Proc. 29th IAHR Congress, Theme D, Vol. 2, Tsinghua Univ. Press, Beijing, pp. 611-617 (ISBN 7-302-04676-X/TV).

INTERACTION BETWEEN FREE-SURFACE AERATION AND CAVITY RECIRCULATION IN SKIMMING FLOWS DOWN STEPPED CHUTES

Jorge Matos[1], Youichi Yasuda[2] and Hubert Chanson[3]

[1] Department of Civil Engineering ,Technical University of Lisbon, Lisbon, Portugal
[2] Department of Civil Engineering , College of Sience and Technology, Nihon University, Tokyo, Japan [3] Department of Civil Engineering, The University of Queensland, Brisbane, Australia

Technical University of Lisbon, IST, DECivil, Av. Rovisco Pais, 1049-001 Lisbon

Tel: (351 21) 8418145/3; Fax: (351 21) 8497650; E-mail: jm@civil.ist.utl.pt

Abstract: Experimental investigations have been conducted in stepped spillway model chutes assembled at the National Laboratory of Civil Engineering (LNEC), Lisbon, at Nihon University (UNIHON), Tokyo and at the University of Queensland (UQLD), Australia. In the present paper, the research is focussed on the interactions between entrained air bubbles and cavity recirculation in the skimming flow regime. The experimental results emphasise that the air concentration distribution in between the steps, in the vicinity of the pseudo-bottom formed by their external edges, is notably different from that observed at the adjacent step edges. They also show that the air concentration profiles become similar for distances normal to the chute of the order of magnitude of the width of the air concentration boundary layer, namely in the gradually varied air-water flow region.

Keywords: air concentration distribution; air concentration boundary layer; cavity recirculation

1 INTRODUCTION

Experimental studies in skimming flow over model and prototype stepped chutes provided data on the air concentration distribution which was found to be similar to that observed on smooth spillways of identical slope (e.g., Ruff and Frizell 1994, Matos and Frizell 1997, Chamani and Rajaratnam 1999 and Chanson et al. 2000).

This paper addresses the influence of the cavity recirculation on the notable increase of the air concentration near the pseudo-bottom, as observed in between the step edges. These findings are believed to be of importance on the understanding of the drag reduction phenomenon as well as on predicting the safety against cavitation damage.

2 EXPERIMENTAL FACILITIES

Experimental data were collected in stepped chutes assembled at LNEC, UNIHON, and at UQLD, namely on air concentration (void fraction) and velocity distributions (LNEC, UNIHON, UQLD), turbulent velocity fluctuations (UNIHON), and bubble size and bubble frequency distributions (UQLD).

The main characteristics of the stepped chutes and respective instrumentation embraced by this study, as well as the analysed skimming flow conditions, are shown in Table 1. Further and more complete information on the overall instrumentation and facilities can be found in Chanson (1995, 1997), Ohtsu and Yasuda (1997), Yasuda and Ohtsu (2000) and Matos et al. (1997, 2000).

Table 1 Experimental investigations

Facility	Stepped chute				Flow conditions				Instrumentation
	α (deg.)	L (m)	b (m)	h (m)	q_w (m^2/s)	d_c/h	Re ($*10^5$)	We	(void fraction)
LNEC	53.1	3.74	1.00	0.08	0.080 & 0.180	1.09 & 1. 86	0.8 & 1.8	135 & 158	Conductivity probe (ϕ = 0.2 mm)
UNIHON	30.0	5.00	0.40	0.025	0.026	1.62	0.3	46 – 47	Optical void probe (ϕ = 0.1 mm)
	55.0	5.00	0.40	0.025	0.026	1.62	0.3	42	
UQLD	21.8	2.70	1.00	0.10	0.114 & 0.182	1.10 & 1.50	1.1 & 1.8	186 & 202	Single (ϕ = 0.35 mm) and double tip conductivity probes (ϕ = 25 μm)

Notes:

α - chute slope; L - chute length; b – chute width; h – step height; q_w – unit water discharge; d_c – critical depth; ϕ - diameter of the probe tip, Re – Reynolds number ($Re = q_w/\nu$); We – Weber number defined as $We = U/(\sigma/(\rho_w L_s))^{1/2}$; L_s – distance between step edges; U – depth averaged velocity (in the normal to the step edge); ν - kinematic viscosity of water; σ - surface tension between air and water; ρ_w - water density.

3 AIR ENTRAIMENT AND CAVITY RECIRCULATION

Air entrainment

Dimensionless air concentration profiles are shown in Figs. 1 to 6. In those Figures, y is the distance normal to the pseudo-bottom formed by the step edges, Y_{90} the characteristic depth where the air concentration is 90% and $X = x/L_s$, where x is the distance along the chute with origin at the upstream step edge and L_s the distance between step edges. The profiles shown in Fig. 1 were obtained in stepped chutes of slopes typical of those on embankment dams. In Fig. 1a, the profiles were obtained at the UQLD chute, in the rapidly varied flow downstream of the point of inception, whereas in Fig. 1b, they were obtained at the UNIHON chute, in the upstream end of the gradually varied flow. Also included in Fig. 1 are the air concentration profiles at the step edge (X = 1), estimated by the advective diffusion model (ADM) developed by Chanson (1995, 1997) for smooth-invert chute flows.

The following observations can be drawn from Fig. 1: (i) The profiles obtained at X = 0.5 and X = 1.0 (Fig. 1a) as well as all the profiles included in Fig. 1b show that the air concentration close to the pseudo-bottom is much larger in between step edges than at step edges. Identical conclusion may be drawn from the data of Tozzi et al. (1998) (despite the observed scatter in the data) as well as from Boes and Hager (1998); (ii) the air concentration profiles presented in Fig. 1a show a large increase in mean air concentration along the flow direction (X = 0 and X = 1), because they were obtained in the rapidly varied flow region; (iii) Chanson's advective diffusion model (ADM) fits reasonably well the experimental data, in particular that included in Fig. 1b. It should be noted that the model has been developed for the gradually varied flow, whereas Fig. 1a refers to the rapidly varied flow.

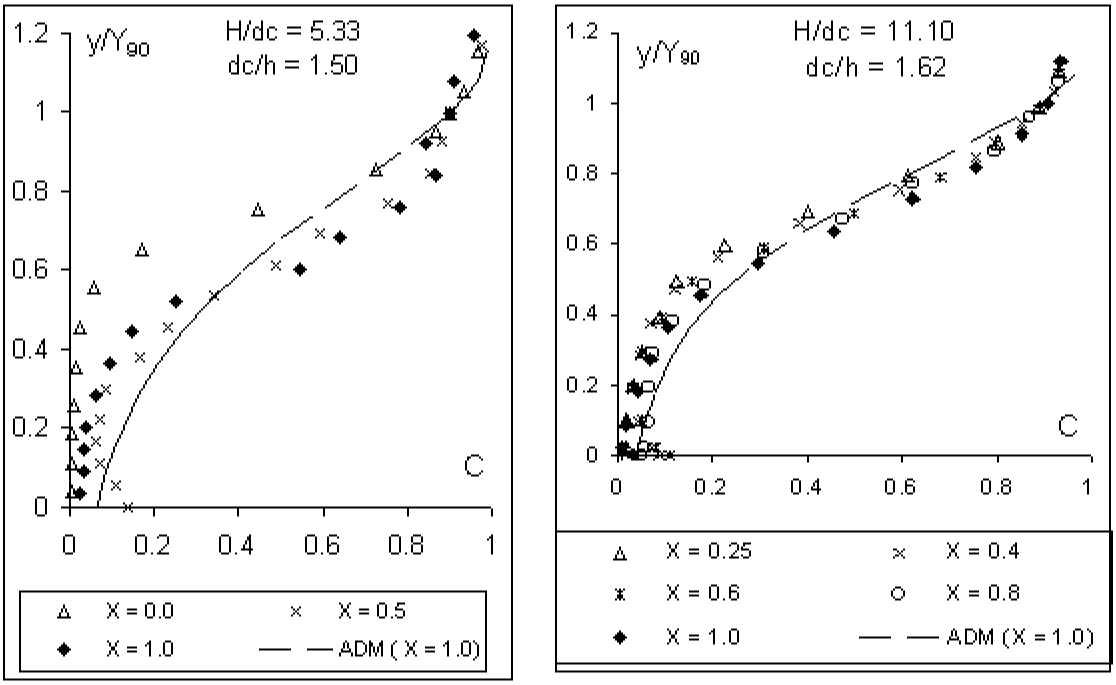


Fig. 1 Air concentration distribution in the rapidly or gradually varied flow region:

(a) UQLD chute, α = 21.8 degrees; (b) UNIHON chute, α = 30.0 degrees When comparing the profiles obtained in between the step edges at the UQLD and UNIHON chutes (Fig. 2) one can note the similar shapes, in particular close to the pseudo-bottom. The greater air concentrations experienced at UQLD (flatter slope and not dissimilar d_c/h) might be essentially explained by the sharp increase in the air concentration in a very short distance near the point of inception, as observed in steep stepped chutes (Matos, 2000). Therein it was shown that the mean air concentration (C_{mean}) in the rapidly varied flow may attain values of the order of magnitude of the expected equilibrium mean air concentration, for the same slope (Ce_{mean}). On UQLD chute, the equilibrium mean air concentration is expected to be about 0.34, while for this location the obtained C_{mean} was 0.38 (X = 1). In contrast, for a 30 degrees sloping chute Ce_{mean} is about 0.43, whereas C_{mean} (X = 1) was 0.34.

The air concentration profiles obtained in the quasi uniform flow region at the UNIHON 30 degrees sloping chute are plotted in Fig. 3 where Chanson's advective diffusion model (ADM) fits fairly well the experimental data (X = 1).

The profiles shown in Figs. 4, 5 and 6 were obtained in stepped chutes of slopes typical of RCC dams. Fig. 4 was obtained at the LNEC chute, both in the upstream and downstream ends of the gradually varied flow. Fig. 5 refers to the data gathered at the UNIHON 55 degrees sloping chute, in the quasi uniform flow region. Both Figures show that the air concentration in between the step edges are much larger than those at the edge of the adjacent steps, as already noted in Fig. 1. Also, Chanson's advective diffusion model (ADM) fits well the experimental data (X = 1). Fig. 6 compares the data obtained in steep chutes. The shape of the air concentration profiles is analogous, even though lower values of the air concentration were obtained for UNIHON chute, namely for $y/Y_{90} < 0.5$. The observed differences in the air concentration profiles may in part be due to scale effects, of which the latter data may not be completely exempted ($Re < 10^5$ and $We < 100$), as suggested by the findings of Boes (2000)

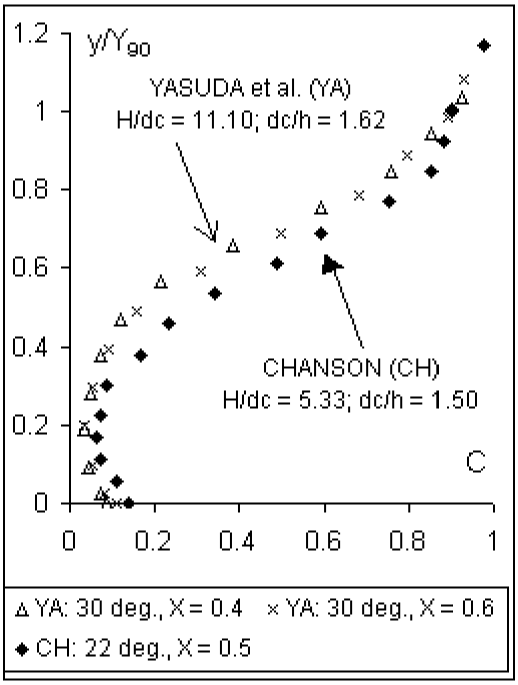


Fig. 2 Air concentration distribution:Comparison of profiles obtainedat the UQLD and the UNIHONchutes

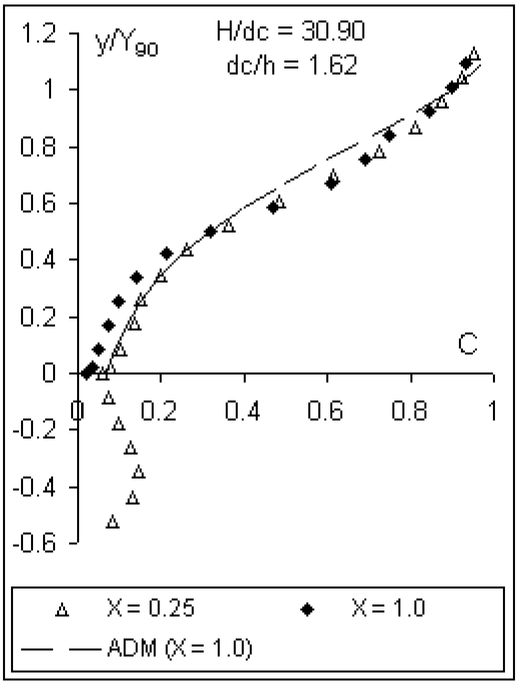
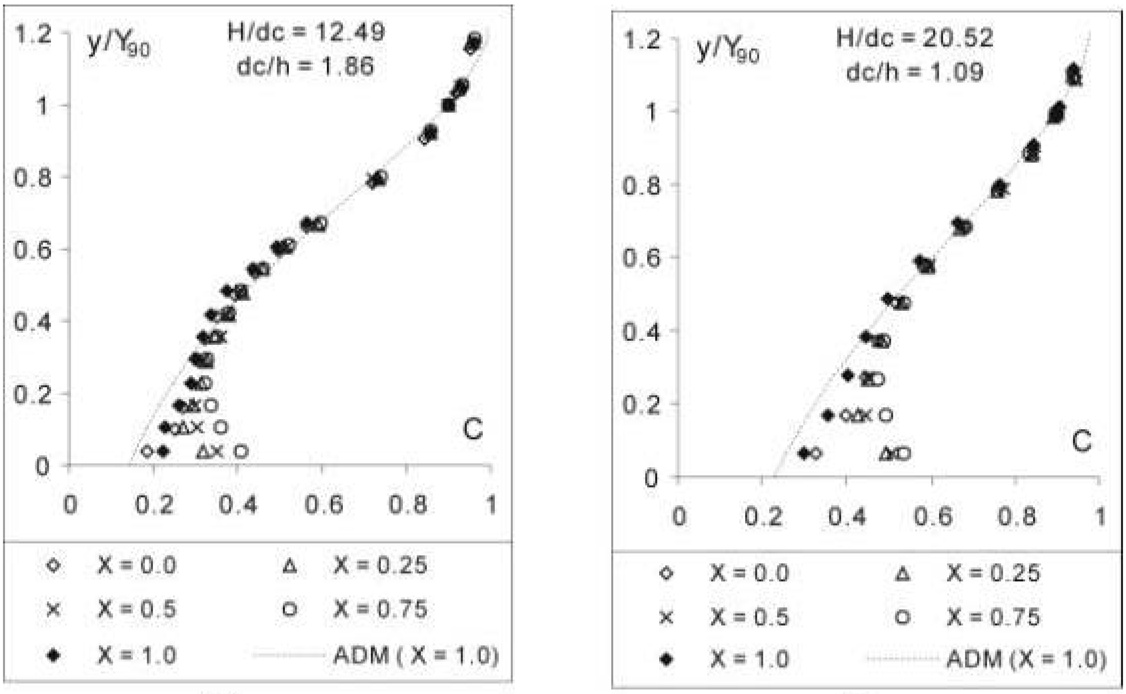
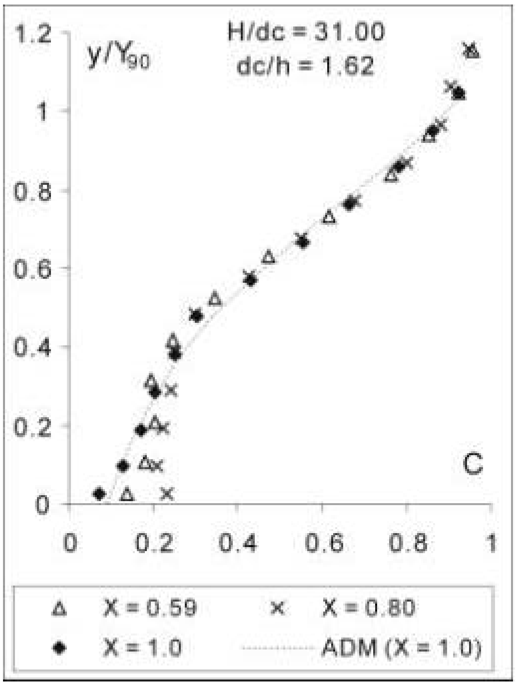


Fig. 3 Air concentration distribution in the quasi uniform flow region at the UNIHON 30 degrees sloping chute



(a) (b)

Fig. 4 Air concentration distribution at the LNEC 53 degrees sloping chute: (a) in the upstream end of the gradually varied flow region; (b) approaching the quasi uniform flow region



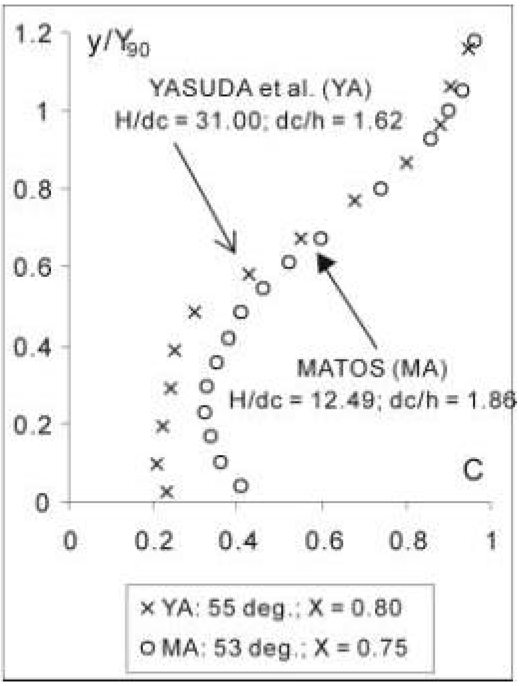


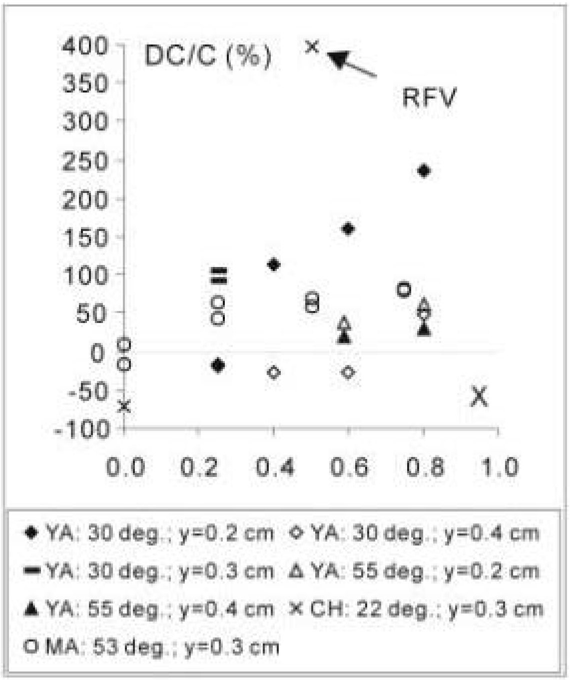
Fig. 5 Air concentration distribution in the quasi uniform flow region at the UNIHON 55 degrees sloping chute

Fig. 6 Air concentration distribution. Comparison of profiles obtained at the UNIHON and the LNEC chutes

4 THE RECIRCULATING FLOW AND AIR entrainment. discussion

To evaluate the influence of the cavity recirculation on the air concentration close to the pseudo-bottom, the relative differences of the air concentration in between adjacent steps ($X < 1$) and at the step edge ($X = 1$), DC/C, were evaluated for given distance from the pseudo-bottom: (a) close to the pseudo-bottom, for varying X (Fig. 7), and (b) at about the mid distance between adjacent step edges ($X \sim 0.5$), along the normal to the flow, i.e., for varying y (Fig. 8). The results presented in Fig. 7 show a relative increase in air concentration close to the pseudo-bottom of up to 400% on the rapidly varied flow region (UQLD), and of up to 50 to 100% in the gradually varied flow regions (LNEC and UNIHON). This is believed to be due to the interaction between the recirculating vortices and the flow direction near the pseudo-bottom, which is curved and highly fluctuating in time. Maximum shear stresses and resulting low air concentration in between step edges do not occur in the line connecting the step edges. It is believed that vortex trapping of air bubbles might be the main mechanism leading to higher air content next to the pseudo-bottom. Air bubbles are trapped in the core of the vortex by inertial force. This is clearly seen in laboratory with high speed video camera showing entrained air bubbles acting as markers of the vortical structures. Fig. 7 suggests the tendency of increase of DC/C with X, the larger values being obtained at $X \sim 0.75$ to 0.8, regardless of the chute slope.

The influence of the recirculating cavity on the air concentration decreases significantly with the increase with the distance normal to the pseudo-bottom, in particular for $y/Y_{90} > 0.2$, in the gradually varied flow region. This value is of the order of magnitude of the width of the air concentration boundary layer in smooth chutes (Chanson 1989, 1997) and also in stepped chutes (Matos et al. 1997, 2000).



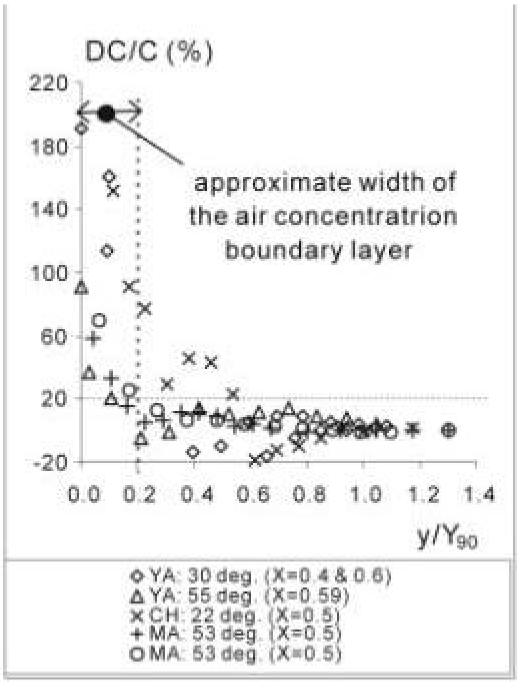


Fig. 7 Relative differences between the air concentration in between the tip of adjacent steps ($X < 1$) and the step edge ($X = 1$), in the vicinity of the pseudo-bottom, for given y

Fig. 8 Relative differences between the air concentration on homologous points in the verticals at mid position of adjacent steps ($X \sim 0.5$) and at the step edge ($X = 1$)

5 CONCLUSION

Experimental investigations were conducted in stepped spillway model chutes assembled at LNEC, UNIHON and UQLD. The results show that the air concentration in between the steps, in the vicinity of the pseudo-bottom formed by their external edges, is markedly different from that observed at the adjacent step edges, due to the interaction of the recirculating cavity with the outer flow.

The research program is continuing and will include detailed velocity, turbulent velocity fluctuation, and bubble size and bubble frequency measurements.

Acknowledgements

The authors wish to thank the personal support of A. Quintela (IST), C. Matias Ramos (LNEC), M. Takahashi and I. Ohtsu (UNIHON), and L. Toombes (UQLD). They would also like to acknowledge the support of the following institutions: INAG and LNEC (Portugal).

References

BOES, R. M. (2000). “Scale Effects in Modelling Two-Phase Stepped Spillway Flow.” Intl. Workshop on Hydraulics of Stepped Spillways, Zürich, Switzerland, H.E. MINOR & W.H. HAGER Editors, Balkema Publ., pp. 53-60.

BOES, R. M. and HAGER, W. H. (1998). “Fiber-optical experimentation in two-phase cascade flow”. Proc. Int. RCC Dams Seminar, K. HANSEN Editor, Denver, USA.

CHAMANI, M. R. and RAJARATNAM, N. (1999). “Characteristics of Skimming Flow over Stepped Spillways”. Jl. of Hyd. Engrg., ASCE, Vol. 120, No.6, pp. 500-510.

CHANSON, H. (1989). “Flow Downstream of an Aerator - Aerator Spacing”. Jl. of Hyd. Research, IAHR, Vol. 27, No. 4, pp. 519-536.

CHANSON, H. (1995). “Air Bubble Entrainment in Free-surface Turbulent Flows. Experimental Investigations.” Report CH46/95, Dept. of Civil Engineering, University of Queensland, Australia, June, 368 pages.

CHANSON, H. (1997). “Air Bubble Entrainment in Free-Surface Turbulent Shear Flows.” Academic Press, London, UK, 401 pages.

CHANSON, H., YASUDA, Y., and OHTSU, I. (2000). “Flow Resistance in Skimming Flow : a Critical Review.” Intl. Workshop on Hydraulics of Stepped Spillways, Zürich, Switzerland, H.E. MINOR & W.H. HAGER Editors, Balkema Publ., pp. 95-102.

MATOS, J. (2000). “Hydraulic Design of Stepped Spillways over RCC Dams”. Intl Workshop on Hydraulics of Stepped Spillways, Zürich, Switzerland, H.E. MINOR & W.H. HAGER Editors, Balkema Publ., pp. 187-194.

MATOS, J., SÁNCHEZ, M., QUINTELA, A. and DOLZ, J. (2000). “Air Entrainment and Safety Against Cavitation Damage in Stepped Spillways over RCC Dams”. Intl Workshop on Hydraulics of Stepped Spillways, Zürich, Switzerland, H.E. MINOR & W.H. HAGER Editors, Balkema Publ., pp. 69-76.

MATOS, J. and FRIZELL, K.H. (1997). “Air Concentration Measurements in Highly Turbulent Aerated Flow”. Proc. 27th IAHR Congress, Theme B, San Francisco, USA, Vol. 1, pp. 149-154.

OHTSU, I. and YASUDA, Y. (1997). “Characteristics of Flow Conditions on Stepped Channels”. Proc. 27th IAHR Congress, Theme D, San Francisco, USA, pp. 583-588.

RUFF, J. F. and FRIZELL, K. H. (1994). Air Concentration Measurement in Highly-Turbulent Flow on a Steeply-Sloping Chute. Proc. Hydraulic Engineering Conference, ASCE, Buffalo, N.Y., 999-1003.

TOZZI, M., TANIGUCHI, E. and OTA, J. (1998). “Air Concentration in Flow Over Stepped Spillways”. Proc. 1998 ASME Fluids Eng. Conf., FEDSM’98, Washington DC, USA, Paper FEDSM98-5053, 7pp. (CD-ROM).

YASUDA, Y. and OHTSU, I. (2000). “Characteristics of plunging flows in stepped channel chutes”. Intl. Workshop on Hydraulics of Stepped Spillways, Zürich, Switzerland, H.E. MINOR & W.H. HAGER Editors, Balkema Publ., pp. 147-152