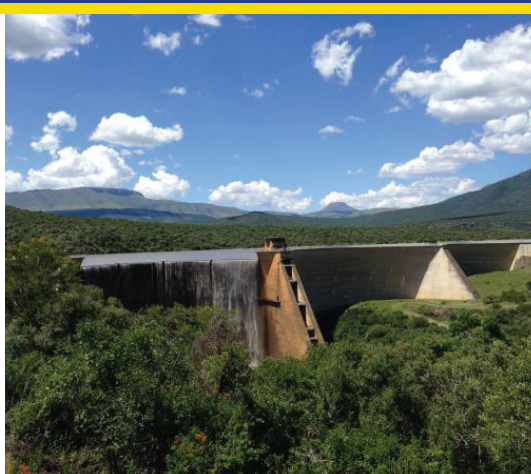
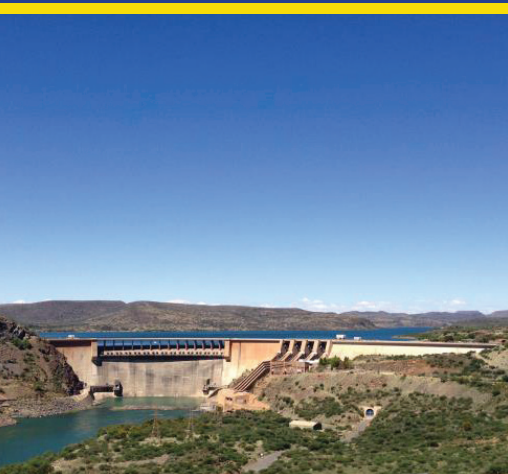




# 84<sup>th</sup> ICOLD ANNUAL MEETING



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



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# 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 84<sup>th</sup> 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.

*D.B. Badenhorst*

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 84<sup>st</sup> 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. Hartingh  
Editor

# Table of contents

<i>Symposium organisation</i>	<i>ii</i>
<i>Foreword</i>	<i>iii</i>
<i>Preface</i>	<i>iv</i>
 <i>Theme 1. Social and environmental impacts and mitigation measures</i>	
Public Safety and Security of Dams are not Mutually Exclusive <i>WF Foos, F Calcagno, &amp; PG Schweiger (USA)</i> .....	1-1
Health and Development in Large Projects <i>SA Kaul, M Kumalo &amp; E Barendse (Lesotho)</i> .....	1-9
Assessment of the Relationship between Dams Owners and the Host Territory: The Italian Experience <i>G Mazzà, &amp; A Frigerio (Italy)</i> .....	1-17
Conflict Management for Existing Water Resource Projects and Dams <i>P Mulvihill (New Zealand)</i> .....	1-27
Improvement of the Procedure for Conflict Resolution of Dam Projects in Korea <i>Hye Jin Kim, Seong Won Jin &amp; Bong Soo Kim (South Korea)</i> .....	1-33
Veľká Domaša Dam – Current State in Water Management as a Result of Socio-Economic Changes in the Catchment Area <i>D Mydla &amp; R Ivančo (Slovakia)</i> .....	1-39
Social Issues and Land Acquisition Mitigation in Construction of Nipah Dam and Gongseng Dam – East Java Indonesia <i>NA Fady, A Rahmat &amp; S Inasih (Indonesia)</i> .....	1-45
Resettlement and Livelihood Restoration in the Context of Large Dams: Phase II of the Lesotho Highlands Water Project <i>TA Sekhesa &amp; EG Barendse (Lesotho)</i> .....	1-55
Implementation of the LHWP Phase II - Approach towards Social Matters <i>T Tente, M Thokoa, G Mokone &amp; M Phakoe (Lesotho)</i> .....	1-65
Effectiveness and the Role of Social Studies in the Localization and Selectivity Normal Level of Dams (Case Study: Layleh Dam and Hydro Power Plant) <i>A Nourisani, RG Rad (Iran)</i> .....	1-75
Rehabilitation of Bell Springs as a Symbol of Corporate Social Responsibility- A Case Study of Daryan Dam and Power Plant <i>A Nourisani (Iran)</i> .....	1-83
Construction of Chitgar Dam's Artificial Lake - Social and Environmental Impact Assessment <i>A Emam, M Zolfagharian, Kh Binazadeh, H Alavi Deilami, A Eslaminia &amp; J Bayat (Iran)</i> .....	1-91
Environmental and Social Aspects of the Lom Pangar Reservoir Filling Program <i>JP Grandjean, G Gwét &amp; M Lino (France)</i> .....	1-101
Environment Management of Jinping-I Hydropower Project during Construction <i>W Shiyong, C Wei, W Hongmei (China)</i> .....	1-109
The Challenges of Implementing Mega Projects in Urban Areas – A Case Study of BWP And MMTS-2 <i>K Naidoo, J Nyakale &amp; T Tente (South Africa/Lesotho)</i> .....	1-119
Hydropower Reservoirs as Ramsar Sites: Dams to Support the Protection of Wetland Conservation Areas <i>E Branche (France)</i> .....	1-127
Practical Solutions for Accommodating Ecological Water Requirements in the Design and Operation of Dams in South Africa <i>H Pieterse, P Scherman, M Shand, G de Jager &amp; J Lombaard (South Africa)</i> .....	1-137
Managing Ecological Flow Releases from the Berg River Dam in South Africa <i>M Shand, B Abban, D Van Wyk &amp; N Rossouw (South Africa)</i> .....	1-147

Adapting to Environmental Demands: High Capacity Coanda Intake <i>S Løvfall, HT Ose &amp; T Bakken (Norway)</i> .....	1-157
Promoting Eco-Friendly River Basin Development Solutions <i>A Abdulmit &amp; S Ionescu (Romania)</i> .....	1-165
De-Commissioning of Hammarsdale Dam by Transforming it from a Contaminated Problem Child into a Sustainable Wetland <i>S Reynolds &amp; W van der Westhuizen (South Africa)</i> .....	1-175
Environmental Vulnerability Assessment of Basin Climate Change and its Effects on Adaptive Conservation Countermeasures for Key Fishes involved with Huge Hydropower Station Operation in Yangtze River <i>G Yong, Z Xu , C Yongbo &amp; S Zhiyu (China)</i> .....	1-185
Change of Redoks Potential in Aquatic Ecosystem at Djuanda Dam <i>M Amron, H Idrus, R Mayasari &amp; E Dwi P (Indonesia)</i> .....	1-191

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

Design Flood Estimation in South Africa: Challenges and Developments <i>JC Smithers (South Africa)</i> .....	2a-1
New Methodology for a Robust Estimation of Large Return Period Floods for Design of Large Dam Spillways <i>E Cifres (Spain)</i> .....	2a-11
Risk Governance Implementation for a Cascade System on Drini River, Albania <i>I Escuder-Bueno, A Jovani, J Moralo-García &amp; JM Alonso Muñoz (Spain/Albania)</i> .....	2a-21
The Advantages of Performing a Probabilistic Spillway Assessment in an Arid Environment – The Namibia Example <i>A Mostert &amp; LC Hattingh (Namibia/South Africa)</i> .....	2a-29
Generation of Extreme Events for Flood Risk Assessment - Single Events and Continuous Discharge Time Series <i>H Lohr (Germany)</i> .....	2a-39
Devils Lake Flood Risk Management <i>SL McCaskie, PD Madison &amp; BK Greenleaf (USA)</i> .....	2a-49
A Study of the Effective Hydrological Safety of Concrete Dam <i>S Cho, S Jang &amp; D Cha (South Korea)</i> .....	2a-59
Flood Control Ability Improvement Project for the Peace Dam in Korea <i>HS Park, DH Kwon &amp; HI Kim (South Korea)</i> .....	2a-69
A Comparative Study of Telemetric Rainfall Data in Three Gorges Project <i>Y Xu &amp; L Zhiwu (China)</i> .....	2a-77
Hydraulic Scaled Model Tests for the Optimization of Approach Channel Excavation and Approach Flow Conditions of Haraz Morning Glory Spillway <i>S Emami &amp; AJ Schleiss (Iran/Switzerland)</i> .....	2a-87
Existing Shaft Spillway Enhancement Based on Physical Modelling <i>M Broucek , L Satrapa, M Zukal &amp; M Kralik (Czech Republic)</i> .....	2a-97
Investigation into the Fluid and Structural Behaviour of Piano Key Weirs <i>FJM Denys, GR Basson &amp; JAvB Strasheim (South Africa)</i> .....	2a-107
Breach Formation in a Fuse Plug – Evaluation of Field and Laboratory Tests <i>J Lagerlund, A Vazquez, M Svensson, M Billstein &amp; P Viklander (Sweden)</i> .....	2a-117
Dam Kjøljua, Efficient Spillway Design Reassessment using CFD <i>C Thomas-Lepine, (Norway)</i> .....	2a-127
The Development of the Vc-Ogee Relationship which Incorporates Upstream 3-Dimensional Flow Conditions <i>SJ van Vuuren &amp; GL Coetzee (South Africa)</i> .....	2a-137
Rehabilitation of Dams owned by the Department of Water and Sanitation in South Africa <i>W Ramokopa &amp; W van der Westhuizen (South Africa)</i> .....	2a-147

“Smaller” Dam Spillway Rehabilitation <i>H Anderson (South Africa)</i> .....	2a-157
Planning and Design of Additional Discharge Facilities in Japan <i>N Hakoishi, T Sakurai &amp; T Ikeda (Japan)</i> .....	2a-161
Kariba Dam Rehabilitation Project – Improving Spillway Capacity through Reshaping of the Plunge Pool <i>MC Munodawafa, DZ Mazvidza &amp; SZ Mhlanga (Zambia)</i> .....	2a-171
Hazelmere Dam Raising <i>AJ Botha, D Booyse &amp; IP Fitz (South Africa)</i> .....	2a-181
Reconstruction of Emergency Spillway on the Vihorlat Dam <i>M Miščík &amp; O Hrabovský (Slovakia)</i> .....	2a-191
Safety Improvement of Massingir Dam <i>LP Mandlate, P Anthinac &amp; F Del Rey (Mozambique/France)</i> .....	2a-195
Decreasing of Nipah Spillway Crest Elevation due Social Issue, Sampang - Indonesia <i>CD Yuliningtyas, B Prasetyo, N Hidayat &amp; AI Ambara (Indonesia)</i> .....	2a-205
Practical Lessons Learnt from the Rehabilitation of Spillway Gates at Cahora Bassa Dam <i>AJ Botha, A Campos De Carvalho, J Chipuazo, E Carvalho L Boulat, D Hensi &amp; C Chatron (South Africa/Mozambique)</i> .....	2a-209
Re-Commissioning Storfinnforsen’s Bottom Outlet after over 60 years’ idling <i>J Yang, J Larsson &amp; C-O Nilsson (Sweden)</i> .....	2a-219
Refurbishment of the Phalaborwa Barrage <i>A Chaminuka, AJ Botha, F Shabalala &amp; M Motaung (South Africa)</i> .....	2a-229
Hydro-Mechanical Equipment Design for the Rehabilitation of the Corumana Dam <i>RSJ van Wyk, AM Hay, RJ Minnaar, M Perduh &amp; H Barnard (South Africa)</i> .....	2a-239
Strategies for Improving the Safety of Spillway Gates <i>BW Leyland (New Zealand)</i> .....	2a-249
Automatic Self Actuating Spillway Gates to Improve Dam Safety and Storage in Dams <i>PD Townshend (South Africa)</i> .....	2a-259
Assessment and Surveillance of Erosion Risk in Unlined Spillways <i>SE Pells (Australia)</i> .....	2a-269
A Tale of Two Spillways <i>PJN Pells, S Pells &amp; M van Schalkwyk (Australia)</i> .....	2a-279
Mechraa Homadi Dam Bottom Outlet Rehabilitation <i>A Kwayep, F Bouajaj &amp; M El Alaoui (Morocco)</i> .....	2a-289
Computational Fluid Dynamic (CFD) Modelling of the Outlet Control Valve of Ncora Dam <i>O Sawadogo, P Townshend &amp; GR Basson (South Africa)</i> .....	2a-297
Power Intake Structure Model Testing of Mica Project <i>W Yihong, Z Jinxiong, Y Fan, Z Wenyuan &amp; Z Dong (China)</i> .....	2a-307

***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***

Natural Pozzolan Effects on Aggregate A.S.R. Delimitation in Sharyar Dam <i>H Khadiv (Iran)</i> .....	2b-1
Dam Rehabilitation in the presence of AAR – the Matala HEP <i>G Casagran, L Pradolin &amp; J Victor (Canada)</i> .....	2b-11
Analysis of Inhibiting the Alkali Activity of Concrete Aggregate for Nierji Reservoir Project <i>Z Zhu, P Zheng &amp; Z Wang (China)</i> .....	2b-21
A Unique Case: New Works at Chambon Dam <i>A Scuero, G Vaschetti, &amp; J Machado do Vale (Switzerland)</i> .....	2b-27
Kariba Dam Rehabilitation Project – Structural Improvements to the Kariba Dam Spillway Upstream Control Facility to Mitigate the Effects of Alkali Aggregate Reaction <i>MC Munodawafa, DZ Mazvidza &amp; SZ Mhlanga (Zambia)</i> .....	2b-37



The RCC Moula Dam: Reinforcement Work and Appropriate Instrumentation to Challenge a Weak Foundation <i>NeH Dhiab &amp; M Belaid (Tunisia)</i> .....	2b-45
Safety Assessment of an Arch-Gravity Dam with a Horizontal Crack <i>A Hadrović, M Partovi &amp; M Selimotić (Bosnia-Herzegovina)</i> .....	2b-55
Stability Analysis and Repair Measures Assessment of Concrete Dam Cracks in High Water Level Operation <i>S Guo, E Zhai, D Li &amp; H Jin (China)</i> .....	2b-65
Performance Based Approach for Rehabilitation of Golestan Historical Masonry Gravity Dam <i>M Safi (Iran)</i> .....	2b-73
Reconstruction and Reinforcement New Techniques for Masonry Gravity Dams Upstream Anti-Seepage Panels <i>P Qi, G Dashui &amp; W Min (China)</i> .....	2b-83
Application of Reliability Analysis to Slope Stability of an Embankment Dam: A Case Study <i>A Noorzad &amp; H Alimoradi (Iran)</i> .....	2b-93
Rehabilitation of Downstream Slope of Cacaban Dam due to Wetting <i>D Djarwadi (Indonesia)</i> .....	2b-103
Improving Slope Protection of Nahand Dam <i>SH Partovi Azar, A Mihandoost, &amp; M Akbarzad (Iran)</i> .....	2b-111
Engineering Characterization of Aging Cores of Earth-Cored Fill Dams <i>P DongSoon &amp; S Dong-Hoon (South Korea)</i> .....	2b-119
Impact of Lime Treated Soils Performance on Design of Earthfill Dams and Dikes <i>N Nerinx, S Bonelli, D Puiatti, G Herrier, J-J Fry, R Tourment &amp; S Nicaise (France)</i> .....	2b-129
Using ICOLD Bulletin 164 to Develop Good Practice Against Internal Erosion in Dams <i>R Bridle (United Kingdom)</i> .....	2b-139
Probability of Failure of an Embankment by Backward Erosion Using the Formulas of Sellmeijer and Hoffmans <i>T Mallet &amp; J-J Fry (France)</i> .....	2b-149
A Theoretical Framework to Understand the Mechanical Consequences of Internal Erosion <i>CJ MacRobert (South Africa)</i> .....	2b-159
Investigation of Piping Phenomenon in Embankment Dams Utilizing Dams Risk Assessment <i>A Noorzad , F Bagheri , I Vaezi &amp; M Gharavi (Iran)</i> .....	2b-169
The Filtration Stability Safety Assessment of the Dam Liptovská Mara after Grouting Curtain Reconstruction <i>E Bednárová, D Grambličková, M Minárik, J Škvarka &amp; B Kopčáková (Slovakia)</i> .....	2b-179
Rehabilitation Works to Control the Foundation Internal Erosion and to Mitigate the Effects of Alkali - Aggregate Reaction at Dridu Dam <i>D Ștematiu, A Popovici, C Voinitchi &amp; C Ilinca (Romania)</i> .....	2b-189
Quantification on the Probability of Dam Failure due to Internal Erosion Using Event Tree Anaysis <i>G Heo &amp; C-K Chung (South Korea)</i> .....	2b-199
A 70m depth Cut-off Wall to Control Seepage on an Operating Clay Core Dam <i>AF Chraibi, M Benyahia, &amp; A Mhirech (Morocco)</i> .....	2b-207
Importance of Geological and Geotechnical Understanding for Mitigation of Reservoir Leakage and Slope Instability Problems: The Case of Tendaho Reservoir <i>DN Abraha (Ethiopia)</i> .....	2b-217
Foundation Failure of Gheisaragh Dam, Causes and Solutions <i>SP Azar (Iran)</i> .....	2b-227
Evaluation of Grout Curtain Efficiency Due to Instrumentation Data Analysing <i>MA Toosi (Iran)</i> .....	2b-235
Design for Rehabilitation of an Embankment Dam for Seismic Safety Improvement <i>E Yıldız &amp; F Gürdil (Turkey)</i> .....	2b-245
The Seismic Analysis of an Earth-Fill Dam on Thick Liquefiable Ground and Countermeasures against a Large Earthquake <i>T Kato, T Honda &amp; S Kawato (Japan)</i> .....	2b-253

Pull Out Tests of 50-years old Rock Bolts <i>R Hellgren, FR Bayona, R Malm &amp; Fredrik Johansson (Sweden)</i> .....	2b-263
Rock Treatment around Morning Glory Spillway Shaft of Sefidrud Dam <i>A Faghimhaddess, H Abbasi &amp; F Farhadi (Iran)</i> .....	2b-273
Baihetan Dam – China: Rock Mechanics Control of Columnar-Jointed Basalt <i>H Lianxing, Z Endi, F Yilin &amp; L Shaojun (China)</i> .....	2b-283
Slope Stability Analysis of Jinping Dam using Limit Equilibrium Method and Finite Element Methods <i>WJ Herweynen &amp; H Liu (Australia)</i> .....	2b-291
Condensed History and Samples of Water-stop's Development for CFRDs in China <i>F Minghui, L Yihui, L Chun, X Yao &amp; H Jutao (China)</i> .....	2b-299
Brush-Coated Flexible Waterstop Structure of CFRD Joints <i>X Yao &amp; S Zhiheng (China)</i> .....	2b-307
Mohale Dam Crack Stage 2 Rehabilitation <i>L Matete, S Mojela &amp; T Maseatile (Lesotho)</i> .....	2b-313
Rehabilitation and Long Time Behaviour of Asphalt Concrete Faced Reservoirs and Dams <i>P Tschernutter (Austria)</i> .....	2b-323
Lessons from Geotextile Use in Embankment Dams <i>J-J Fry, GE Degoutte &amp; D Poulain (France)</i> .....	2b-333
Selection of Liner Type for Raw Water Storage <i>DJ Hagen &amp; AJ Botha (South Africa)</i> .....	2b-343
Adaptation of a Geosynthetic Clay Liner to a Cofferdam using a Decision Matrix <i>Ö Özen, H Kúsmez, E Üzücek &amp; T Dinçergök (Turkey)</i> .....	2b-353
Controlled Demolition Techniques during raising of the Hazelmere Dam Spillway in KwaZulu Natal, South Africa <i>JR Brinkmann, AJ Botha &amp; A Olden (South Africa)</i> .....	2b-361
Blasting for a Large Pollution Control Dam Directly Beneath Overhead Powerlines <i>CVB Cunningham (South Africa)</i> .....	2b-371
Talybont Dam Tunnel Pipework Repair Following Damage Caused by a Pressure Shock Wave <i>TA Williamson &amp; AL Warren (United Kingdom)</i> .....	2b-381
Mohale Tunnel Dewatering System: The System still to be Commissioned <i>L Matete &amp; E Mathaba (Lesotho)</i> .....	2b-391
Renovation of Långed Hydro Power Plant, Sweden <i>A Engelmarm Hofgaard &amp; R Ascila (Sweden)</i> .....	2b-397
Raising of Clanwilliam Dam Design and Construction Considerations <i>P Barnard, H Swart, H Durieux &amp; A Thobejane (South Africa)</i> .....	2b-407

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

Orange Senqu Shared International Basin: Importance of a Common Understanding of Water Resource Modelling Capabilities and Results for Decision Makers involved in the Planning and Operation of the System <i>HG Maré, CJ Seago &amp; C Talanda (South Africa)</i> .....	3-1
Drought Management: The Case of Hluhluwe Dam, Kwazulu-Natal, South Africa <i>AS Sikosana &amp; C Ntuli (South Africa)</i> .....	3-11
Analysis of Multiple-Target Optimized Regulation of the Three Gorges Reservoir under Changed Operating Environment and its Integrated Benefits <i>X Tao, Z Man &amp; L Changchun (China)</i> .....	3-21
Cause-Effect Analysis of River Basin Management Options - Case Study of a Small Dam in Thailand <i>H Lohr &amp; R Treitler (Germany)</i> .....	3-29
The Practice and Discussion on the Joint Operation of Cascade Hydropower Plants on the Upstream Catchment of Yangtze River <i>B Zhengfeng, X Ge &amp; W Yuhua (China)</i> .....	3-39
Reservoir Operation Rule Changing to Maintain Sustainability of Gajah Mungkur Life Time, Central Java - Indonesia <i>DAS Kubontubuh, CD Yuliningtyas &amp; N Hidayat (Indonesia)</i> .....	3-47

Operation of Citarum Cascade Reservoirs to Optimize Water and Power Requirement and Flood Control <i>M Khan, I Samoon &amp; D Pranowo (Pakistan)</i> .....	3-53
Role of the Dams in the Strategy for Prevention and Reduction of the Destructive Consequences of Floods <i>I Asman, S Randasu &amp; C Ban (Romania)</i> .....	3-63
Using Topographic Dams to Increase the Energy Production Potential and Flood Management <i>AAN Pourkiaei &amp; S Emami (Iran)</i> .....	3-73
Challenges of Water Management in Trans-Basin Diversion Systems <i>B Kamaladasa &amp; J Meegastenna (Sri Lanka)</i> .....	3-81
Modernisation of the LHWP Royalties Computation using Water Evaluation and Planning (WEAP) Tool to Determine Benefits Sharing <i>K Lepholisa, R Molapo &amp; F Tlhomola (Lesotho)</i> .....	3-89
The Use of Cultural Ecological Knowledge, the Pranata Mangsa as Comparative Tool for Shifted Seasonal Pattern in Sermo Dam Operation, Yogyakarta, Indonesia <i>V Ariyanti, Aa Wicaksono, Tb Adji &amp; A Anung (Indonesia)</i> .....	3-97
The Dams Master Plan for Kurdistan Region – Iraq. Getting the Job Done <i>C Popescu, P Mazilu, I Dragan, A Mihai, N Sirbu, R Sarghiuta &amp; M Segarceanu (Romania)</i> .....	3-107
Technical and Economical Assessment of Large Dams Design Flood Selection in Iran <i>M Fadaeifard &amp; S Daneshvar (Iran)</i> .....	3-115
Low Submersible Dams <i>F Lemperiere, M Hotakhanh &amp; N Nerincx (France)</i> .....	3-125

#### **Theme 4. Reservoir sedimentation and management**

Sediment Management at Reservoirs and Hydropower Plants: New World Bank Technical Note <i>Gw Annandale, GI Morris, &amp; P Karki (USA)</i> .....	4-1
Positive Effects of Reservoir Sedimentation Management on Reservoir Life: Examples from Japan <i>C Auel, SA Kantoush &amp; T Sumi (Japan)</i> .....	4-11
Comprehensive Basin-Wide Sediment Management in Brantas River Basin, Indonesia <i>R Erwando, MA Satria, H Fahmi, RR Valiant &amp; Harianto (Indonesia)</i> .....	4-21
Run of River Hydro - Latest Innovations in Diversion Dams and Sediment Exclusion <i>S Mottram, K Ainsley &amp; E Scherman (Canada)</i> .....	4-29
Design of Run-Of-River Hydropower Schemes to Limit Sediment Diversion <i>M Van Heerden, &amp; GR Basson (South Africa)</i> .....	4-39
Development of a Bedload Transport Measuring System for Sediment Bypass Tunnels in Japan <i>T Koshiba, T Sumi, D Tsutsumi, Sa Kantoush &amp; C Auel (Japan)</i> .....	4-49
Dredging with Riverine Disposal to the Channel below the Dam for Supporting Sustainable Sedimentation Management of the Selorejo Dam <i>A Yhadhianto, F Hidayat, A Santoso, S Bachri &amp; Harianto (Indonesia)</i> .....	4-59
A Practical Example of Change of River Bed Environment Downstream from Dam Reservoir by Sediment Replenishment <i>Y Musashi, Y Nakata, T Suzuki, M Oshima &amp; S Demizu (Japan)</i> .....	4-67
Study and Practice on Sedimentation Reduction of Three Gorges Reservoir under the New Water and Sand Inflow Condition <i>B Zhengfeng (China)</i> .....	4-77
Study of Sediment Excavation in the Tail of the Three Gorges Reservoir based on Unsteady Flow-Sediment Model <i>X Tao &amp; G Xiao (China)</i> .....	4-87
Research on Flow and Sediment Flux into the Three Gorges Reservoir and the Sedimentation Change Trend <i>J Zhongwu &amp; W Huali (China)</i> .....	4-95
Sediment Control Interventions in the LHWP Muela Catchment <i>G Mokone, P Monongoaha &amp; R Nts'Ohl (Lesotho)</i> .....	4-105
2D Hydrodynamic Modelling of Sediment Deposition Processes and Flushing Operation of Boegoeberg Dam, South Africa <i>O Sawadogo &amp; Gr Basson (South Africa)</i> .....	4-113

2D Reproduction Analysis of Reservoir Sedimentation Caused by Flood <i>N Sorimachi, K Hashimoto &amp; T Sato (Japan)</i> .....	4-123
The Response Law of Fluid Mud to Density Current in the Xiaolangdi Reservoir in the Yellow River, China <i>L Kunpeng, M Huaibao &amp; W Yuanjian (China)</i> .....	4-133
Rehabilitation of the Kat River Barrage, Fort Beaufort, Eastern Cape, South Africa <i>BJ Krieglner, O Sawadogo &amp; GR Basson (South Africa)</i> .....	4-139
HPP Vrhovo Operation under Reservoir Sediment Management <i>L Javornik, M Mikoš &amp; A Kryžanowski (Slovenia)</i> .....	4-149
Sedimentation Problem at TNB Ringlet Hydroelectric Power Stations <i>R Radzi, A Hasnul &amp; S Akib (Malaysia)</i> .....	4-157
Automatic Scour Gates to Keep Small Dams Free of Sediment <i>JF von Holdt (South Africa)</i> .....	4-167

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

Key Steps for Conducting Tailings Dam Breach Studies <i>AJ Strauss, V Martin, D Fontaine &amp; J Cathcart (South Africa/Canada)</i> .....	5-1
Prediction of Potential Tailings Storage Facility Inundation Zones <i>M Rust &amp; S Dressler (South Africa)</i> .....	5-9
Requirements for Stability Assessments of Tailings Dams <i>M Theron, M Rust &amp; E Rust (South Africa)</i> .....	5-19
Common Practice and Innovations in Tailings Dams using Geosynthetic Tubes <i>MT Van Keßel, M Breytenbach &amp; M Wilke (Germany/South Africa)</i> .....	5-29
Reliability of Tailings Dams with Possible Disturbance of the Impervious Elements and Seismic Impacts <i>V Glagovsky, S Golubev, S Sosnina, T Sinitsyna &amp; N Yurova (Russia)</i> .....	5-39
Review of Finnish Tailings Dam Safety <i>JP Laasonen (Finland)</i> .....	5-47
Application of Rock-Filled Concrete on Tailings Reservoir Project <i>F Jin, Y Wang, H Zhou, M Huang &amp; X Cui (China)</i> .....	5-53
Operation and Maintenance of Ash Dams in South Africa: Challenges and Shortcomings <i>PJ Gouws (South Africa)</i> .....	5-63

### ***Theme 6. Strategies for proper surveillance of dams***

Effect of Common Cracks on Structural Behaviour of Concrete Dams <i>M Westberg Wilde, M Hassanzadeh, M Janz &amp; T Ekström (Sweden)</i> .....	6-1
The Behaviour of a RCC Dam Raised with RCC...10 Years on <i>CI Dankers &amp; C Oosthuizen (South Africa)</i> .....	6-11
High Resolution Distributed Fiber Optic Temperature Measurement of Massive Concrete in Concrete Dams at an Early – Age <i>N Humar, S Milevski, D Zupan, A Vidmar &amp; A Kryžanowski (Slovenia)</i> .....	6-21
Monitoring the Behavior Changes of an Unreinforced Multi Domed Buttress Dam during Rehabilitation <i>Jl Schoeman &amp; C Oosthuizen (South Africa)</i> .....	6-29
Long-Term Integrity Monitoring of a Concrete Arch Dam using Continuous Dynamic Measurements and a Multiple Linear Regression Model <i>P Bukenya, P Moyo &amp; C Oosthuizen (South Africa)</i> .....	6-39
Identifying Behavioural Trends and the Development of Calibrated Finite Element Models for a Double Curvature Arch Dam <i>ZJ Prins, CN Mahlabela &amp; P Moyo (South Africa)</i> .....	6-47
Notes on the Behaviour of a 65 Year Old Concrete Arch Dam affected by AAR (Based on Visual Observations only) <i>O Human &amp; C Oosthuizen (South Africa)</i> .....	6-57
Safety Monitoring and Controlling System for Xiaowan Arch Dam <i>Z Lichun, Z Zhiyong &amp; C Shenghong (China)</i> .....	6-67

Geodetic Deformation Monitoring System of the 185 m High Katse Dam in Lesotho <i>CJ Pretorius, S Mojela &amp; T Maseatile (South Africa)</i> .....	6-77
Monitoring System of Cahora Bassa Dam....The Past, Present and Way Forward <i>EF Carvalho, BT Matsinhe &amp; C Oosthuizen (Mozambique)</i> .....	6-87
The Application of Fuzzy Comprehensive Evaluation Method on Large Concrete Dam Safety Monitoring System Evaluation <i>C Wenbo, T Yuanyuan &amp; Y Jin (China)</i> .....	6-95
Analysis of Potential Failure Modes and Re-Instrumentation of a Concrete Dam <i>R Malm, E Nordström, C-O Nilsson, R Tornberg &amp; J Blomdahl (Sweden)</i> .....	6-101
Improving Longevity of High Embankment Dam Instrumentation <i>D Salehi (Iran)</i> .....	6-111
Behaviour Monitoring of Driekoppies Dam – 18 Years on <i>L Hattingh, C Zwane, L Nkozi, E Khoza &amp; C Oosthuizen (South Africa)</i> .....	6-119
Surveillance of Lom Pangar Dam during First Filling of the Reservoir <i>T Guillemot, A Towa, M Lino, C Daux, L Vauloup &amp; E Remy (France)</i> .....	6-129
Evaluation and Monitoring Response to Upstream Slope Failure at an Embankment Dam <i>JN Stateler &amp; J Wormer (USA)</i> .....	6-139
Analysis Method for the Monitoring of Pore Water Pressure in Embankment Dams <i>AG Simon &amp; T Guilloteau (France)</i> .....	6-149
Development of Emergent Monitoring System for Leakage from the Dam <i>T Higuchi, T Sugai, T Sato, &amp; T Kayukawa (Japan)</i> .....	6-159
Seepage Control and Monitoring of Zirdan Dam <i>A Bagherzadehkhalhali &amp; M Karimi (Iran)</i> .....	6-165
Application of Response Surface Method in Analysis of Hydraulic Structures <i>M Klun, A Kryžanowski &amp; S Schnabl (Slovenia)</i> .....	6-175
Thermal-Hydraulic-Mechanical Coupled Analysis to Diagnose Condition of Earthen Dams and Reservoirs <i>B-H Choi &amp; KT Chang (South Korea)</i> .....	6-185
External Deformation Monitoring of Five Rockfill Dams in the same Radar Satellite Data <i>H Sato, T Sasaki, T Kobori, Y Enomura, Y Yamaguchi, W Sato, N Mushiake, K Honda &amp; N Shimizu (Japan)</i> .....	6-193
Surveillance of CFRD Built on Deep Alluvium Foundation <i>Z Xu (China)</i> .....	6-203
Performance Analysis and Safety Monitoring Key Points for Concrete Face Rockfill Dams <i>L Nenghui, Z Ganwu &amp; L Denghua (China)</i> .....	6-213
Rehabilitaion of Seepage Monitoring System of Rockfill Dam for Dam Safety <i>L Jongwook (South Korea)</i> .....	6-221
Behaviour of the Spring Grove Dam During and After Construction <i>M Trümpelmann, D Badenhorst &amp; J Nyakale (South Africa)</i> .....	6-231
Surveillance of Bedford and Bramhoek Dams <i>E Lillie (South Africa)</i> .....	6-241
Improving Seismic Monitoring in the Active East African Rift System for Detailed Seismic Hazard Assessments: A Case Study in Malawi <i>VA Dimas, PRN Chindandali &amp; B Kendaragama (Australia)</i> .....	6-249
Outcomes of the Devastating Mw 7.8 April 2015 Nepal-Gorkha Earthquake and Establishing a Seismology Research and Monitoring Centre in the Kingdom Of Bhutan <i>VA Dimas, B Kendaragama &amp; N Arora (Australia)</i> .....	6-259
Use of Hydrogeological Parameters in the Performance Monitoring of Dams and Their Foundations <i>W Riemer (Germany)</i> .....	6-269
Hydrologic Information Measuring Application based on Redundant System Framework <i>L Yu &amp; Y Xiao (China)</i> .....	6-277
Inspection of Submerged Area with the use of an Underwater-Camera Surveying Vehicle <i>Y Sakamoto, S Akimoto, &amp; K Kera (Japan)</i> .....	6-285
Monitoring of the Submerged Structures of Dams <i>E Isomäki &amp; K Hänninen (Finland)</i> .....	6-295

Organization of Surveillance of Dams in Russia <i>EN Bellendir, EA Filippova &amp; OA Buriakov (Russia)</i> .....	6-305
Implementation of a Dam Monitoring Management System in the Tagus River Basin Authority <i>S Hoppe &amp; E Moreno Calle (Spain)</i> .....	6-311
Aloha: An Innovative System for Proper Surveillance of Hydraulic Structures <i>P-H Faure, F Zenss, V Gbiorczyk, V Degezelle &amp; V Morisseau (France)</i> .....	6-319
New Ideas for Dam Safety Monitoring System Establishment in the Smart Basin <i>S Hui, Z Lan &amp; L Qi (China)</i> .....	6-329
The Thinking about Dam's Safety Monitoring Based on the Full Life Cycle <i>C Gang &amp; G Fawang (China)</i> .....	6-335
Implementation of Failure Mode-based Monitoring of Dams <i>A Isander, U Kuoljok, P Wilén &amp; J Oestberg (Sweden)</i> .....	6-345
A Study on the Development of Performance Evaluation Method on Existing Dams in South Korea <i>KJ Hye, KY Soo, P Jiyeon, SC Shik &amp; KH Ki (South Korea)</i> .....	6-347
Dam Safety Management in the Brantas and Bengawan Solo River Basins, Indonesia <i>Hariato, RV Ruritan, F Hidayat, F Sarifudin, K Windianita &amp; MTB Raharjo (Indonesia)</i> .....	6-353
Suggestions for Dam Crisis Management Learned through the 2011 off the Pacific Coast of Tohoku Earthquake <i>H Okumura, T Matsumoto &amp; K Koyama (Japan)</i> .....	6-361
Telemetry System as a New Approach for Dam Surveillance in Indonesia <i>M Anissa &amp; DK Nofyar (Indonesia)</i> .....	6-371
The Use of Bio-Location in the Safety Evaluation of Dams <i>LC Hattingh &amp; C Oosthuizen (South Africa)</i> .....	6-381

## **Theme 7. Sustainable hydropower development in developing countries**

Important Policy Considerations for Hydropower Development in Developing Countries in an Era of Climate Change <i>GW Annandale (USA)</i> .....	7-1
Challenges in Development of Small Hydropower in Africa: A Technical and Financial Perspective <i>H-J Wright, BR Collet &amp; H Hawarden (South Africa)</i> .....	7-11
The Rehabilitation of the Mt Coffee Hydropower Project in Liberia <i>WD Hakin, QHW Shaw, R Guimond &amp; B Taraldsten-Brunes (Canada)</i> .....	7-21
Analysis of Future Hydropower Development and Operational Scenarios on the Zambezi River Basin <i>JP Matos, T Cohen Liechti &amp; AJ Schleiss (Switzerland)</i> .....	7-31
Study Approach into the Hydropower Development along the Luapula River <i>SG Renecke (South Africa)</i> .....	7-41
LHWP Phase II Hydropower Feasibility, Further Studies <i>JR Sawyer &amp; T Mochaba (Lesotho)</i> .....	7-51
Monont'sa Pumped Storage Scheme – Sustainable Hydroelectric Development In Africa <i>CF Logan (South Africa)</i> .....	7-61
Study on Hydro Power Potentials in Existing Major Reservoirs in Sri Lanka <i>WB Palugaswewa (Sri Lanka)</i> .....	7-71
Sustainable Hydropower Development in I.R. of Iran <i>S Salavitarab &amp; A Salavitarab (Iran)</i> .....	7-81
Oiești Development Scheme Conversion <i>ID Iacob &amp; C Abdulamit (Romania)</i> .....	7-91
Development of a Novel System for Improvement of Operation and Maintenance Works in Dams and Hydropower Plants in Iran <i>K Nasser, E Hassan &amp; Yousefi Saied (Iran)</i> .....	7-99

## **Theme 8. Other**

Ambarau Hardfill Dam - Appropriate Dam Technology for Central Africa <i>D Cameron-Ellis (South Africa)</i> .....	8-1
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The Cemented Soil Dam (CSD): A New Concept of Cemented Dam <i>M Lino, F Delorme, D Puiatti, P Agresti &amp; F Lempérière (France)</i> .....	8-9
Simple RCC Dams for Developing Countries <i>F Ortega (Spain)</i> .....	8-19
RCC Mixtures Study for the Design of a Large Dam in Mexico <i>A Garduno-Gallo &amp; M Montero (Mexico)</i> .....	8-29
Global Stability of High Gate Dam Based on Deep Overburden Layers by Geomechanical Model Test <i>D Bin, H Zhonghui &amp; Z Lin (China)</i> .....	8-39
Design Features of Koyunbaba Concrete Faced Sandy Gravel Dam founded on Deep Alluvium <i>MH Askeroglu, H Kusmez &amp; N Pelen (Turkey)</i> .....	8-49
Analysis of Factors Affecting the Stability of the Mosul Dam <i>ZA Aladwani, N Younis &amp; AA Mahmood (Iraq)</i> .....	8-57
Research on Structural Safety Design of High Embankment Dams <i>B Li (China)</i> .....	8-67
Application of Monte-Carlo Simulation for Slope Optimization of CSG Dams using Fuzzy Uncertainty Set <i>A Noorzad, E Badakhshan, I Vaezi &amp; M Gharavi (Iran)</i> .....	8-73
Geological Studies for Increasing the Operating Level of Karun1 (Shahid Abbaspour) Dam, Iran <i>A Barjasteh (Iran)</i> .....	8-83
Partial Factor Calibration Based on Non-Numerical Method of Gravity Dam Foundation Material <i>B Li (China)</i> .....	8-93
Criteria for the Selection of Dam Types in Areas of High Seismicity <i>M Wieland (Switzerland)</i> .....	8-101
Seismotectonic Modelling for Seismic Hazard Assessments in Low-Seismicity Regions of Africa: Western Africa <i>VA Dimas, UA Kadiri &amp; B Kendaragama (Australia)</i> .....	8-111
Seismic Vulnerability Analysis of Tendaho Dam in Ethiopia <i>A Aman, T Mammo &amp; M Wieland (Ethiopia)</i> .....	8-121
Seismic Safety Evaluation of a RCC Gravity Dam under Maximum Credible Earthquake <i>D Li, J Tu, S Guo, H Wang &amp; W Wang (China)</i> .....	8-131
Seismic Responses of Conventional Concrete Gravity Dams on Weak Foundations <i>K Tayyebi, MS Gilani &amp; M Ghaemian (Iran)</i> .....	8-141
Modeling of Earthquake-Induced Settlement in Embankment Dam by new Approach <i>D Behnia, A Noorzad, M Behnia &amp; K Ahangari (Iran)</i> .....	8-151
Case Studies of Reservoir-Induced Geo-Hazards for the Jiansha River Hydropower Projects in China <i>E Zhai, Q Fan &amp; H Jin (China)</i> .....	8-159
Some Lessons Learnt from the Failure of Earthfill Dams in Burkina Faso: Case Stories <i>A Nombre, E Somda &amp; M Kabore (Burkina Faso)</i> .....	8-169
Regulatory Dam Safety Inspections and Evaluations in South Africa <i>CL van den Berg (South Africa)</i> .....	8-179
Eastern Nile Transboundary Cooperation on Dam Safety: Challenges and Opportunities <i>M Abebe (Ethiopia)</i> .....	8-185
Dam Safety Assessment of FAN Dams in Ethiopia <i>F Shiferaw (Ethiopia)</i> .....	8-193
Dam Construction Key in Future Dream of Water in Africa <i>Ei Ekpo (Nigeria)</i> .....	8-201
Dam Safety Regulations in Norway; Relationship between Rehabilitation Project Cost and Resulting Added Dam Safety <i>H Kjærås, L Basberg &amp; Ø Lier (Norway)</i> .....	8-207
Evaluation of Dam Safety Using Limit States <i>J Riha &amp; M Spano (Czech Republic)</i> .....	8-217
Risk-Informed Decision-Making in Dam Safety - Federal Agency Perspectives Based on 20 Years of Experience <i>N Snorteland, D Osmun, &amp; BC Muller (USA)</i> .....	8-227

Application of Risk Analysis in Membrío Dam (Spain) to Inform Safety Investments <i>M Setrakian, I Escuder-Bueno, A Morales-Torres &amp; D Simarro (Spain)</i> .....	8-237
A Description of the Application of a New Quantitative Dam Safety Risk Screening Tool to assist a Remote Northern Community in Making Risk Informed Decisions on the Dam Safety Risks and Remedial Actions <i>CR Donnelly, K Jamieson, CDSS Perkins &amp; M Orton (Canada)</i> .....	8-245
Risk Issues and Mitigations for Very High Concrete Arch Dams <i>M Safi &amp; M Gharavi (Iran)</i> .....	8-255
Dam Hazard Analysis using GIS and Nationally Coordinated Emergency Preparedness Plans <i>M Jewert, G Sjödin, M Hautakoski &amp; M Björk (Sweden)</i> .....	8-265
Evaluation of Life Safety Criteria for South African Dams <i>S Reynolds &amp; C Viljoen (South Africa)</i> .....	8-275
Is the S-Shaped Curve a General Law? An Application to Evaluate the Damage Resulting from Water-Induced Disasters <i>M Chen, J Ma, F Zhou, Y Hu, J Li &amp; L Yan (China)</i> .....	8-285
The Main Technological Innovative Practice in Construction of Jinping I hydroelectric Project <i>W Jimin, D Shaohui, Z Jiang, H Shuhong &amp; J Xuelin (China)</i> .....	8-295
Use of a Cushion Layer to Reduce the Cost and Installation Time of a Vibrating Generator Foundation and Spiral Case: A 3D Nonlinear Study <i>SM Yousefi &amp; T Dell (Canada)</i> .....	8-305
Application of Data Driven Models in River Flow Forecasting <i>A Khazaiepour &amp; M Shourian (Iran)</i> .....	8-315
The Ntabelanga and Lalini Dams Conjunctive Scheme – A Water Food Energy Nexus <i>SV Johnson, M Mugumo, AJ Pepperell &amp; T Moore (South Africa)</i> .....	8-323
Feasibility Study for Foxwood Dam, Eastern Cape, South Africa <i>J Hampton, L Spasic-Gril, J Bristow &amp; R Gilbert (United Kingdom)</i> .....	8-333
Analysis of Vulnerability to Climate Change in terms of Water Supply for San Jose Hydroelectric Project (Bolivia) <i>MF Villazón, D Inturias, P Pardo, O Zarate &amp; G Rodríguez (Bolivia)</i> .....	8-343
Value Add of Remote Sensing in the Planning of Dams in Africa <i>DR De Witt &amp; R Nel (South Africa)</i> .....	8-353
Gate Operation of Small Dams for Flushing the Pollutants Accidentally Released into the Nakdong River <i>MJ Kim &amp; KS Jun (South Korea)</i> .....	8-361
A Quantitative Approach to Optimizing the Fuel Consumption of Dump Trucks in Earthmoving Projects to Decreasing Emission <i>D Bahadorbeygi, NH Alaei &amp; ER Azar (Iran)</i> .....	8-371



*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

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## 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, asymmetry 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, (m <sup>2</sup> )
e	-	Euler's mathematical constant (approx. = 2.71828)
CFD	-	Computation Fluid Dynamics
H <sub>a</sub>	-	velocity head, (mm)
H <sub>sd</sub>	-	measured water depth upstream relative to the crest, (mm)
H <sub>e</sub>	-	total head (sum of H <sub>d</sub> and H <sub>a</sub> ), (mm)
H <sub>d</sub>	-	design head of the Ogee spillway, (mm)
H <sub>o</sub>	-	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 <sub>p</sub>	-	turning point (apex position) on the lower nappe of the Ogee profile
SCW	-	sharp-crested weir
v <sub>o</sub>	-	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 20<sup>th</sup> century using physical modelling and applying empirical and mathematical curves. The increased computational resources available in the 21<sup>st</sup> 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.

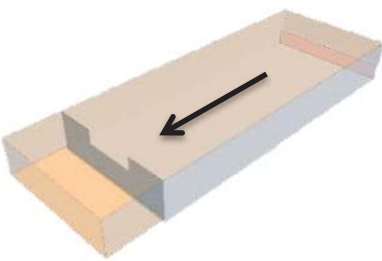
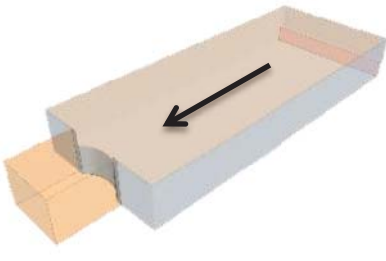
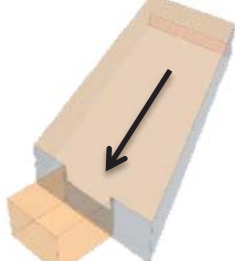
The workflow, adapted for STAR-CCM+ from Ho, *et al.* (2003), for setting up a CFD model was summarized as follows:

- 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 from 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			Units
	A	B	C	
H <sub>sd</sub> (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	m <sup>2</sup>
v <sub>o</sub> (Mean flow velocity in approach channel)	0.05	0.05	0.05	m/s
H <sub>a</sub> (Upstream energy head)	0.12	0.12	0.12	mm
H <sub>e back calc</sub> (Total head back calculated)	129.16	129.19	128.75	mm
H <sub>d back calc</sub> (Design head back calculated)	129.04	129.07	128.63	mm
H <sub>e</sub> (Actual total head)	134.39	131.70	132.68	mm
H <sub>d</sub> (Actual design head)	134.28	131.58	132.56	mm
ΔH <sub>e</sub> (Change in total head)	+4.052%	+1.940%	+3.053%	-
ΔC <sub>d</sub> (Change in discharge coefficient)	-5.784%	-2.841%	-4.411%	-
C' (Elevation of inflection point)	17.84	17.40	19.76	mm
P/H <sub>d</sub> (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):

$$Q_{ogee} = C_d \sqrt{2g} L H_e^{\frac{3}{2}} \quad \text{Equation 1}$$

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

And 
$$H_e = H_d + H_a \quad \text{Equation 3}$$

Where: 
$$H_a = \frac{v_0^2}{2g} \quad \text{Equation 4}$$

And 
$$\chi = \frac{H_0}{H_d} \quad \text{Equation 5}$$

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  $Z = \frac{z}{H_e}$ .

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

With 
$$X^* = 1.3055 \cdot (X + 0.2818) \quad \text{Equation 7}$$

and 
$$Z^* = 2.7050 \cdot (Z + 0.1360) \quad \text{Equation 8}$$

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

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

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 intercept at  $\frac{dz}{dx} = 0$ . This ensures a smooth uniform transfer of the curvature without any discontinuities.

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

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

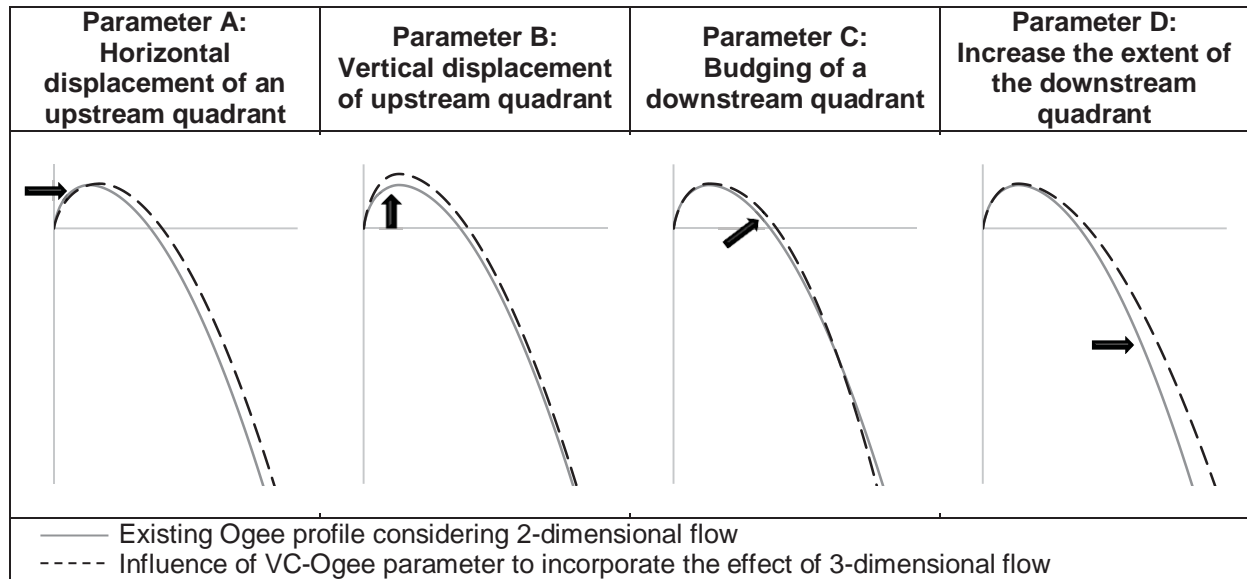


Table 5. VC-Ogee parameter set for the different layouts

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  $\approx$  1% was met. Equation 12 determined the SPVD between the CFD profile and the VC-Ogee profile.

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

#### 4. RESULTS AND DISCUSSION

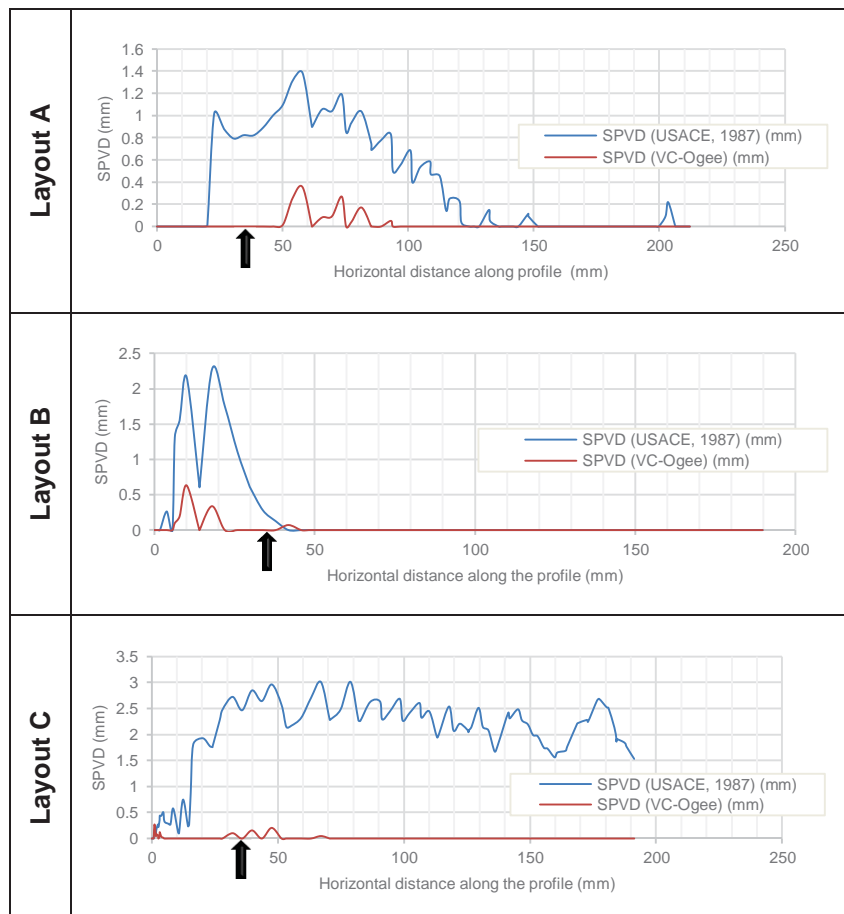
The profile of the lower nappe, perpendicular to the plane of the sharp crested weir, was extracted at seven locations along the crest of the SCW. The SPVD was calculated along the Ogee profile where separation from the theoretically approximated profile was the greatest. The profiles with the greatest 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  $\approx$ 1% for the proposed VC-Ogee profile was also met.

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

Relationship	Parameter	Layout			Units
		A	B	C	
USACE (1987)	SPVD	26.54	13.29	186.94	mm
VC-Ogee		1.34	1.36	1.19	
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**



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).

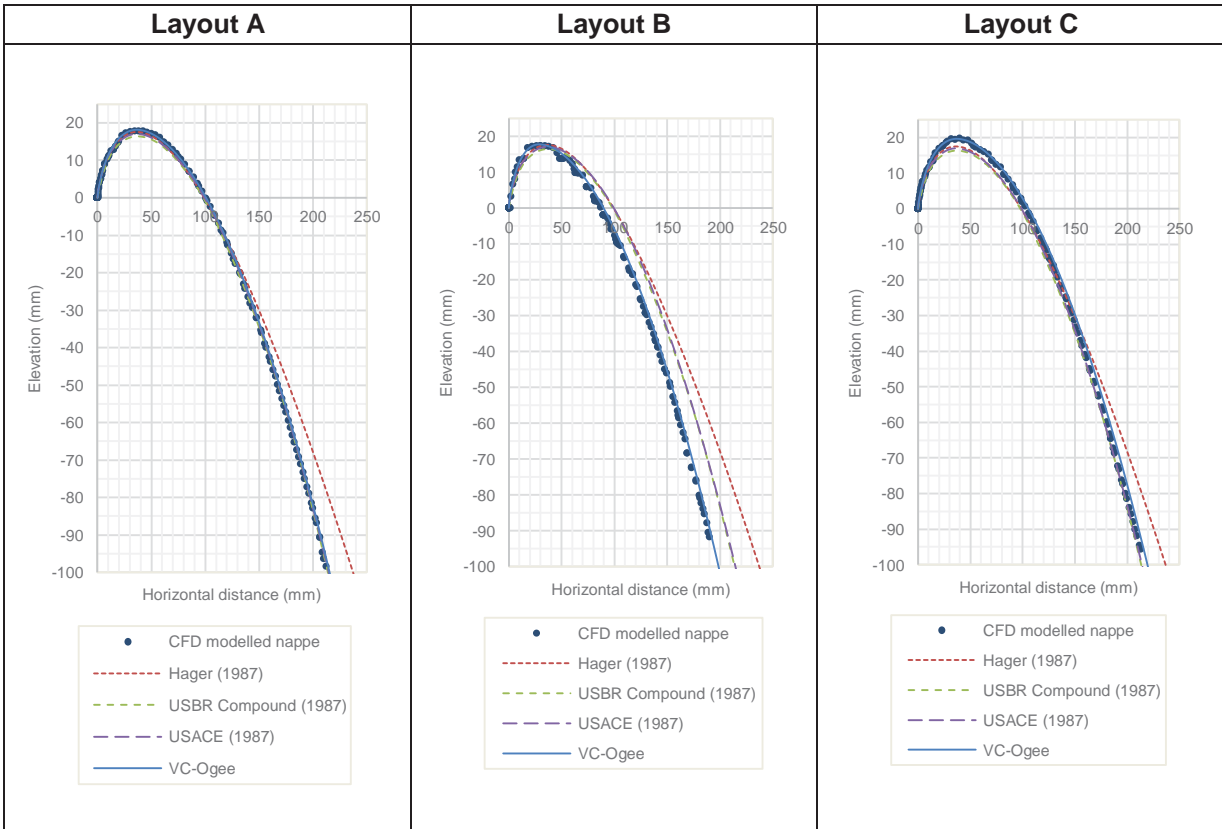
Breakaway from the theoretically estimated profiles are apparent where the observed lower nappe extended above the numerically approximated Ogee relationship's surface. Breakaway tends to be



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  $T_p$  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 9. Observed head upstream of the weir and adjusted discharge coefficients**

Parameter	Scenario			Units
	A	B	C	
$H_e$	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	
$\Delta H_e$	4.052%	1.940%	3.053%	-
$\Delta C_d$	-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  $\frac{R}{H_d} < 5$ .

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