Overflowing erosion modelling of embankment and concrete dams: state of the art and research needs

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Abstract

Overflowing erosion of embankment dams and levees and overflowing erosion of bedrock downstream of concrete dams (through crest overflowing or spillway flow impact) are of major concern for dam and levee owners. Despite extensive research efforts performed in North America and Europe since the late 1990s, many gaps in knowledge still need to be answered in order to provide engineers with validated numerical tools able to predict the erosion mechanisms to an acceptable level of certainty. As addressing these gaps in knowledge will likely require a substantial and expensive research effort, international research collaboration in this field seems the most efficient way to reach these objectives. In order to structure and launch such international collaboration, an international workshop was organized in Aussois, France, from 11th to 14th December 2017, on behalf of the European Group of ICOLD and the French Committee on Dams and Reservoirs. This paper presents the outcomes of this workshop and includes a presentation of the state of the art in overflowing erosion of embankment dams and levees, overflowing erosion of bedrock downstream of concrete dams, the main knowledge gaps which need to be addressed and the outlines of a future international research project to solve these issues.

1 Introduction

Overflowing erosion of embankment dams and levees and overflowing erosion of bedrock downstream of concrete dams (through crest overflowing or spillway flow impact) are among the main causes of dam and levee failures or severe dam incidents. According to Foster and Fell [1], overflowing erosion is the failure mode for 48% of large embankment dam failures. Spillway erosion caused severe incidents, such as the recent problems at Oroville Dam and overflowing erosion downstream of concrete dams is of major concern for many existing dams and new projects. Despite extensive research efforts performed in North America and Europe since the late 1990s, many gaps in knowledge still need to be addressed in order to provide engineers with validated numerical tools which are able to predict the erosion mechanisms to an acceptable level of certainty. As addressing these gaps in knowledge will likely require a substantial and expensive research effort, international research collaboration in this field seems the most efficient way to reach these objectives. In order to structure and launch such international collaboration, an international workshop was organized in Aussois, France, from 11th to 14th December 2017, on behalf of the European Group of ICOLD and the French Committee on Dams and Reservoirs. This workshop was split into two 2-day sessions: the first session dedicated to overflowing erosion of embankment dams and dikes and the second session dedicated to overflowing erosion of bedrock downstream of concrete dams. Both sessions were structured in the same way: a first part was dedicated to the dam owners' perspectives, a second part dedicated to the presentation of the state of the art by leading researchers and experts and a third part dedicated to synthesizing the research needs and research interests for each participant.

2 Part I: Overflowing erosion of embankment dams and levees

2.1 Objectives of Part I

Part I of the workshop, dedicated to the overflowing erosion of embankment dams and levees, was structured in four sessions:

Session 1 was focused on the problems, questions and needs of dam and levee owners:

- Is overflowing erosion an issue?
- What kind of problems associated with overflowing erosion need to be solved?
- Is the engineering toolbox satisfactory?

The synthesis of Session 1 will help answering the question: what gaps need to be filled?

Sessions 2 and 3 were devoted to a presentation of the state of the art by researchers and experts with the aim to answer the following questions:

- What problems are already properly solved with an engineering perspective? Which tools and methodologies are available to engineers?
- What are the researches under development?
- What should the main topics and directions be to answer the questions that came up by dam and levee owners?

The synthesis of Sessions 2 and 3 will allow an answer to the question: what gaps need to be filled? These sessions will also allow an answer to the question: what are the main lines of an international research project to fill these gaps?

Session 4 was a synthesis of Part I, focused on how moving forward to launch an international research project to fill the gaps:

- Which organizations would be ready to fund such an international research project?
- Which research teams could be involved to perform this research project?

2.2 Session 1: the dam owners' perspectives: issues and engineering needs

Dam owners who contributed to this session included the following:

- Hydropower utilities: Hydro-Québec, EDF, CNR (Compagnie Nationale du Rhône, France);
- US federal agency (hydropower and levees' owner) : USACE;
- Non hydropower dams and levees' owners: Environment Agency (UK), Rijkswaterstaat (Netherland), Symadrem (Levees of South part of the Rhône river, France), Flanders Hydraulic Research (representative of the owner of state owned levees in Flanders); Bavarian Environment Agency (LfU);
- UK dam owners were represented by a British Dam Society representative.

Overflowing erosion was presented by all dam and levee owners, except Hydro-Québec, as an issue. For Hydro-Québec, overflowing is a situation of hydraulic loading which cannot be taken into account for their dams. The issue presented by Hydro-Québec is a hydraulic loading leading to core overtopping, the hydraulic head remaining below the dam crest.

A summary of problems, questions and needs related to overflowing erosion that were presented by the dam and levee owners is presented in the Table 1 below.

Organization	Problems, questions and needs
UK EA	Improving guidance/assessment techniques to minimise the risk of catastrophic breach and minimise costs in maintenance. A shared data platform (collaborative home for accessible data/experience).
EDF	Need for a validated engineering numerical modelling able to represent the overflowing erosion of zoned embankment dams and the overflowing erosion of homogeneous embankments constituted with non-cohesive materials.
CNR	Need for a methodology to predict an overflowing erosion process of the CNR dikes – also delivering a time to failure.
USACE	Modelling overflowing erosion of embankments constituted with non-cohesive materials. Better knowledge of erosion resistance parameters. Wave overtopping erosion thresholds and rates.
BEA	Assessing the ageing of earth structures. Modelling the breach widening process.
Flanders HR	Better assessment of the erosion resistance of materials. Modelling overflowing erosion. Need for

	best practice for emergency measures.
Symadrem	Breach development (widening) and breach out-flow prediction. Better knowledge of erosion re-sistance parameters for various types of materials.
RWS	Overflowing erosion process behind the grass cover, for embankments constituted of various materials (from fine cohesive to coarse materials).
UK dams	Risk-based tools, delivering time to failure, grass reinforced spillways, best practice for mainte-nance.

Table 1: Summary of issues related to overflowing erosion for dam and dikes owners

2.3 Sessions 2 and 3: the state of the art

The researchers and experts who made presentations during these sessions were:

Sherry Hunt (USDA-ARS-HERU), Tony Wahl (USBR), Mark Morris (HR Wallingford), Miguel Angel Toledo (University of Madrid, UPM), Antonia Larese (CIMNE), Judith Bouchard (Hydro-Québec), Leif Lia (University of Trondheim, NTNU), Stéphane Bonelli (IRSTEA), Rémi Béguin (geophy*Consult*).

Judith Bouchard made a presentation on ongoing research performed by Hydro-Québec on core overtopping erosion. Despite this mechanism not being included in the external erosion-type processes (i.e. erosion due to a free surface flow over the top of a dam or a dike), it is an important issue for many dam owners. Very few ready-to-use engineering tools and methodologies are currently available to assess the risk of core overtopping erosion. Hydro-Québec pointed out the following research needs:

- research on contact erosion with well graded materials (till) base soil is needed
- lab experimental research representing typical HQ dam cross sections is needed
- How does erosion progress for a real dam crest where hydraulic gradients, stresses, porosity, grain size distributions, etc. vary in time and space?
- There is little information on the progression of erosion and few modelling tools available.

To address these gaps, Hydro-Québec has launched three research projects based on laboratory testing or numerical modelling [1, 2]. Preliminary observations from this research included the following:

- Erosion was initiated by piping and not at the contact parallel to the flow.
- Even if the till (core material) didn't respect filter criteria, often there was no erosion, or the erosion was started and then stopped due to paving and clogging.
- Contact erosion with well-graded base soil (till) is not only based on geometric parameters but also on water velocities.

Three presentations were focused on the failure of rockfill dams. Miguel Angel Toledo presented on rockfill dam failure mechanisms, based on real case studies (the Hans Strydom Cofferdam which failed in 1977 in South Africa and the Tous Dam which failed in 1982 in Spain) and based on medium scale laboratory testing performed at UPM [3]. The failure mechanism of rockfill dams described by Miguel Angel Toledo can be summarized as follows:

1. Erosion of the downstream rockfill. During this first phase, the downstream face of the core is exposed and remains unsupported.
2. Mechanical failure of the core (the core overturns very quickly). Lower parts of the core remain.
3. Large chunks of core material are projected far downstream the dam.

From the laboratory testing performed at UPM, the following results can be highlighted:

- Rockfill failure comprises a series of processes which can occur quickly. The dam slope determines the prevailing failure mechanism (mass sliding or particle dragging). Failure develops from the dam toe back to the crest.
- Core failure can be structural and sudden.
- Overflow discharge for rockfill failure and core failure are quite similar.

This research is still underway and is complementary-with research performed by CIMNE and presented by Antonia Larese. CIMNE research is focused on advanced numerical modelling, using the Kratos multi-physics open source platform. This numerical tool is used to model in 2D or 3D both rockfill failure and clay core failure mechanisms [4].

The research on rockfill dam failure modelling performed jointly by UPM and CIMNE has not yet led to ready-to-use engineering tools but it has already provided the important result that some overflowing erosion mechanisms in zoned embankment dams are not always governed by erosion processes, but sometimes by mechanical processes. This research needs to be continued in both large scale experimental testing and numerical modelling to provide engineering tools dedicated to the failure of clay core rockfill dams.

The third presentation dedicated to rockfill dams was presented by Leif Lia, from NTNU. Pr. Lia made an overview of the past and present research performed in Norway on the downstream erosion of rockfill dams [5, 6].

Before 2001, the main focus of this research in Norway was the stability of the dam toe, considering dumped stones. After 2001, the main focus has been the downstream slope. From 2001 to 2005 the Stability and Breaching / EC Impact project was run, including laboratory and full-scale testing. From 2011 to 2013, preliminary tests with full-scale riprap were performed. These preliminary tests were followed by the PlaF project, which ran from 2013 to 2017, and which focused on the stability of riprap on the downstream slope of rockfill dams. This project is now followed (from 2017) by the PlaF 2 project, which focuses on the design of the dam toe and steep abutments.

This extensive Norwegian research effort performed laboratory tests (H = 0.3 – 1.2m), large scale tests with full-scale materials (H = 3 – 4m) and full-scale dam tests (H = 6m). The most important parameters influencing the downstream stability were detected, as well as the critical unit discharge. The failure mechanisms were investigated. This research provides ready-to-use findings and tools for engineers. The fields which still need to be investigated are the time factor, dam toes protected by riprap and the key stones in steep abutments (ongoing research at NTNU).

Six other presentations were focused on the understanding of physical processes, numerical modelling, laboratory testing and field testing of the overflowing erosion of earth embankments.

Sherry Hunt presented an overview of the past and ongoing research performed on modelling overflowing and internal erosion of embankment dams at the USDA-ARS-HERU in Stillwater, OK [7]. The extensive research performed in this laboratory led primarily to the understanding and description of the main physical processes which occur during an overflowing erosion process of a homogeneous embankment dam constituted with a cohesive soil. This overflowing erosion process is called headcut advance and it has been modelled by a simplified and physically-based approach. This modelling approach needs erosion resistance parameters which can be derived from the Jet Erosion Test, performed in the lab or in the field. The Jet Erosion Test was also developed in this laboratory. The modelling approach led to the WinDAM engineering numerical model (Currently WinDAM C), which is a ready-to-use freeware able to predict the overflowing headcut erosion or internal erosion processes of a homogeneous cohesive embankment dam.

The HERU Project Plan – 2017 – 2022 to further improve the capabilities of the WinDAM model has the objective to predict the erosion of complex embankment geometries and composite materials, and the allowable overtopping flows for alternative materials, including articulated concrete blocks or riprap integrated with vegetation.

Tony Wahl presented the results of the second phase of the DSIG (CEATI Dam Safety Interest Group) "Erosion and Breaching of Embankment Dams" project devoted to the evaluation of dam breach models [8].

The objective of this project was to evaluate physically-based breach models by running and comparing against lab and case study data. From an initial review of breach models, three were identified as having industry potential:

- SIMBA (USDA-ARS), which evolved later into WinDAM
- HR BREACH (HR Wallingford) (which has later evolved into EMBREA)
- Firebird (Ecole Polytechnique de Montréal).

It appeared soon during this project that the Firebird model was not developed enough to be used in an engineering perspective. The evaluation was then focused on the SIMBA and HR BREACH models.

Seven case studies were chosen for modelling:

- 2 ARS dam breach tests;
- 3 tests from the Norwegian/Impact project;
- 2 real dam failures (Oros, Brazil and Banqiao, China).

The quality of case studies varied from very good to poor depending on the origin of the data.

The quality of the USDA tests was very good. There was a good knowledge of materials, compaction, in situ JET tests to measure the erodibility parameters.

The quality of the Norwegian/Impact tests was fair. Some key material properties were not well known. There were limited measurements of erodibility, and gravel materials beyond our ability to directly measure K_d. In some tests there was poor control of inflow and reservoir conditions.

The quality of the Oros and Banqiao case study data was poor, with very limited information on materials and many uncertainties about inflow, outflow and reservoir levels.

For the evaluation approach, it was decided that modelers provide two results for each application of each model to each case study:

1. An initial (blind) run based on available situation data (but not results) and group discussion of how to best interpret the limited information;
2. An improved (aware) run in which adjustment of inputs and modelling options was allowed (within reason) to gain a better fit to observed results.

The key conclusions of this project were:

- SIMBA/WinDAM and the HR-BREACH models were both very capable.
    - Similar in many aspects.
    - A few differences that gave each an advantage in specific cases.
    - Both models are being supported by organizations working to sustain their development.
- Modelling expertise of users is crucial.
    - Many options and complex interactions of erosion processes and boundary conditions.
    - User understanding of soil erodibility and availability of good information is crucial.

This project pointed out the following research needs:

- Erodibility parameters for coarse-grained soils and mixtures of coarse-and fine-grained soils are needed;
- Criteria are needed to determine when headcut erosion or surface erosion processes will develop.

Mark Morris presented a literature review on the erosion of coarser materials [9]. The context of this study started from the aim of reliably predicting breaching processes with the goal of providing industry engineers with a practical, usable, reliable breach prediction tool. The focus of this study was on the prediction of erosion of coarser materials, complementing the rigorous work undertaken by USDA-HERU on headcut erosion (through finer, cohesive materials). The conclusions of this study were:

- Factors affecting soil erodibility
    - No simple or clear method for predicting soil erodibility. No single solution found.
    - Many approaches use the excess stress equation – or some variation thereof. Unclear whether linear or more complex form (or different form altogether) is more appropriate.
- Soil erosion processes
    - We still do not know when the transition from headcut to surface erosion macro processes occurs or when surface erosion of slopes flattens, steepens, parallel retreat etc.
    - Research has focused on narrow windows of soil type and state, missing the bigger picture.

  - Starting to look at the role of seepage in relation to erodibility (including dilatancy).
  - Starting to look at the role of fines in relation to erodibility.
- Shear stress and erodibility measurement / estimation techniques
  - We have a variety of methods developed in relation to specific, observed processes (jets, holes, surface erosion etc). But, we have not resolved why we estimate different values for erodibility and critical shear stress when applying each test to the same soil.
  - Systems are typically applicable to fine material rather than coarse grained and larger. We need a solution for representing and measuring erodibility of larger sized material.
- Modelling methods and approaches
  - Computational models are advancing. 2D/3D models of breach are becoming a reality.
  - But we are lacking reliable, large scale data for a variety of soil types and conditions (as found in dams and levees) that allow us to validate those models.
  - As we learn more about breaching processes we learn more about what data we need, and what processes we should be watching as part of future large-scale tests / data collection.
- Experiments and investigations
  - There is a scatter of experiments, looking at different aspects of breach for different soils. However, most are narrowly focused.
  - We miss the big picture: an overview of processes by soil type and state, from clay to cobbles.
  - Too many tests are undertaken at too small scale meaning that processes are not correctly recreated.

The different topics which need further investigations according to this literature review are the following:

- Differences between erodibility measurement equipment;
- Develop solutions for erodibility measurement of coarser material;
- Investigate and map macro erosion processes – from headcut to surface erosion (and variations thereof);
- Collate large scale, quality data for model validation (from clay to cobbles);
- Continue investigation into specific processes (internal seepage; dilation;effect of fines).

Tony Wahl presented the research performed at USBR on the erosion testing of zoned rockfill embankments. Three medium scale dam breach tests were performed in the hydraulic laboratory of USBR during the period 2015-2017: an initial test simulated internal erosion in a homogeneous silty clay embankment and two further tests were undertaken on a zoned embankment, one test of overtopping and one test of internal erosion. The objectives of this research were to:

- observe erosion and breach development mechanics, compare to numerical models;
- Concerning materials:
  - Establish erodibility parameters of soils;
  - Demonstrate consistent relationships between applied stress, erosion resistance, and observed erosion.

The first test was modelled with WinDAM C. A good match was found for predicted breach outflows and internal erosion conduit sizes with values of input parameters close to actual conditions.

Observations from the overtopping of a zoned embankment have shown that although core and gravel zones both showed cohesive behaviour (near-vertical sidewalls), erosion did not adopt a headcut pattern. Surface erosion was dominant.

Concluding remarks included:

- Erodibility (K_d) of the gravel zone estimated from embankment test observations, matches well with JET test results.
- Understanding the erodibility of mixed gravel and cohesive soils is a big challenge as the ratio of coarse-to-fine soil changes.

- This gravel had enough fines to behave like a cohesive soil, but what about cleaner rockfills, cobbles and boulders?
- There is still uncertainty predicting when headcut erosion or surface erosion will take place.

Stephane Bonelli presented an overflowing field test system under development at IRSTEA aimed to determine the resistance of embankment soils to overflowing in the field.

The objectives of this overflowing field test were to:

- Quantify the soil resistance of the embankment to overflow;
- Be able to test the dike without modifying the soil in place;
- Better understand overflowing erosion processes;
- Better understand the relationship between overflow erosion and a jet test erosion result.

The overflowing test was performed on a real dike in the south of France, on two different sections. One section made of a homogeneous soil and another section made of a lime-treated soil. The test consisted of reproducing overflow across the dike crest and downstream slope inside a 61cm wide and 15m long channel. Flow rate, flow velocity and flow depth were measured during the tests. Terrestrial Lidar was performed during the tests to measure erosion. The maximum flow rate was 600 l/s/m, the maximum flow velocity at the downstream toe was 6 m/s, the maximum flow depth at crest was 30 cm and the test duration was 4h30’. The flow rate was increased during steps of 30’ each.

The test measurements have been used to study the overflow with both CFD numerical modelling and the Chanson model (1994). These tests have also been used to show the better resistance to overflowing erosion of the lime-treated soil compared to the non treated soil.

Rémi Béguin presented development of a Large Jet Erosion Test equipment developed jointly by geophy-*Consult* and EDF in order to estimate the erosion resistance of coarser materials, as the classical Jet Erosion Test is suitable for soil with no or few particles larger than 5mm. The Large JET can be used with three different diameters of the nozzle head: 6.35mm (as the classical JET), 10mm and 20mm. This Large JET has been validated by comparison with the classical JET. It provides a wider operating range and expands measurement possibilities. However, several questions remain open:

- In which cases can we perform tests on soil < 5mm and use the result to predict the behaviour of the undisturbed soil?
- What is the influence of the nozzle diameter on JET test results for fine soils? For coarse soils? Which diameter should be used for what?
- What is the best method to deal with coarse particles that stay inside the jet test scour hole?

2.4 Session 4: what gaps need to be filled?

During Session 4, research gaps which need to be addressed were discussed and were structured into 4 themes:

1. Zoned rockfill embankments
2. Homogeneous structures with coarser materials
3. Homogeneous structures with finer materials
4. Widely applicable, cross cutting issues.

For the zoned rockfill embankments, the main gaps in knowledge which should lead to upcoming research are the following:

- Mechanical failure of the core;
- Erosion failure of the core;
- Erosion / sliding of the downstream shell / riprap;
- Failure of any concrete / bituminous face;
- Development and validation of numerical models (including defining and how to determine key modelling parameters).

For the homogeneous structures with coarser materials, the main gaps in knowledge which should lead to upcoming research are the following:

- Investigation and definition of macro erosion processes (ranging headcut to surface erosion to rockfill);
- Development and validation of engineering models (including defining and how to determine key modelling parameters);

- Extension and validation of models to address layers and zones of different material erodibility within the structure.

For the homogeneous structures with finer materials, the main gaps in knowledge which should lead to upcoming research are the following:

- Adding complex geometries;
- Adding zoning (different layers and erodibilities);

Widely applicable and cross cutting issues which should lead to upcoming research are the following:

- Grass performance (strength and limitations of grass cover to resist overflow and delay the onset of the breach processes);
- Effects of woody vegetation on overflow erosion;
- Performance of surface reinforcement systems;
- Performance of riprap;
- Effect of hard cover (roads, etc) on inhibiting erosion;
- Transitions (geometric, structure interactions).

3 Part II: Overflowing erosion of bedrock downstream of concrete dams

3.1 Objectives of Part II

Part II was introduced by a key note lecture given by John France (Aecom, USA) regarding the Oroville 2017 incident. As the leader of the of the forensic team, the incident was presented in detail. Root failure causes were explained including design and construction issues, but also systemic factors regarding long term maintenance and surveillance of large dams and appurtenant structures such as spillways.

As per Part I, Part II of the workshop, dedicated to overflowing erosion of bedrock downstream of concrete dams, was structured in four sessions:

Session 5 was focused on the problems, questions and needs of concrete dam owners:

- Is bedrock overflowing erosion an issue?
- What kind of problems associated with overflowing erosion need to be solved?
- Is the engineering toolbox satisfactory?

The synthesis of Session 5 will help answering the question: what gaps need to be filled?

Sessions 6 and 7 were devoted to a presentation of the state of the art by researchers and experts with the aim to answer the following questions:

- What problems are already properly solved with an engineering perspective? Which tools and methodologies are available to engineers?
- What research is under development?
- What should the main topics and direction be to answer the questions that came earlier from concrete dam owners?

The synthesis of Sessions 6 and 7 will allow to complete the answer the question: what gaps need to be filled? These sessions also provided an answer to the question: what are the main lines of an international research project to fill these gaps?

Session 8 was a synthesis of Part II, focused on how to move forward to launch an international research project to fill the gaps:

- Which organizations would be ready to fund such an international research project(s)?

Which research teams could be involved to perform this research project?

3.2 Session 5: the dam owners' perspectives: issues and engineering needs

A summary of problems, questions and needs related to overflowing erosion that were presented by the concrete dam owners is provided in Table 2 below.

Organization	Problems, questions and needs
VERBUND (Austria)	Need for a validated engineering numerical modelling able to represent the overflowing erosion of bedrock downstream of a dam, including the banks and dam abutments. Need to clarify design rules for energy dissipation structures (extension, length). Need a method to take into account the flow energy rather than the power for short overflowing events.
ALPIQ (Switzerland)	Need for improved engineering method to assess rock erosion strength. Need a method to take into account the flow energy rather than the power for short overflowing events.
EDF (France)	Need for an improved engineering method to assess rock erosion strength. Assessing the

	power stream when overflowing over a concrete gravity dam in addition to classical free plunging jet. Need a method to take into account the flow energy rather than the power for short overflowing events.
EDP (Portugal)	Need for in-situ measurement of water velocity and pressures. Design of economical mitigation measures against erosion.
UNIPER (Sweden)	Assessment of residual risks and margins. Design of cheap mitigation or protection measures such as rock bolts.
NTNU (Norwegian University of Science and Technology	Rock erosion strength against extreme floods. Time and stream power dependence for extreme floods compared to usual flood events.
UK Dams	Need of tools for rock erosion risk analysis. Assessment of failure mode: fragile or ductile. Damage estimate, rate of scour and time dependence
Vietnam Dams	Quantification of stream power, β factor (Mason, Irvine)
HydroQuebec (Canda)	Effect of rock excavation with explosives on rock erosion index, consistent method to determine stream power, improvement of gates operation to minimize rock erosion
USBR (USA)	Scour rate and taking into account time / energy rather than power. Assessment of dynamic pressures and stream power. Set up data bases of downstream geology. Improvement of modern tools to carry out accurate downstream rock topographic surveys.

Table 2: Summary of issues related to overflowing erosion for concrete dam owners

3.3 Sessions 6 and 7: the state of the art

The researchers and experts who made presentations during these sessions were:

Stefano Pagliara (Pisa University, Italy), Luis Castillo / Jose Carrillo (Cartagena University, Spain), Yvan Berkowitz and Gregory Guyot (EDF Lab and EDF CIH), Tony Wahl (USBR, USA), Ali Saedi and Lamine Boumaiza (HydroQuebec and UQAC university, Canada), Johannes Wibowo (USACE, USA), Pedro Manso (EPFL Lausanne university, Switzerland), Lucie Alazard (Artelia, France).

Four keynote lectures were also given by George Annandale (USA), Steven Pells and Kurt Douglas (Australia), Mike George (USA) and Anton Schleiss (Switzerland).

Stefano Pagliara presented the effect of plunging jets on erodible foundations. Erosion versus time was studied and a logarithmic based law was proposed. The influence of crossing plunging jets was also studied. Pr Castillo presented research work on stream power of plunging jets. A numerical approach (flow3D) was also proposed to try and simulate the flow properties in rock cracks. Results were very preliminary and still required much development. The use of numerical methods to properly assessed highly complex hydraulics of plunging jets on cracked rock remains an accurate issue regarding the phenomenon to be observed (effects of turbulence in cracks, high frequency “hammer” pulsations etc..).

Gregory Guyot and Yvan Berkowitz presented two experimental set-ups developed by EDF to study the characteristics and effects of plunging jets in the EDF Lab and CERG lab facilities. The EDF Lab installation allows study of a 15 m high plunging jet into a 2 m high pool. The CERG installation shows a 12 m high plunging circular jet into a 10 m high dissipation pool. Research work is ongoing. These large-scale experimental facilities provide very consistent results with fewer scale effects. It has already provided interesting results regarding length and modes of disintegration EDF highlighted that the EDF Lab experimental facilities could be made available to any research team which would like to use it for further experiments.

Tony Wahl (USBR) presented some of the research actions led by USBR. An internal USBR publication (2007, Frizell) was noted, assessing the uplift pressures under spillway chutes according to joint slab properties. Following Oroville, USBR is launching further research projects to try and design “modern’ construction joints, and to assess the strength of waterstop joints. The propagation of uplift pressures in plain concrete cracks will also be studied and numerical hydraulic simulation (flow3D) undertaken.

HQ and UQAC presented their research on a better assessment of the Kirsten erosion index. Emphasis was laid upon the assessment of the Js factor, representing the influence of the rock cracks orientation against the main flow direction.

Johannes Wibowow (USACE) presented research works regarding risk analysis tools based on available Annandale data. It aimed at providing failure probability rather than deterministic yes / no methods. This topic is an important need with regards to the development of risk analysis tools for dam safety in general.

Lucie Alazard (Artelia) presented the volumetric stream power index which is supposed to provide the dumping effect of the plunge pool. The method was developed based on observations made on the Marèges dam (France). In addition, Artelia underlines principles of energy dissipation upstream of the jet by the use of systems such as Colonel Roberts splitters (Katse dam, Lesotho…). Other tools are available (aeration of jet, increase of jet downstream area) and can also be used to dramatically decrease the downstream stream power.

Session 7 was introduced by a key note lecture given by George Annandale (USA). 30 years of research work was presented. We were reminded about the semi-empirical "Annandale" method including its limits and research needs. The method was compared to Van Schalkwirk and Pells approaches. Annandale presented a preliminary approach to take time and energy into account. Rock erosion mitigation solutions were also presented. Annandale underlined the importance of a smart design reducing the impacts of stream power (splitters, water jet spatial distribution …).

S. Pells and J. Douglas presented their research work undertaen in Australia. Pells proposed another erodability index by replacing the Kisten Index by the e-GSI index. Pells opinion was that the Kisten index assessment was not reliable enough and might strongly depend upon the geologist carrying out the field observations.

Mike George (USA) presented a detailed description of the failure modes and destabilization of fractured rock. In-situ, full scale experiments were carried out. He also studied the kinematics of rock extractions for tangential flows. He emphasised the requirement to know the downstream topography precisely before and after flood events.

Finally Anton Schleiss (EPFL) summarized research work carried out over the past 20 years in Switzerland. Complex hydraulic behaviour such as hammer strokes and high frequency waves were underlined. They form an essential part of the destruction of fractured rock. Anton Schleiss explained the differences between fragile failure modes and ductile failure modes by fatigue (such as water pulsation in rock cracks). The Kariba case study was also presented with both numerical and physical models. Proposed mitigation measures were also presented. According to historical flood events on dams, it was noted that equilibrium profile in the downstream plunge profile was sometimes reached for overflowing duration time between 100 and 300 h. This figure shall be considered as typical duration as a first approach. It can vary a lot from one dam to another one .

3.4 Session 8: what gaps need to be filled?

During Session 8, gaps which need to be filled were discussed and were structured into 6 themes:

- Stream Power assessment
- Rate of scour and time-energy dependence
- Numerical simulation
- Geological model and erodibility index
- Data base of floods and overflowing events
- Mitigation measures

For Theme 1 "Stream Power", the main gaps in knowledge which should lead to upcoming research are the following:

- Stream power and energy calculation
- Stream power of overflowing flows across concrete gravity dams
- Stream power of water jet impacting downstream rock without a downstream water level

For Theme 2 "Rate of scour and time-energy dependence ", the main gaps in knowledge which should lead to upcoming research were the following:

- Cumulative energy versus instantaneous power
- Failure mode determination (fatigue, fragility..)
- Development of analytical formulas to quantify scour rate.
- Spatial distribution of energy in the plunge pool.

For Theme 3 "Numerical simulation ", the main gaps in knowledge which should lead to upcoming research were the following:

- Open question. There currently is no available hydraulic numerical model able to properly simulate complex flow patterns at very different scales (air / water mix, turbulences, flow in small cracks etc…).

For Theme 4 "Geological model and erodibility index ", the main gaps in knowledge which should lead to upcoming research were the following:

- What erodibility index (Kisten, e-GSI…)
- Knowledge required to analyse impact of changes in fault and discontinuity characteristics on the scour of rock
- Identify and quantify the role of faults, shear zones and 3D geologic structure (kinematics) on scour progression in rock masses.
- Changes in rock mass properties as scour progresses; how is rock removability affected / narrative on approach

For Theme 5 "Data base of floods and overflowing events ", the main gaps in knowledge which should lead to upcoming research are the following:

- Lack of adequate field data. Collect discharge events from dams/spillways are typically well documented for flow magnitude and duration such that each discharge is essentially a large-scale erosion test. Correlate scour quantities over multiple discharges events. Develop insight into erosion rates in rock to be used as benchmarks for calibration of scour models.
- Research could focus on the use of high resolution remote sensing technologies and/or field instrumentation to document 3D scour geometries before/after flood events as well as flow conditions during flood events

For Theme 6 "Mitigation measures ", the main gaps in knowledge which should lead to upcoming research are the following:

- Lack of guidance on how to approach mitigation design. Design of rock anchors to stabilize rock subject to the erosive capacity of flowing water. Development of design criteria
- Risk Analysis / Decision Making Methods to assess the reliability / risk of certain conditions of rock and hydraulic loading; when to do what? Development / write up of risk analysis procedures / way to calculate risk and reliability

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