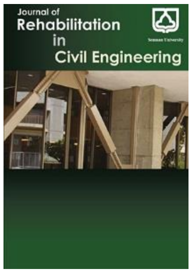
Journal of Rehabilitation in Civil Engineering 7-3 (2019) 96-102



Journal homepage: http://civiljournal.semnan.ac.ir/

Experimental Study of Hydraulic Flow of Circular Piano-Key Inlet in Shaft Spillways

Z. Kashkaki[1*], H. Banejad[2], M. Heydari[1] and E. Olyaie[3]

1. Water Engineering Department, Faculty of Agriculture, Bu-Ali Sina University, Hamadan, Iran
2. Water Engineering Department, Faculty of Agriculture, Ferdowsi University, Mashhad, Iran
3. Young Researchers and Elite Club, Hamedan Branch, Islamic Azad University, Hamedan, Iran

Corresponding author: *zkashkaki@gmail.com*

ARTICLE INFO

Article history:
Received: 12 November 2017
Accepted: 14 July 2018

Keywords:
Circular Piano-Key Spillway,
Piano-Key Weir,
Shaft Spillway,
Physical Model,
Discharge Coefficient.

ABSTRACT

One of the most important conflicts that shaft spillways have to deal with is vortex formation. This phenomenon leads to some unfavorable effects such as vibration in the body of structures, air entrainment and reduced overflow capacity of the spillway. Among all solutions for disrupted vortex formation, an innovative one called circular piano-key spillway, based upon piano key weir principles has not been noticed as well as other solutions. Hence, in this study, experiments were conducted on circular piano-key spillway models. Results showed that in a constant head, the greater amounts of discharge have been measured for circular piano key inlet with an angle of 90 degrees. Comparison between discharge coefficients of three circular piano key inlet models showed that for a constant amount of H/D (Head/Diameter), circular piano key inlet with an angle of 90, 60 and 45 degrees have the greater amount of discharge coefficients, respectively. Experiment results indicated that circular piano-key spillway (with an angle of 90 degrees) increases overflow discharge capacity about 15.16% compared with shaft spillway. Among circular piano key inlets, the model with an angle of 90 degrees has the best hydraulic performance.

1. Introduction

The shaft spillway is simply a closed conduit in which the flood flow is carried rapidly from a high to a low elevation. This type of spillway can be used advantageously at dam sites in narrow canyons where the abutments rise steeply or where a diversion tunnel or conduit is available for use as the downstream leg. Another advantage of this type of spillway is that near-maximum capacity is attained at relatively low heads and this characteristic makes the spillway ideal for use where the maximum spillway

DOI: 10.22075/JRCE.2018.13050.1237

outflow is to be limited. For this reason, they are most suited where temporary storage space in the reservoir is large enough to significantly attenuate the incoming flood [1]. The weir can be sharp-crested, flared, or ogee in cross section [2].

In shaft spillways with a great head, the flow velocity at the transition point from the vertical shaft to the horizontal conduit attains considerable values. Under certain conditions, this may cause cavitation and pressure fluctuations with all their unfavorable effects on the structure and these must be eliminated by a suitably designed shape. Also, vortex in these spillways may decrease both the discharge and discharge coefficient of spillway [3].

Free surface vortex and air entrainment are not favorable experiences in hydropower and pumping projects. In severe hydropower cases, free surface vortices deform the free surface to draw air into the hydraulic machinery, resulting in potential damage to the mechanical components by provoking strong vibrations, loss of efficiency and possible cavitation. While complete omission of vortex and entrainment is not always cost effective, partially weakened free surface vortex flow is more economical and practice [4].

Some structures are used to disrupt the vortex and to increase the viability of the spillways such as using vortex breakers, morning glory and star shaped inlet, stepped chamber and using circular piano key inlet.

Piano Key Weir (PK weir) was developed by Hydrocoop France in collaboration with laboratory hydraulic developments and environment of the University of Biskra (Algeria) [5]. PK weirs are simple solutions as safe and easy to operate as traditional free flow spillways and much more efficient. They may increase the specific flow fourfold, reduce substantially the cost of most new dams and guarantee their safety, increase the storage of many existing reservoirs, improve the flood control by many existing dams and increase the spilling capacity of many existing dams [6].

Various configurations of Piano Key weirs set on a morning glory spillway have been studied on hydraulic models at LNH hydraulic laboratory. They allow for morning glory spillways, as for straight crested spillways, to reduce the required head of water and thus to maximize the increase in storage capacity, in case the hydraulic performances of the spillway are to be upgraded (re-evaluation of the design flood for instance). An innovative solution based upon PK weir principle better shares the flow between the central part of the shaft and the external part. Findings are rewarding, as even for high flows, the discharge is very stable without any vortex. The optimization can be done on hydraulic for any specific project [7]. This innovative solution is called papaya spillway (Fig. 1).

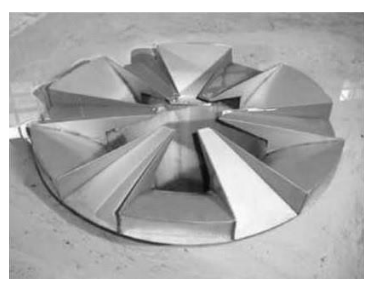


Fig. 1. View of papaya spillway model [8].

Papaya spillway, mixing the PK weir principles on a morning glory spillway was tested on a 1/20 scale model of the Bage dam, and the hydraulic performances were compared to the results of the current morning glory spillway. With a lower diameter, the Papaya spillway showed better hydraulic performances than the traditional morning glory. The central water supply of the shaft avoid the risks of vortex formation and of air entrainment and the spillway can operate at higher discharges without being submerged. The Papaya spillway increases the release capacity especially at low heads where it can be four times higher than a traditional morning glory of the same diameter. The improvement of the release capacity decreases with the head but remains greater than 30% [8].

In 2010s, one of Scottish Water's most ambitious projects has been started to raise the height of the Black Esk dam and increase the reservoir's storage capacity and improve the security of the water supply. Significant research took place to identify the most effective solution for Black Esk. One major challenge was that the overflow for the reservoir, which needed to be raised along with the dam, represented a significant engineering hurdle. Its bell-mouth spillway is an unusual 12-sided design and is of 56ft mean diameter at crest level. At the end, a circular piano key configuration that will be mounted atop the existing bell mouth spillway has been proposed [9], illustrated in Fig.2.

Fig. 2. Papaya spillway, Black Esk Dam, Scotland, UK [10].

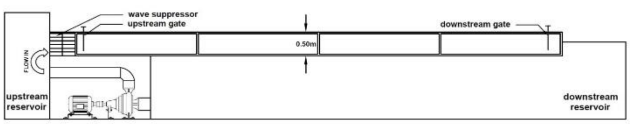
The overflow level is being raised, increasing the storage volume about 40%, by the innovative adoption of precast piano key (PK) weirs around the rim of the bell mouth. The initial hydraulic design was undertaken by adapting published empirical relationships and then refined using computational fluid dynamics (CFD) analyses. For circular piano key inlet design, two configurations have been considered; 12 and 24 cycle weirs. Unfortunately, 24-cycle design gave slightly poorer hydraulic performance than the 12-cycle design, but were nevertheless favored because they would be small enough to allow prefabrication of individual units, as well as offering a smaller external overhang which would be helpful during construction [11].

The circular piano-key spillway constitutes a proper hydraulic structures to increase the design flow and capacity of the related dam reservoirs. It increase the release capacity approximately 2 and 1.5 times higher than morning glory spillway and papaya spillways, respectively, for the same original shaft spillway [12].

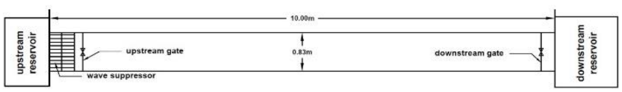
This study tried to compare the hydraulic performance of this innovative solution (circular piano-key spillway) with shaft spillway with non-reformed inlet. Also the comparison of three circular piano key models with different angles has been presented.

2. Material and Methods

This study was carried out in hydraulic laboratory of water engineering department, Bu-Ali Sina University, Hamadan, Iran. Main reservoir of hydraulic laboratory was made in rectangular shape with dimensions: 920cm length, 150cm width and 135 cm height. Water flows through the reservoir by a centrifuge pump with power and discharge of 15kw and 330 m^3/h, respectively. After passing through wave suppressor, water flows through the flume. Dimensions of this flume i.e. length, width and height were 10m, 0.83m, 0.5m, respectively. Flume's walls were made of glass, 1cm thick. Sketch of hydraulic laboratory flume configuration is shown in Fig.3.



(a)



(b)

Fig. 3. (a) Front view, (b) Top view of laboratory flume.

This research was performed using physical models. Models of circular piano key spillway were made of acrylic sheets to observe the flow and air entrainment inside. Thickness and substance of acrylic sheets were chosen in a way that the models wouldn't be under torsion by rotational flow around the shaft and weight of PK weir models were chosen in a way that they could be fixed on horizontal shaft and the bend.

Acrylic sheets were warmed up by a flame thrower to make it flexible and then put on a galvanized iron template to shape them as a cycle of piano key weir. Then, precast units were stuck together by a kind of glue which resists against pressure and humidity of water as well and also does not increase the thickness of models. Three models of circular piano key weirs with different angles were made. Dimensions of these models are presented in Table 1 and Fig.4.

Table 1. Dimensions of circular piano-key spillway models.

P(cm)	D(cm)	L(cm)	b(cm)	α
7.5	7.5	7.5	30	45,60,90

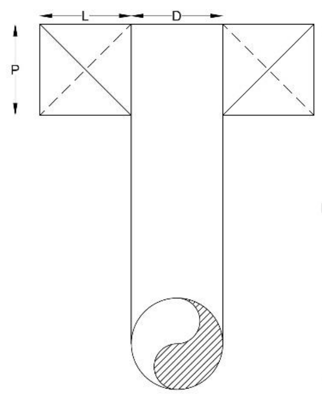


Fig. 4. Dimensional parameters of circular piano-key spillway model.

As it is illustrated in Fig.5, the reservoir was a part of the main flume which has been built using iron plates by a thickness of 4 mm to separate the main flume from the reservoir. Flow discharge was measured by an ultrasonic flowmeter which has been calibrated for this research and level of water was measured by a point gage (±1mm accuracy).

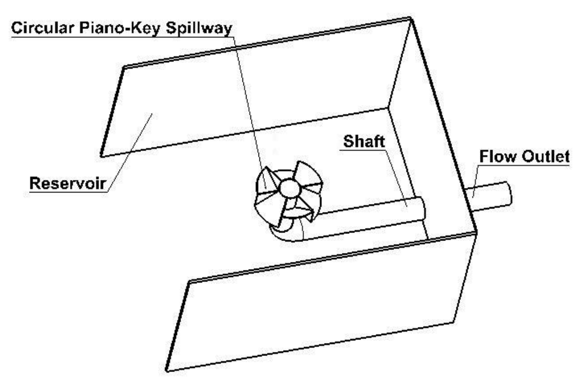


Fig. 5. Isometric view of circular piano-key spillway in the reservoir.

3. Result and Discussion

In this research, 99 experiments were conducted on 4 physical models (including 3 circular piano-key models and one shaft model). A shaft model with non-reformed inlet was experimented as an index to indicate the effects of using circular piano key inlet much better.

Shaft model with non-reformed inlet overflows low discharge flow with strong vortex. In this situation, expanding of vortex flow in the direction across the water surface and increasing the diameter of vortex core occurred rapidly. It leads to a decrease of flow cross section area and an increase of water level in low discharge.

As it is shown in Fig.6 vortexes have been formed around the simple vertical shaft spillway. These vortexes lead to notable vibration in shaft spillway which can lead to disruptive profound effects on the structures and the body of reservoir.

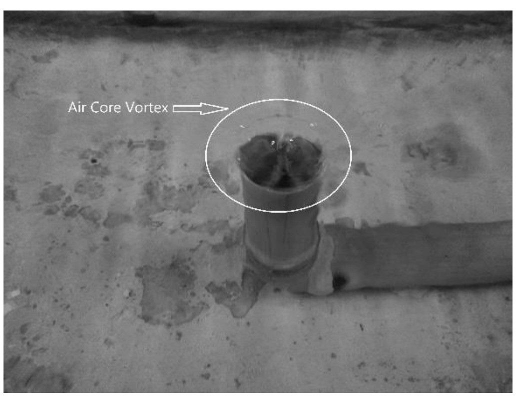


Fig. 6. Vortex formation on shaft spillway.

By fixing piano key inlet, the flow crossing the shaft is classified to two categories: free flow and orifice flow. In low discharge, spillway has free flow and after submergence threshold, orifice flow will begin and then by increasing discharge, vortex flow will be shaped in reservoir. In spillway with piano key inlet, submergence threshold for orifice flow is higher than shaft spillway so the spillway reaches orifice flow mode later and it postpones the occurring of vortex flow, therefore productivity of spillway will increase. The results of experiments is shown in Table 2.

Table 2. Numerical Results of experiments.

PK45			PK60			PK90			Shaft		
No	Q (l/s)	H (cm)	No	Q (l/s)	H (cm)	No	Q (l/s)	H (cm)	No	Q (l/s)	H (cm)
1	5.1	25.5	25	5.3	17.6	50	4.6	10.9	80	5.0	16.4
2	5.3	16.2	26	4.9	16.8	51	5.7	17.9	81	5.0	14.8
3	5.1	15.9	27	4.8	14.2	52	5.2	16.2	82	4.6	11.6
4	4.9	15.0	28	4.9	14.3	53	5.5	15.5	83	5.1	12.9
5	4.7	13.8	29	5.1	14.7	54	5.4	15.0	84	4.8	12.4
6	4.6	10.8	30	4.8	13.1	55	5.0	12.1	85	4.4	10.8
7	4.8	12.9	31	4.8	13.6	56	5.6	13.7	86	4.4	10.2
8	4.6	12.0	32	4.8	12.8	57	5.7	13.1	87	4.4	11.9
9	4.8	10.0	33	4.8	11.8	58	4.6	10.8	88	4.2	9.5
10	4.4	9.7	34	4.4	10.8	59	5.2	11.6	89	4.2	6.7
11	4.6	9.4	35	4.5	9.7	60	4.7	9.5	90	3.6	4.8
12	3.9	8.3	36	4.8	12.8	61	5.2	13.1	91	4.1	6.1
13	4.6	9.7	37	4.6	8.8	62	4.7	9.1	92	3.8	3.3
14	4.4	7.1	38	4.5	10.3	63	3.5	10.9	93	3.9	4.3
15	3.9	5.8	39	4.3	6.9	64	4.6	7.7	94	3.1	3.2
16	3.4	5.2	40	4.0	7.0	65	4.3	7.1	95	2.8	1.7
17	1.9	5.9	41	3.3	5.8	66	3.1	5.9	96	2.7	1.3
18	3.7	4.8	42	1.8	7.9	67	4.3	5.8	97	2.6	2.6
19	4.1	3.8	43	4.5	8.6	68	2.3	4.6	98	3.1	1.8
20	1.7	3.0	44	3.6	2.8	69	2.4	5.1	99	0.7	0.6
21	1.9	2.2	45	1.9	2.3	70	2.8	5.6			
22	1.9	5.1	46	3.3	5.4	71	0.9	0.9			
23	4.1	5.3	47	3.5	2.8	72	2.0	2.4			
24	1.5	3.5	48	1.1	2.2	73	1.2	1.6			
			49	1.1	0.7	74	1.4	1.5			
						75	1.5	1.1			
						76	1.6	0.7			
						77	1.6	0.5			
						78	1.6	0.7			
						79	1.6	1.9			

Using circular piano-key inlet decreases the strength of vortex and also leads to avoiding of vibration in the reservoir which is very important in the reservoir and dam structures' safety. Fig.7 shows flow over shaft spillway with circular piano-key inlet in the reservoir, as it is illustrated for the same amount of discharge (discharge in Fig.6) the vortex core is much smaller than shaft spillway itself and the water surface is quite steady with no vibration.

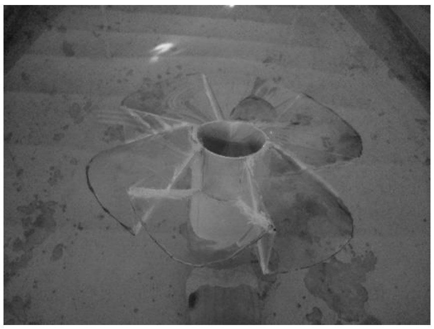


Fig. 7. Vortex formation on circular piano-key spillway.

Experiments data were analyzed and results are presented in Fig.8. Rating curve for 4 models were compared and illustrated in a unit graph in Fig.8. According to this figure, in a constant head, circular PK inlet with an angle of 90 degrees overflows greater amount of discharge. The greater amounts of discharge were measured on circular piano key models with an angle of 60 and 45, respectively. Shaft spillway with no reformed inlet overflow lower amount of discharge compared with circular PK inlet. So circular piano key inlet has better performance compared with shaft spillway.

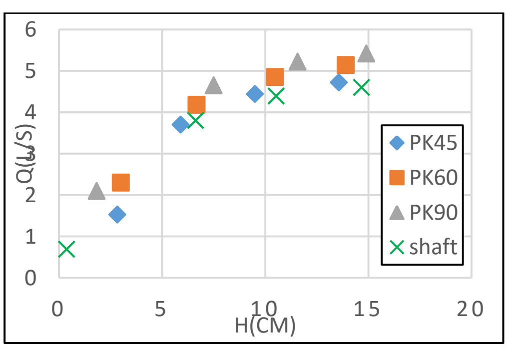


Fig. 8. Rating curve for different models.

Comparison between discharge coefficients of 3 circular piano-key inlet models is illustrated in Fig.9. In this figure discharge coefficient is shown versus dimensionless parameter of H/D. As it is shown, for a constant amount of H/D, circular PK with an angle of 90, 60 and 45 degrees have greater amount of discharge coefficient, respectively. It means circular piano key with an angle of 90 degrees has the best performance beyond comparison.

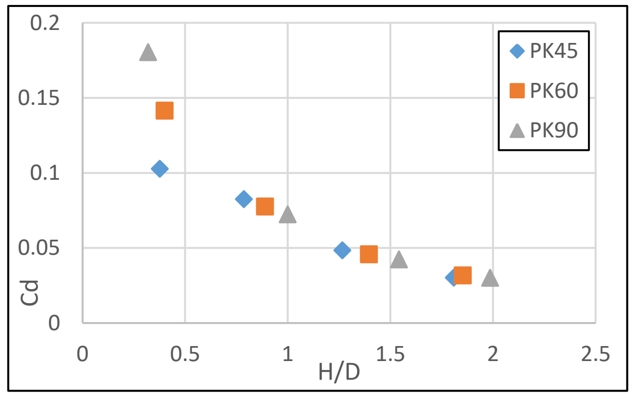


Fig. 9. Discharge coefficient vs H/D for different models.

4. Conclusions

An innovative solution called "circular piano-key spillway" mixing the piano-key weir principle on a morning glory spillway was tested in hydraulic laboratory by using physical models. The hydraulic performances were compared with the shaft spillway with no reformed inlet.

Circular piano key inlet showed better hydraulic performance, experiments results showed. Circular piano key inlet increases overflow discharge capacity about 15.16% compared with shaft spillway.

Among models which were tested in this research, Circular piano key spillway with an angle of 90 degrees showed greater amount of discharge coefficient. Comparison of 3 circular piano-key spillway models in geometric aspect indicates that circular piano-key spillway with an angle of 90 degrees has the best performance.

REFERENCES

[1] Khatsuria, R. M. (2005). Hydraulics of Spillways and Energy Dissipators. (M. D. Meyer, Ed.). New York: Marcel Dekker.

[2] Ricketts, J. T., Loftin, M. K., & Merritt, F. S. (2004). Standard Handbook for Civil Engineers. McGraw-Hill.

[3] Novak, P., & Cabelka, J. (1981). Models in hydraulic engineering: physical principles & design applications. (pp. 205-222). Pitman Press.

[4] Kabiri-samani, A. R., & Borghei, S. M. (2013). Effects of anti-vortex plates on air entrainment by free vortex. Scientia Iranica, 20(2), 251–258. http://doi.org/10.1016/j.scient.2012.10.041.

[5] Ouamane, A., Lemperiere, F. (2013). “PK Weir – design of a new economic shape of weir.” Symp. Dams in the societies of the 21st century, Barcelona, Spain.

[6] Lempérière, F., & Ouamane, A. (2003). The Piano Keys weir: A new cost-effective solution for spillways. International Journal on Hydropower and Dams.

[7] Barcouda, M., Cazaillet, O., Cochet, P., Jones, B. A., Lacroix, S., Laugier, F., Vigny, J. P. (2006). Cost effective increase in storage and safety of most dams using fusegates or PK Weirs. In 22nd ICOLD Congress (Vol. 22, pp. 1289–1326).

[8] Cicero, G. M., Barcouda, M., & Luck, M. (2011). Study of a piano key morning glory to increase the spillway capacity of the Bage dam. In Proceedings of the International Conference on Labyrinth and Piano Key Weirs - PKW2011 (pp. 81–86). London: Taylor & Francis.

[9] Ancell, W. (2013). Black Esk Reservoir Dam Raising. UK Water Projects 2013, Water Treatment and Supply, 295–297.

[10] www.moore-concrete.com

[11] Ackers, J. C., Bennett, F. C. J., Scott, T. A., & Karunaratne, G. (2014). Raising the bellmouth spillway at Black Esk reservoir using Piano Key Weirs. In Proceedings of the 2nd International Workshop on Labyrinth and Piano Key Weirs - PKW2013 (pp. 235–242).

[12] Shemshi, R., & Kabiri-Samani, A. (2016). Swirling flow at vertical shaft spillways with circular piano-key inlets. Journal of Hydraulic Research, 55(2), 248–258. http://doi.org/10.1080/00221686.2016.1238015.