84th ICOLD ANNUAL MEETING



Proceedings of the

International Symposium on

“Appropriate technology to ensure proper Development, Operation and Maintenance of Dams in Developing Countries”



18 May 2016

Johannesburg, South Africa

Proceedings of the

International Symposium on

"*Appropriate technology to ensure proper Development, Operation and Maintenance of Dams in Developing Countries*"

Johannesburg, South Africa, 18 May 2016

Organised as part of the 84th ICOLD Annual Meeting, Johannesburg, South Africa, 15 to 20 May 2016.

The information contained in this publication regarding commercial projects or firms may not be used for advertising or promotional purposes and may not be construed as an endorsement of any product or firm by the South African National Committee on Large Dams (SANCOLD). SANCOLD accepts no responsibility for the statements made or the opinions expressed in this publication.

Copyright © 2016 South African National Committee on Large Dams (SANCOLD)

ISBN 978-0-620-71042-8

South African National Committee on Large Dams (SANCOLD)
PostNet Suite, #498
Private Bag X025
Lynnwood Ridge
Pretoria, 0040, South Africa
secretary@sancold.org.za
www.sancold.org.za

Symposium organisation

Editor

Louis Hattingh

Secretariat

Louis Hattingh

Paul Roberts

Paul Vinagre

Review panel

Mr Michael Abebe (Ethiopia)
Prof Mark Alexander (South Africa)
Ms Henriette Anderson (South Africa)
Dr George Annandale (USA)
Ms Ilse Aucamp (South Africa)
Mr Christian Auel (Japan)
Dr Markus Aufleger (Germany)
Mr Danie Badenhorst (South Africa)
Dr Gerrit Basson (South Africa)
Mr Andrea Baumer (Switzerland)
Mr Johan Beukes (South Africa)
Ms Michelle Blaeser (South Africa)
Ms Terry Calmeyer (South Africa)
Mr David Cameron-Ellis (South Africa)
Dr Robin Charlwood (USA)
Dr Pierre Choquet (Canada)
Dr Ahmed Chraibi (Morocco)
Mr Bertrand Collet (South Africa)
Mr Ross Cooper (South Africa)
Mr Andrew Copeland (South Africa)
Mr Gerald de Jager (South Africa)
Dr Manuel Gomez de Membrillera Ortuño (Spain)
Dr Michael Detering (Germany)
Prof Ignacio Escuder Bueno (Spain)
Mr Jurgen Fleitz (Spain)
Mr Leon Furstenburg (South Africa)
Prof AndréGorgens (South Africa)
Mr Duncan Grant-Stuart (South Africa)
Mr Thierry Guilloteau (France)
Mr DJ Hagen (South Africa)
Mr Louis Hattingh (South Africa)
Mr Dieter Heinsohn (South Africa)
Dr Andy Hughes (UK)
Dr Sam Johansson (Sweden)
Dr Andrzej Kijko (South Africa)
Mr Helmut Knoblauch (Austria)
Mr Johan Koekemoer (South Africa)
Mr Ian Landon-Jones (Australia)
Dr Aldu le Grange (South Africa)
Mr Stephen Mallory (South Africa)
Dr Peter Mason (UK)
Dr Ronnie McKenzie (South Africa)
Mr Andre Mostert (Namibia)
Mr Dawid Mouton (South Africa)
Dr Laurent Mouvet (Switzerland)
Prof Pilate Moyo (South Africa)
Mr Chris Muir (Namibia)
Ms Kogi Naidoo (South Africa)
Mr Jan Nortje (South Africa)
Dr Chris Oosthuizen (South Africa)
Dr George Papageorgiou (South Africa)
Dr Alan Parrock (South Africa)
Dr Alejandro Pujol (Argentina)
Mr Peter Pyke (South Africa)
Dr Paul Roberts (South Africa)
Dr Tendai Sawunyana (South Africa)
Mr Ivor Segers (South Africa)
Dr Mike Shand (South Africa)
Dr Quentin Shaw (South Africa)
Mr Frezer Shiferaw (Ethiopia)
Mr Jay Stateler (USA)
Mr Gawie Steyn (South Africa)
Mr T Sumi (Japan)
Mr Martin Teal (USA)
Mr Tente Tente (Lesotho)
Dr Michel Tremblay (Canada)
Ms Mari Trumpelmann (South Africa)
Mr Leo van den Berg (South Africa)
Mr Danie van der Spuy (South Africa)
Mr Walther van der Westhuizen (South Africa)
Mr Marco van Dijk (South Africa)
Mr Pieter van Rooyen (South Africa)
Dr Martin van Veelen (South Africa)
Mr Dawid van Wyk (South Africa)
Mr John Wates (South Africa)
Dr Pieter Wessels (South Africa)
Mr Henry-John Wright (South Africa)

Foreword

From the Chairperson of the Local Organising Committee of ICOLD 2016 and Chairperson of the South African National Committee on Large Dams (SANCOLD)

We are extremely happy that this ICOLD Symposium was staged in South Africa as part of the 84th ICOLD Annual Meeting held in Johannesburg in May 2016.

Sunny South Africa is known:

- for its friendly "rainbow" nation as demonstrated during the highly successful 2010 Soccer World Cup event;
- for its beautiful scenery with the Big Five animals in our National and Private Game Parks, the Drakensberg Mountains with its Lesotho Highlands dams and Cape Town with its world heritage site Table Mountain;
- to have 5 030 registered dams of which more than 1 114 are large dams;
- for contributing significantly since 1965 to ICOLD and Africa regarding development of the art and science of dam engineering.

Our SANCOLD Local Organising Committee worked very hard to ensure that this event was well organised, had a high technical content and could provide a forum to experience Africa.

This Symposium reflects much of local, regional and international experience with dams with an emphasis on the developing Africa. The keen interest we received from authors reflects that the subject matter is apt and we hope that these Proceedings together with the delivered Symposium Presentations will form a valuable resource for the future of dams throughout the world.

Danie Badenhorst
Chairperson of the Local Organising Committee of ICOLD 2016
Chairperson of SANCOLD

Preface

Not only do many countries in Africa and other developing countries still require major water resources and dam engineering development for both water and energy supply but these countries also experience problems with proper long term operation and maintenance of their existing infrastructure. These problems in many cases lead to unsafe and unsustainable conditions that negatively impacts on the surrounding communities as well as the environment.

To try and mitigate this and share the some of the collective wisdom and knowledge available in the larger ICOLD family it was decided have organise an International Symposium titled "Appropriate technology to ensure proper Development, Operation and Maintenance of Dams in Developing Countries" to address some of these issues, in conjunction with the 84st Annual Meeting of the International Commission on Large Dams (ICOLD). The ICOLD Meeting host, the South African National Committee on Large Dams (SANCOLD), organized the Symposium.

These Proceedings contain papers on 9 different themes. Before the Symposium call for papers, 8 different themes were identified as appropriate. A number of relevant abstracts that satisfied the main theme but that did not necessarily satisfied any of the 8 chosen themes were received and subsequently categorised under a theme called "Other". The 9 themes for the Symposium therefore are:

1) Social and environmental impacts and mitigation measures;
2) Advances in the rehabilitation of dams and appurtenant works to extend their service life including the following:
   a) Improving spillway capacity and flood hydrology determination;
   b) Structural improvements to mitigate the effects of Alkali aggregate reaction, internal erosion potential, foundation failure;
3) Innovative river basin management including the optimisation of the operation of dams;
4) Reservoir sedimentation and management;
5) The state of the art of the tailings dams for their complete lifespan;
6) Strategies for proper surveillance of dams;
7) Sustainable hydropower development in developing countries; and
8) Other

We have received a total number of 333 papers for the Symposium. After the review process 245 papers from 42 different countries were chosen for publication in the proceedings. Of these 245 papers, 96 papers from 34 different countries were chosen for oral presentation in 4 parallel sessions and another 68 papers from 26 different countries were chosen for poster presentation.

All papers submitted for the Symposium were subjected to a full process of peer review and the proceedings contain only those papers that were accepted following this process. The review of the papers was undertaken by the members of the review panel acting independently on one or more assigned papers. This invaluable assistance, which has greatly enhanced the quality of the Proceedings, is gratefully acknowledged.

Finally, the editor wishes to thank the authors for their efforts at producing and delivering quality papers of appropriate quality and relevance. We trust that the Proceedings will be a valued reference for those working in the various fields covered and that it will form a suitable basis for discussion and future development and research.

Louis C. Hattingh
Editor

Table of contents

Theme 2a. Advances in the rehabilitation of dams and appurtenant works to extend their service life including improving spillway capacity and flood hydrology determination

Theme 2b. Advances in the rehabilitation of dams and appurtenant works to extend their service life including structural improvements to mitigate the effects of alkali aggregate reaction, internal erosion potential, foundation failure

Theme 3. Innovative river basin management including the optimisation of the operation of dams

Theme 4. Reservoir sedimentation and management

Theme 5. The state of the art of the tailings dams for their complete lifespan

Theme 6. Strategies for proper surveillance of dams

Theme 7. Sustainable hydropower development in developing countries

Theme 8. Other

Theme 2a. Advances in the rehabilitation of dams and appurtenant works to extend their service life including improving spillway capacity and flood hydrology determination

THE DEVELOPMENT OF THE VC-OGEE RELATIONSHIP WHICH INCORPORATES UPSTREAM 3-DIMENSIONAL FLOW CONDITIONS

SJ van Vuuren[1], GL Coetzee[1 & 2]

1. Department of Civil Engineering, University of Pretoria, Pretoria, South Africa
2. Knight Piésold (Pty) Ltd., Rivonia, Johannesburg, South Africa

PRESENTER: LOUIS COETZEE

ABSTRACT

The widely used Ogee relationship is one of the most studied hydraulic relationships in the world (Savage & Johnson, 2001). Various attempts were made to accurately describe the shape of the lower nappe of water flowing over a sharp-crested weir, known as the Ogee profile. The current Ogee profile relationship was formulated from 2-dimensional hydraulic assessments. Recent studies, which included varying upstream geometry layouts, have indicated that the 2-dimensional approach flow conditions may be insufficient and, that 3-dimensional flow should be considered (van Vuuren, et al., 2011). An accurate Ogee flow profile is hydraulically efficiency and minimizes the possible occurrence of sub-atmospheric pressures on the surface of the spillway. An asymmetrical and/or skew approach channel causes 3-dimensional flow over the Ogee spillway that may contribute to the separation of the lower nappe from the surface that was designed with a 2-dimensional flow relationship.

Based on the results obtained from physical model studies and numerical analyses the VC-Ogee relationship was developed to incorporate the upstream 3-dimensional flow conditions. The VC-Ogee relationship utilizes the Hager formula (1987) for the upstream quadrant and the power function of the WES profile for the downstream quadrant. These relationships were extended to include the upstream topography, asymmetricity of the approach channel, orientation of flow relative to the spillway as well as the curvature of the spillway. The VC-Ogee relationship, which incorporates the influence of 3-dimensional flow conditions, reduces the potential of sub-atmospheric pressures and provides a more realistic discharge relationship.

LIST OF SYMBOLS

A	-	cross sectional flow area in the approach channel, (m²)
e	-	Euler's mathematical constant (approx. = 2.71828)
CFD	-	Computation Fluid Dynamics
H_a	-	velocity head, (mm)
H_{sd}	-	measured water depth upstream relative to the crest, (mm)
H_e	-	total head (sum of H_d and H_a), (mm)
H_d	-	design head of the Ogee spillway, (mm)
H_o	-	actual head measured at the Ogee spillway (mm)
n	-	number of observations
SPVD	-	Sum of the Positive Vertical Differences (mm)
P	-	upstream depth of the weir, (m)
Q	-	flow rate, (l/s)
T_p	-	turning point (apex position) on the lower nappe of the Ogee profile
SCW	-	sharp-crested weir
v_o	-	mean velocity in the approach channel, (m/s)
z	-	actual elevation of the observed/modelled Ogee profile, (mm)
$\hat{z}$	-	numerical estimated elevation of the Ogee profile, (mm)
R	-	radius of the curvature of the crest, (m)
s	-	curvilinear co-ordinate along the crest shape

1. INTRODUCTION

The Ogee profile is one of the most studied hydraulic relationships used for the design of spillways (Savage & Johnson, 2001) and due to its high discharge efficiency, the nappe-shaped profile is used for most spillway control crests (Khatsuria, 2005). The Ogee spillway can be divided into three regions: the upstream quadrant, the downstream quadrant, and the rear slope.

Improvements of the Ogee relationship continued throughout the 20th century using physical modelling and applying empirical and mathematical curves. The increased computational resources available in the 21st century introduced detailed numerical assessments by means of Computational Fluid Dynamics (CFD) modelling. Data obtained from a detailed physical model study and extensive CFD modelling (Van Vuuren & Coetzee (2015a)) provided a qualitative and quantitative comparison of the fluid flow over a sharp-crested weir (SCW). CFD models were extended to incorporate different upstream approach channel layout configurations for straight and curved spillways. The algorithms used to solve the 3-dimensional flow regime in the CFD model included turbulent flow -, aeration - and cavitation modules.

2. THEORETICAL CONSIDERATION

The Ogee spillway relationship (USBR, 1987; Hager, 1987) describes the bottom nappe associated with the flow over a sharp-crested weir. The historical development of the Ogee profile relationship based on a singular mathematical function is summarized in Table 1.

Table 1. Historical development of the Ogee profile relationship (Chanson, 2004)

Relationship	Equation	Comment
Creager (1917)	$x=(z-0.063)^2\cdot\frac{g}{2v_h^2}-0.261$	For $x \geq 0$; derived from Bazin's (1888-1898) experiment
Scimemi (1930)	$z=0.50\frac{x^{1.85}}{{H_e}^{0.85}}$	For $x \geq 0$; also called WES profile (as given by Chanson, 2004)
Knapp (1960)	$z=\left(\frac{x}{H_e}-\ln\left(1+\frac{x}{0.689\cdot H_e}\right)\right)\cdot H_e$	Continuous spillway profile for crest region only (as given by Chanson, 2004)
Hager (1987)	$\frac{z}{H_e}=0.1360+0.482625\left(\frac{x}{H_e}+0.2818\right)\cdot\ln\left(1.3055\left(\frac{x}{H_e}+0.2818\right)\right)$	Continuous spillway profile with continuous curvature radius: $-0.498 < \frac{x}{H_e} < 0.484$
Montes (1992)	$\frac{R_l}{H_e}=0.05+1.47\frac{s}{H_e}$ $\frac{R}{H_e}=R_l\left(1+\left(\frac{R_u}{R_l}\right)^{2.625}\right)^{1/2.625}$ $\frac{R_u}{H_e}=1.68\left(\frac{s}{H_e}\right)^{1.625}$	Continuous spillway profile with continuous curvature radius R R_l = Lower asymptote: i.e. for small values of s/H_e Smooth variation between the asymptotes R_u = Upper asymptote: i.e. for large values of s/H_e

Note: x, z - horizontal and vertical co-ordinates with the dam crest as origin
z - measured positive downwards

If the nappe detaches from the surface of the spillway due to 3-dimensional flow, it may lead to cavitation. This emphasizes the need to incorporate the influence of 3-dimensional flow, and mitigate the formation of sub-atmospheric pressure (U.S. Army Corps of Engineers, 2009).

The existing Ogee relationship only accommodates 2-dimensional flow parameters and fails to accommodate the 3-dimensional flow in the upstream approaching channel (van Vuuren, et al., 2011).

In this paper, the VC-Ogee relationship, which was developed by including the upstream 3-dimensional flow conditions, is discussed. The VC-Ogee relationship applies a uniform smooth sloped numerical function for determining the Ogee profile of the spillway.

3. CFD MODELLING - THE NUMERICAL MODEL

The results obtained from the physical model described in van Vuuren, *et al.* (2015) was used to calibrate the numerical model, which was setup in the computational fluid dynamics (CFD) software package STAR-CCM+ V. 9.06. The baseline scenario consisted of a symmetrical approach channel with the flow being directed perpendicular onto the weir and included symmetrical contraction from both sides (**Layout A**). A curved spillway and a spillway with an oblique approach channel, both with symmetrical side contractions, (**Layout B** and **Layout C**, respectively) were also investigated.

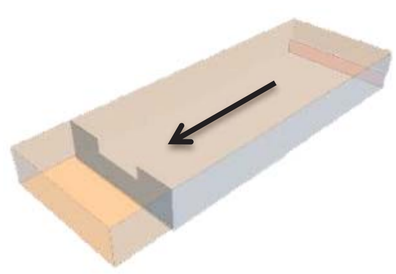
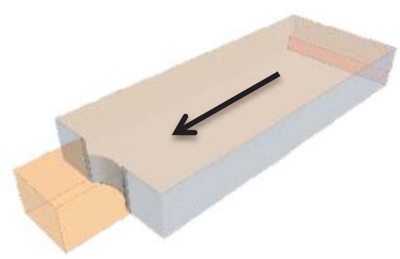
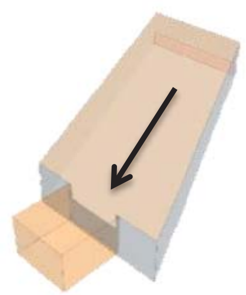
The workflow, adapted for STAR-CCM+ from Ho, *et al.* (2003), for setting up a CFD model was summarized as follows:

- Create the 3-dimensional flow domain and geometry that represent flow and no flow regions;
- Select the governing physics equations, fluid properties and method for calculating the Reynolds stresses i.e. the turbulence model to be solved (k-ε turbulence model) (turbulent kinetic energy dissipation equations);
- Create a mesh continuum to generate an appropriate solving grid that can be refined where high resolution detailed results were required;
- Define the boundary and initial conditions for the model i.e. mass flow rate through the model, upstream head and surface boundary conditions;
- Initiate the solver to compute the velocities in each cell by using the initial conditions as specified or the previous time-step values for all advectives, pressures, and other accelerations based on the explicit approximations of the Navier-Stokes equations;
- Post-process the results to extract the desired information for the design – in this case the lower nappe (Ogee profile).

The software solves the Navier-Stokes equation by the finite difference method. The volume of fluid (VOF) multiphase model is applied to capture the sharp interface of the free surface motion (Hirt & Nichols, 1981). A transient flow analysis was carried out for a period of time until pseudo- steady state condition was attained. This was achieved by inspecting the net mass transfer rate and the residuals calculated for the system.

The 3-dimensional flow domain and geometry of the different layouts are shown in Table 2.

Table 2. 3-dimensional flow domain and geometry of the Layouts A-C

Layout A	Layout B	Layout C
		

A constant weir length of 1 201 mm was used for all the layouts. The width of the approach channel was 3 125 mm and had a total length, measured perpendicular form the inlet of the approach channel to the weir, equal to 7 660 mm. The extended approach channel allowed the formation of a realistic upstream approach velocity distribution at the weir.

Table 3 indicates the principal hydraulic parameters recorded for the different layouts.

Table 3. Principal hydraulic parameters recorded for the different layouts

Parameter	Layout A	Layout B	Layout C	Units
H_{sd} (Upstream head at SCW)	152.12	148.98	152.32	mm
Q (Flow rate)	122.20	122.25	121.62	l/s
A (Cross sectional area of approach channel)	2.56	2.55	2.56	m²
v_o (Mean flow velocity in approach channel)	0.05	0.05	0.05	m/s
H_a (Upstream energy head)	0.12	0.12	0.12	mm
$H_{e\ back\ calc}$ (Total head back calculated)	129.16	129.19	128.75	mm
$H_{d\ back\ calc}$ (Design head back calculated)	129.04	129.07	128.63	mm
H_e (Actual total head)	134.39	131.70	132.68	mm
H_d (Actual design head)	134.28	131.58	132.56	mm
ΔH_e (Change in total head)	+4.052%	+1.940%	+3.053%	-
ΔC_d (Change in discharge coefficient)	-5.784%	-2.841%	-4.411%	-
C' (Elevation of inflection point)	17.84	17.40	19.76	mm
P/H_d (Ratio of upstream wall height to the design head)	5.161	5.160	5.178	-

For each of the layouts, a 2-dimensional Ogee profile was back calculated based on the unit discharge over the weir. The discharge can be estimated by applying Equation 1 to Equation 5 (USBR, 1987; Vischer & Hager, 1999):

$$Q_{ogee}=C_d\sqrt{2g}LH_e^{\frac{3}{2}}$$ **Equation 1**

With:

$$C_d=\frac{2}{3\sqrt{3}}\left[1+\frac{4\chi}{9+5\chi}\right]$$ **Equation 2**

And

$$H_e=H_d+H_a$$ **Equation 3**

Where:

$$H_a=\frac{v_0^2}{2g}$$ **Equation 4**

And

$$\chi=\frac{H_0}{H_d}$$ **Equation 5**

The calculated Ogee profile represents the profile for the design head (discharge) and therefore the ratio of $\frac{H_0}{H_d}=1$. This indicates that the coefficient of discharge (C_d) for the equivalent Ogee spillway will be 0.49487 provided that $\frac{P}{H_d}$ exceeds 3. By ensuring that the ratio of $\frac{P}{H_d}$ exceeds 3 the velocity component in the approach channel will be marginal and $H_d \cong H_e$. The head during flow for this condition was referred to as the design head (H_d) for which the pressures over the Ogee crest profile were expected to be atmospheric for the discharge of a 2-dimensional flow layout.

Previous research by van Vuuren, et al. (2015) has indicated that the existing Ogee relationships, based on 2-dimensional flow, were insufficient to accommodate upstream 3-dimensional flow. Hager (1987) has derived a relationship for a continuous Ogee profile based on the compound curve formulation by the USBR (1987). The relationship by Hager shown in Equation 6 was used for a transformed coordinate system where $X=\frac{x}{H_e}$ and $Z=\frac{z}{H_e}$.

$$Z^*=-X^*\ln X^* \text{ valid for } X^*>0.2818$$ **Equation 6**

With

$$X^*=1.3055\cdot(X+0.2818)$$ **Equation 7**

and

$$Z^*=2.7050\cdot(Z+0.1360)$$ **Equation 8**

By re-arranging and applying numerically manipulation of the Hager (1987) relationship, it can be represented as:

$$z=-H_e\cdot B\left(\left(\frac{x}{H_e\cdot A}+\frac{1}{e}\right)\cdot\ln\left(\frac{x}{H_e\cdot A}+\frac{1}{e}\right)+\frac{1}{e}\right)$$ **Equation 9**

The coefficients A and B can be used to manipulate the horizontal and vertical geometry of the Ogee profile respectively. The default values of these coefficients were A = 0.766 and B = 0.3697. By reviewing Equation 9 it is clear that the lognormal-term (ln-term) $\left(\frac{x}{H_e\cdot A}+\frac{1}{e}\right)$ > 0 defines the vertical asymptote. Depending on the slope of the upstream wall, this term can be used to determine a tangent point on the upstream side of the Ogee profile. This will ensure a smoother transfer of the curvature from the upstream wall to the Ogee profile.

The downstream quadrant of the Ogee profile was defined by using a modified version of the WES power function (Equation 10). This corresponds to the approach followed by the USBR (1987) and USACE (1970). The upstream and downstream quadrants intercepts at $\frac{dz}{dx}$ = 0. This ensures a smooth uniform transfer of the curvature without any discontinuities.

$$z=\frac{x^C}{D\cdot H_e^{(C-1)}}$$ **Equation 10**

The default values for a vertical dam wall for parameters C (used to adjust the curvature of the downstream quadrant) and D (magnitude of the profile) were 1.85 and 2 respectively (USBR, 1987).

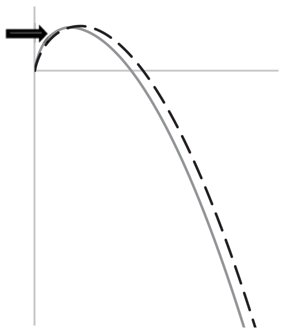
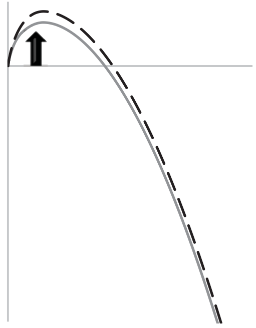
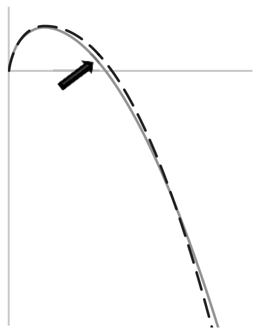
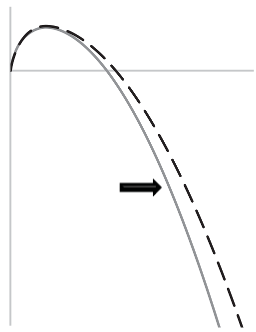
The proposed VC-Ogee relationship in the Macaulay notation is reflected in Equation 11:

$$\text{VC-Ogee}=\begin{cases} z=-H_e\cdot B\left(\left(\frac{x}{H_e\cdot A}+\frac{1}{e}\right)\cdot\ln\left(\frac{x}{H_e\cdot A}+\frac{1}{e}\right)+\frac{1}{e}\right) & \text{for the upstream quadrant} \\ z=\frac{x^C}{D\cdot H_e^{(C-1)}} & \text{for the downstream quadrant} \end{cases}$$

Equation 11

The four parameters A, B, C & D that denotes the horizontal spread (A), vertical elongation (B), curvature (bulging effect) (C) and magnitude (D) of the Ogee profile were altered (increased and/or decreased) to provide a profile (VC-Ogee profile) which incorporate the 3-dimensional flow conditions and hence will alleviate sub-atmospheric pressures (Table 4). The values of the parameters to be used in the VC-Ogee relationship for future design of these types of spillways are given in Table 5. Interpolation between the default parameter set and the different calculated layout parameters are recommended for layouts that differ from the layouts that were assessed.

Table 4. Exaggerated illustration of the influence of the different parameters

Parameter A: Horizontal displacement of an upstream quadrant	Parameter B: Vertical displacement of upstream quadrant	Parameter C: Budging of a downstream quadrant	Parameter D: Increase the extent of the downstream quadrant
			

——— Existing Ogee profile considering 2-dimensional flow
- - - - - Influence of VC-Ogee parameter to incorporate the effect of 3-dimensional flow

Table 5. VC-Ogee parameter set for the different layouts

Layout	Parameter A: Horizontal	Parameter B: Vertical	Parameter C: Curvature	Parameter D: Magnitude
Default 2-D flow	0.7660	0.3697	1.850	2.000
A	0.7725	0.3820	1.825	1.975
B	0.6000	0.3725	1.850	1.825
C	0.7800	0.4150	1.850	2.050

This profile, (as determined by the VC-Ogee relationship) would differ in dimension to that of the theoretical Ogee profile that was derived for 2-dimensional flow. The vertical difference between the profiles as determined by the different relationships (USACE and VC-Ogee) was compared with the results obtained by the CFD modelling. To determine the extent of optimally increasing the 2-dimensional Ogee profile required for accommodating the 3-dimensional flow, a specific parameter which can be used to assess the extent of the positive vertical differences between the observed (3-dimensional CFD modelled) profile and 2-dimensional profile was used. This parameter is referenced to as the SPVD: **sum of the positive vertical differences**. In the case where the calculated CFD profile was higher than the profile determined by applying the different 2-dimensional ogee relationships, this parameter is positive. All the negative outcomes were discarded because it implied that the 2-dimensional relationships provided a conservative (over-designed) profile. Over-designing of the Ogee profile were mitigated by adjusting the VC-Ogee parameters (A, B, C & D) in such a manner that the threshold of the SPVD/He ≈< 1% was met. Equation 12 determined the SPVD between the CFD profile and the VC-Ogee profile.

$$\text{SPVD}=\sum +(\hat{z}\text{-z})$$ **Equation 12**

4. RESULTS AND DISCUSSION

The profile of the lower nappe, perpendicular to the plane of the sharp crested weir, was extracted at seven locations along the crest of the SCW. The SPVD was calculated along the Ogee profile where separation from the theoretically approximated profile was the greatest. The profiles with the greatest SPVD were selected to determine the VC-Ogee relationship. The calculated SPVD for the different layouts are given in Table 6 and are graphically presented in Table 7. The SPVD of the proposed VC-Ogee profile was significantly lower for all the layouts compared to that determined by the relationship based on 2-dimensional flow. The threshold of ≈1% for the proposed VC-Ogee profile was also met.

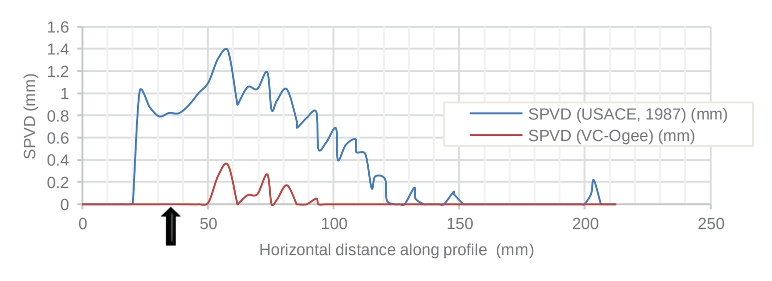
Table 6. Calculated SPVD and threshold for Layouts A to C

		Layout			
Relationship	**Parameter**	**A**	**B**	**C**	**Units**
USACE (1987)	SPVD	26.54	13.29	186.94	mm
VC-Ogee		1.34	1.36	1.19	mm
USACE (1987)	Threshold	20.55%	10.29%	145.20%	
VC-Ogee		1.03%	1.05%	0.92%	

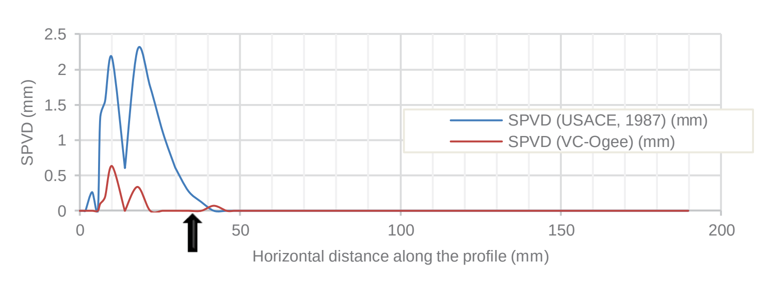
The graphs in Table 7 indicated that breakaway would most likely occur on the downstream quadrant of the spillway for Layouts A and C. Likewise, it would be more likely to occur on the upstream side of the crest for the curved spillway of Layout B. All the profiles were under-estimated by the 2-dimensional Ogee relationships. The crest of the spillway is located at approximately 35 mm measured horizontally along the profile. The black vertical arrow in each graph in Table 7 reflects this position. By applying the VC-Ogee relationship (Equation 11), which accounts for the effect of 3-dimensional flow, an improved spillway profile was determined.

Table 7. Graphical view of SPVD for Layouts A to C

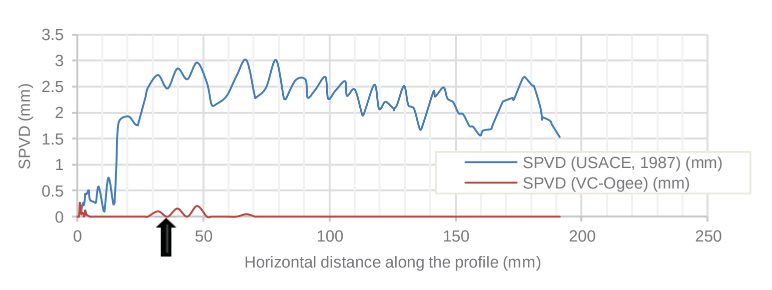
Layout A



Layout B



Layout C



The section plots of the profiles for the different layouts are given in Table 8. From these plots, a similar trend can be observed as noted in the plots of the SPVD (Table 7).

The VC-Ogee relationship has a smooth slope similar to that of the relationships developed by the USACE and USBR, but with the added advantage of no discontinuities. The VC-Ogee relationship was also an improvement on the profile of the downstream quadrant suggested by Hager (1987).

Breakaway from the theoretically estimated profiles are apparent where the observed lower nappe extended above the numerically approximated Ogee relationship's surface. Breakaway tends to be most severe in the centre of the spillway for Layout A. The curved weir of Layout B increased the occurrence of breakaway at the upstream quadrant of the spillway. While the oblique approach channel of Layout C resulted in the most severe divergence of the lower nappe, which occurred off-centre to the spillway. The VC-Ogee relationship, was setup to accommodate a downstream slope of the dam wall up to 1:0.8 (V:H) and showed a significant improvement compared to the 2-dimensional relationships. All the discontinuities of compound arcs that were present in the 2-dimensional relationships are also eliminated.

The 3-dimensional flow in the upstream approach channel contributed to a reduction of the discharge coefficient. The recorded head upstream of the spillway was in all cases higher than the theoretically estimated head (using Equation 1). It was also noted that the Tp was under-estimated compared to the position for an uncontacted weir approximated by Rajaratnam et al. (1968). Since the observed upstream heads were larger than the theoretical head, an adjustment to the discharge coefficients needed to be made. The adjustment of the discharge coefficients are shown in Table 9.

Table 8. XZ-plot of the Ogee profiles for the different layouts

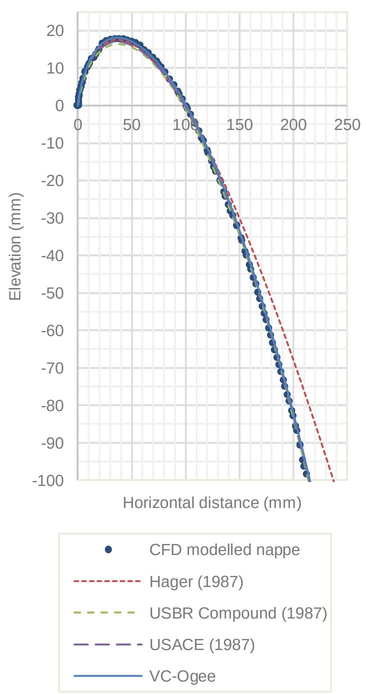
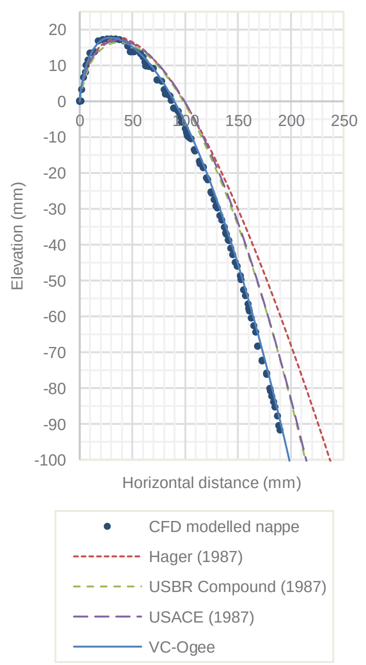
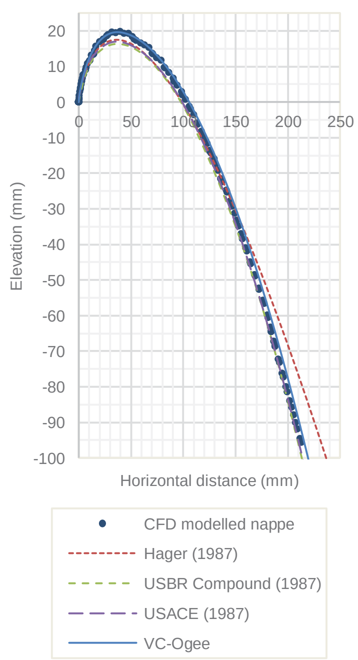
<table>
<tr><th>Layout A</th><th>Layout B</th><th>Layout C</th></tr>
<tr>
<td>
</td>
<td>
</td>
<td>
</td>
</tr>
</table>

Table 9. Observed head upstream of the weir and adjusted discharge coefficients

	Scenario			
Parameter	**A**	**B**	**C**	**Units**
H_e	134.39	131.70	132.68	mm
H_d	134.28	131.58	132.56	mm
$C_{d\ USBR}$	0.49487			
$C_{d\ ADJUSTED}$	0.46625	0.48081	0.47304	
ΔH_e	4.052%	1.940%	3.053%	-
ΔC_d	-5.784%	-2.841%	-4.411%	-

5. CONCLUSION AND RECOMMENDATIONS

The VC-Ogee relationship accommodates upstream 3-dimensional flow regimes. By using the VC-Ogee relationship, a safer design was achieved that would reduce the occurrence of sub-atmospheric pressures that may contribute to the formation of cavitation damage on the spillway. The VC-Ogee relationship has the added benefit of a smooth curvature with no discontinuities.

The current formulation of the VC-Ogee relationship (Equation 11) is valid for:

1. $\frac{P}{H_d}$ exceeding 3;
2. Oblique approach channels of up to 25°;
3. Curved dam walls with $\frac{R}{H_d} < 5$.

6. REFERENCES

Chanson, H (2004). *The Hydraulics of Open Channel Flow: an Introduction*. 2nd ed. Oxford: Butterworth-Heinemann.

Creager, WP (1917). *Chapter VII: The design of solid spillway gravity dams*. In: Engineering for Masonry Dams. London: John Wiley & Sons, Inc., pp. 105 - 110.

Hager, WH (1987). *Continuous crest profile for standard spillway*. Journal of Hydraulic Engineering, 113(11), pp. 1453-1457.

Hirt CW & Nichols BD (1981). *Volume of Fluid (VOF) method for the dynamics of free boundaries*. Journal of Computational Physics, 39(1), pp. 201-225.

Ho D, Boyes K, Donohoo S & Cooper B (2003). *Numerical flow analysis for spillways*. Hobart, ANCOLD.

Khatsuria, RM (2005). Chapter 4: *Ogee or Overflow Spillways*. In: M. D. Meyer, ed. Hydraulics of Spillways and Energy Dissipetors. New York: Marcel Dekker, pp. 41 - 62.

Montes, JS (1992). *Curvature analysis of spillway profiles*. In: M. R. Davis & G. J. Walker, eds. 11th Australasian Fluid Mechanics Conference: Papers. s.l.:University of Tasmania, pp. 941 - 944.

Rajaratnam N, Subramanya K & Muralidhar D (1968). *Flow profiles over sharp-crested weirs*. Journal Hydraulics Division ASCE, 94(HY3), pp. 843-847.

Savage B & Johnson M (2001). *Flow over Ogee Spillway: Physical and Numerical Model Case Study*. Journal of Hydraulic Engineering, 127(8), pp. 640-649.

U.S. Army Corps of Engineers (2009). *Dam Safety Risk Analysis Best Practices Training Manual*. Version 2.2 - April 2011 ed. Denver, Colorado: U.S. Department of Interior Bereau of Reclamation.

USACE (1970). *Hydraulic Design Criteria*, Vicksburg, MI: Army Waterways Experiment Station.

USBR (1987). *Chapter 9: Spillways. In: Design of Small Dams*. 3rd ed. Washington: U.S. Government Printing Office, pp. 339-434.

van Vuuren SJ & Coetzee GL (2015a). *Comparison between CFD analyses and physical modelling of an Ogee profile*. Cape Town, South Africa, SANCOLD, pp. 195-208.

van Vuuren SJ, Coetzee GL & Roberts, CPR (2015). *Investigating the bottom free surface nappe (ogee profile) across a sharp crested weir caused by the flow in an asymmetrical approach channel*. Journal of the South African Institution of Civil Engineers, 57(3), pp. 57-63.

van Vuuren S, Steyn G, Pilz N & Koch H, (2011). *Influence of 3D approaching flow on a curved ogee spillway section - Neckartal Dam Namibia*. Stellenbosch, UP Printers.

Vischer D & Hager W (1999). *In: Dam Hydraulics*. s.l.:John Wiley and Sons, pp. 40-44. 0000

0000