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PREDICTION OF DISSOLVED OXYGEN ON STEPPED SPILLWAY WITH DIFFERENT CONFIGURATION

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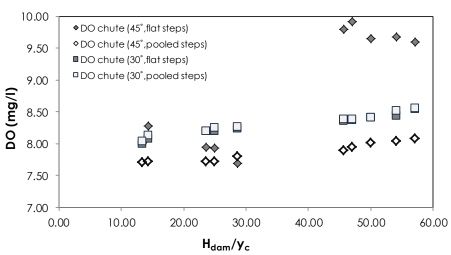
Graphical abstract



Abstract

The increase of water quality is related to the presence of dissolved oxygen. Even, the oxygen concentration in surface waters is a main indicator of the water quality for human use as well as for the aquatic biota. Air entrainment on stepped spillway is also recognised for its contribution to the oxygen transfer. The oxygen transfer on stepped spillways in skimming flow regime is increased due to earlier self-aeration and slower flow velocities in comparison to smooth spillways. This paper presents the results gained on a physical model by using a variety of different configurations of stepped spillway. The slopes of stepped spillway (θ) used are 30˚ and 45˚, the number of step (N) are 40 and 20, and two types of steps are flat steps and pooled steps. The experiments were conducted for ten Froude number (Fr) run ranging from 1.117 to 9.909. This research aimed to investigate the influence of different configuration in stepped spillway for predicting of dissolved oxygen. The results showed that the dissolved oxygen of the stepped spillway increases with an increase in chute of slope, number of step, and surface roughness on steps. The increases of Froude number as a function of discharge will cause turbulence flow becomes decreases, and the concentration of air bubble in the water will be decreased. The decreased value of turbulence flow will make dissolved oxygen level decrease. In skimming flow condition, the dissolved oxygen level decreases with increasing discharge per unit width especially for steep bed slope.

Keywords: Dissolved oxygen, skimming flow, stepped spillway, water quality, pooled steps

1.0 INTRODUCTION

As is known, the energy dissipation and oxygen transfer on stepped spillways in skimming flow regime increasedue to earlier self-aeration and slower flow velocities in comparison to smooth spillways. Stepped spillway flows are characterised by the strong turbulent mixing, the large residence time and substantial air bubble entrainment. Air bubble entrainment is caused by turbulence fluctuations acting next to the air-water free surface. Through this interface, air is continuously tapped and released. Air entrainment occurs when the turbulent kinetic energy is large enough to overcome both surface tension and gravity effects. The turbulent velocity normal to the free surface must overcome the surface tension pressure, and be greater than the bubble rise velocity component for the bubbles to be carried away [6].

Stepped flows can be classified into skimming flow, transition flow, and nappe flow. For narrow steps or larger discharges such as the design discharge of the water skims over the step corners and recirculating zones develop in triangular niches formed by the step faces and the pseudo−bottom are shown in Figure 1d. In skimming flow, the water flows as a coherent stream over the pseudo−bottom formed by the step corners. For a range of intermediate discharges, a transition flow regime takes place. The dominant feature is stagnation on the horizontal step face associated with significant splashing and a chaotic appearance (Figure 1c). For nappe flow the steps act as a series of over falls with the water plunging from one step to another (Figure 1a). Generally speaking nappe flow is found for low discharges and wide steps [6].

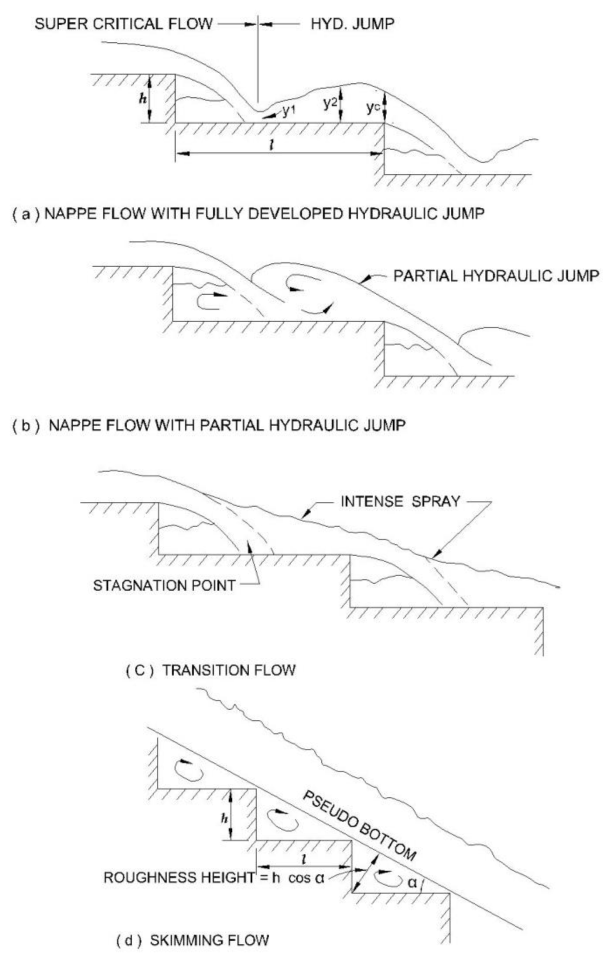


Figure 1 Flow regime on stepped spillway

Self−aeration on stepped cascades is now recognised for its substantial contribution to the air-water transfer of atmospheric gases such as oxygen and nitrogen. Stepped cascades are very efficient means of aeration because of the strong turbulent mixing, the large residence time and the substantial air bubble entrainment. Stepped cascades are used in water treatment for re-oxygenation, denitrification or VOC removals. In the treatment of drinking water, cascade aeration may be used to remove chlorine and to eliminate or reduce offensive taste and odour [16].

Essery *et al*. [10] studied nappe flow in pooled stepped channel. Toombes and Chanson [16] considered aeration in small slope stepped channel. Chanson and Toombes [7] conducted gas−liquid interface measurements in stepped cascade. Local void fractions, bubble count rates, bubble size distributions and gas−liquid interface areas were measured simultaneously in the air-water flow region using resistivity probes. However, they stated that future work is needed to compare aeration efficiencies estimated with detailed interfacial area data and based upon dissolved gas measurements.

Moreover, [1] did some detailed studies on the aeration efficiency in three flow regimes. They stated that nappe flow regime has the greater aeration efficiency than the other flow regimes. The major reason because the increased turbulence, residence time, and air bubble entrainment.

Dermawan [9] investigated the dissolved oxygen level on stepped model with two flow regimes. The measurement results showed the increased dissolved oxygen from upstream to downstream after hydraulic jump by an average of 0.68% for the nappe regimes and 0.58% for skimming regimes. This means that research [9] agreed with [1] that the aeration efficiency on nappe flow regimes are higher than the skimming flow regimes.

Based on Regulation of Indonesian Government, No. 82 of 2001 [15] about water quality management specified that the minimum value of dissolved oxygen (DO) for good water quality criteria is 6.0 mg/l. In aeration, process can increase the depth of flow and also the amount of dissolved oxygen. Factors affecting the level of dissolved oxygen on the stepped spillway are water temperature, water quality, high of waterfall / high of steps (h), and weir crest. Therefore, dissolved oxygen is considered as an important indicator of water quality. The higher of dissolved oxygen level showed a better of water quality. Stepped spillway can increase dissolved oxygen level by creating turbulent conditions with variation of the surface roughness on steps.

This research aimed to investigate the dissolved oxygen level toward different configurations on stepped spillway such as flat stepped and pooled stepped, slopes of stepped spillway (θ = 30°, 45°), and number of step (N = 20, 40). The flow regime in this research is skimming flow regime which sets in for relative large discharges or relative small step heights.

2.0 METHODOLOGY

The tests were carried out in a recirculating flume located at the hydraulic laboratory of Water Resources Engineering Department, Brawijaya University, Indonesia. Schematic of experimental apparatus is shown in Figure 2. Water was pumped from reservoir to upstream tank and flow to the rectangular notch as disharge measurement gauge and water flowing to the stepped channel through stilling tank.

The flume is 7 m length and 0.5 m width, in which the steps are installed. The stepped spillways are made from transparent acrylic with thickness of 0.01 m and side walls with height of 0.6 m to follow flow regime. The slopes of stepped spillway (Θ) are 45˚ and 30˚ with number of steps 20 and 40, respectively. For all slopes test, steps with h equal to 2.5 cm and 5 cm were used. Further details on the experimental configurations are provided in Figure 3.

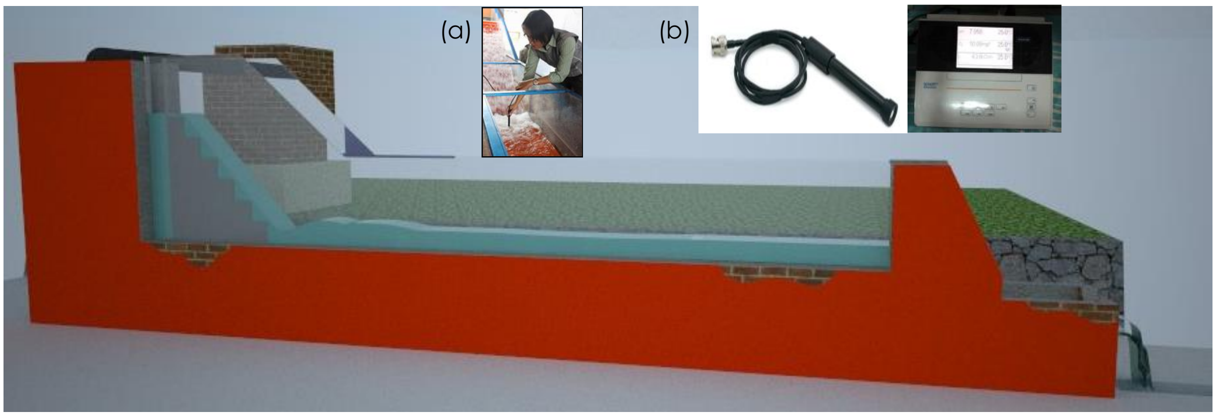


Figure 2 Experimental setup for stepped spillway facility, (a) taking of measurement data, (b) DO meter

Two types of step were tested in the studies that are flat and pooled steps. The dimensions of the step can be defined as h/l, where h = step height and l = horizontal length. For the case of pooled steps, the characteristic height (m) of end sill were 7.5 mm for number of step (N) = 20 and 3.75 mm for number of step (N) = 40. Configurations and notations of step used in the present study are shown in Figure 3. To investigate the effect of step geometry on the value of dissolved oxygen are shown in Table 1.

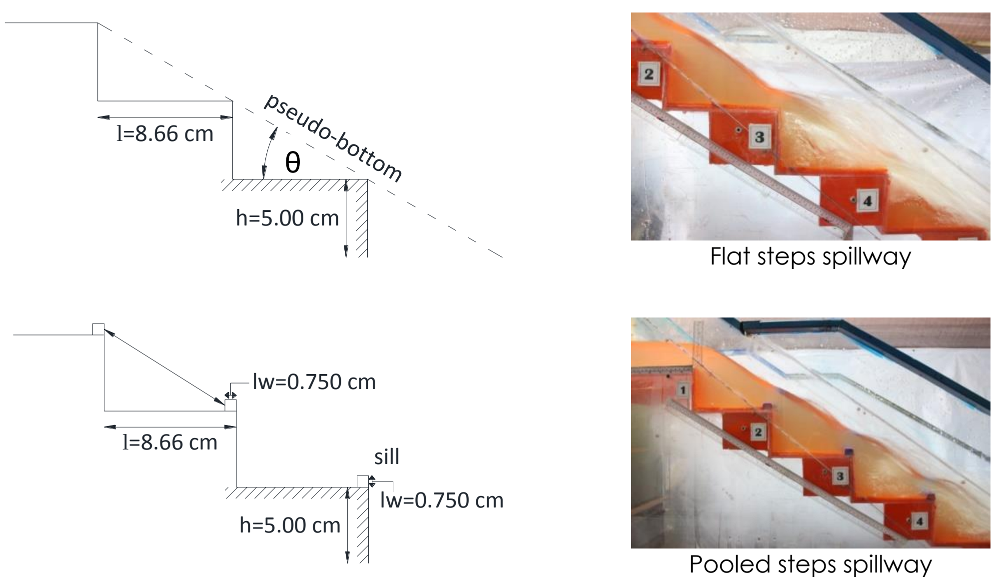


Figure 3 Profile of the stepped configuration (θ = 30˚, N = 20)

The depth across of channel width was measured by a point gauge. The velocity was measured by three methods, first by a pitot tube, second by current metre, and third by calculating discharge flow on the rectangular notch. For the calibration results on three measurement devices above, it was found that the relative error of pitot tube, current metre and rectangular notch was 6.72%, 3.16%, and 2.76% respectively. The result of velocity data of three measurement devices are illustrated to the height of water level flow over on the crest of rectangular notch, as shown in Figure 4.

DO metre is used to measure the value of dissolved oxygen in water flow connected with data recording device (Figure 2). It is used to measure dissolved oxygen on the upstream, middle of chute, and downstream of stepped spillway model simultaneously. Temperatures are measured in Celsius degrees. Hydraulics behavior on stepped spillway model plays a major role in the mechanism of oxygen transfer, so the selection and determination of variable range becomes very important. The discharge per unit width (q) varied from 69.13-613.38 cm^2/s and Froude number ranging between 1.12 and 9.91.

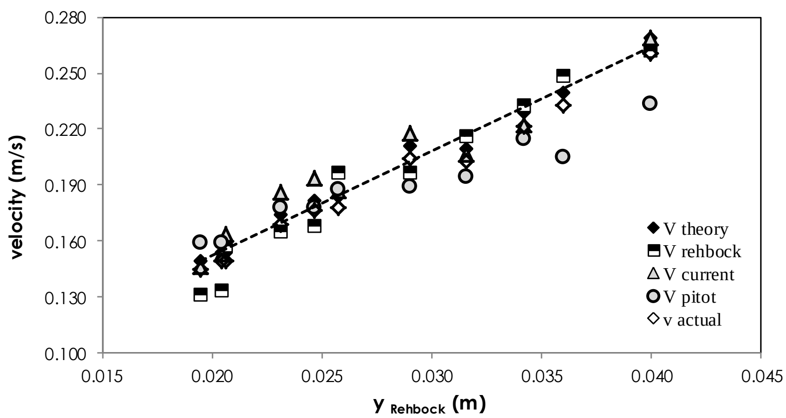


Figure 4 Depth of flow above the Rehbock weir crest vs average flow velocity in the flume

DO metre is calibrated using the cleaning solution with types of Ox921. DO metre is considered good if the display in the measurement device indicates the saturation level of DO < 1% after two minutes of observation.
The units of measurement are mg/l. This device has a limit of the measuring range of dissolved oxygen 0 - 50 mg/l and minimal depth of immersion is allowed of 6 cm - 20 m. Measurements on these observations have a range of 6 cm - 18 cm.

3.0 RESULTS AND DISCUSSION

The results of data obtained after experiment were found that increasing discharge would decrease the value of dissolved oxygen (DO). For measurement of dissolved oxygen in the crest of spillway (upstream), chute, and stilling basin (downstream) of stepped spillway, the result showed that the value of dissolved oxygen in the crest of spillway is smaller than downstream of spillway. These can be seen in Table 1, which displays comparison data of dissolved oxygen value for each discharge in different configurations.

Table 1 shows the DO level for steps N = 20 has a range of better value than the steps N = 40. Based on research [1], the increase of step number and the slope of the spillway will affect the increase of aeration flow. It means that increase of aeration is related with increasing level of DO in the flow. The results from Table 1 show the opposite pattern with [1]. This is because measurement using DO metre done sequentially and not at the same time. The difference of time measurement also affects the water temperature, water quality, and water saturation.

In experiments done by [1], dissolved oxygen levels were measured at two points, upstream and downstream of the stepped spillway. In this study, it only used one DO metrr that it can affect the outcome of measurement each amount of steps. Although each number of steps has a trend of DO level increases from upstream to downstream. The increase of dissolved oxygen from the upstream to the downstream of stepped spillway average between 0.30% - 0.57%.

The relation of decreasing DO level as a function Froude number on the flat steps with N = 40 described in Figure 5.

Table 1 Result of the experimental data for stepped spillway model

No	y_c	h	w	H_{dam}/y_c	q	Do (mg/l)			Fr*	Do (mg/l)			Fr*
	(cm)	(cm)	(cm)		(cm^2/s)	upstream	chute	downstream		upstream	chute	downstream	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Flat steps, N = 40						**θ = 45˚**				**θ = 30˚**			
1	1.750	2.500	-	57.143	69.135	9.250	9.577	9.593	1.117	8.630	8.758	8.540	0.980
2	1.850			54.054	75.144	9.188	9.639	9.680	1.214	8.622	8.752	8.433	1.065
3	2.000			50.000	84.466	9.265	9.578	9.650	1.364	8.550	8.699	8.410	1.197
4	2.125			47.059	92.507	9.525	9.734	9.915	1.494	8.542	8.626	8.372	1.311
5	2.187			45.725	96.585	9.603	9.776	9.800	1.560	8.534	8.621	8.350	1.369
6	3.500			28.571	195.542	7.790	7.931	7.690	3.159	8.286	8.386	8.240	2.771
7	4.000			25.000	238.907	7.694	7.902	7.926	3.859	8.280	8.358	8.200	3.386
8	4.250			23.529	261.650	7.755	7.940	7.945	4.227	8.250	8.342	8.190	3.708
9	7.000			14.286	553.077	7.850	8.183	8.272	8.935	7.840	8.316	8.080	7.839
10	7.500			13.333	613.381	7.600	7.949	8.010	9.909	7.700	8.240	8.000	8.694
Pooled steps, N = 40						**θ = 45˚**				**θ = 30˚**			
1	1.750	2.500	0.375	57.143	69.135	9.250	8.040	8.073	0.906	8.630	8.863	8.550	0.795
2	1.850			54.054	75.144	9.188	8.021	8.030	0.984	8.622	8.690	8.520	0.864
3	2.000			50.000	84.466	9.265	8.002	8.010	1.106	8.550	8.654	8.410	0.971
4	2.125			47.059	92.507	9.525	7.937	7.940	1.212	8.542	8.551	8.378	1.063
5	2.187			45.725	96.585	9.603	7.928	7.890	1.265	8.534	8.506	8.380	1.110
6	3.500			28.571	195.542	7.790	7.858	7.790	2.561	8.286	8.516	8.260	2.247
7	4.000			25.000	238.907	7.694	7.807	7.720	3.129	8.280	8.473	8.250	2.746
8	4.250			23.529	261.650	7.755	7.814	7.720	3.427	8.250	8.448	8.200	3.007
9	7.000			14.286	553.077	7.850	7.880	7.710	7.245	7.840	8.400	8.130	6.356
10	7.500			13.333	613.381	7.600	7.800	7.700	8.035	7.700	8.400	8.040	7.049
Flat steps, N = 20						**θ = 45˚**				**θ = 30˚**			
1	3.500	5.000	-	28.571	195.542	10.025	10.106	10.158	1.117	8.220	8.500	8.530	0.980
2	3.750			26.667	216.863	9.750	9.941	10.050	1.239	8.080	8.380	8.450	1.087
3	4.000			25.000	238.907	9.896	9.978	10.020	1.364	8.130	8.430	8.470	1.197
4	4.125			24.242	250.192	9.285	9.986	10.045	1.429	8.170	8.450	8.490	1.254
5	4.250			23.529	261.650	9.966	10.109	10.160	1.494	8.500	8.530	8.530	1.311
6	4.375			22.857	273.278	10.000	10.142	10.180	1.561	8.370	8.410	8.540	1.369
7	7.000			14.286	553.077	10.030	10.100	10.120	3.159	8.340	8.340	8.550	2.771
8	7.500			13.333	613.381	10.040	10.066	10.155	3.503	8.560	8.570	8.560	3.074
Pooled steps, N = 20						**θ = 45˚**				**θ = 30˚**			
1	3.500	5.000	0.750	28.571	195.542	10.025	10.039	10.027	0.906	8.220	8.934	8.636	0.795
2	3.750			26.667	216.863	9.750	10.098	10.082	1.004	8.080	8.487	7.912	0.881
3	4.000			25.000	238.907	9.896	10.031	10.168	1.106	8.130	8.633	8.322	0.971
4	4.125			24.242	250.192	9.285	10.012	10.033	1.159	8.170	8.452	8.290	1.017
5	4.250			23.529	261.650	9.966	10.132	10.215	1.212	8.500	8.500	8.242	1.063
6	4.375			22.857	273.278	10.000	10.035	10.160	1.266	8.370	8.297	8.278	1.110
7	7.000			14.286	553.077	10.030	10.691	10.308	2.561	8.340	8.565	8.706	2.247
8	7.500			13.333	613.381	10.040	9.883	10.190	2.841	8.560	8.447	8.588	2.492

Figure 5 shows that Fr* < 2.00 for stepped spillway with slopes θ = 45˚ has aeration rate higher than θ = 30˚. This is because higher slope of stepped spillway will make air concentration tend to increase and therefore contributes to the increase of the level of dissolved oxygen. But for Fr* > 2.00 have decreased dissolved oxygen level on stepped spillway θ = 45˚. Decreasing level of dissolved oxygen due to the increase of flow, and it causes the increase of kinetic energy of flow.

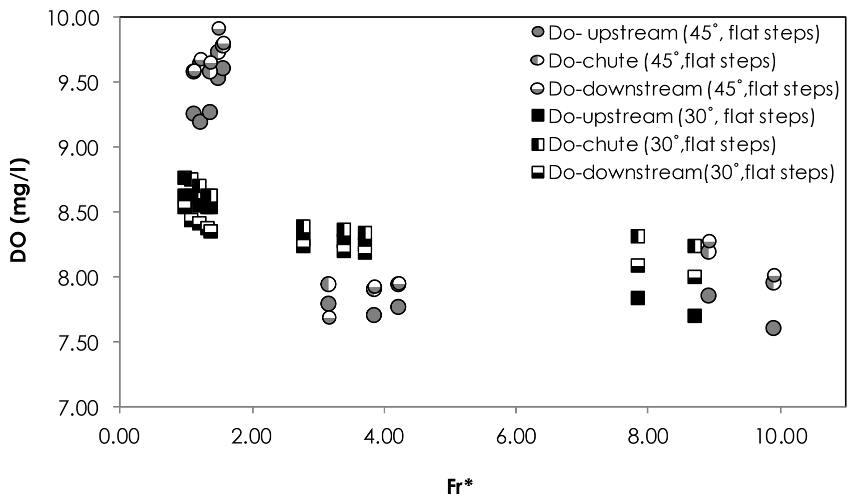


Figure 5 Decrease level of DO as a function of Froude number on flat steps spillway (N=40)

A kinetic energy is the energy that is produced when something moves. On a stepped spillway, the steps increase drastically the rate of kinetic energy dissipation taking place in the spillway, thus eliminating or reducing greatly the need for an energy dissipator at the downstream of stepped spillway.

The overflow on stepped spillway with θ = 45˚ have trend such as smooth flow at ogee spillway at the higher discharge. Since the discharge increases, it causes turbulence flow to become smaller, and the concentration of air bubble in the water decreased. The decreased value of turbulence flow will decrease dissolved oxygen level. The increases discharge along with increasing the velocity of flow. The flow velocity will influence aeration on pseudo-bottom, so that level of dissolved oxygen to be decreased. Thus, the increases of Froude number cause dissolved oxygen level decreases.

While the level of dissolved oxygen on slopes of stepped spillway θ = 30˚ is relatively constant as compared with stepped spillway θ = 45˚. Air concentration at stepped spillway θ = 30˚ influenced by the width of the step (l) is longer than θ = 45˚. Length of step is longer in slopes of 30˚. It causes the vortex that occurred under pseudo-bottom flow has longer time as compared with slopes of 45˚. This reason cause the stepped spillway with slopes θ = 30˚ does not significantly affect the decrease of DO level as compared with θ = 45˚.

Figure 6 shows the result comparison of dissolved oxygen on flat steps spillway and pooled steps spillway for θ = 45˚, 30˚ and number of steps (N) = 40.

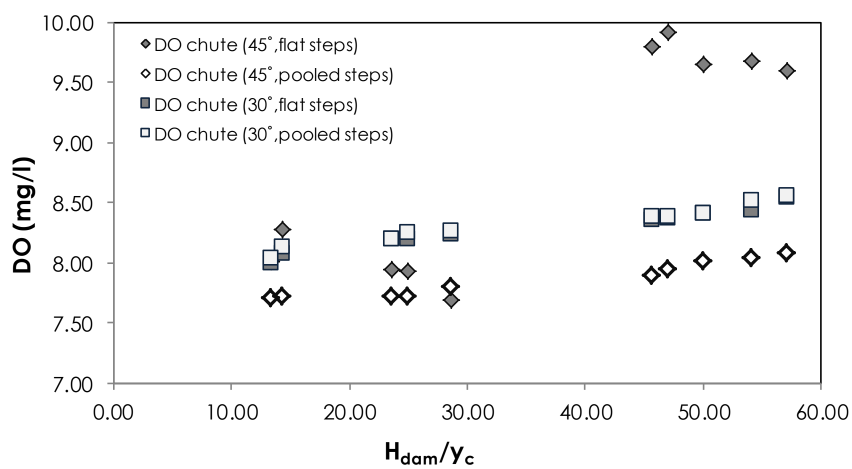


Figure 6 Increase level of DO as a function of dam height per critical height on stepped spillway (N = 40)

Figure 6 shows the level of dissolved oxygen on stepped spillway increases with increasing slope of channel. For flat stepped spillway θ = 45˚, dissolved oxygen level higher than pooled stepped spillway. But for flat stepped spillway θ = 30˚, dissolved oxygen level is closed to / coincident with pooled stepped spillway. The use configuration of sill on step spillway shows the results of data tend to be flat and do not give effect to increased oxygen level in flow.

Flow instabilities due to addition of end sill at the edge of step affecting the measurement data. Research conducted by [11] also showed that the pooled stepped spillways are influenced by three-dimensional flow patterns lead to various concentrations of the flow. Guenther *et al*. [11] recommends further investigation of aerated flow and process of cavitation in pooled stepped spillway.

The result in present study shows that increased level of dissolved oxygen on stepped spillway is influenced by an increase in slope of channel and surface roughness of steps.

4.0 CONCLUSION

Hydraulic structures can increase dissolved oxygen level by creating turbulent conditions where small air bubbles are carried into the bulk of the flow. Chute aeration is a particular instance of this model. A chute is characterized by a steep bed slope associated with skimming flow condition.

The present paper investigates influence of channel slope, number of step, configuration of macro roughness towards the value of dissolved oxygen level on stepped spillway. The results indicate that increased dissolved oxygen level on stepped spillway are influenced by an increase in slope of channel especially at the $Fr^* < 2.00$. If the discharge as function of Froude number increases, it will decrease turbulence flow and the concentration of air bubble in the water. The decreased value of turbulence flow will decrease dissolved oxygen level.

In addition, increased dissolved oxygen levels are also influenced by the surface roughness of the step. So that the pooled steps give value of dissolved oxygen level are higher than flat steps.

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References

[1] Baylar, A., Bagatur, T., & Emiroglu, M. 2007. Prediction of Oxygen Content of Nappe, Transition, and Skimming Flow Regime Is Stepped Channel Chutes. *J. Environ. Eng. Sci*. 6: 201-208.

[2] Baylar, A., Emiroglu, M., & Bagatur, T. 2009. Influence of Chute Slope on Oxygen Content in Stepped Waterways. *G.U. Journal of Science*. 22(4): 325-332.

[3] Bung, D. B., Schlenkhoff, A. 2009. Self–aerated Skimming Flow on Embankment Stepped Spillways - The Effect of Additional Micro-Roughness on Energy Dissipation and Oxygen Transfer. *33rd IAHR Congress*. Vancouver, Canada.

[4] Chanson, H. 1993. Stepped Spillway Flows and Air Entrainment. *Canadian Journal of Civil Engineering*. 422-435.

[5] Chanson, H. 1994b. Hydraulics of Skimming Flows over Stepped Channels and Spillways. *Journal of Hydraulic Research*. 445-460.

[6] Chanson, H. 2002. *The Hydraulics of Stepped Chutes and Spillways*. 1th edition. Balkema, Lisse, The Netherlands.

[7] Chanson, H., Toombes, L. 2002. Experimental Study of Gas-Liquid Interfacial Properties in a Stepped Cascade Flow. *Environmental Fluid Mechanics.* 2(3): 241-263.

[8] Chanson, H. 2004. *The Hydraulics of Open Channel Flow: An Introduction*. Second Edition. Oxford: Elsevier.

[9] Dermawan, V. 2011. Uji Model Fisik Hidraulik Perilaku Aliran dan Peredaman Energi Pada Bangunan Pelimpah Bertangga. Disertation. Surabaya: ITS Surabaya.

[10] Essery, I. T. S., Tebbutt, T. H. Y., Rasaratnam, S. K. 1978. Design of Spillways for Reaeration of Polluted Waters. Rep. 72, CIRIA, UK.

[11] Guenther, P., Felder, S., & Chanson, H. 2013. Flow Aeration, Cavity Processes and Energy Dissipation on Flat and Pooled Stepped Spillways For Embankments. *Environmental Fluid Mechanics*. 13(5): 503-525.

[12] Khatsuria, R. 2005. *Hydraulics of Spillways and Energy Dissipators*. New York: Marcel Dekker.

[13] Krisnayanti, D. S. 2016. Pemodelan Geometri Pelimpah Bertangga Terhadap Titik Pemasukan Udara (*Inception Point*) Pada Kondisi Aliran Tenggelam. Disertation. Fakultas Teknik, Universitas Brawijaya, Malang, Indonesia.

[14] Krisnayanti, D. S., Dermawan, V. 2014. Study Investigation of Hydraulic Model on Stepped Spillway. *Proceedings of Third International Conference on Sustainable Built Environment, Islamic University of Indonesia, Yogyakarta, Indonesia*.

[15] Peraturan Pemerintah No. 82 Tahun 2001. 2001. Pengelolaan Kualitas Air dan Pengendalian Pencemaran Air.

[16] Toombes, L., Chanson, H. 2000. Air-Water Flow and Gas Transfer at Aeration Cascades: A Comparative Study Of Smooth And Stepped Chutes. *Proceedings of the International Workshop on Hydraulics of Stepped Spillways, Zurich, Switzerland*. 22-24, 7784.