Re-aeration of nappe flow over a prototype stepped spillway

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ABSTRACT
Re-aeration through macro-roughness is a well-known principle in water treatment. Stepped spillways, with step elements acting as macro-roughness, are considered highly effective structures for water re-aeration, particularly in the nappe flow regime. This study investigated the re-aeration potential of nappe flow over a prototype stepped spillway and compared the findings with literature. The experiments were conducted at the HECE Laboratory, University of Liege, using a prototype 15° stepped spillway with six identical steps, each 0.5 m high and 1.87 m long, with critical depth to step height ratio ranging from 0.319 to 0.664 (Reynolds number from 1.99 $*10^5$ to 5.97 $*10^5$). The results indicated reaeration of about 60% to 70% across the six steps at different flow rates. However, as the flow rates increased, the overall aeration efficiency decreased. The data aligned well with the empirical formula proposed in the literature and derived in a similar range of parameters value.

Keywords: Re-aeration, Stepped spillway, Nappe flows, Air-water flows, Prototype-scale model.

1 INTRODUCTION

Reaeration of water, or the process of oxygen transfer, occurs through the air-water interfaces, governed by the concentration gradient between atmospheric oxygen and dissolved oxygen in water. Increasing the air-water interfaces, either through natural processes such as self-aerated flows or through artificial methods like air injection, can increase the amount of oxygen transferred.

Stepped spillways, which are designed as energy dissipators in dam's spillway, are particularly effective for the reaeration of water, especially when operating in a nappe flow regime. These spillways induce significant turbulence and aeration due to their macro-roughness step elements. The nappe flow regime creates extensive air-water interfaces including air entrainment and entrapment at the free-falling jet, through the free surface downstream of the free-falling jet, and within cavity regions (Felder et al, 2019). Additionally, nappe flows are characterized by prolonged residence times compared to transition and skimming flow regimes, which increase the duration of air bubbles contact with water (Fig 1). The effectiveness of these aeration mechanisms is largely dependent on the kinetic energy of surface eddies, which must overcome surface tension—conditions typically achieved in full-scale structures (Baylar et al. 2007, Pfister and Chanson, 2014). However, when scaling these free surface flows to laboratory settings based on Froude similitude, there is often inadequate scaling of viscous forces and surface tension. This discrepancy can lead to differences in air entrainment and transport capacity between laboratory models and full-scale prototypes. To mitigate these so-called "scale effects", literature suggests criteria such as Weber numbers ($We^{0.5}$) greater than 110 to 170 and Reynolds numbers (Re) between 1×10^5 and 3×10^5. Numerous researchers have studied aeration efficiency in stepped spillways under a nappe flow regime, resulting in the development of various empirical equations (Table 1).

Table 1. Previous experimental studies of oxygen transfer in nappe flows on stepped spillways, summary of flow conditions and stepped spillways geometry, (q= specific flow rate, Re= Reynolds number, h_c= critical flow depth, H_{dam}= height of dam, θ= slope of spillway, h_s= step height).

Reference	$q(m^2/s)$	Re = q/ν (10^5)	h_c(m)	H_{dam}(m)	θ (°)	h_s(m)
Essery et al. 1978	0.012–0.145	0.11 – 1.44	0.024 –0.128	1.0 – 2.0	11.3 - 45	0.025 - 0.50
Baylar et al. 2007	0.016-0.166	0.15 – 1.65	0.030 - 0.141	1.24 – 2.5	14.4 - 50	0.05 -0.10- 0.15
Khdhiri et al. 2014	0.002 – 0.025	0.019 -0.249	0.007 - 0.03	0.25 – 0.50	64 - 78	0.05 – 0.10
Felder et al. 2019	0.16 – 0.64	1.59 – 6.36	0.137 - 0.347	1.5 – 3.0	15	0.50

This study, as part of a global investigation to quantify the scale effects impact on oxygen transfer, aimed to assess aeration efficiency on a prototype-scale stepped spillway. The findings were compared with existing literature, and particularly the results of Felder et al. (2019) gained on the same model, to validate the new instrumentation and to identify the most suitable empirical formula for predicting re-aeration on such spillways. The prototype model included six identical steps, 0.5 m high, 1.87 m long, and 0.2 m wide, and was run with flow rates ranging from 0.2 to 0.6 m²/s ($0.318 < h_c/h_s < 0.664$ and $1.99\times10^5 < Re < 5.97\times10^5$).The experiments were conducted in the HECE Laboratory, University of Liege, and dissolved oxygen concentration was measured at the end of each steps using eight Hamilton VisiWater DO P Arc 150 FC10 optical sensors.

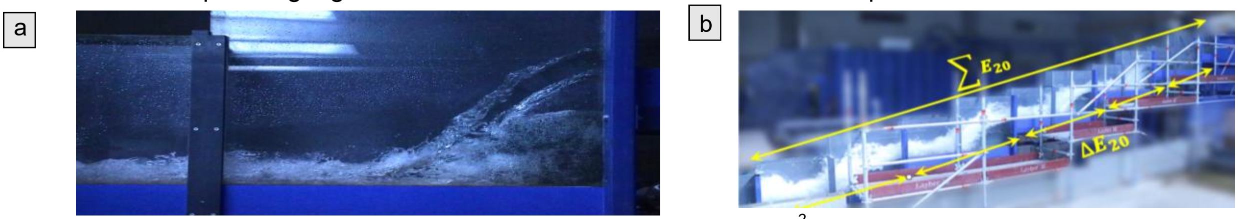

Figure 1. a) Nappe flow condition along step No. I at flow rate = 0.2 m²/s. b) Nappe flow condition along the prototype stepped spillway at flow rate = 0.6 m²/s

2 Results

The results showed that the total aeration efficiency (ΣE_{20}) increased by approximately 60% to 70% across the six steps, with the greatest variation in consecutive steps (ΔE_{20}) at steps II and III, and the smallest variation at step I (Fig. 2a). While higher flow rates intensified both aeration and turbulence, the overall aeration efficiency decreased due to the shorter residence time along the stepped spillway. A comparison with the literature revealed a comparable trend to the findings of Essery et al. (1978) and Felder et al. (2019), particularly for dam heights (H_{dam}) of 1.5 to 3 m. Baylar et al. (2007) empirical formula indicated higher aeration efficiency for H_{dam}= 2, 2.5 and 3 m, and significant discrepancies for H_{dam} values lower than 2 m. Lastly, the formula from Khdhiri et al. (2014) did not align well with the obtained results which may be linked to different geometry and initial flow conditions.

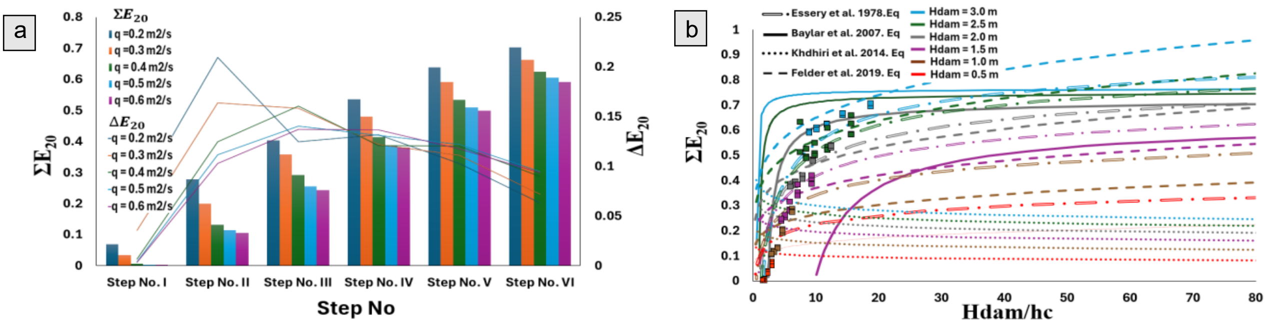

Figure 2. a) Aeration efficiency along the stepped spillway in nappe flow regime at various flow rates. b) Comparison between the findings of the present study and empirical equations from literature.

3 CONCLUSIONS

- Depending on flow rate, the flow was re-aerated by approximately 60-70% over 6 steps creating a chute of 3 m on a distance of 11.20 m.
- As the flow rate increased, aeration efficiency decreased due to reduced residence time.
- The results showed similar trends to the empirical formula from Essery et al (1978) and Felder et al. (2019), specifically for H_{dam} ranging from 1.5 to 3 m, while Baylar et al. (2007) formula showed higher aeration efficiency at $H_{dam} \geq 2$ m, with discrepancies below this range.

4 ACKNOWLEDGMENTS

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