Using a Deflector and Crest Design to Make a Safe Spillway Operation

Sorosh Esmaelizadeh
Jundi Shapur University of Technology
Babak Lashkar-Ara (babak_lashkarara@yahoo.com)
Jundi Shapur University of Technology https://orcid.org/0000-0001-7112-2548

Research Article

Keywords: Orifice flow, Entrance profile, Vertical shaft throat, Discharge coefficient, Vortex type.

Posted Date: September 28th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-830208/v1

Abstract

Floods are an important hazard throughout the world. The origins of some floods are a dam failure, hydraulic structure failure as well as an improper performance of the spillway. Among these, shaft spillways are known as a flood drainage system in dams, which is submerged by increasing the level of the reservoir, so that reduces the spillway efficiency and causes over topping. Investigations show that using deflector and aeration in shaft spillways will cause the flow pattern to improve. In this study, it has been tried to experiment on the impact of a deflector located in the throat and inlet geometry of the crest on the improvement of the hydraulic performance of the shaft spillway, and decrease to some extent the hazard induced by lack of timely drainage of floods in dam reservoirs. In order to investigate the deflector effect, three constriction specimens in shaft throat with constriction area to shaft area ratio (A_d/A_i) of respectively 0.75, 0.5 and 0.25 were considered as scenarios. In each scenario, the conditions of the flow passing through 12 different specimens of spillway with Crown Wheel inlets were tested and the results were compared with the flow conditions in crown wheel spillways without deflector (reference model). The results showed that the use of deflector has an important role in reducing vortex flows and stabilizing changes in the water level of the reservoir, and also increases the discharge coefficient of the flow. The studies on reference models also showed that Crown Wheel inlets (C.W.) improved shaft spillway performance, with C.W. spillways having an average discharge coefficient of 32% higher than shaft spillways. Finally, considering optimal deflector factors and C.W. geometry, an optimal model was proposed for flood reservoir conditions.

1. Introduction

Lack of proper control of the flood is one of the greatest levels of hazards for dams located upstream of residential areas. As these dams contain significant volumes of water, their safety versus failure is the main issue. The two most famous dam failures in Europe occurred in the Malpasset dam and Vajont dam, which killed more than 2000 people in total. Reports on incidents of dam failure have shown that almost a third of accidents is related to insufficient capacity of the spillway (Machiels, 2012). The spillway, is the safety component of the dam regarding flood release. It consists in a structural breach created in the dam body or in the reservoir bank to allow the evacuation of extreme floods, acting like an overflow. The geometry of the breach crest and the difference between the breach crest and the maximal reservoir elevations determine the maximal discharge which can be released over the weir. As long as this discharge capacity stays over the maximal flood discharge, the dam safety is ensured. A shaft spillway can be used effectively on a dam site in a narrow valley or where a diversion tunnel can be used as a downstream leg outlet. Another feature of the shaft spillway is that near-maximal capability of release can be reached during an early flood duration with a small head. The associated downside, however, is that if a flood occurs more extensively than the design flood, there is no improvement in discharge capacity for heads above the designed heads. If the heads rise on the shaft spillways, the control shifts from the free flow on the crest to the orifice flow in the transition, and then to the full pipe in the downstream end. It is not recommended that the full pipe flow design be used for drop inlet spillways.

Problems commonly found in this type of structures include unstable flow, cavitation and vortex action. Local topography can vortex patterns in the adjacent spillway approach flow, resulting in flow instability, shaft and tunnel surges and decrease capacity. Experiment studies show that the vortex can reduce the discharge by as much as 75 percent over a submerged circular orifice. To suppress vortex behavior, piers and curtain walls can be mounted (Chen, 2015). an creative one among the alternatives, focused on the merger of a shaft spillways with crown wheel (C.W.) Inlet, has been developed and tested. Physical model experiments, however, are crucial for confirming their efficacy. The C.W. spillway was initially designed by (Rouhanipoor and Lashkarara, 2017) to improve the performance of shaft spillways at free vortex flow.

When the flow control moves from the crest (free flow) to the orifice (orifice flow) and contrariwise, a violent surge in the shaft will cause flow pulsations and extreme pressure in the system, air vents and deflectors in the shaft have been used to avoid these pulsations and surges. Only hydraulic physical models can establish the need for air vents and deflectors and verify their design. Unstable flow during the transition from free flow to orifice flow, which will take place for a long of time, is blamed for unpassable noise, extreme vibrations and sudden changes in pressure. The air vent is mounted around the shaft to boost the flow condition, the total cross-section area of which is about (10–15) percent that of the shaft (Chen, 2015).

Therefore, the two control parts in the shaft spillway with a deflector need to be considered: Crest control (free flow) and Deflector control, where a constrained flow is division by a deflector from the shaft contour, followed by an air vent pipe that compensates for the turbulence-engulfed air and provides free flow of the tunnel (Savic et al., 2014). The type of flow control desired depends on the purpose of the spillway. If the purpose is to pass excess flood water without overtopping the dam, the spillway will be designed to discharge freely with weir control throughout the discharge range. If the purpose is flood control where the discharge is to be limited in the river downstream from the dam, the spillway crest will be designed to operate unsubmerged with lower discharges and to operate submerged with higher discharges (Mussalli, 1969). Researches on the dependence of the vortex flow and submergence at the shaft spillways, and intakes are many. (Nevzat and Fikret, 1995), (Yildirim and Kocabaş, 1998) and (Yildirim and Kocabaş, 2002) showed that the critical submergence (CSM) for an intake is predicted employing a potential flow solution. They examined the effect of rotational flow on the CSM of an intake. They also found that the occurrence of an CSM and air-core vortex was strongly dependent on the conditions of geometry and flow. As a case study, the critical submergence has to be calculated for each flow condition and geometry. They showed by Flow visualization that a spherical volume of fluid bounded by a stream surface of a sphere (SSS) is formed for an intake in a pool. This spherical volume shrinks radially and rotates around its vertical axis. When the SSS collapses, the air-entraining vortex happens. The SSS is also a valuable term for the physical interpretation of the air-entraining vortex's incidence. (Sarkardeh, 2017a) in his study, some suggested experiential relationships for predicting the depth of submergence in power intakes were validated with experimental data from various physical and numerical power intake models. (Barcouda et al., 2006) in the LNHE hydraulic laboratory, different profiles of piano key (PK) inlet set on the morning glory spillway (MGS) were studied. PK spillways, relative to straight-crested morning glory spillways, minimize the necessary water head and thereby increase the storage capacity of the reservoir. (Cicero et al., 2011) performed a series of detailed experiments on the PK spillway and compared the hydraulic efficiency to the MGS of similar diameter. A innovative alternative called "Papaya spillway" was tested on a Bage Dam model, which requires combining the PK inlet concepts on a MGS, and the hydraulic performances were compared with the results of the existing MGS. (Shemshi and Kabiri-Samani, 2017) performed experiments to investigate the swirling flow of circular piano-key inlets (CPK) at vertical shaft spillways. Their findings have shown that the rotational flow power for the flow through the CPK spillway is many times smaller than that for shaft spillways; This configuration also produces outstanding hydraulic efficiency, such as raising the spillway crest length by at least 200 percent without altering the shaft spillway's global size, thus increasing the discharge by up to 6 times relative to a shaft spillway. Also (Sarkardeh, 2017b), (Khanarmuei et al., 2019), (Tahershamsi et al., 2018), and (Rabe et al., 2017) examined vortex flows in the intakes. (Taştan and Yıldırım, 2018) investigates the effect of intake geometry on the occurrence of a free-surface vortex. Their findings suggest that there are minimal effects of the intake-entrance profile on the occurrence of the critical submergence and air-core vortex. A common physical mechanism occurs for the formation of free vortexes arising at the intake entrances of the different profiles, regardless of the profile of the intake entrance. It is proven that for the vortex to exist, spherical sink surface sectors (SSSSs) are necessary. The effect of deflector and aeration on the discharge capacity of shaft spillways was studied by (Hajdin, 1979), (Leopardi, 2004) and (Savic et al., 2014). (Hajdin, 1979) and (Savic et al., 2014) found that the deflector discharge coefficient depends on the dimensionless bend curvature the spillway (d/R), and relationships for the discharge coefficient were proposed based on d/R.

Despite the above studies, However, the detailed flow structure of C.W. spillways with deflector under submerged flow has not yet been explored. In addition, owing to the vast number of geometric parameters and the lack of a detailed analysis of the discharge coefficient, a lack of understanding exists about the prevalent flow conditions. In order to enhance the understanding of the head-discharge relationship of the C.W. spillway and to explore the effects of crown wheel geometry and deflector on the hydraulic characteristics of the flow, in particular the vortex type and the discharge coefficient of the submerged flow, this analysis was carried out on the basis of model experiments. The research also helped to explain some contradictory claims about the geometrical effects and the coefficient of discharge.

2. Material And Methods

2.1. Dimensional analyses

The submerged flow mechanism of a shaft is complex and cannot be completely analytically explained. Some studies have been dedicated to analytical solutions for the water-surface profile and the velocity field, while others have conducted experiments to investigate the component of the flow. However, a dimensionless review offers insight into the issue (Yang et al., 2014). The capability of the shaft is controlled by the constriction of the flow at the deflector section (Savic et al., 2014). The classic discharge equation for a circular orifice flow from the side of a wide tank is (Swamee and Swamee, 2010):

$$Q = \pi/_4 C_s d^2 \sqrt{2gh} \tag{1}$$

Where the discharge is of Q, C_s is the discharge coefficient, d the orifice diameter (in the present study, d was considered as D_d), g is the gravity acceleration, h the depth of orifice center below the free surface (in the present study, h was considered as $S+P$ in Fig. 1). In general, the discharge capacity of a C.W. spillway is defined by Eq. (1). On the basis of dimensional analysis theory, all dimensionless parameters can be described under the title of three major modeling elements:

- Liquid characteristics: density ρ, surface tension σ, and dynamic viscosity μ;
- Flow characteristics: water surface level over the C.W. spillway with respect to the C.W. crest S, circulation imposed to flow Γ, velocity at the deflector V, and gravity acceleration g; and
- Geometric characteristics: diameter of the shaft D_i, diameter of the deflector D_d, outside diameter of the C.W. crest D_{cw}, height of the deflector L_d, throat constriction level in the deflector with respect to the C.W. crest P, the total spillway crest length L, slope of the C.W. keys Z, the outlet key cantilever (overhang) length B, the upstream in- and outlet key widths a_o and b_o, the downstream in- and outlet key widths a_i and b_i, and the distance from the center of intake to the reservoir wall r (Figs. 1 & 2).

Considering that in the present study, the parameters D_{cw}, L_d, P, B, and r are considered 0.3, 0.125, 0.315, 0.1 and 0.75 m respectively; also, the parameters of a_o, b_o, a_i and b_i in each of the scenarios and sub-scenarios of this study are considered constant. Therefore considering an spillway of the type shown in Fig. 1 and by performing the dimensional analysis, the flow discharge coefficient C_s of the deflector flow regime can be written as follows:

$$C_s = f\left(\mathrm{Re}, \mathrm{We}, \mathrm{Fr}, K_o, \frac{S}{D_i}, \frac{A_d}{A_i}, \frac{L}{D_i}, Z\right) \tag{2}$$

Where $\mathrm{Re} = \rho V D_i / \mu$ is the shaft Reynolds number, We= $\rho V^2 D_i / \sigma$ is the shaft Weber number, $\mathrm{Fr} = V / (g D_i)^{0.5}$ is the shaft Froude number, and Ko = $\Gamma / V D_i$ is the shaft Kolf number. If surface tension, viscosity, and circulation are negligible, as in the present study, Re, We and Ko can be dropped from Eq. (2).

2.2. Experimental Setup

An experimental tank was built to investigate the effects of C.W. inlets and deflectors on the formation of vortex and hydraulic characters at vertical shaft spillways. This rectangular tank with a circular end is 1.0m deep, 4.0m long, 1.0m width, and 1.5 m diameter (Fig. 2). The tank is shown in Fig. 3 made of galvanized iron and consisting of a pool, the main tank section, and the flume section. Pumped water from the pool was transferred to the model in a horizontal pipe attached to a horizontal, submerged pipe diffusing the water over the pool width, resulting in an asymmetrical approach flow. In order to decrease inflow turbulence, a perforated screen was placed along the inflow pipe. The center of the vertical shaft was set 0.75m from the tank wall. The vertical shaft had a diameter of D_i= 0.1m.

2.3. Spillway Design and Deflector Profiles

Based on existing conditions, twelve different inlets profiles were examined, including two cycle inlets at Z = 0.5, 1 and 1.5, four-cycle inlets at Z = 0.5, 1 and 1.5, six cycle inlets at Z = 0.5, 1 and 1.5 and eight cycle inlets at Z = 0.5, 1 and 1.5 (Table 1). To these sets, a simple shaft was added as the reference case. All C.W. spillway models were fabricated using acrylonitrile butadiene styrene (ABS) material. Also, the deflectors used in this study were of “VIRGIN PTFE” made. Experiments (Hajdin, 1979) and (BUREAU, 1987) suggest that A_d/A_i should be ≤ 0.85 for the aspect ratio of the deflector section area (A_d) to the total section of the shaft above the deflector (A_i). Therefore, three deflector scenarios with an A_d/A_i ratio of 0.75, 0.5, and 0.25 were considered (Table 1). To assurance for free surface flow downstream of the deflector section, four air vents are provided (Fig. 2). Table 1 shows a summary of the geometric parameter ranges for the experiments presented here.

Table 1
Summary of geometric variables

Parameters (dimensionless)	Number of spillway cycle	L/D_i	Z	A_d/A_i
Values	2	10.28	0.5, 1, 1.5	0.75, 0.5, 0.25
	4	14.28		
	6	18.28		
	8	22.28		

2.4. Flow Conditions

Using a calibrated electromagnetic flow meter with ± 0.2 percent reading precision, the flow discharge was measured. A series of piezometers connected to the bottom of the tank with an accuracy of ± 1 mm was used to determine the water surface elevation. The experiments were carried out under the steady-state condition by starting the pump work. After the flow had been allowed to stabilize for at least 20 minutes, flow specifications were measured. Then, observations/measurements for orifice flow, air-entraining vortices, and vortex type were Conducted. The flow discharges were increased until a boundary situation of air-entraining vortex developed. The discharge and water surface elevation were measured at this situation. Various aspects of orifice flow for various hydraulic parameter values were obtained by increasing the flow discharge further.

Gravity is the predominant determinant of vortex formation; however, viscosity and surface tension can also play a part (Yang et al., 2014). If Re > 10^4, viscous effects become negligible, according to (Zielinski and Villemonte, 1968). This criterion was established based on experiments in which the water temperature was about 20 degrees Celsius. (Daggett and Keulegan, 1974) suggested Re > 3.2×10^4, whereas (Jain et al., 1978) suggested Re/Fr = $(gD_i^3/v)^{0.5} > 5 \times 10^4$. According to (Jain et al., 1978) and (Odgaard, 1986), the vortex formation of vertical intakes is unaffected by surface tension if We > 120 and 720, respectively. (Taştan and Yildirim, 2010) discovered that the Re and We limit values that influence air-entraining vortexes are influenced by flow and geometrical conditions. On the other hand, The Kolf number depends on the value of the intake discharge, the tank geometry, and the approach flow. Herein, Kolf number effects can be omitted because the vortex test tank geometry was constant during the experiments and did not impose any circulation. In other words, no circulation on the approach flow was imposed. It should be mentioned that the neglected Kolf Number is related to induced circulation and not the natural circulation of the flow (Naderi and Gaskin, 2018).

Table 2 summarizes the ranges of flow parameters for the studies presented here. It can be seen that the values of Re, Re/Fr, and We are considerably higher than the limits mentioned above, implying that the effects of surface tension and viscosity were negligible in the experiments. As compared to the findings of (Taştan and Yildirim, 2010), this is much more apparent.

Table 2

Summary of flow variables

Parameters (unit)	***Q (m^3/s)***	***V (m/s)***	***S (m)***	**Fr**	**Re**	**Re/Fr**	**We**
Values (ranges)	0.0045-0.03	0.6–4.35	0.02–0.65	0.6–4.1	> 6.3×10^4	> 8.1×10^4	> 5542

3. Results And Discussion

Since the purpose was to investigate the hydraulic flow passing the vertical shaft spillway with crown wheel inlet (C.W. spillway) in submerged flow, the dewatering was performed from the reservoir bottom. Water flow at high discharges during submerged was similar to the case of flowing at intakes, in a way that the spillway inlet was completely submerged in the reservoir water. As the discharge increased, the water depth within the reservoir increased and vortex flows were observed at different levels in the reservoir (Fig. 4). The start of data acquisition began when the flow through the C.W. spillway entered orifice control. In other words, the state of flow regime was transformed from crest control (free flow) to orifice control. It should be noted that the threshold for the conversion of free flow into the orifice state is of a unstable state and is not steady and permanent. Two criteria were then considered to identify the orifice threshold for the flow to pass through the C.W. spillway:

In the first situation, as the discharge increased and approached the orifice threshold, the water level fluctuated due to the transition from free to orifice flow. In other words, this situation was associated with the occurrence of the first vortex and was considered as a condition of threshold submergence. The second situation was that as the flow approached the threshold submergence, the occurrence of a two-phase flow and the passage of air packs through the clear plexiglass portion of the shaft was clearly visible. By observing the mentioned situation, the experiments began, and the initial discharge was recorded for each spillway. It should be noted that the threshold submergence for each spillway, depending on its geometrical characteristics and deflector, is formed in different discharges and occurred for all C.W. inlets in the range of $0.2 \geq S/D_i \geq 2$.

3.1. Vortex Characteristics

To investigate the simultaneous effect of crest inlet geometry and deflector on the vortex type, experiments were performed with twelve types of crown wheel inlets with different geometries in the presence of three deflectors (A_d/A_i) and also without deflector (reference models). The vortex type was recorded for each spillway, gradually with increasing discharge. Figure 3 (a) to (d) is an example of experimental observations showing a Type 5 vortex for C.W. spillways with cycles of two, four, six and eight in key slope (Z) of 0.5 and A_d/A_i of 0.75, respectively.

According to (Hecker, 1987), the parameters of relative submergence depth (S/D_i) and Froude number (Fr) are the most effective parameters influencing the vortex shape, therefore, after all the experiments, samples of vortex type observations for relative submergence depths S/D_i of 2, 4 and 6 and Froude numbers (Fr) of 2.8, 3.3 and 3.8 have been summarized in Table 3. It should be noted that in the reference models because vortex type 6 occurred in all states, they were not reported in Table 3.

Table 3
Vortex type values observed at different S/D_i and Fr

A_d/A_i	C.W. type		Vortex type observation					
	n	Z	**Based on** S/D_i			**Based on Fr**		
			S/D_i=2	S/D_i =4	S/D_i =6	Fr = 2.8	Fr = 3.3	Fr = 3.8
0.75	2	0.5	6	5	5	6	5	5
		1	6	5	4	6	5	4
		1.5	5	5	5	6	5	5
	4	0.5	5	5	5	5	5	5
		1	5	5	4	6	5	5
		1.5	5	5	5	6	6	5
	6	0.5	5	5	5	5	5	5
		1	5	5	4	6	5	5
		1.5	5	5	5	6	6	5
	8	0.5	5	5	5	5	5	5
		1	5	5	4	6	5	5
		1.5	5	5	5	6	6	5
0.5	2	0.5	5	4	4	5	5	4
		1	5	4	1	6	5	4
		1.5	5	4	3	5	4	3
	4	0.5	5	4	4	5	5	4
		1	5	4	1	6	4	4
		1.5	5	4	3	5	4	3
	6	0.5	5	5	5	5	5	5
		1	5	4	3	6	4	4
		1.5	5	4	3	5	4	4
	8	0.5	5	5	5	5	5	5
		1	5	4	3	6	5	4
		1.5	5	4	3	5	4	4

0.25	2	0.5	4	1	1	4	4	1
		1	4	2	1	4	4	3
		1.5	4	1	1	5	4	1
	4	0.5	4	1	1	4	3	1
		1	4	2	1	4	4	3
		1.5	4	1	1	5	4	1
	6	0.5	4	1	1	4	3	1
		1	4	3	1	4	4	3
		1.5	4	1	1	5	4	1
	8	0.5	4	1	1	4	3	1
		1	4	3	1	4	4	3
		1.5	4	1	1	5	4	1

According to the results presented in Table 3, it can be stated that in most cases, regardless of the deflector type, increasing the S/D_i ratio and Fr number will reduce the type of vortex and consequently reduce the strength of vortex formed at the spillway inlet. The cause of this phenomenon can be found in Squeezing and Stretching the vortex air-core. According to studies (Yang et al., 2014) on vertical intakes, the “squeezing” and “stretching” effects interact concurrently with each other; which one is dominant depends on the Fr number. Therefore, increasing the Fr number causes squeezing the vortex air-core and moving it upwards, thus resulting a weaker vortices. On the other hand, with the decrease in the Fr number, the vortex core has a tendency to sink or to be stretched radially outward, which increases the diameter of the vortex core, thereby increasing the vortex type and strength. Also by considering constant S/D_i and Fr, the reduction of A_d/A_i will also reduce the type and strength of the vortex. The cause of this phenomenon can be two factors: one is the increase in the Fr number due to the increase in deflector constriction which increases the vortex squeezing effect and the other is the formation of a spherical sink surface (SSS) in the spillway inlet. This causes the effect of SSS to be reduced in deflectors with a low A_d/A_i ratio in other words, the intensity of the collapses decreases better and reduces the conditions for the formation of a vortex with the air core inside the shaft, as a result, the type and strength of the vortices formed at the inlet of the spillways decreases. On the other hand, with constant S/D_i, Fr and A_d/A_i scenarios, the cycle change and the spillway key slope (Z) did not have a significant effect on the vortex type changes. In other words, the geometry of the spillway inlet had an effect on the distribution of tangential velocities around the crest, not the type of vortex.

3.2. Head-Discharge Curve

Figures 4 (a) to (d) show respectively the head-discharge curves of C.W. spillways with inlets of two, four, six and eight cycles. In each of these curves, spillways with variable key slope (Z) and different deflectors (A_d/A_i) have been investigated. According to the results of the two-cycle C.W. spillway (Fig. 4-a), with increasing discharge in each spillway, the water head on the crest increases. How the displacement head-discharge curves in each spillway vary strongly depends on the A_d/A_i ratio. The lower the A_d/A_i ratio, the faster the spillway enters the orifice conditions as well as the slope of the head-discharge curves increases. In other words, the A_d/A_i ratio determines the position of the curves separation from the transition region (red band in the figure), which causes the spillway to enter the orifice conditions at lower discharges. This is due to the smaller cross-sectional area of the flow in the throat, which rapidly changes the flow conditions from crest control to deflector. Behavior of head-discharge curves with deflector installation and A_d/A_i ratio decrease, in addition to changing from parabolic to linear, also shows the ineffectiveness of Z key slope. In other words, the head-discharge changes in the spillways with different Z values in the deflector with A_d/A_i ratio of 0.25 are very close. The cause of this phenomenon can be found in the formation of SSS which causes the collapses to be affected by the deflector geometric parameters, in fact with greater deflector constriction, in addition to the decrease in the collapses intensity, the effect of Z on collapse and consequently SSS formation is decreased and the discharge is the same for different Z values. However, with the increase of A_d/A_i ratio the effect of Z on the head-discharge curves change in each category is clearly visible and the same water surface elevation occurs for different Z in different discharge. Also at high A_d/A_i ratios, it is observed that the slope of the head-discharge curves in the lower Z inlets is steeper, that is, the increase in water head on the crest, at a lower Z inlet, occurs at a lower discharge. Examination of the head-discharge curves of four, six, and eight-cycle spillways (Figs. 4-b to d) also show that they behave similarly to 2-cycle spillway, with the difference that in higher-cycle spillways, the openness between the head-discharge curves in each category is increased. This indicates the effect of the C.W. inlets on the discharge.

3.3. Discharge Coefficient

Figure 5 shows the values of the discharge coefficient of the submerged (orifice) flow versus S/D_i. The curves have been classified based on the type of deflector used to the better illustrate data. Figure 5 (a) shows the effect of the C.W. inlet on the submerged flow discharge coefficient for reference models. By comparing the spillway discharge coefficient values in this figure, the effect of the number of cycles and key slope (Z) of C.W. on the discharge coefficient increase is visible. So that by increasing the Z from 0.5 to 1.5, maximum values of discharge coefficient of C.W. spillways of two, four, six and eight cycles increased by 13.92, 19.48, 14.93 and 19.08%, respectively. In other words, increasing Z increases the discharge coefficient. However, the effect of increasing the spillway cycle does not follow a specific trend, in other words, the effect of increasing the cycle on the discharge coefficient depends on the slope of the keys and behaves differently on the slope of the different keys.

The reason for this phenomenon is that increasing the key slope of the crowns rather than increasing their number has a greater effect on creating a uniform flow in the near-shaft and farther-shaft ranges and expands the vortex flow, in fact, the slope of the keys has a greater effect on the distribution of tangential velocities around the shaft and takes the vortex flow away from the shaft. Considering the discharge relationship in orifice control, $Q=(\pi/4).C_s.d^2.\sqrt{(2gh)}$ the discharge coefficient of C_s increases with increasing discharge. Also, the C_s has a reverse relationship with the water head. The rate of change of the curves in Fig. 5 (a) shows that, contrary to expectations, with increasing discharge, the discharge coefficient remains constant or decreases. The reason is that as the discharge increases, the diameter of the vortex core (vortex Type 6) extend immediately and the water head on the crest increases significantly. In this case, the inverse ratio of the head and discharge coefficient causes the discharge coefficient to decrease or remain constant, and the effect of discharge increase on the discharge coefficient is diminished.

Figure 5 (b) shows a significant increase in the submerged flow discharge coefficient by installing a deflector with an A_d/A_i Contraction ratio of 0.75. So that the increase of discharge coefficient starts in the lower heads and the reason is the faster transfer of flow conditions to the deflector, which causes the effective cross-section of the flow to decrease and thus increases the discharge coefficient. This increase in discharge coefficient continues until the effect of rapid increase of the head on the spillway by the deflector overcomes the increase of the discharge and due to the fact that the ratio of head and discharge coefficient is inverse, so the discharge coefficient remains reduced or remains constant. Also, by increasing the key slope Z from 0.5 to 1.5, the maximum values of the discharge coefficient of crown wheel spillways of two, four, six and eight cycles increased by 10.12, 12, 11.1 and 8.24 percent, respectively, which were less than the reference models.

The effect of deflector with an A_d/A_i constriction ratio of 0.5 on the discharge coefficient is shown in Fig. 5 (c). The trend of changes in the curves indicates that the discharge coefficient is high at the beginning of the orifice conditions. This is due to the further reduction of the effective cross-section of the flow, which increases the discharge coefficient. The trend of curve changes is such a way that the quick increase and exponential impact of flow head on spillways overcomes the discharge increase by deflector in the initial heads of orifice flow. Also, the inversion of head ratio and that of discharge coefficient cause the discharge coefficient to increase or stay constant. We can say that the geometrical change of the inlet has a slight effect on the discharge coefficient so that maximal values of the discharge coefficient of the Crown-wheel spillways of 2, 4, 6, and 8 cycle increase 5.55, 5, 6.25, and 7.17 percent, respectively. They have less change than A_d/A_i models equivalent to 0.75.

And finally, Fig. 5(d) depicts the changes in discharge coefficient at deflector with a constriction ratio of A_d/A_i equivalent to 0.25. These changes show that the inlet geometry of the spillway affects more slightly the discharge coefficient of the submerged flow. However, the discharge coefficient value of spillways is more than the A_d/A_i models equivalent to 0.5 due to the smaller effective cross-section of the flow. Also, the trend of curve changes is such a way that the quick increase and exponential impacts of flow head on spillways overcome the discharge increase by deflector in the initial heads of orifice flow. Also, the inversion of head ratio and that of discharge coefficient cause the discharge coefficient to increase or stay constant. Increase of the Z-key slope from 0.5 to 1.5 causes the maximal values of discharge coefficient of Crown-wheel spillways of 2, 4, 6, and 8 cycle to increase 3.7, 0.0, 2.15, and 3.57 percent, respectively. So, they have a smaller change than A_d/A_i models equivalent to 0.5.

Overall, Fig. 5 shows that installation of a deflector and an aerator not only increases the discharge coefficient of submerged flow but also reduces the formation impact of the inlet spillway on the discharge coefficient value of the flow. This is because of the effective cross-section reduction of the flow as well as research done by (Lencastre, 1969). According to the researchers (Lencastre, 1969), the outlet flow of the orifice embedded in the bottom of the tank is compressed at a distance of δ. It means that the compressed cross-section at δ is smaller than the orifice cross-section. The reason for this phenomenon is that the orifice discharge coefficient is analytically related to velocity coefficient, C_v, compression ratio, C_c, and distance, δ. The value of C_v is always between 0.96–0.99. But the C_c is obtained by dividing the compressed cross-section into orifice cross-section. The smaller size of the orifice is, the more δ and C_c are. So, installation of deflectors and decrease of A_d/A_i will cause the discharge coefficient to increase. Decrease of A_d/A_i causes the changes in the larger values of C_c to stay constant and the effect of inlet geometry of spillways on discharge coefficient to decrease. It is because of the exponential increase of water head-on orifice as well as the increased compression effect of the deflector. In this situation, the flow is completely surrounded by the deflector.

Figure 6(a)-(d) shows the discharge coefficient values of the submerged flow for reference models and deflector models with A_d/A_i ratio of 0.75, 0.5, and 0.25 based on Froude number, Fr. The trend of curve changes depicts the effect of Fr number on the flow discharge coefficient in reference models and A_d/A_i models equivalent to 0.75. Therefore, in these models, the discharge coefficient also increases when the Fr number increases. Since the Fr number is dependent on deflector inside velocity and velocity at orifices is directly related to the water depth at crest spillway (*S*). increasing Fr number increases the flow head on the spillways and the inverse ratio of the head and discharge coefficient causes the discharge coefficient to decrease or stay constant. Gradually, by decreasing the A_d/A_i ratio, the impact of Fr number on the discharge coefficient of the flow decreases in such a manner that at the A_d/A_i ratio of 0.5 and 0.25, its impact on the flow discharge coefficient decreases. Two factors can justify this trend: 1) deflector compression ratio C_c that increases the flow head, thus, the trend of the discharge coefficient changes becomes constant. 2) increased Fr number leading to increased squeezing effects of the vortex, thus, either eliminating or reducing the rate of vortex entry with air-core into the intake; in other words, the flow condition is transferred into the deflector.

3.4. Discussion

To investigate the simultaneous effect of C.W. inlet and deflector in circular vertical spillways (simple shaft) on the submerged flow discharge coefficient, a comparison was made between the results of simple shaft spillway and shaft spillway with C.W. inlet (C.W. spillway) under different deflector conditions. In this comparison, to simplify the graphs, the six-cycle crown-wheel inlet was selected at various Z. Besides, we used the research results of (Savic et al., 2014) and (Hajdin, 1979) to review the effect of deflectors on the discharge coefficient of submerged flow. Figure 7-a shows the changes in relative discharge coefficient, C_s/C_m, against the S/D_i parameter. Where C_s is the 6 cycle C.W. spillway discharge coefficient and C_m is the simple shaft discharge coefficient or Savic and Hajdin model discharge coefficient. The results show that at the onset of orifice conditions, the values of discharge coefficient of the 6-cycle spillways with Z of 0.5, 1, and 1.5 were 1.38, 1.8, and 2.1 times more than that of simple shaft spillway in the reference models. However, by increasing the discharge, thus, increased S/D_i ratio, gradually, the crown-wheel spillway shows poorer performance to the point that in spillways with Z of 0.5 at Z with S/D_i ratio of 4.5, it would behave similar to a simple shaft spillway. Nevertheless, spillways with Z of 1 and 1.5, within all ranges of S/D_i ratios performed better than the simple shaft spillway. Overall, by increasing the key slope of the wheels (Z), the crown-wheel spillway outperforms the simple shaft spillway, which can be attributed to the complex geometry of the crest. In other words, the presence of C.W. brings about vortex break. Comparison made with the studies by (Savic et al., 2014) and (Hajdin, 1979) on deflectored vertical shaft spillways shows that within all ranges of S/D_i the value of C_s/C_m is always less than 1. In other words, the submerged discharge coefficient of (Savic et al., 2014) and (Hajdin, 1979) models is more than that of crown-wheel spillway because of having the deflector. Moreover, in reference models of the crown-wheel spillway, vortex type 6 occurs leading to reduced discharge coefficient of the flow because the deflector and aerator were not installed.

Figure 7-b depicts the comparison results of the 6-cycle C.W. spillways with the simple shaft in the presence of the deflector with the A_d/A_i ratio of 0.75. In addition, in this Figure, the comparison made with studies of (Savic et al., 2014) and (Hajdin, 1979) is reported. The changes of the curves show that, at the onset of orifice conditions, the value of the discharge coefficient of 6-cycle C.W. spillways with Z of 0.5, 1, and 1.5 is, respectively, 1.28, 1.4, and 1.6 times more than that of simple shaft spillway. This superiority over reference models is less perceivable due to installation of the deflector, thus, mitigating the effect of entrance shape. However, increasing discharge as well as S/D_i ratio causes the relative discharge coefficient of the Crown-wheel spillway in proportion to simple shaft spillway to reduce and approach to 1. Thus, the crown-wheel spillway with Z of 0.5, 1, and 1.5 in proportion to the S/D_i ratios of 3, 4.5, and 6, respectively, shows similar performance to simple shaft spillway. Furthermore, by installing a deflector, at the onset of orifice conditions, the value of C_s/C_m of crown-wheel spillways, in comparison with the results of (Savic et al., 2014) and (Hajdin, 1979), approaches 1 up to the point that the 6-cycle crown-wheel spillway with Z of 1.5 somehow performs like the models introduced by these studies. Overall, the value of C_s/C_m under all situations gradually approaches 1 at A_d/A_i ratio of 0.75 by increasing the S/D_i ratio. Generally speaking, at the onset of orifice conditions in the deflector with A_d/A_i ratio of 0.75, the flow conditions are not completely transferred into the deflector; in other words, half of the flow conditions are allocated to the deflector and the remaining half to the orifice. Note that in the experimental observations, the place and situation of this orifice are observed within the distance between the crest level to the deflector installation level. Therefore, inlet stream lines are strongly influenced by the geometry of the crown-wheel affecting the produced orifice leading to the superiority of the crown-wheel models with low S/D_i ratios. Nevertheless, at high S/D_i ratios, the produced orifice area gradually reduces up to the point where at specific heads it is completely transferred into deflector

making the geometry of the crest ineffective and the C.W. spillways would behave similar to that of a simple shaft spillway. The 6-cycle C.W. spillway changes compared to models introduced by (Savic et al., 2014) and (Hajdin, 1979) follows the same the trend. Gradually, as the deflector becomes smaller, the effect of the C.W. spillway shape on the discharge coefficient decreases. As such, as shown in Fig. 7-c, the deflector with the A_d/A_i ratio of 0.5 makes the value of C_s/C_m to approach to 1 within all ranges. At the onset of the orifice conditions, the discharge coefficient values of 6-cycle spillways with Z of 0.5, 1, and 1.5 are 1.1, 1.17, and 1.2 times more than the discharge coefficient of a simple shaft spillway, respectively. However, as discharge increases, due to further contraction of the throat by the deflector, the water head on the spillway increases causing the flow control to be transferred to the deflector; thus, crown-wheel spillways perform poorer up to the point where spillway with Z of 0.5 with S/D_i ratio of 2 would behave similar to the simple shaft spillway. Accordingly, the spillways with Z of 1 and 1.5 with S/D_i ratio of 3 would behave similar to simple shaft spillway. Comparing the 6-cycle crown-wheel spillway with the model introduced by (Savic et al., 2014) and (Hajdin, 1979) reveals that (Hajdin, 1979) represents more convergence with the results of crown-wheel spillway.

Finally, Fig. 7-d compares the spillways at the deflector with the A_d/A_i ratio of 0.25. As shown, C_s/C_m is approximately equal to 1 in all cases, indicating similar performance of all models that could be due to the complete control of the flow by the deflector. Despite slight difference between the models, (Savic et al., 2014) model is more convergent with the results of C.W. spillway.

4. Conclusions

This experimental study explored the simultaneous effect of deflector and inlet geometry on the hydraulic flow of the shaft spillways. To this aim, in addition to installing symmetrical deflectors at spillway throat, the crown-wheel inlets were also used in shaft spillways. According to the findings, the type of vortex formed in the tank reduces by installing a deflector; in other words, the deflector stabilizes the changes in the water level of the tank. Moreover, the deflector causes the squeezing effects of vortex to increase; besides, it affects the formation of the spherical sink surface in such a manner that it reduces the collapses and mitigates the condition for forming vortex with air-core into the shaft. However, for completely submerged flow condition, changing the cycles and key slopes does not have any effects on the vortex type.

In addition, the changes of rating curve and discharge coefficient strongly depend on the deflector so that decrease of the A_d/A_i ratio causes the spillway enter into the orifice conditions increasing the discharge coefficient. Furthermore, the lower the A_d/A_i ratio is, the less significant the inlet geometry effect including the cycle and key slope on flow hydraulic will become. Moreover, the discharge coefficient acts independently with increasing the Fr and S/D_i.

Our findings shows that in spillways without deflector, i.e. reference models, the 4-cycle C.W. spillway with a key slope (Z) of 1.5 has the higher discharge coefficient at submerged flow conditions and its discharge coefficient is 19% higher than that of a simple shaft spillway. In addition, in deflector models with A_d/A_i

ratio of 0.75, 4-cycle C.W. spillway with a key slope (Z) of 1.5 has the highest discharge coefficient, which in comparison with the 4-cycle reference model, its discharge coefficient increased 4.55%. Thus, according to the augmenting effects of the C.W. inlet and deflector on flow discharge coefficient and the optimal effects of deflector on the hydraulic performance of the spillway, it is essential to consider these items while designing the spillway in submerged conditions or reservoir in flood conditions. Therefore, to maintain the simultaneous effects of the deflector and geometry of inlet shaft spillways, a 4-cycle C.W. spillway with a key slope (Z) of 1.5 with the A_d/A_i of 0.75 is suggested as the most optimal model.

Declarations

Acknowledge

The authors of this study are grateful to the Jundi-Shapur University of Technology, Dezful, Iran for providing their supports and the possibility of using the Hydraulic Model Laboratory.

References

1. BARCOUDA, M., CAZAILLET, O., COCHET, P., JONES, B., LACROIX, S., LAUGIER, F., ODEYER, C. & VIGNY, J. Cost effective increase in storage and safety of most dams using fusegates or PK Weirs. Transactions of the International Congress on Large Dams, 2006. 1289.
2. BUREAU, O. R. 1987. Design of small dams. Washington, DC: US Dept. of the Interior, Bureau of Reclamation. A Water Resources Technical Publication.
3. CHEN, S.-H. 2015. Shore Spillways. Hydraulic Structures. Springer.
4. CICERO, G., BARCOUDA, M., LUCK, M. & VETTORI, E. Study of a piano key morning glory to increase the spillway capacity of the Bage dam. Proc Int Conf Labyrinth Piano Key Weirs-PKW2011, London: Taylor & Francis, 2011. 81-6.
5. DAGGETT, L. L. & KEULEGAN, G. H. 1974. Similitude in free-surface vortex formations. Journal of the Hydraulics Division, 100**,** 1565-1581.
6. HAJDIN, G. Two contributions to spillway designing based on experimental studies. Proceedings of 13th Congress Commission Internationale Des Grand Barrages, New Delhi, India, 1979. 781-788.
7. HECKER, G. 1987. Fundamentals of vortex intake flow, swirling flow problems at intakes. IAHR hydraulic structures design manual**,** 13-38.
8. JAIN, A. K., GARDE, R. J. & RANGA RAJU, K. G. 1978. Vortex formation at vertical pipe intakes. Journal of the Hydraulics Division, 104**,** 1429-1445.
9. KHANARMUEI, M., RAHIMZADEH, H. & SARKARDEH, H. 2019. Effect of dual intake direction on critical submergence and vortex strength. Journal of Hydraulic Research, 57**,** 272-279.
10. LENCASTRE, A. 1969. Manuel d'hydraulique générale. Eyrolles.
11. LEOPARDI, M. Experimental study and design aspects of morning-glory spillways. New Developments in Dam Engineering: Proc., 4th Int. Conf. on Dam Engineering, Nanjing, M. Wieland, Q.

Ren, and JSY Tan, eds., Taylor & Francis Group, London, 2004.

12. MACHIELS, O. 2012. Experimental study of the hydraulic behaviour of Piano Key Weirs. Université de Liège, Belgium.
13. MUSSALLI, Y. G. 1969. A study of flow conditions in shaft spillways. Georgia Institute of Technology.
14. NADERI, V. & GASKIN, S. 2018. An experimental study of the performance of an ogee-shaped vertical intake: geometrical parameters of cross-vane vortex inhibitor.
15. NEVZAT, Y. & FIKRET, K. 1995. Critical submergence for intakes in open channel flow [J]. Journal of Hydraulic Engineering, ASCE, 121**,** 900-905.
16. ODGAARD, A. J. 1986. Free-surface air core vortex. Journal of Hydraulic Engineering, 112**,** 610-620.
17. RABE, B. K., NAJAFABADI, S. H. G. & SARKARDEH, H. 2017. Numerical simulation of air-core vortex at intake. Current Science**,** 141-147.
18. ROUHANIPOOR, K. & LASHKARARA, B. 2017. EVALUATING THE IMPACT OF THE DECLINE IN THE SWIRLING FLOW ON DISCHARGE CAPACITY IN TWO CYCLE CROWN WHEEL WEIRS.
19. SARKARDEH, H. 2017a. Minimum reservoir water level in hydropower dams. Chinese Journal of Mechanical Engineering, 30**,** 1017-1024.
20. SARKARDEH, H. 2017b. Numerical calculation of air entrainment rates due to intake vortices. Meccanica, 52**,** 3629-3643.
21. SAVIC, L., KAPOR, R., KUZMANOVIC, V. & MILOVANOVIC, B. Shaft spillway with deflector downstream of vertical bend. Proceedings of the Institution of Civil Engineers-Water Management, 2014. Thomas Telford Ltd, 269-278.
22. SHEMSHI, R. & KABIRI-SAMANI, A. 2017. Swirling flow at vertical shaft spillways with circular piano-key inlets. Journal of Hydraulic Research, 55**,** 248-258.
23. SWAMEE, P. K. & SWAMEE, N. 2010. Discharge equation of a circular sharp-crested orifice. Journal of Hydraulic Research, 48**,** 106-107.
24. TAHERSHAMSI, A., RAHIMZADEH, H., MONSHIZADEH, M. & SARKARDEH, H. 2018. An experimental study on free surface vortex dynamics. Meccanica, 53**,** 3269-3277.
25. TAŞTAN, K. & YILDIRIM, N. 2010. Effects of dimensionless parameters on air-entraining vortices. Journal of hydraulic research, 48**,** 57-64.
26. TAŞTAN, K. & YıLDıRıM, N. 2018. Effects of intake geometry on the occurrence of a free-surface vortex. Journal of Hydraulic Engineering, 144**,** 04018009.
27. YANG, J., LIU, T., BOTTACIN-BUSOLIN, A. & LIN, C. 2014. Effects of intake-entrance profiles on free-surface vortices. Journal of Hydraulic Research, 52**,** 523-531.
28. YILDIRIM, N. & KOCABAŞ, F. 1998. Critical submergence for intakes in still-water reservoir. Journal of Hydraulic Engineering, 124**,** 103-104.
29. YILDIRIM, N. & KOCABAŞ, F. 2002. Prediction of critical submergence for an intake pipe. Journal of Hydraulic Research, 40**,** 507-518.

30. ZIELINSKI, P. B. & VILLEMONTE, J. R. 1968. Effect of viscosity on vortex-orifice flow. Journal of the Hydraulics Division, 94**,** 745-752.

Figures

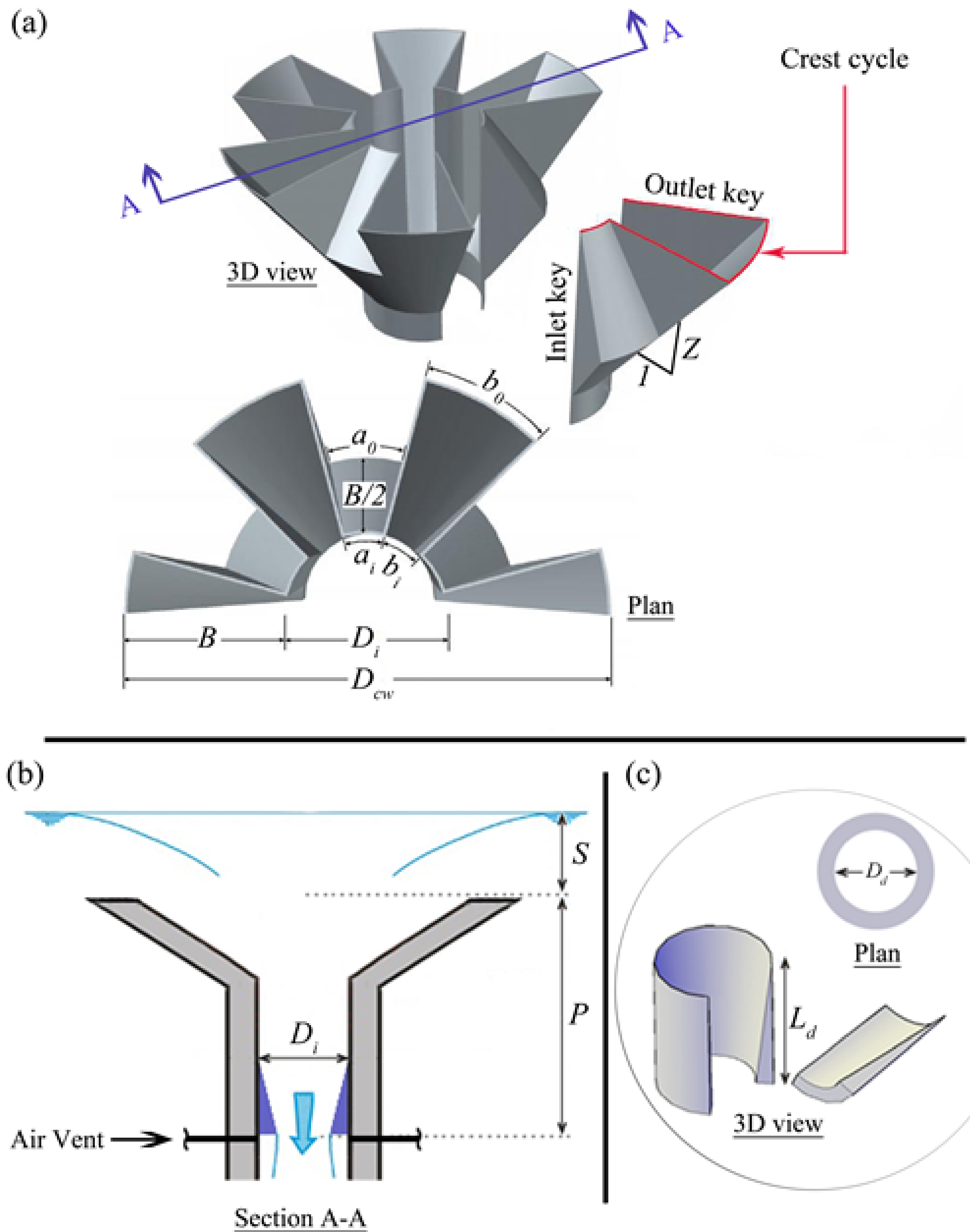

Figure 1

C.W. spillway with Symmetric deflector at the throat. (a) 3D model C.W. spillway (b) Cross section spillway (c) Details of the deflector

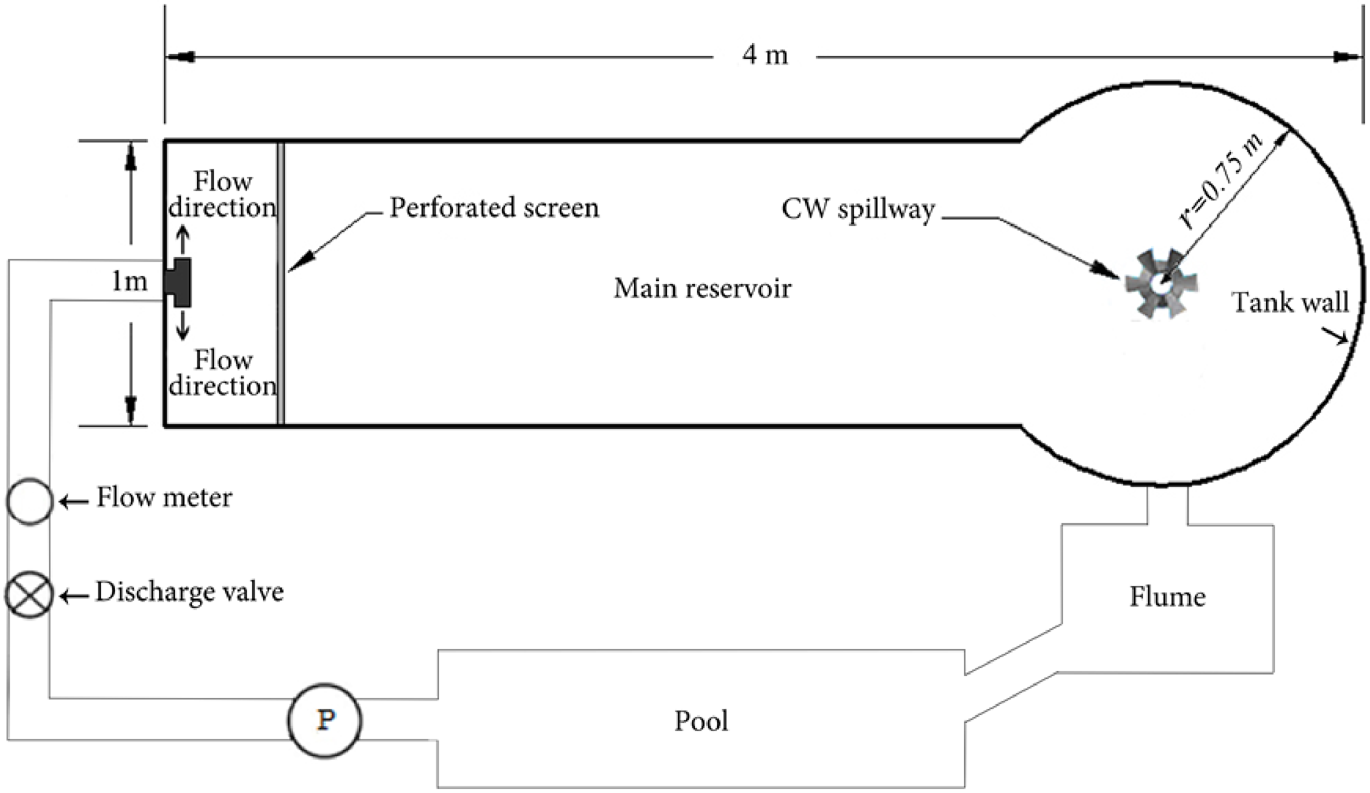

Figure 2

Plan view of the experimental set-up

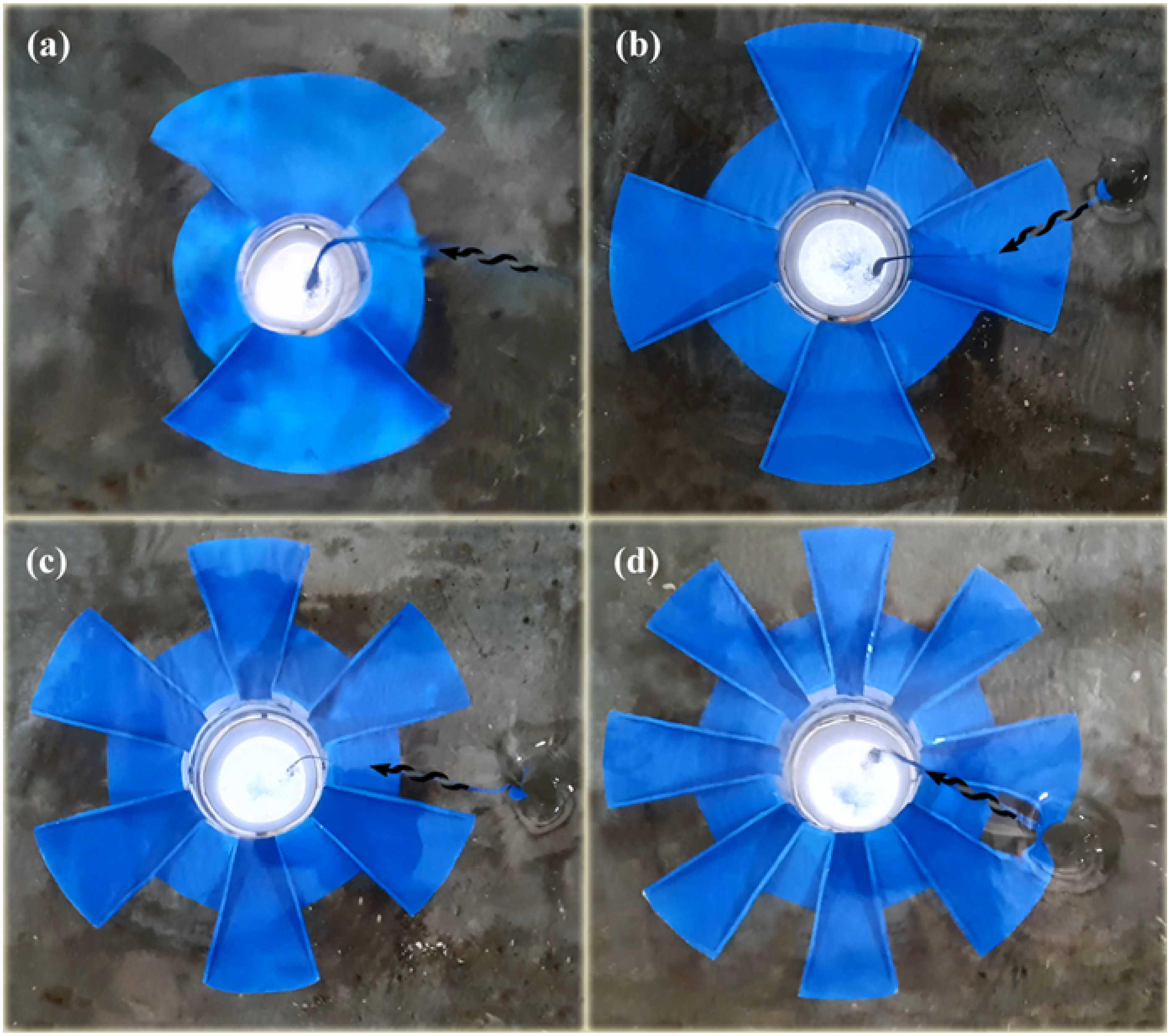

Figure 3

Type 5 vortex formation and cross-sectional influence of air into the vertical shaft of spillways (a) Two-cycle C.W. spillway at Fr= 3.4, S/Di = 3.75 (b) Four-cycle C.W. spillway at Fr= 2.85, S/Di = 2.15 (c) Six-cycle C.W. spillway at Fr= 2.8, S/Di = 2 (d) Eight-cycle C.W. spillway at Fr= 2.7, S/Di = 1.7

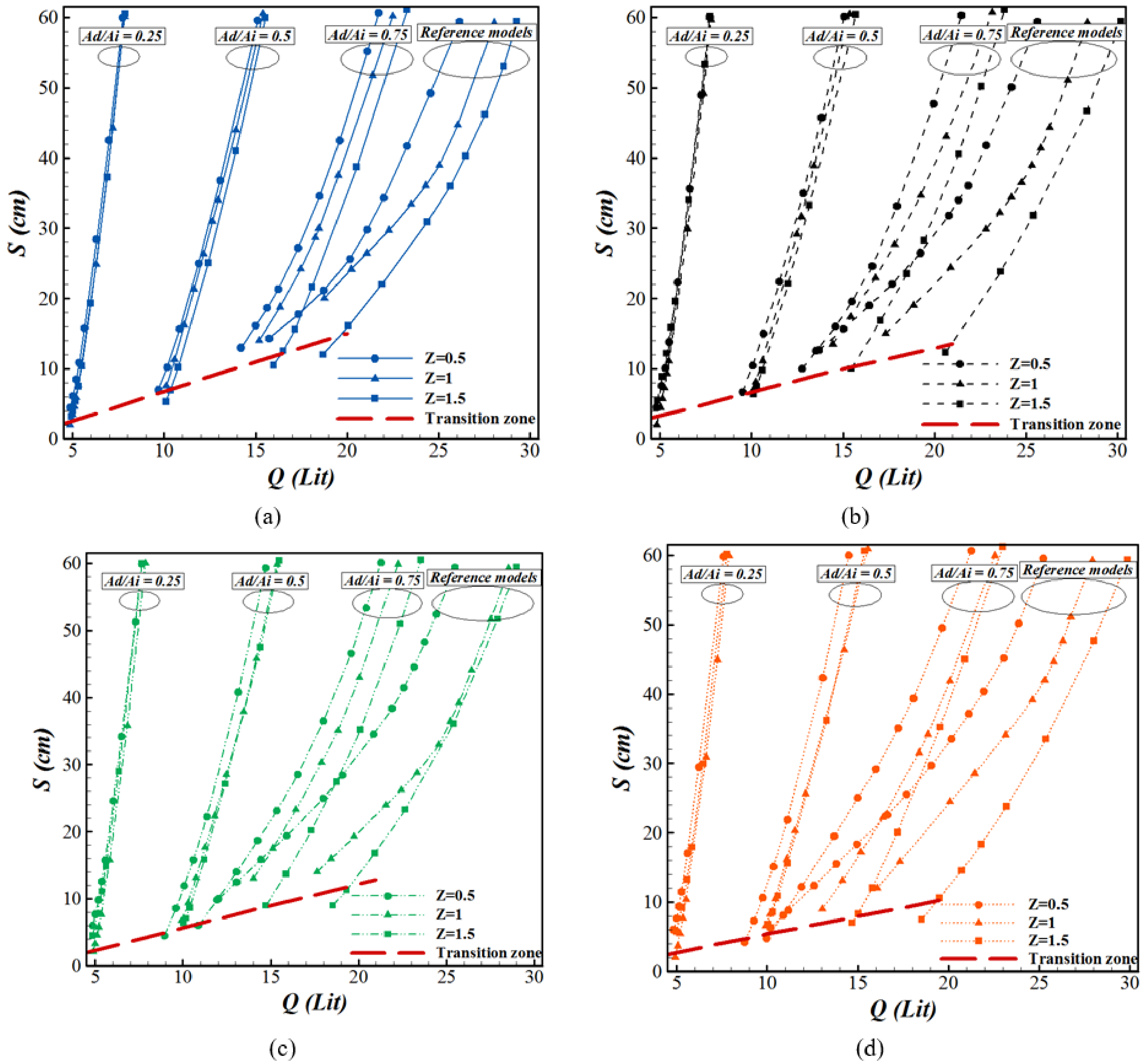

Figure 4

Variation of S versus Q for different C.W. spillways (a) 2 Cycle spillway (b) 4 Cycle spillway (c) 6 Cycle spillway (d) 8 Cycle spillway

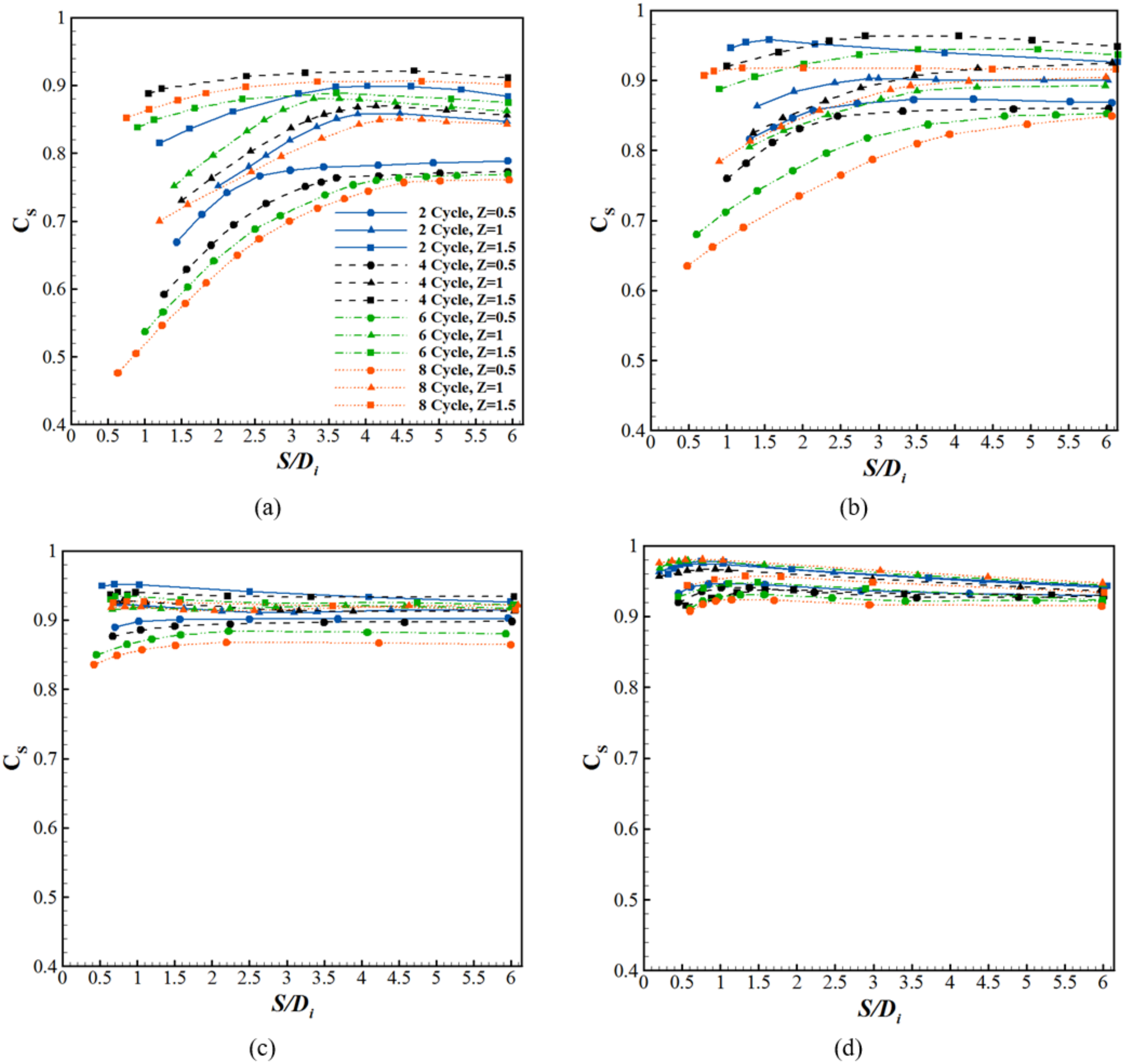

Figure 5

Variation of Cs versus S/Di for different C.W. spillways (a) Reference models (b) Ad/Ai=0.75 (c) Ad/Ai=0.5 (d) Ad/Ai=0.25

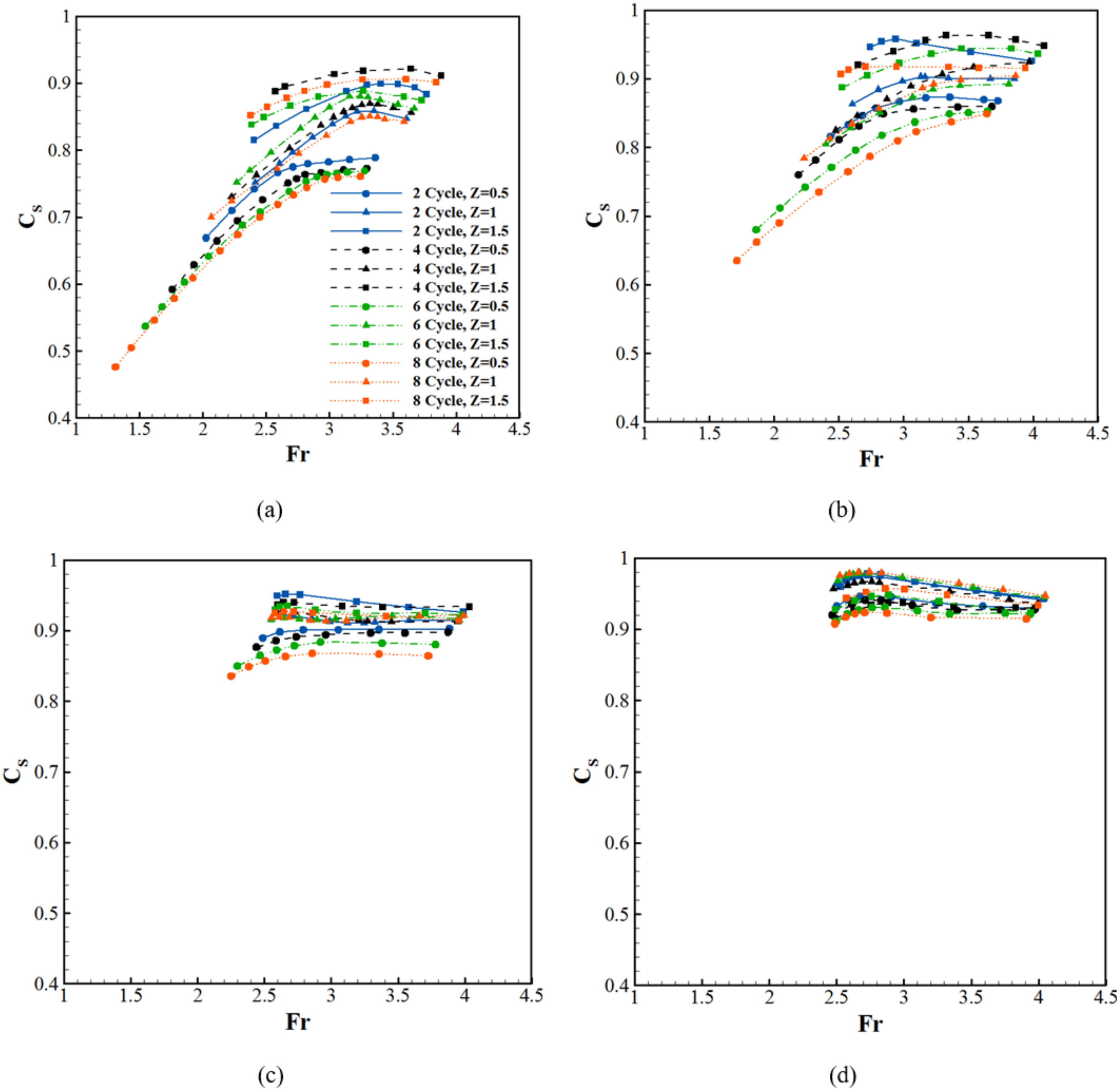

Figure 6

Variation of Cs versus Fr for different C.W. spillways (a) Reference models (b) Ad/Ai=0.75 (c) Ad/Ai=0.5 (d) Ad/Ai=0.25

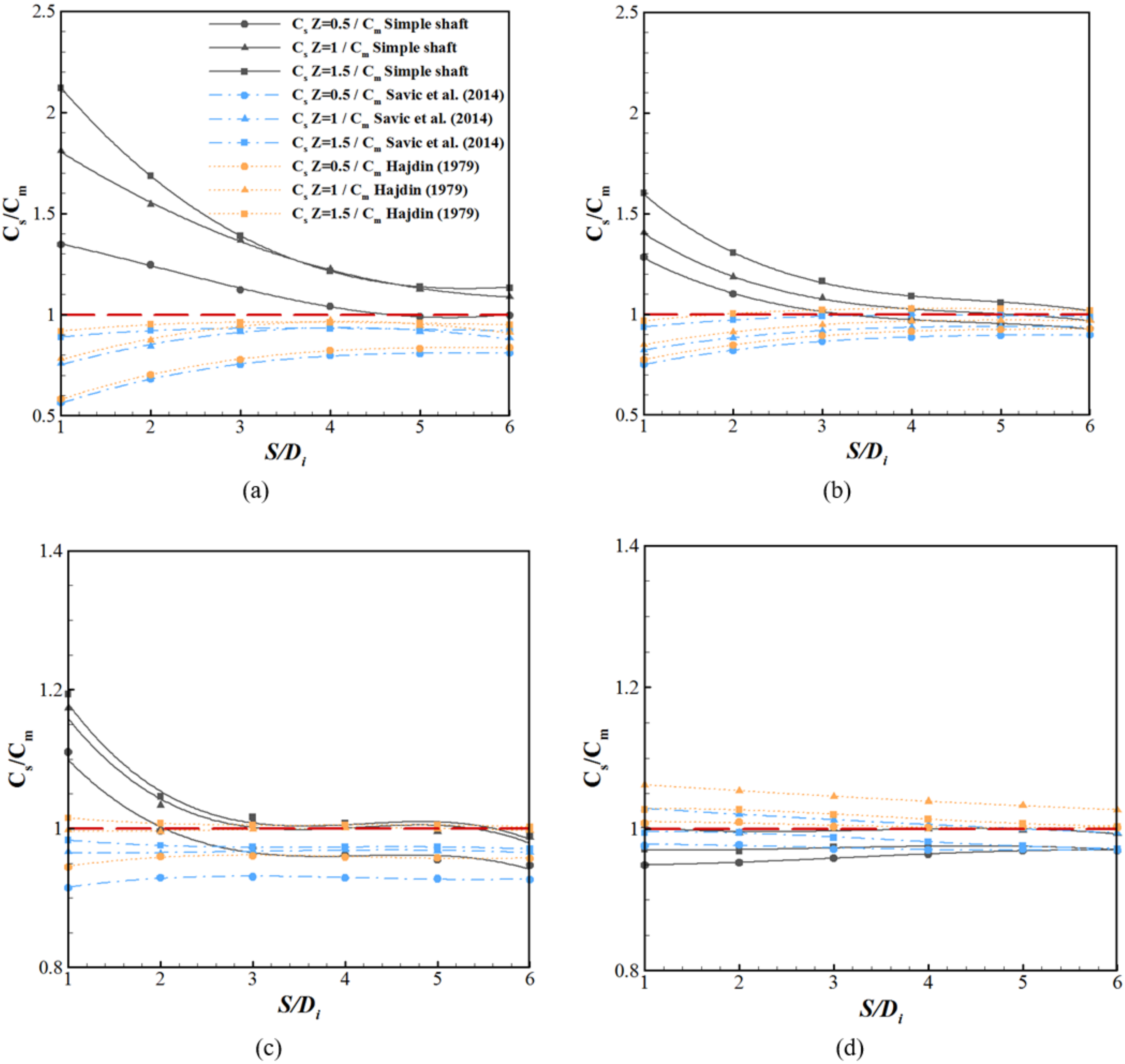

Figure 7

Comparison of discharge coefficient of 6-cycle C.W. spillway compared to simple shaft spillway discharge coefficient and studies conducted by other researchers (Cs/Cm) (a) Reference models (b) Ad/Ai=0.75 (c) Ad/Ai=0.5 (d) Ad/Ai=0.25