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Experimental study of skimming flow on the stepped spillway in the non-aerated area using PIV

Kamyab Habibi[1], Farinaz Erfani Fard[2], Seyed Amin Asghari Pari[3*]

1- Department of Civil Engineering, Behbahan Khatam Alanbia University of Technology, Behbahan, Iran.
2- Department of Civil Engineering, Behbahan Khatam Alanbia University of Technology, Behbahan, Iran.
3-Associate Professor, Department of Civil Engineering, Behbahan Khatam Alanbia University of Technology, Behbahan, Iran.

Abstract

Understanding the flow behavior over stepped spillways has been the subject of many previous studies. Most of the studies on stepped spillways have been in skimming flow conditions and the aerated parts of the spillway. Also, many of these results have been the result of observing the flow behavior on the side of the spillway, and there is still no complete view of the flow behavior in the depth of the spillway. The present study investigates the skimming flow behavior on a short and wide stepped spillway in a non-aerated area. The main goal of this research is to investigate the skimming flow behavior at different cross sections in a short-stepped spillway. For this purpose, the image processing technique called Particle Image Velocimetry (PIV) has been used to process the movement path, velocity, and behavior of the flow and analyze it in the side sections and depth of the spillway. In a few previous studies, the more detailed behavior of the skimming flow has been investigated. The results of these studies have defined some of the characteristics of two sub-regimes of the skimming flow regime. However, the behavior of the sub-regimes mentioned by the researchers was mostly described as laboratory observations. This article takes a closer look at this issue. The results showed that the behavior of the skimming flow sub-regime (under the name of SKI) in different sheets in the width of the spillway is different from each other. Also, in this study, it was shown that the flow behavior in the areas above the pseudo bottom line is almost similar to other cross-sections, but in the areas under the pseudo bottom line, the flow behavior experiences significant changes, so that its effects on the velocity profiles are quite evident.

Keywords: Skimming flow, Stepped Spillway, Non-aerated Area, PIV.

1. Introduction

In a general classification, flows on stepped spillways are divided into two categories: skimming flow and nappe flow: in skimming flow, the velocity is high, and permanent or temporary air pockets (holes) are not formed in most of the spillway body, especially the initial steps. There are also vortices in the inner corner of the steps. At low flow rates, a flow known as nappe flow occurs on stepped spillways, one of its prominent characteristics is the presence of air pockets on most of the steps and the collision of the main flow path with the bottom of all the steps. In the continuation of the studies on the determination of flow regimes, Ohtsu and Yasuda (2004) reported for the first time the existence of a flow that has behaviors between skimming and nappe flow; A flow in which air pockets temporarily exist in some steps, as well as vortices that are temporarily formed in the inner corner of the steps. They called this flow the transitional flow regime.

The design of spillways is often based on the skimming flow regime. Therefore, the main focus of the studies has been on the flow characteristics in the range of the skimming flow regime (Pegram et al., 1999; Amador et al., 2004; Gonzalez et al., 2008; Bung, 2011; Simo et al., 2013; Leandro et al., 2014). Also, most of the studies have been conducted in aerated areas and few studies have been conducted on non-aerated regions (Carvalho & Amador, 2009; Meireles & Matos, 2009; Bombardeli et al., 2010). In further studies, Chanson (2002) and Ohtsu et al. (2004) proposed another classification for the skimming flow regime: SK1 and SK2. SK1 sub-regime is for the lower limit and SK2 sub-regime is for the upper limit of flow rates in which the flow is skimming. In the SK1 sub-regime, a vortex (recirculation zone) is formed on the steps, which does not extend to the end of the steps (the edge of the steps), and the water flow has direct contact with the horizontal part of the steps. Also, the water level is parallel to the horizontal side of the steps. In the SK2 sub-regime, the recirculation zone extends over the entire length of the step, and the water level is parallel to the pseudo bottom line (Chanson, 2002; Ohtsu et al., 2004; Gonzalez & Chanson, 2006). Fig. 1 shows the prediction of changes in flow regimes based on the flow rate and the geometry of the steps in stepped spillways presented by Chanson (2002) and Ohtsu et al. (2004).

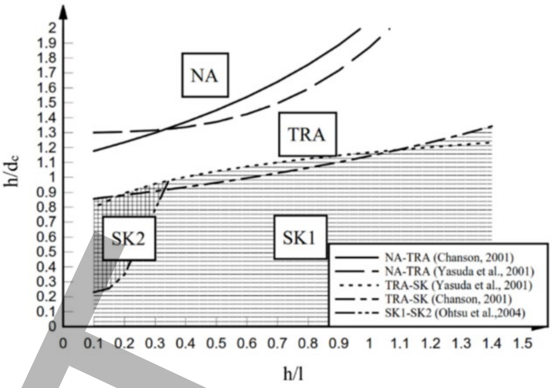


Fig. 1 Predicting the type of flow regime in stepped spillways (Image taken from Gonzalez & Chanson, 2006).

In an experimental and numerical study, Lopes et al. (2017) investigated the skimming flow on two spillways with widths of 0.3 and 0.5 m. Their observations showed that in the spillway with a width of 0.3 m, the type of regime formed on the entire width of the spillway was of the SK1 type, where the length of the recirculation zone was less than the length of the step. However, by examining the spillway with a width of 0.5 m, they found that the skimming flow formed on the spillway changes periodically (both in width and length of the spillway) as SK1 and SK2. Furthermore, they added that in the areas where the flow is of SK1 type, due to the short length of the recirculation zone, the depth of the flow (near the edge of the step) decreases. While in the areas where the flow is of SK2 type, the depth of the current is high. Therefore, at the meeting points of these two types of currents (sub-regimes SK1 and SK2), there is a height difference in the water, which is called the seesaw pattern, which was previously reported by Yasuda & Chanson (2003) and Felder & Chanson (2009).

1.1. Specific Aims

In the present research, the experimental investigation of skimming flow behavior on a wide four-step spillway has been done using an image processing technique (PIV). As it was said, most of the studies conducted on spillways have been carried out in the aerated area. Therefore, in the current research, the focus has been on investigating the flow in the non-aerated area. Also, the results of many studies related to spillways have been the result of investigating the flow on the side of the spillway, so the flow on the side of the spillway is known as a representative of the flow in other cross-sections (Hager, 1992). Therefore, another goal of this study was to investigate the flow behavior in the cross sections of the spillway using the PIV technique. In fact, the main goal of this article is whether the flow shows different behavior at different points in the width of the spillway, even without considering the effect of the spillway wall.

2. Experimental Setup

The experiments are conducted in the hydraulic research lab at Behbahan Khatam Alanbia University of Technology (BKATU). The flume has a straight length, width, and height of 10, 1.2, and 1 m, respectively. It should be noted that for the first two meters, the flume's height is 1.2 m. The system includes two 8-in pumps with a total flow rate of 150 l/s, as measured by an ultrasonic flowmeter. To quell the oscillations caused by water pumping into the flume, two layers of vertical metal netted mesh are used at the entrance of the flume, and a piece of Styrofoam is employed at the flow surface to prevent the surface oscillations of water. Moreover, an image processing system known as PIV (particle image velocimetry) is employed to closely study the flows at the bottom of the spillway steps. The PIV technique is an optical method using laser beams that simultaneously measure the velocity field at any moment and take images of the flow. In this method, velocity is measured using a plane parallel to the flow's direction. For this purpose, an FS5 SONY slow-motion camera (maximum 965 fps) with an AT-X11-20mm PRO DX lens from Tokina Co. is used for imaging, and a 2.5w BG-0205 laser manufactured by Takfam Sazan is employed. In PIV, two images are taken shortly after one another from the flow field that contains added particles to the water. When the particle displacement is calculated within specific intervals using the images, velocity is measured in any given field part (LaVision, 2002). The particles used for the velocimetry method should properly reflect the light so the camera can identify the trajectory of particles after the laser light incident on them. The lab environment should be dark to use this system, with only the laser light being applied. Amador et al. (2006) used 70μm ceramic particles to describe the non-aerated flow above a stepped spillway. In the present study, 80μm alumina (aluminum oxide) particles (ρ = 3.95 g/cm3) are used. Fig. 2 shows a schematic view of the flume, the spillway layout, and the PIV system. Due to the surface flow oscillation above the spillway, high-resolution images cannot be recorded. Therefore, a piece of transparent plexiglass with a thickness of 5mm is placed and fixed on the water surface. Further, the laser light is incident on the surface of the plexiglass to remove the optical distortion caused by the surface turbulence of the water. Poggi & Kudryavtseva (2019) and Jenssen & Manhart (2020) also employed this method to create a suitable optical sheet in studies on the scouring of bridge piers. In the following, a fixed concentration of alumina particles is added to the spillway upstream. When alumina particles pass through the part where the optical sheet is made, the light is refracted after incidence to the particles, and the camera records the trajectory of the particles as a slow-motion and low-quality video. Then, the video is converted into consecutive images and analyzed in MATLAB in the PIVLAB code (Thielicke & Stamhuis, 2014); finally, the trajectory of the particles is obtained as the output of the given code. Amador et al. (2004b) were able to study a zone with no air bubbles using the PIV technique. Ryu et al. (2005) were the first researchers to use BIV (bubble image velocimetry) and investigate the region where the air enters the flow to measure and analyze the wave impact and air entering. In fact, PIV and BIV methods operate similarly, except that air bubbles play the role of particles in the aerated zone in the water, and there is no need for laser light and particles. In addition, the flume's transverse distance from the camera was selected to be 50cm based on the recommendation made by Emadzadeh & Chiew (2017) and Bung & Valero (2015).

The stepped spillway used here has a fixed slope of 1V:1.9H (ϴ = 27.7º) and four steps, with a step height (h) of 10.5 cm, step length (L) of 20 cm, and the total spillway height of 42 cm. The crest length (Lcrest) of the spillway is also 60 cm. According to the suggestion made by Felder (2013), the critical depth over the spillway is measured after the initial flow curve within a distance from the spillway edge, which is 2 to 3 times the flow depth.

3. Results

At high flow rates on an unobstructed stepped spillway, where the flow regime is skimming, two zones under the pseudo bottom line are formed on the step called the recirculation zone (RZ) and the mixing zone (MZ) (Zare & Doering, 2012). Fig. 3 shows the output images

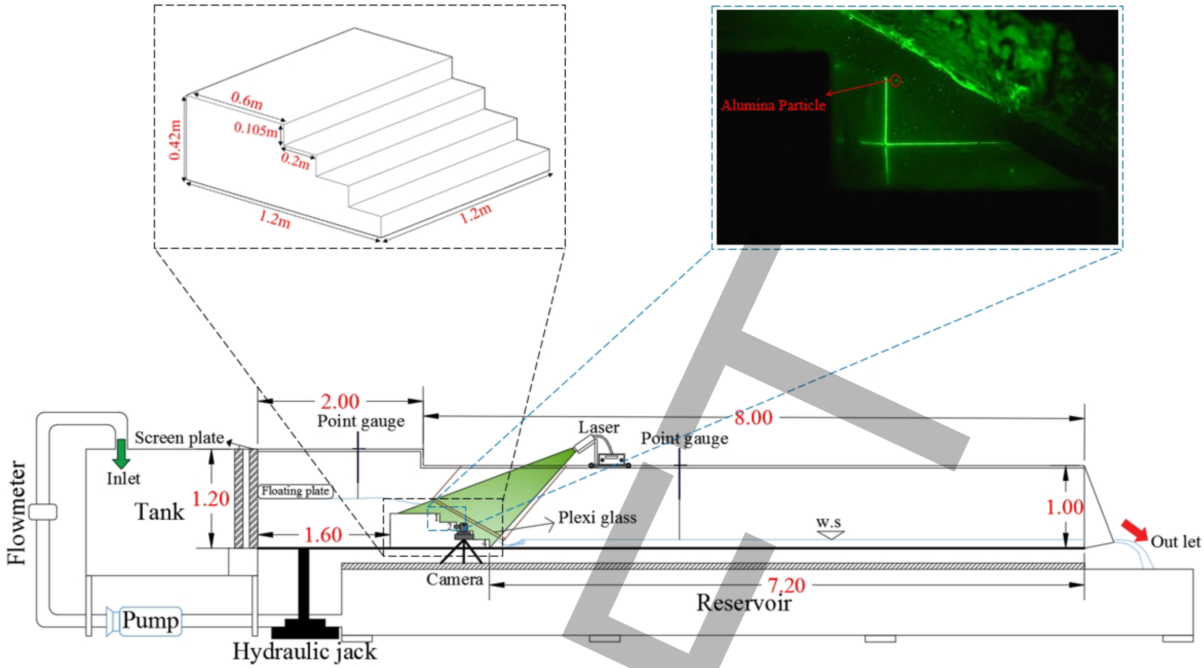
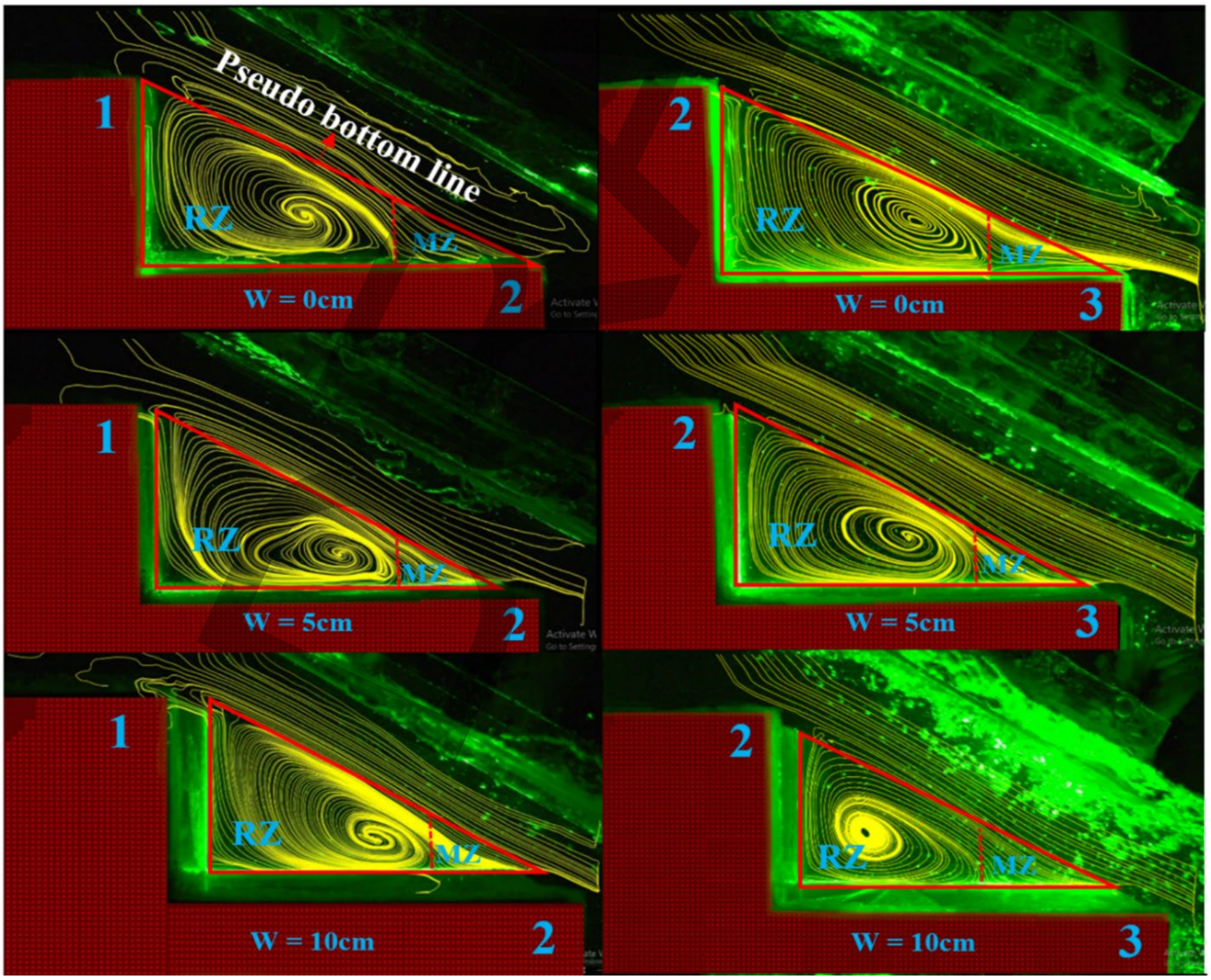


Fig. 2 The schematic view of the flume, the PIV system, and the spillway layout.



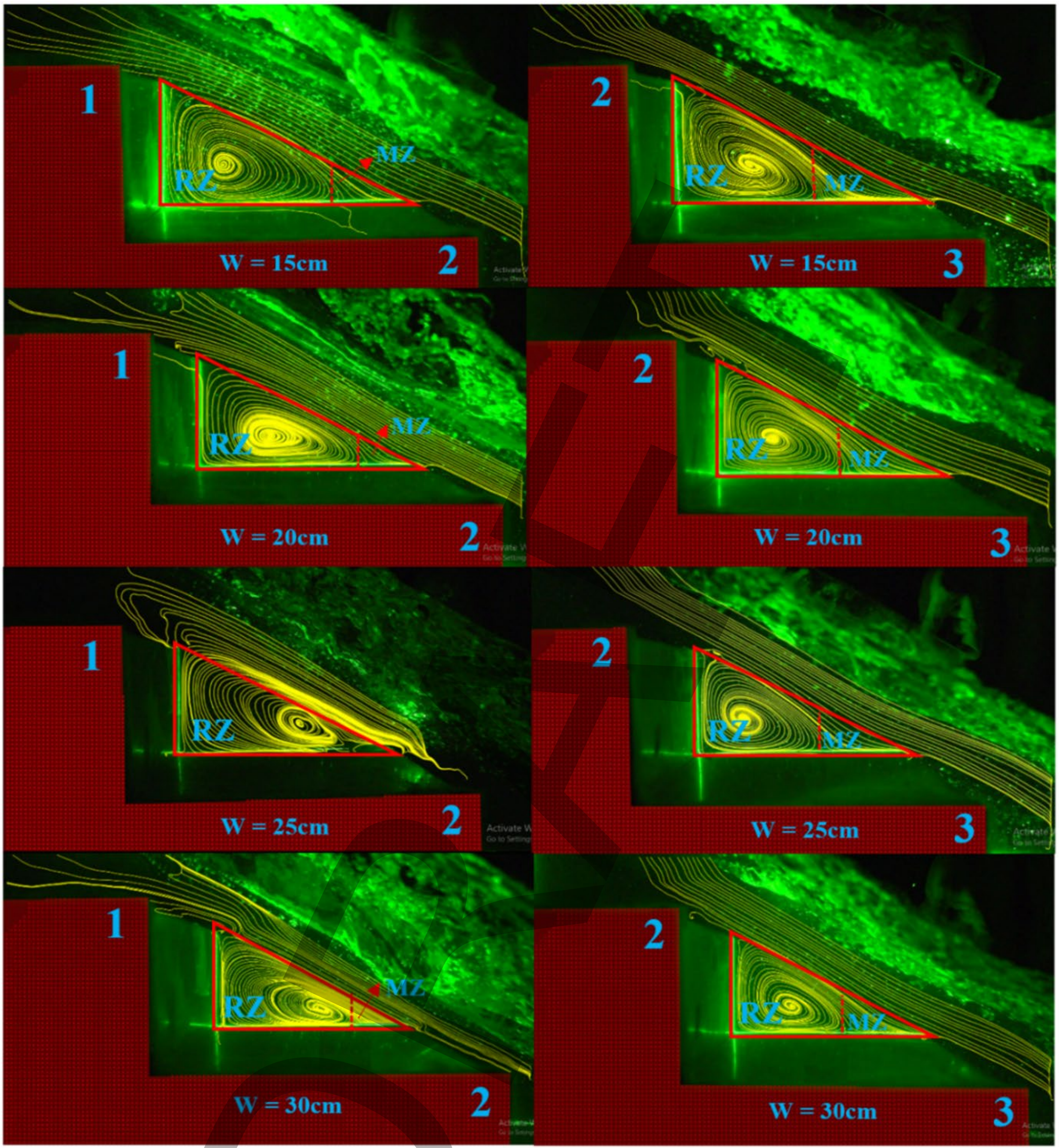


Fig. 3 The images of the zones developed under the pseudo-bottom line in the research's stepped spillway using PIV ($d_c/h = 1.09$).

from PIV image analysis for the free-stepped spillway (without obstacles) for steps 2 and 3 at a flow rate of 150 l/s (dc/h = 1.09). Due to the presence of a small concentration of air bubbles in step 4, it was not possible to take images in depth using the PIV method. The range of the images taken is up to a distance of 30 cm from the side of the spillway, where every 5 cm an optical sheet is created by laser, and the movement of the flow is filmed. The reason for choosing this distance was the proper and more accurate focus of the camera on the movement of particles to this depth. The images show that the shape and dimensions of the RZ and MZ areas of two successive steps in the same cross-section are different, and in each step, as we move towards the middle of the spillway, the size of the RZ and MZ areas fluctuate.

According to Fig. 1 and the descriptions of skimming flow sub-regimes by Chanson (2002) and Ohtsu et al. (2004), the type of sub-regime formed on the spillway studied in the current research is of the SK1 type. The results of Fig. 3 show that the behavior of the SK1 sub-regime formed in different cross-sections up to a distance of 30 cm from the side is not the same, and the size of the RZ and MZ regions are different in each of them. The change in the size of the RZ and MZ regions as well as their formation location can affect the velocity of the flow passing through the spillway. In Fig. 4a,b each step is divided into four areas, and the average flow velocity in those areas was obtained using particle motion analysis in the PIV lab and shown in Fig. 5. Also, velocity profiles at three points on each step (marked in Fig. 4c) were obtained and shown in Fig. 6.

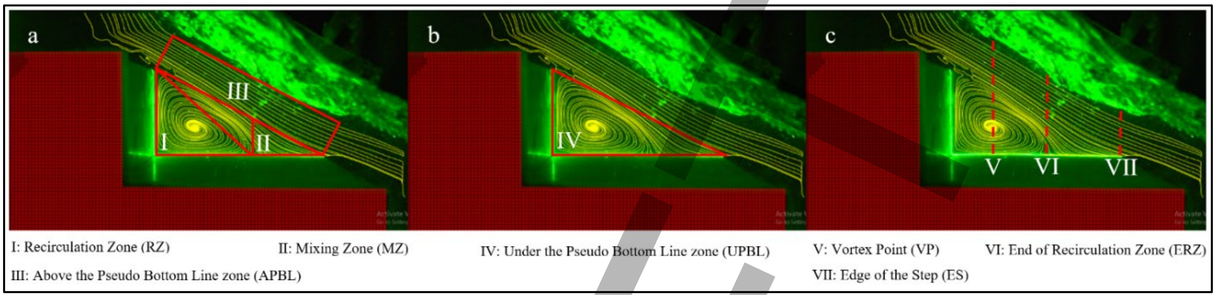


Fig. 4 Areas and points of collection of flow velocity on the steps.

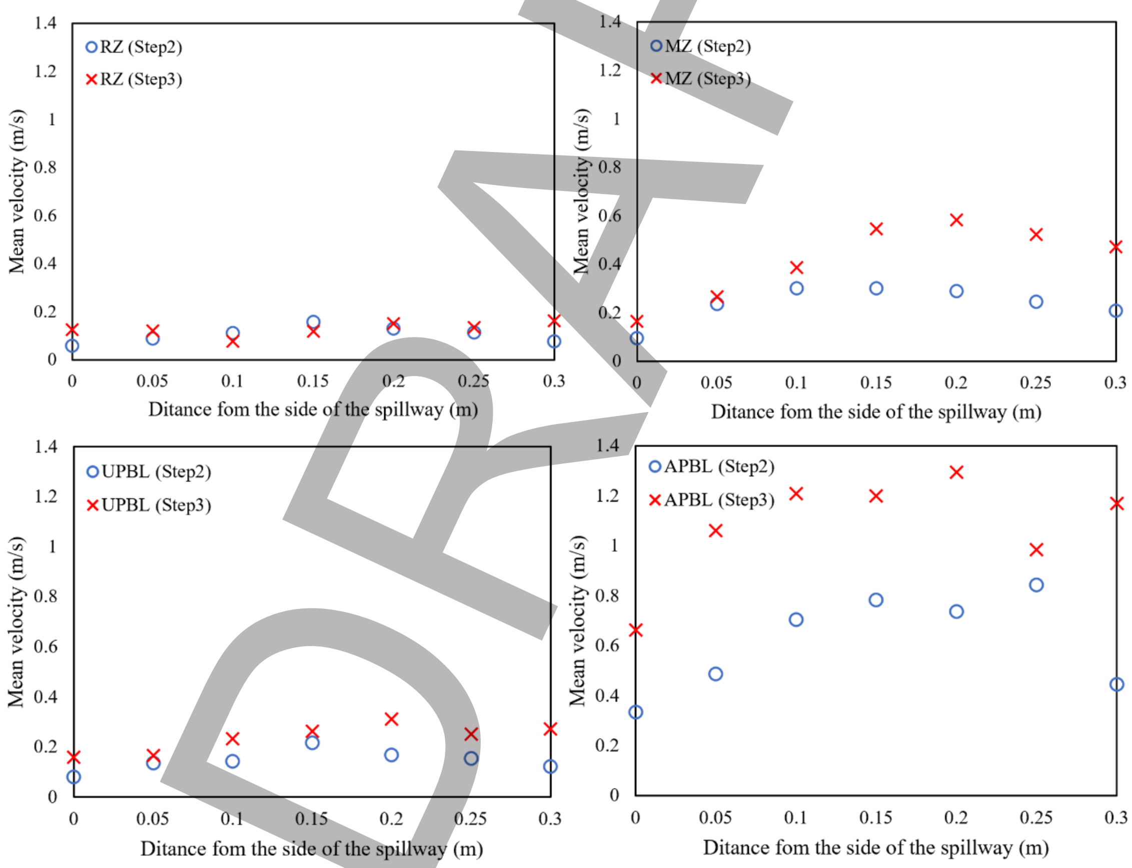


Fig 5 Average velocity values on the areas formed on each step.

Lopes et al (2017) stated that the existence of an intermittent skimming flow (alternation between SK1 and SK2) in the area under the pseudo bottom line (UPBL region) is more evident than the free flow (APBL region). Also, Felder and Chanson (2015a) found in their study that the characteristics of the air-water flow measured in the free flow (APBL region) do not experience deep changes despite the intermittent skimming currents. In the present study, as mentioned, most of the sub-regimes formed on the investigated range (W: 0-30cm) are of SK1 type. However, the direction of the free flow is parallel to the pseudo bottom line, and some of the MZ areas formed on the steps (especially the second step) are small, and the

RZ area in these regions tends to fill the floor of the steps (Fig. 3), which this behavior it is one of the features of SK2 sub-regime. As a result of the observations of this study, it is possible to report behaviors of alternating skimming flow within the scope of the present research experiments. Also, similar to the studies conducted by previous researchers (Felder & Chanson, 2015a; Lopes et al., 2017), the behavior of the alternating skimming flow is more visible and scrutinized than the free flow behavior due to the areas formed under the pseudo bottom line. In addition to these results, this study shows that the shape of the free flow also does not change significantly in the SK1 sub-regimes.

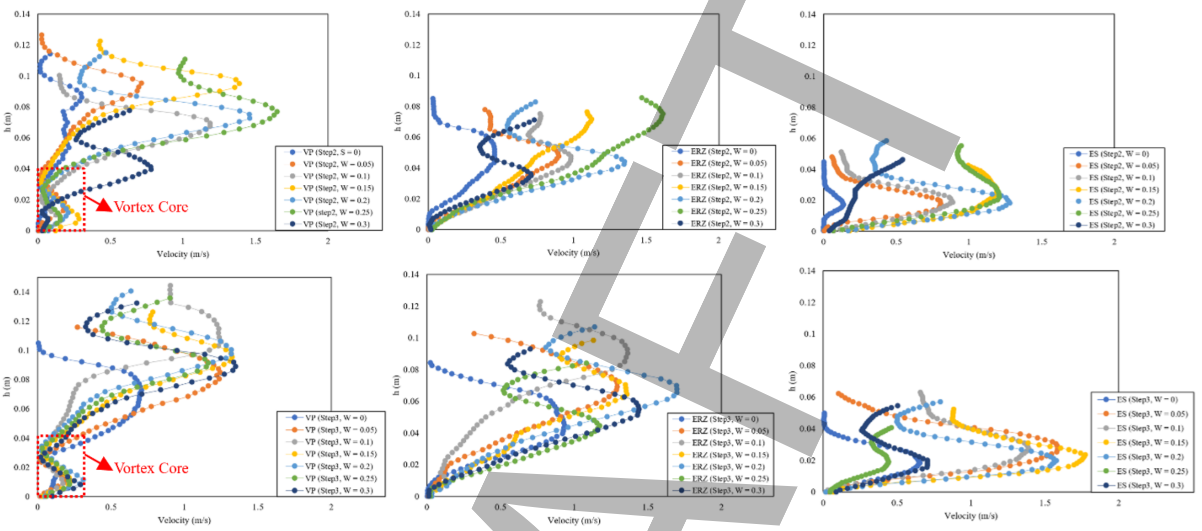


Fig. 6 Velocity profiles on the steps.

In Fig. 4 it can be seen that in general, the average velocity of the flow on steps 2 and 3 in the RZ and UPBL regions is not much different, but the average velocity in the MZ area, which is actually the result of the free flow hitting the bottom of the step and also the release of the trapped flow in the vortex system of the RZ area, is different and is higher in the 3rd step. It is also clear that the average velocity on the downstream steps of a common stepped spillway in the APBL area must have a significant difference from the upstream steps.
Fig. 5 shows the velocity profiles on the floor of the steps at three points VP, ERZ, and ES; As it is known, the behavior of the flow in all three points for both steps on the side of the spillway (W = 0) is different from other velocity profiles, which can be completely related to the effect of the spillway wall. Also, this effect can be seen in the results of Fig. 4. The results of the velocity profiles at the VP point and in the area of the central core of the vortex show that despite the different locations of this core on the step (both along the step and in the height), no significant changes in velocity have been recorded. Also, the velocity profiles taken on each step and in the transverse sheets are largely similar. The maximum values of the recorded velocities at the ERZ and ES points are very close to each other in several sheets, which, as mentioned, indicates the smallness of the MZ area in those areas, the extension of the RZ area to the edge of the step, and as a result, the existence SK2 sub-regimes.

4. discussion

In previous studies (Chanson, 2002; Ohtsu et al., 2004; Felder & Chanson, 2015a; Lopes et al., 2017), the behavior of SK1 and SK2 sub-regimes on stepped spillways was investigated, but despite the definition of a specific experimental range (Fig. 1) of flow rate and geometry of steps to distinguish the type of SK1 and SK2 sub-regimes, there is no mention of the possibility of differences in the behavior of similar sub-regimes at different transverse sections. In this study, with the help of the PIV technique, it was shown that the sub-regime formed on the spillway in different cross-sections is mostly of SK1 type, but it shows different behaviors in each cross-section (Fig. 3), also the examination of the velocity profiles in transverse sections confirmed the same issue. According to the results obtained from this study, it seems that if the flow conditions and the geometry of the steps are created for the formation of the SK2 sub-regime, differences can be observed in this sub-regime in different transverse sections; in such a way that the shape and location of the formation of the central core of RZ are different in the transverse sections. To further investigate the findings of the current research, it is necessary to conduct more studies on spillways with different dimensions and under wider hydraulic conditions.

5. Further Research

The PIV technique can be used to investigate the flow at depth only if there are no bubbles inside the flow. In this technique, depending on the type of study, imaging equipment model, laboratory conditions, particles used (in this study, 80µm alumina), and laser light intensity, the results can be somewhat variable. Therefore, it is recommended to verify the results with laboratory data or accurate simulations of laboratory conditions to find the appropriate setup for testing. An important point regarding the use of the image processing method is the possibility of a percentage of error in the estimation of the flow velocity field so that there is a possibility of particles leaving the optical sheet created by the laser. This percentage of error is inevitable and it is recommended to consider the mentioned cases as possible errors in studies where the turbulence structures and flow characteristics are investigated in detail.

6. Conclusions

In the present study, the behavior of skimming flow on a short-stepped spillway was investigated. For this purpose, a wide spillway with a width of 1.2 m and a flow rate of 150 l/s (dc/h = 1.09) was used as a laboratory model. Also, the PIV image processing technique was used to check the flow performance on the spillway. The results showed that the shape and dimensions of the RZ and MZ areas of two consecutive steps in the same cross sections are different. Also, by moving away from the side of the spillway towards the middle of the spillway, the shape and behavior of these areas are constantly changing. In addition, in this study, it was shown that the shape and behavior of the SK1 sub-regime formed in each section is different from the other section, and this difference is also evident in the velocity profiles as well as the average velocities of the areas under and above the pseudo bottom line. The results of the average velocities showed that the average velocity in the RZ areas in successive steps and also in different transverse sections of each step is close to each other and does not experience many changes, but this difference is large in the MZ and APBL areas. It was also observed that to investigate the flow behavior, the focus should be placed under the pseudo bottom line because the changes in the flow behavior in free flow (APBL) are not significant. Nevertheless, the velocity profiles in the transverse sections for this area also show the difference.

7. Acknowledgments

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8. References

Amador A, Sa´nchez-Juny M, Dolz J, Sa´nchez-Tembleque F, Puertas J (2004) Velocity and pressure field in skimming flow in stepped spillways. In: F. Yazdandoost and J. Attari Edition (ed.) Intl Conf. on Hydraulics of Dams and River Structures, pp. 179–285. Balkema Publ., The Netherlands.

Amador, A., Sánchez-Juny, M., & Dolz, J. (2006). Characterization of the nonaerated flow region in a stepped spillway by PIV.

Amador, A., Van der Graaf, G., Sánchez-Juny, M., Dolz, J., Sánchez-Tembleque, F., Puertas, J., & Girona, C. J. (2004, July). Characterization of the flow field in a stepped spillway by PIV. In Proc. 12th Symp. Applications Laser to Fluid Mechanics (pp. 12-15).

Bombardelli FA, Meireles I, Matos J (2010) Laboratory measurements and multi-block numerical simulations of the mean flow and turbulence in the non-aerated skimming flow region of steep stepped spillways. Environ Fluid Mech 11(3):263–288. doi:10.1007/s10652-010-9188-6.

Bung DB (2011) Developing flow in skimming flow regime on embankment stepped spillways. J Hydraul Res 49(5):639–648. doi:10.1080/00221686.2011.584372.

Bung, D. B., & Valero, D. (2015, June). Image processing for bubble image velocimetry in self-aerated flows. In 36th IAHR World Congress (pp. 6594-6601).

Carvalho RF, Amador AT (2009) Physical and numerical investigation of the skimming flow over a stepped spillway. Adv Water Resour Hydraul Eng, pp 1767–1772. doi:10.1007/978-3-540-89465-0_304.

Chanson H (2002) The hydraulics of stepped chutes and spillway. CRC Press, Inc.

Emadzadeh, A. D. E. L., & Chiew, Y. M. (2017). Bubble Dynamics and PIV Measurements in a Hydraulic Jump. In The 37th IAHR World Congress August 13–18, Kuala Lumpur, Malaysia.

Felder S, Chanson H (2009) Turbulence, dynamic similarity and scale effects in high-velocity free surface flows above a stepped chute. Experim Fluids 47(1):1–18. doi:10.1007/s00348-009-0628-3.

Felder S, Chanson H (2015a) Closure to ''Aeration, flow instabilities, and residual energy on pooled stepped spillways of embankment dams'' by Stefan Felder and Hubert Chanson. J Irrigat Drain Eng 141(2):07014,039. doi:10.1061/(ASCE)IR.1943-4774.0000627.

Felder, S. (2013). Air-water flow properties on stepped spillways for embankment dams: Aeration, energy dissipation, and turbulence on the uniform, non-uniform, and pooled stepped chutes.

Gonzalez CA, Takahashi M, Chanson H (2008) An experimental study of effects of step roughness in skimming flows on stepped chutes. J Hydraul Res 46(1):24–35. doi:10.1080/00221686.2008.9521937.

Gonzalez, C. A., & Chanson, H. (2006). Flow resistance and design guidelines for embankment stepped chutes. Dams and Reservoirs, Societies and Environment in the 21st Century, Vols 1 and 2, 1, 1015-1022.

Hager WH (1992) Spillways: shockwaves and air entrainment: review and recommendations. Commission Internationale des Grands Barrages.

Jenssen, U., & Manhart, M. (2020). Flow around a scoured bridge pier: A stereoscopic PIV analysis. Experiments in Fluids, 61, 1-18.

LaVision. 2002. Davis flow master software manual. Germany.

Leandro J, Bung DB, Carvalho RF (2014) Measuring void fraction and velocity fields of a stepped spillway for skimming flow using non-intrusive methods. Exp Fluids 55(5). doi:10.1007/s00348-0141732-6.

Lopes, P., Leandro, J., Carvalho, R. F., & Bung, D. B. (2017). Alternating skimming flow over a stepped spillway. Environmental Fluid Mechanics, 17(2), 303-322.

Meireles I, Matos J (2009) Skimming flow in the nonaerated region of stepped spillways over embankment dams. J Hydraul Eng 135(8):685–689. doi:10.1061/(ASCE)HY.1943-7900.00000470.

Ohtsu, I., Yasuda, Y., & Takahashi, M. (2004). Flow characteristics of skimming flows in stepped channels. Journal of Hydraulic Engineering, 130(9), 860-869.

Pegram GGS, Officer AK, Mottram SR (1999) Hydraulics of skimming flow on modeled stepped spillways. J Hydraul Eng 125(5):500–510. doi:10.1061/(ASCE)0733-9429(1999)125:5(۵۰۰)

Poggi, D., & Kudryavtseva, N. O. (2019). Non-intrusive underwater measurement of local scour around a bridge pier. Water, 11(10), 2063.

Ryu, Y., Chang, K. A., & Lim, H. J. (2005). Use of bubble image velocimetry for measurement of plunging wave impinging on structure and associated water. Measurement Science and Technology, 16(10), 1945.

Simo˜es A, Schulz H, Porto R, Gulliver J (2013) Free-surface profiles and turbulence characteristics in skimming flows along stepped chutes. J Water Res Hydra Eng 2(1):1–12.

Thielicke, W and Stamhuis, E J. (2014). PIVlab – Towards User-friendly, Affordable, and Accurate Digital Particle Image Velocimetry in MATLAB. Journal of Open Research Software, 2: e30.

Yasuda, Y., & Chanson, H. (2003). Micro-and macroscopic study of two-phase flow on a stepped chute.

Zare, H. K. and Doering, J. C. (2012). Energy dissipation and flow characteristics of baffles and sills on stepped spillways. Journal of hydraulic research, 50(2), 192-199.