transported down towards the intake, and in the strongest vortices a stable air core is formed in the centre of the vortex and air is entrained steadily into the tunnel.

To prevent formation of an air core vortex a minimum operating depth, or critical submerged depth (S_c), is recommended for the intake. The submerged depth (S) is defined as the distance between the water surface and the axis of the intake (Figure 1).

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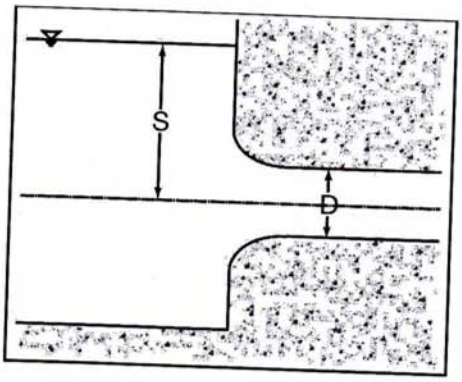

Figure 1. Submerged depth at an intake (*courtesy of Sarkardeh [14]*)

Much research has been carried out to find a relationship for S_c, based on both prototype and physical model studies. Some of these research relationships correlate relative critical submerged depth S_c/D, where D is the diameter of the tunnel, to flow velocity in the tunnel, V [6], and some have correlated it to the intake Froude number (Fr), which is defined as $V/(gD)^{1/2}$, where g is the gravitational acceleration [3, 13, 4, 2, 9, 11].

The three equations for estimating critical submerged depth at horizontal intakes are shown below.

Gordon [7] suggested an equation for S_c based on intake Fr as:

$$S_c/D = \lambda \times Fr \tag{1}$$

where λ is a coefficient related to intake geometry.

Amphlett [1] confirmed that the Reddy and Pickford equation in the following form can be used for the horizontal intakes:

$$S_c/D = C \times Fr^{0.5} - 0.5 \tag{2}$$

where C is an empirical coefficient between 3.3 to 3.95.

Sarkardeh *et al* [14] suggested an equation, based on vortex strength and many experiments, for critical submerged depth at power intakes with regard to the intake head wall slope (Z), Froude number (Fr), and opening percent of trash rack (T), as follows:

$$S_c/D = 2(1/Z)^{0.008}(Fr)^{0.334}(T)^{0.369} \tag{3}$$

In the present work, by using physical models and considering the scale effects, the vortex formation at orifice spillways was investigated. Owing to the importance of the discharge coefficient at intakes, the effect of vortex occurrence on the discharge coefficient of the intake was also studied. Moreover, based on vortex observations, the effect of operating orifice spillways together was evaluated. Finally, the performance of the three aforementioned equations in predicting the critical submerged depth (*Sc*) of orifice spillways was evaluated.

2. DESIGN OF MODELS AND EXPERIMENTAL SET-UP

The Karun III dam and hydro power plant was constructed on the Karun River in the province of Khuzestan, Iran. The dam consists of three types of spillway with a total capacity of 20,000m^3/sec. The dam is of double arch concrete type, 205m high from the foundation and 185m high from the river bed. Four orifice spillways, placed mid-height on the dam body, operate as the emergency spillway. Their maximum capacity is equal to 5740m^3/sec at maximum reservoir operating level (Figure 2).

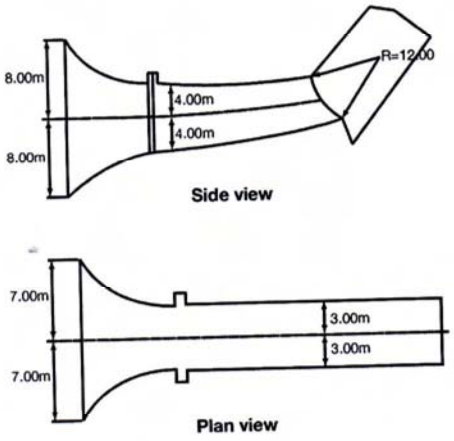

Figure 2. Side and plan views of the orifice spillways

Following previous research works by, for example, Anwar *et al* [2], and Hite & Mih [8], Froude similarity was considered as the basis of the model studies. To evaluate the hydraulic performance of orifice spillways, a partial model with a scale of 1:33.33 was constructed. A head tank with a diameter of 5.1m, a height of 6m, and a capacity of 120m^3, was designed and constructed. The orifice was located 2.5m above the laboratory floor (Figure 3).

Figure 3. The partial model of an orifice spillway
(*courtesy of Water Research Institute (WRI), affiliated to the Ministry of Energy, Tehran, Iran*)

To provide a more reliable simulation of flow upstream of the spillway, part of the dam body in the reservoir was constructed (Figure 4). The orifice was made from Perspex to provide more accuracy during observations (Figure 3). Two pumps were used to supply the maximum water discharge needed for the model, which was equal to 250l/sec (Figure 4).

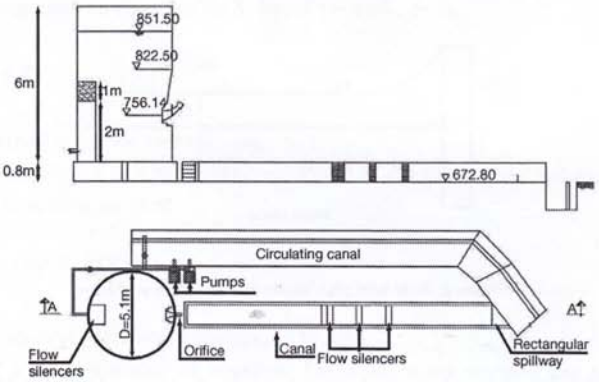

Figure 4. Side and plant view of partial model

To examine vortex formation during simultaneous operation of the orifice spillways a comprehensive model of the Karun III dam, with a scale of 1:80, was constructed. This model consisted of dam body, spillways, stilling basin, and dam reservoir (Figure 5).

Figure 5. Comprehensive model of Karun III dam
(courtesy of WRI)

To avoid scale effects in the physical model studies, and eliminate the effects of viscosity and surface tension, various minimum values were suggested for *Re* and *We* numbers as follows:

- $Re \geq 5 \times 10^4$ [5]
- $Re > 7.7 \times 10^4$ [12]
- $Re > 1.1 \times 10^5$ [11]
- $We > 120$ [9]

Minimum *Re* and *We* values in the present work were more than the minimum values suggested by other researchers.

3. EXPERIMENTAL RESULTS

3.1 PARTIAL MODEL RESULTS

Experiments showed that when an orifice spillway was in operation, strong air core (Class A) was formed at $S/D = 3.7$. To verify this with the equations previously presented in this paper for critical submerged depth in horizontal intakes, they are compared with the results of this research work in Figure 6.

It should be noted that in Gordon's [7] equation, $\lambda = 2.3$ for asymmetric intake geometry, in Amphlett's [1] equation $C = 3.3$, and in Sarkardeh *et al*'s [14] equation, $Z = 1/3$ and $T = 1$ is selected here for comparison.

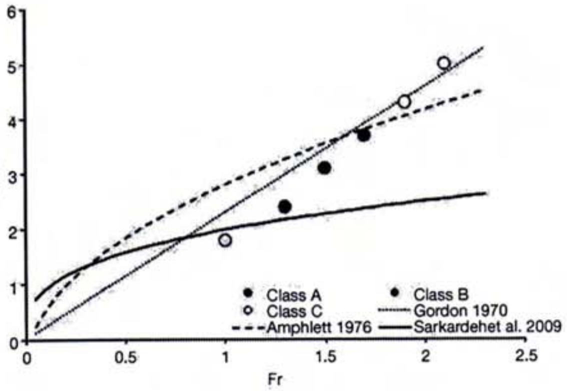

Figure 6. Comparison between empirical equations and experimental results.

As can be seen in Figure 6, conditions in orifice spillways are not the same as in horizontal intakes. Therefore the presented relationships for horizontal intakes could not be considered safe for estimating the critical submerged depth at orifice spillways. The main reason for this could be that at horizontal power intakes, decreasing the reservoir elevation increases the vortex strength. It should be noted that in the power intakes, discharge is constant and does not change at different reservoir elevations. However, in the present case (orifice spillway), discharge does change with reservoir elevation, and decreasing reservoir elevation decreases the discharge.

To provide an assessment of vortex formation at the entrance of an orifice spillway, the class of vortices which formed at the intake of the orifice were recorded. Experiments were carried out at different reservoir elevations, and showed that weak vortices (Class C) were observed at $S/D = 5$. By decreasing the elevation of the reservoir, the strength of the vortices was increased at $S/D = 3.1\text{-}3.7$, and strong vortices (Class A) with air core were formed. For $S/D = 2.4\text{-}1.8$, the strength and class of vortices was reduced until at $S/D = 1.2$ no vortex was observed. The results of each step of this experiment are presented in Table 1.

S/D	Fr	Vortex class	Vortex stability	Direction of circulation
5.6	2.2	-	-	-
5	2.1	C	Unstable	Clockwise
4.3	1.9	C	Unstable	Clockwise
3.7	1.7	A	Stable	Clockwise
3.1	1.5	A	Unstable	Clockwise
2.4	1.3	B	Unstable	Clockwise
1.8	1.0	C	Unstable	Clockwise
1.2	0.5	-	-	-

Table 1. Class, stability and direction of circulation of vortices in different *Fr* and *S/D*

The discharge coefficient of the intake is the ratio of flow velocity in the section after the intake transition to the calculated velocity at that section, neglecting head losses, i.e.:

$$Cd = V/(2g\,(S - P/\gamma))^{0.5} \tag{4}$$

where P/γ is the pressure head which was measured after the intake transition.

Vortex occurrence at intake entrances can cause a reduction in intake efficiency. On the other hand, in orifice spillways vortex presentation causes a reduction in discharge coefficient. At this stage, experiments were conducted to evaluate the effect of different classes of vortex on the discharge coefficient by taking pressure measurements along the orifice tunnel. The pressure at the centre of the tunnel was calculated by averaging the measured piezometers which were installed around the tunnel section (Table 2).

S/D	*Fr*	h_f	C_d	Vortex class
8.2	2.8	3.12	0.92	-
7.5	2.6	2.65	0.93	-
6.9	2.5	2.00	0.94	-
6.2	2.4	1.82	0.95	-
5.6	2.2	2.25	0.92	-
5	2.1	1.66	0.93	C
4.3	1.9	0.92	0.96	C
3.7	1.7	2.21	0.86	A
3.1	1.5	1.62	0.90	A
2.4	1.3	0.78	0.92	B
1.8	1.0	0.38	0.93	C
1.2	0.5	0.08	0.95	-

Table 2. Discharge coefficients and vortex class at different *S/D* and *Fr*

In Table 2 the discharge coefficient was calculated by estimating head loss from orifice entrance to measurement section. The measurement section in all experiments was the section immediately after the gate. The discharge coefficient is plotted against the Froude number in Figure 7.

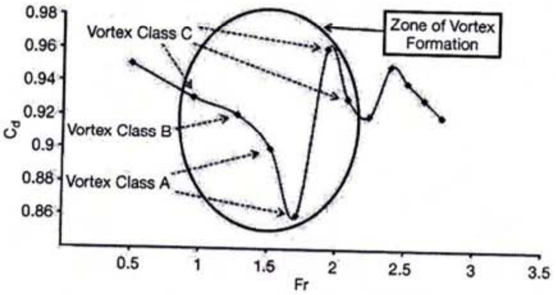

Figure 7. Discharge coefficient *vs*. *Fr* with presenting vortex class

As can be seen in Figure 7, when the class of vortex was increased and a stronger vortex was formed, discharge coefficient was reduced considerably. For example, the formation of a Class A vortex was reduced by approximately 10% of the orifice spillway discharge coefficient. This meaningful reduction is produced by forming an air core tube which continued from the reservoir vortex to the orifice tunnel.

Moreover, Figure 7 presents the effect of different classes of vortices on the discharge coefficient. It can also be observed that vortices with a weak rotation on the reservoir surface could not have any considerable effect on the discharge coefficient, and can thus be considered safe from the viewpoint of the designers.

However, vortices which draw air and trash (Class A and B) into the tunnel should be considered dangerous and must therefore be avoided in the design process [15].

3.2 COMPREHENSIVE MODEL RESULTS OF KARUN III

Another effective parameter on the class and strength of vortices is the effect of forming more than one vortex in a constant period of time. By carrying out many experiments on a comprehensive model it is evident that this effect is positive from a dam designer's point of view, and reduces both the class and strength of formed vortices at the entrance of the intakes. Therefore, at the time of operation of all four orifice spillways at the Karun III dam, the results of the partial model cannot be certain.

All observations of the comprehensive model of Karun III Dam are presented in Table 3.

	Orifice No. 1		Orifice No. 2		Orifice No. 3		Orifice No. 4	
S/D	Vortex class	Direction of circulation	Vortex class	Direction of circulation	Vortex class	Direction of circulation	Vortex class	Direction of circulation
8.2	-	-	-	-	-	-	-	-
6.9	C	Clockwise	-	-	-	-	-	-
5.6	B	Clockwise	-	-	-	-	-	-
5.0	A	Clockwise	-	-	-	-	-	-
3.7	A	Clockwise	-	-	B	Clockwise	-	-
2.4	C	Clockwise	C	Clockwise	C	Clockwise	C	Counterclockwise
1.2	-	-	-	-	-	-	-	-

Table 3. Presenting vortex observations in comprehensive model of Karun III dam when operating four orifice spillways together

Any disturbance in the path of a vortex causes a reduction in its strength as well as its position. The results presented in Table 3 show the effect of operating all orifice spillways together on the reduction, or elimination, of formed vortices. Reduction on the class of vortices is also a result of the interaction between two circular path lines, as shown in Figure 8.

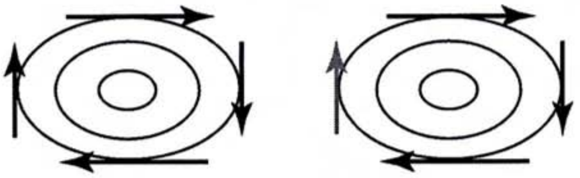

Figure 8. Schematic plan view of interaction between two vortex path lines

4. CONCLUSIONS

Vortex formation is expected at lower reservoir levels. The stronger the vortex, the greater its negative effects on intake performance. Among various intakes, orifice spillways constructed mid-height on a dam body are encountered with vortex phenomenon. Although much research has been carried out on vortex formation, no comprehensive research exists for orifice spillways.

In the present research, efficiency of orifice spillways with regard to vortex formation was studied in two physical models. The physical models were designed to minimize the scale effects. By changing the submerged depth of the intake and also its flow discharge, hydraulic performance of the structure was evaluated.

To determine the efficiency of orifice spillways when operating simultaneously, a comprehensive model of the Karun III dam with four orifice spillways was tested. Experiments showed that in orifice spillways, by changing the reservoir elevation, a change in discharge can be expected, and by decreasing the relative submerged depth (S/D), at first the strength of vortices was increased and after reaching a maximum decreased.

In addition, experiments showed that vortex formation reduces the discharge coefficient of the orifice spillways. The results from the comprehensive model also revealed that operating orifice spillways together has a positive effect on vortex elimination.

5. ACKNOWLEDGEMENT

All experiments were conducted at the Water Research Institute, which is affiliated to the Ministry of Power in Tehran, Iran. Their cooperation is highly appreciated.

6. NOTATIONS

The following symbols were used in this paper:

C_d = Discharge coefficient
D = Tunnel diameter
Fr = Froude number
g = Gravitational acceleration
h_f = Head loss
P = Piezometric pressure
Q = Discharge through intake
Re = Reynolds number
S = Submerged depth above intake axis
S_c = Critical submerged depth
V = Tunnel velocity
We = Weber number
γ = Specific gravity of water

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