Ultimate overflow resistance of concrete dams

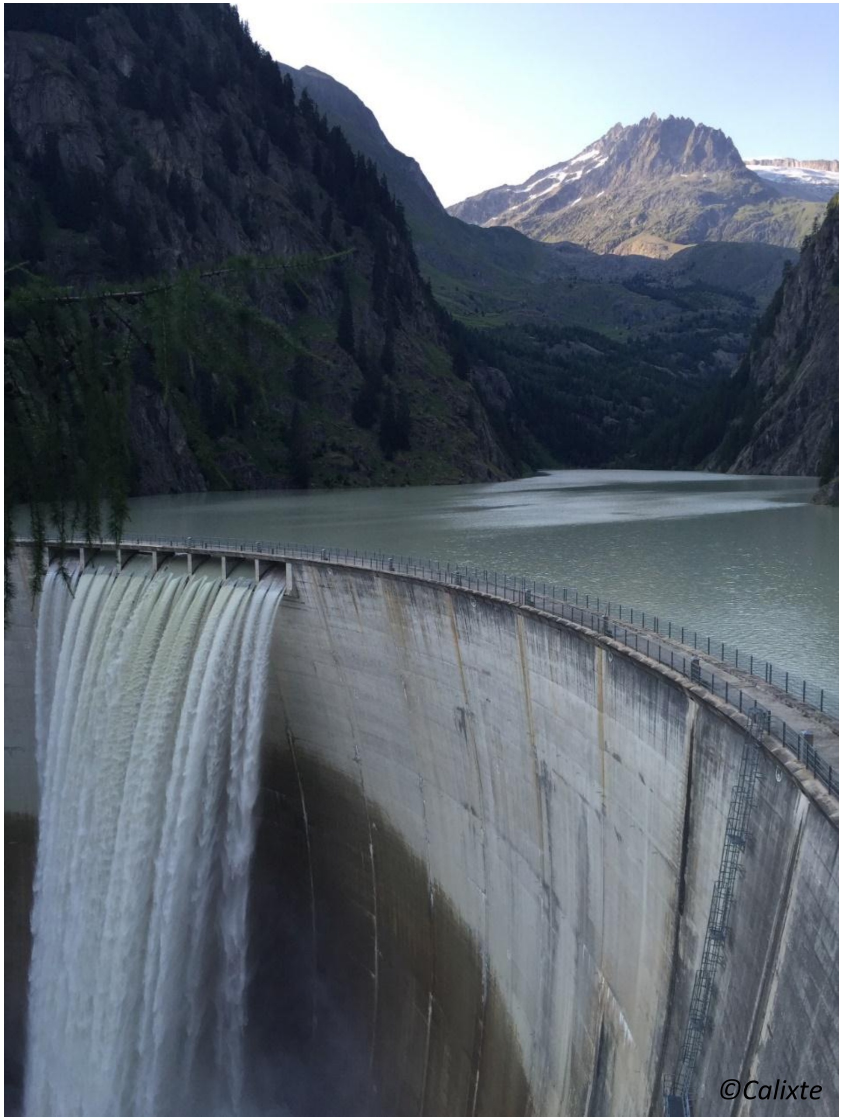
State-of-the-art practice and open questions

Dr Pedro MANSO

13-14 December – Aussois, France

Outline

1. Historical cases
2. Research on rock scour
3. Dam safety regulations
4. State-of-the-art practice
5. Open questions and missing design criteria



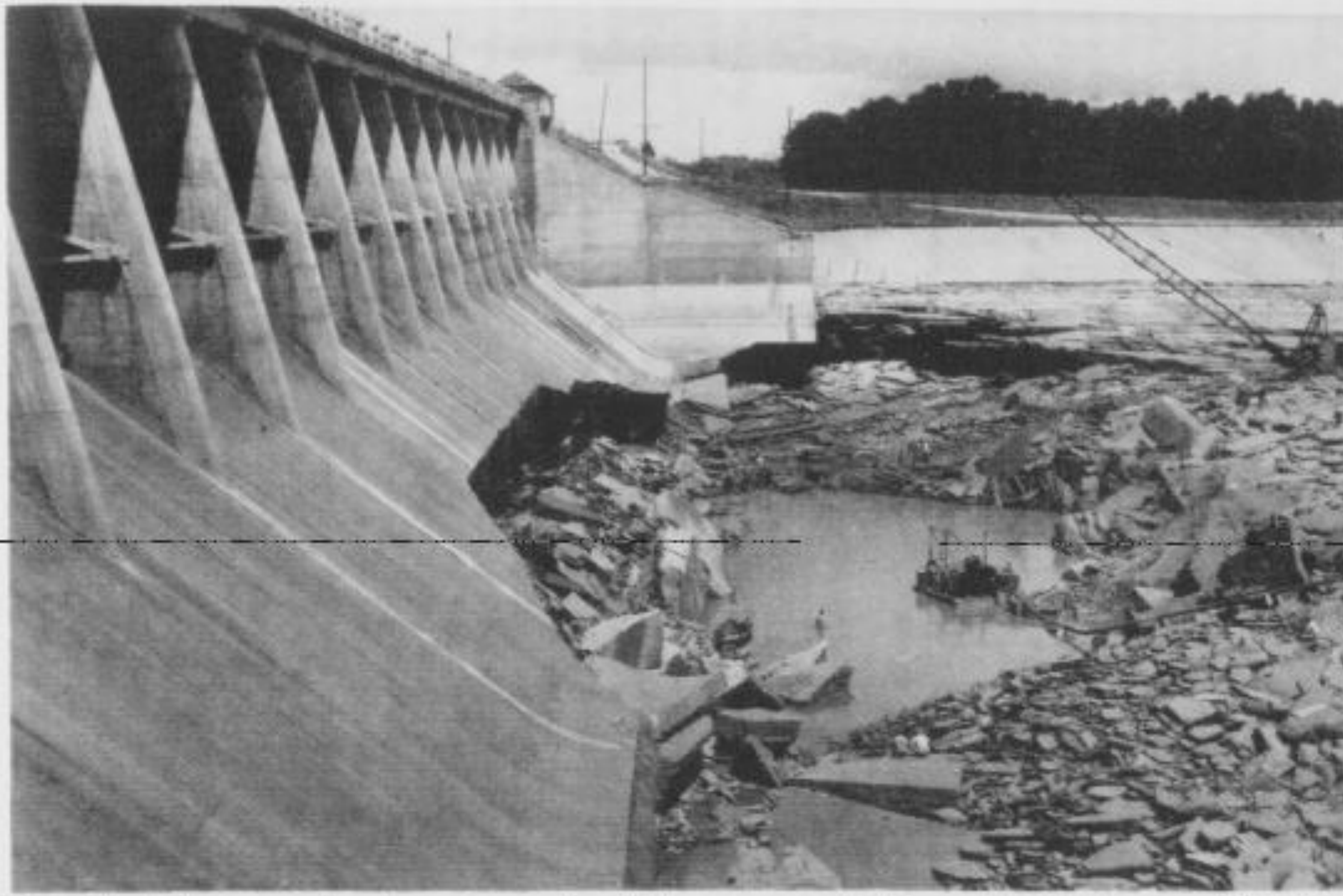


FIG. 20-4. Damage due to scour and uplift pressure at Waco Dam, Texas. (*Courtesy of Waco City Water Department.*)

Elevatorski, (1959)

Cambambe dam, Angola

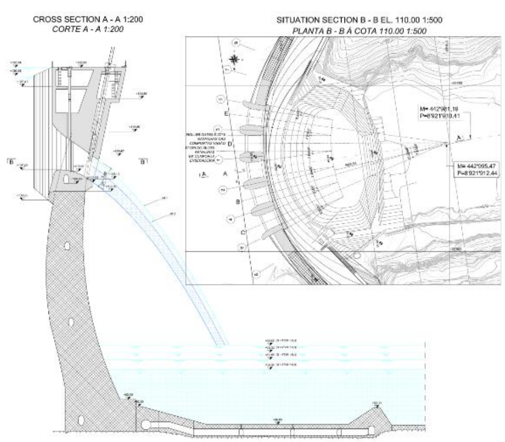
Downstream View

Cambambe dam heightening

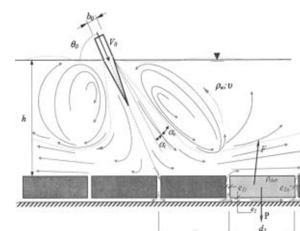
1963-2012

>2015

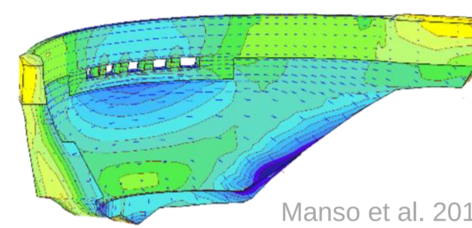
ENE, Angola
Odebrecht
Stucky



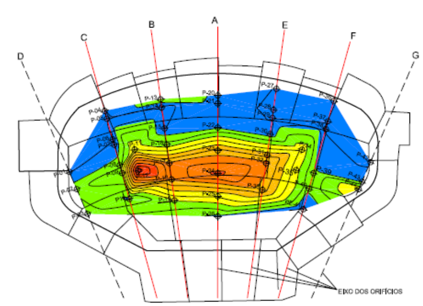
Hydraulic model studies at CEHPAR, Curitiba, BR

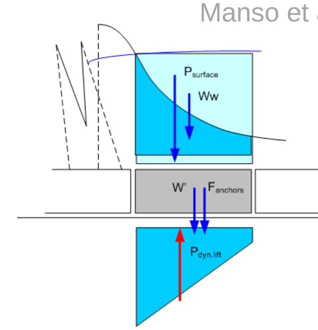


Melo et al. 2006



Manso et al. 2012
Manso et al. 2013





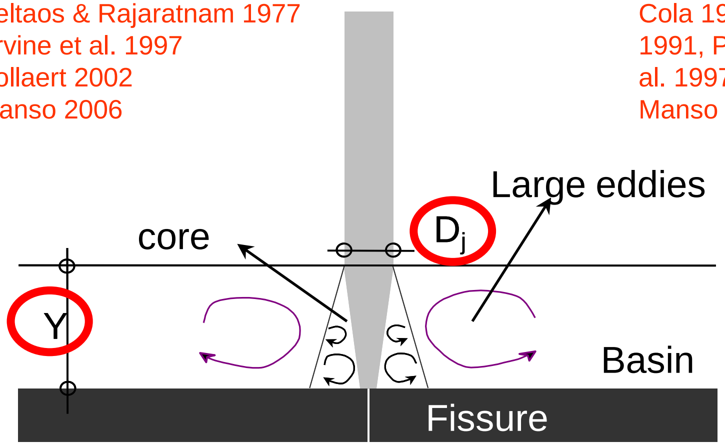
Physical model studies at CEHPAR

Heightened Cambambe dam, Angola

Impact conditions in flat surfaces

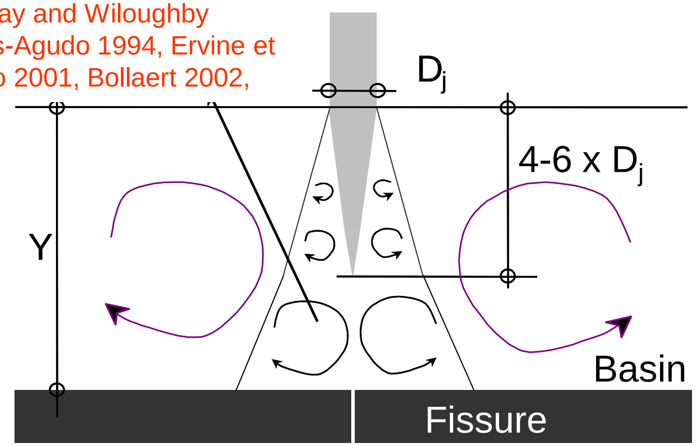
Core impact

Beltaos & Rajaratnam 1977
Ervine et al. 1997
Bollaert 2002
Manso 2006



Developed jet impact

Cola 1965, May and Wiloughby 1991, Puertas-Agudo 1994, Ervine et al. 1997, Melo 2001, Bollaert 2002, Manso 2006



Shallow pools

. High mean pressures

. Low fluctuations

. Y < 4 – 6 D

. Unaerated core

Deep pools

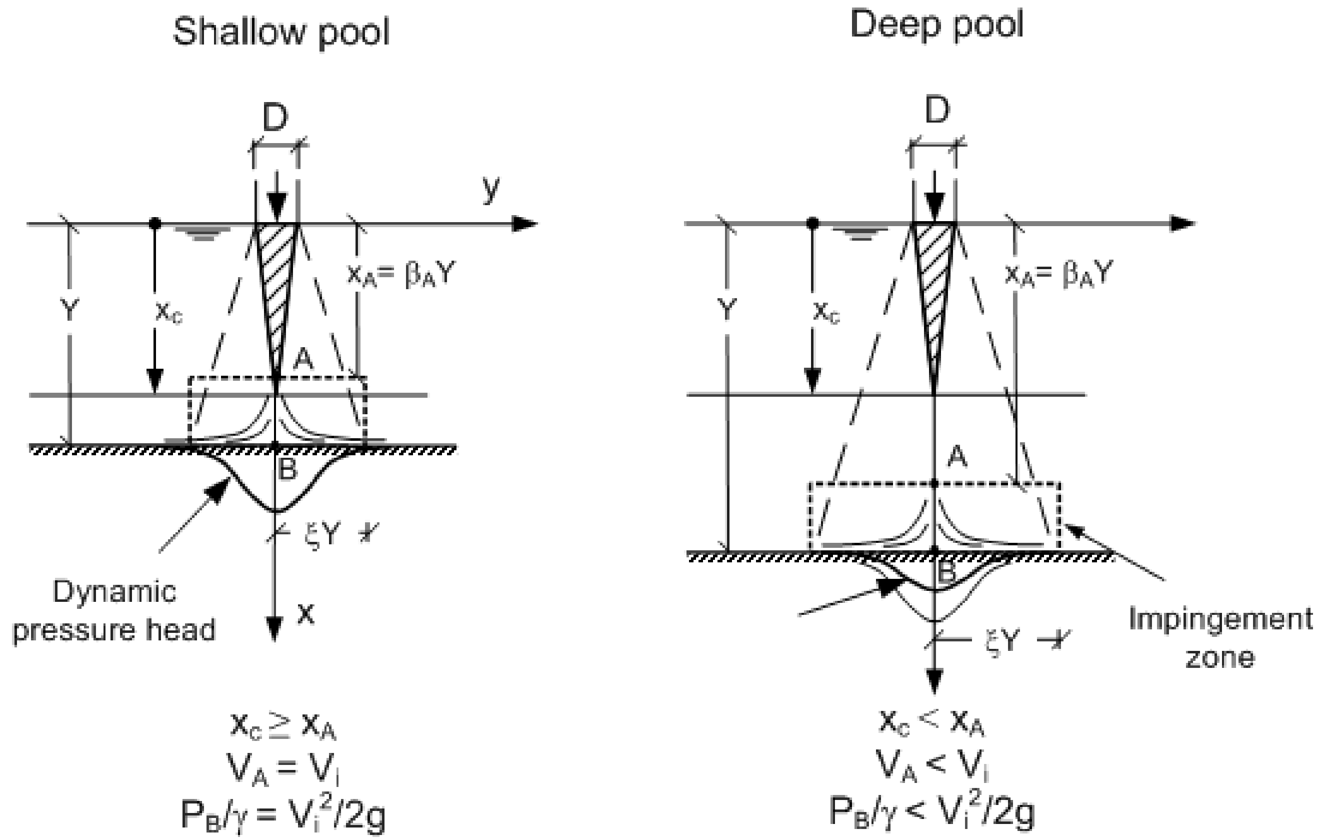
. Low mean pressures

. High fluctuations

. Y > 4 – 6 D

. Air-water shear layer

Limited-depth diffusion model (LDDM)

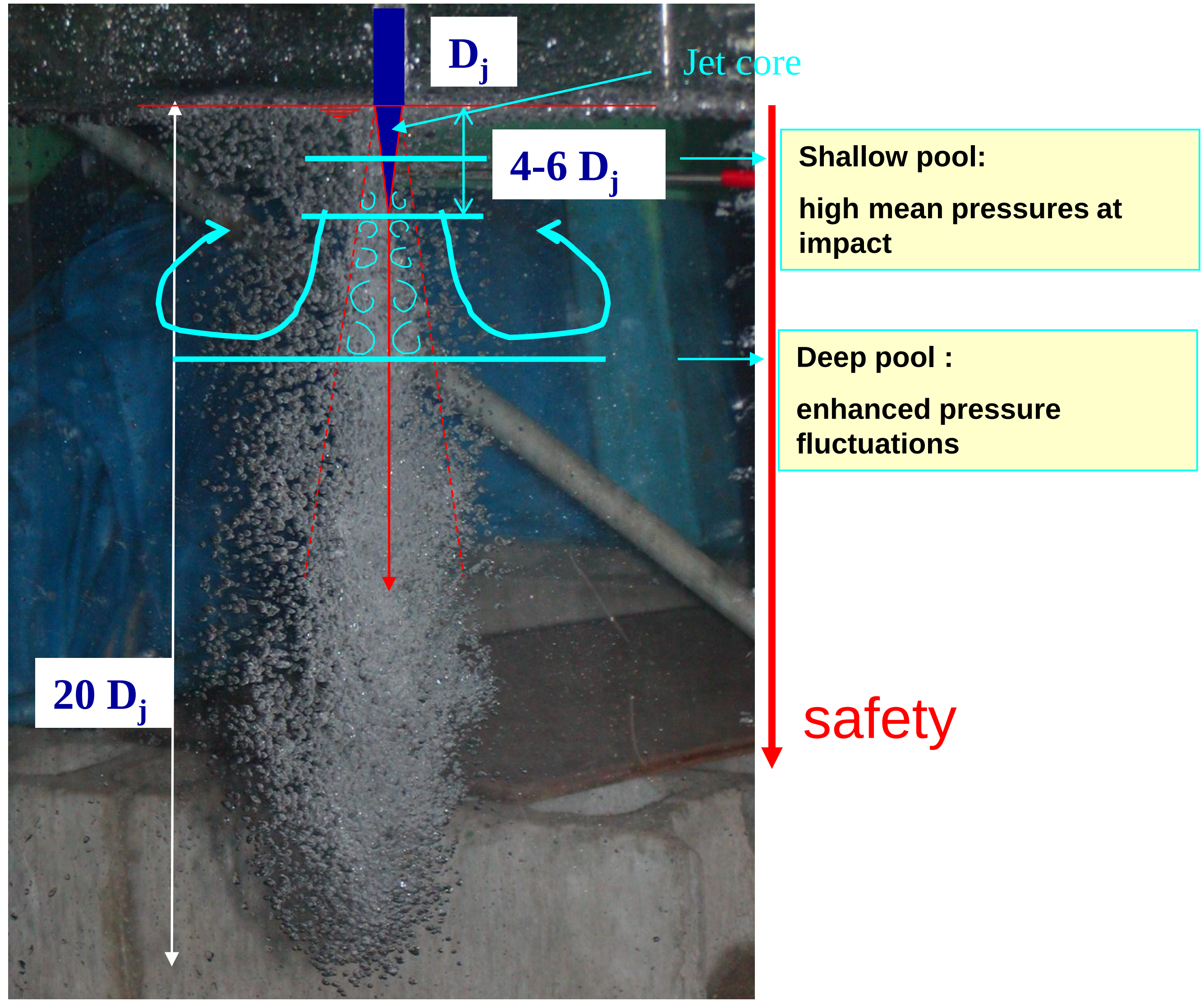


Manso 2006
Manso et al. 2009, JHE

energy dissipation efficiency $\eta = \dfrac{E_1 - E_2}{E_1}$

$$E_2 = \frac{P_B}{\gamma} = \frac{V_i^2}{2g} \quad \text{for } Y < \frac{C_d.D_i}{\beta_A}$$

$$E_2 = \frac{P_B}{\gamma} = \left[\frac{C_v D_i V_i}{\beta A Y}\right]^2 \frac{1}{2g}(1 - C_{air})^{1.345} \quad \text{for } Y > \frac{C_d.D_i}{\beta_A}$$



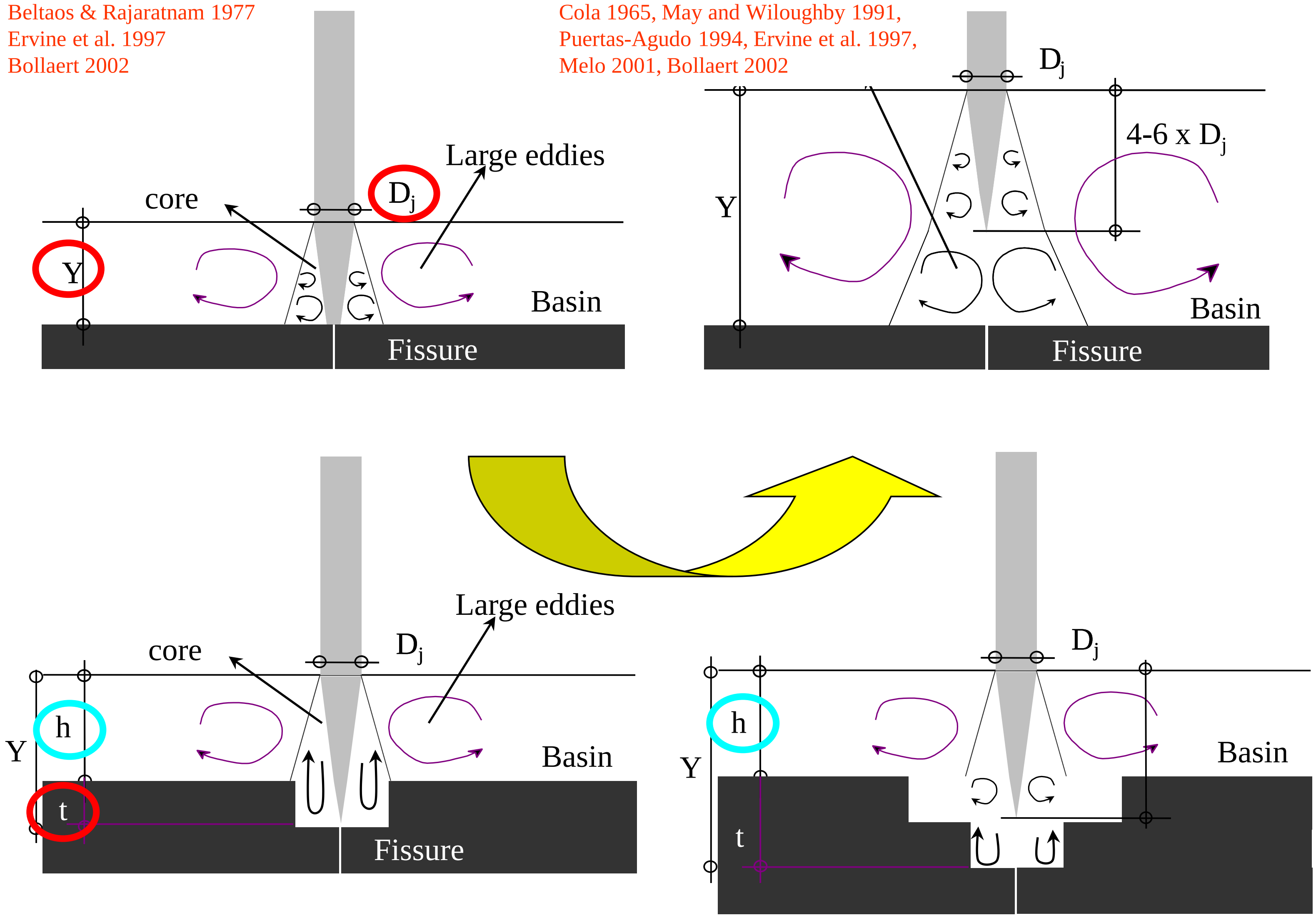
Hartung & Häusler (1973) :

•70 to 85% of the E_c is dissipated at 20Dj

•Purely hydrodynamic estimate of t_u

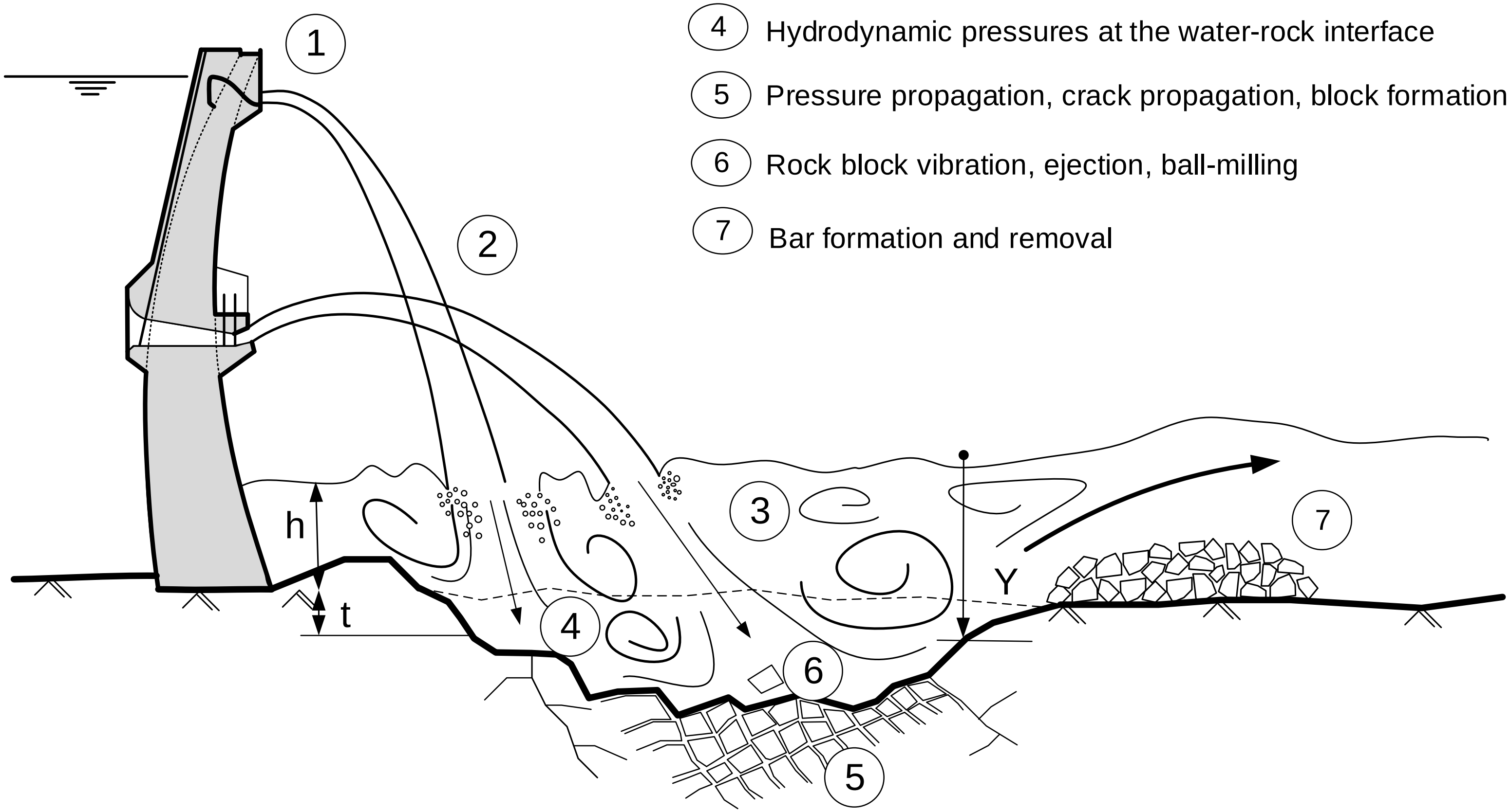
Photo courtesy of H. CHANSON,
Queensland University, Australia

Impact conditions



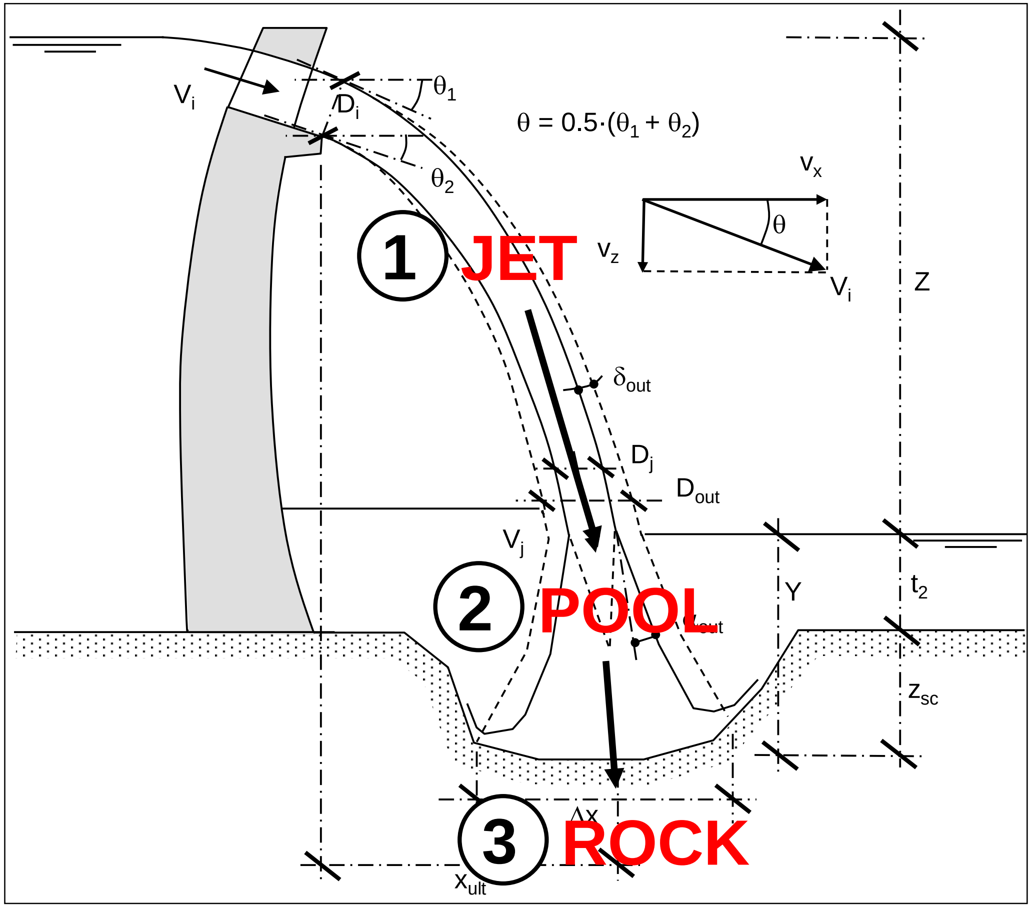
Conceptual rock scour

1. Jet issuance
2. Jet diffusion in the air (spreading and core contraction)
3. Jet diffusion in the water, macroturbulent pool flows
4. Hydrodynamic pressures at the water-rock interface
5. Pressure propagation, crack propagation, block formation
6. Rock block vibration, ejection, ball-milling
7. Bar formation and removal



EPFL scour model – SM

(Bollaert & Schleiss 2005, Manso 2006, Federspiel 2010, Duarte 2014)



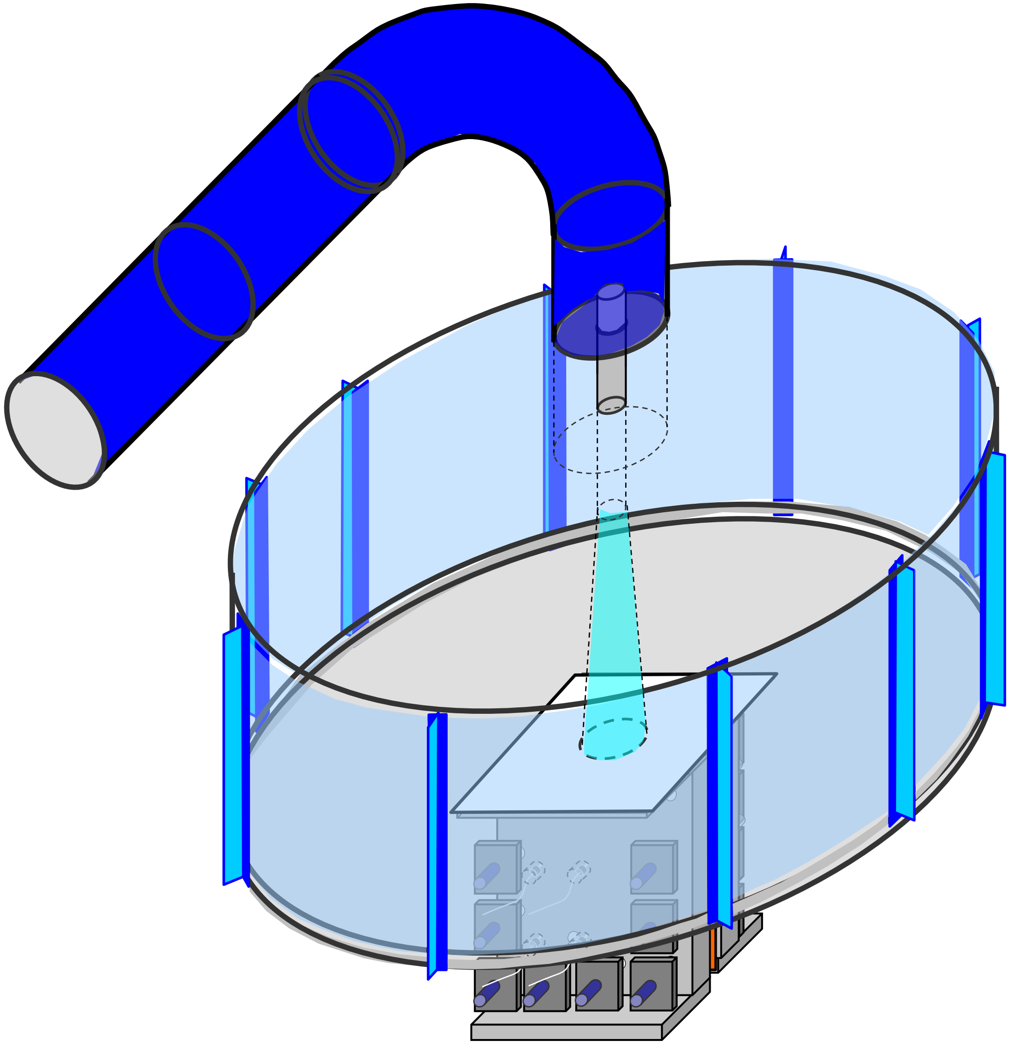
- Physically based
- Transient pressures
- Time-evolution

Flat bottom
Confined pools

FM model for crack propagation
Instantaneous pressure values for confined pools

Block displacement
1D….2D….and 3D models

Experimental installation (III)



EPFL-LCH facility in operation

Laterally confined pools

Manso 2006
Manso et al. 2009, JHE

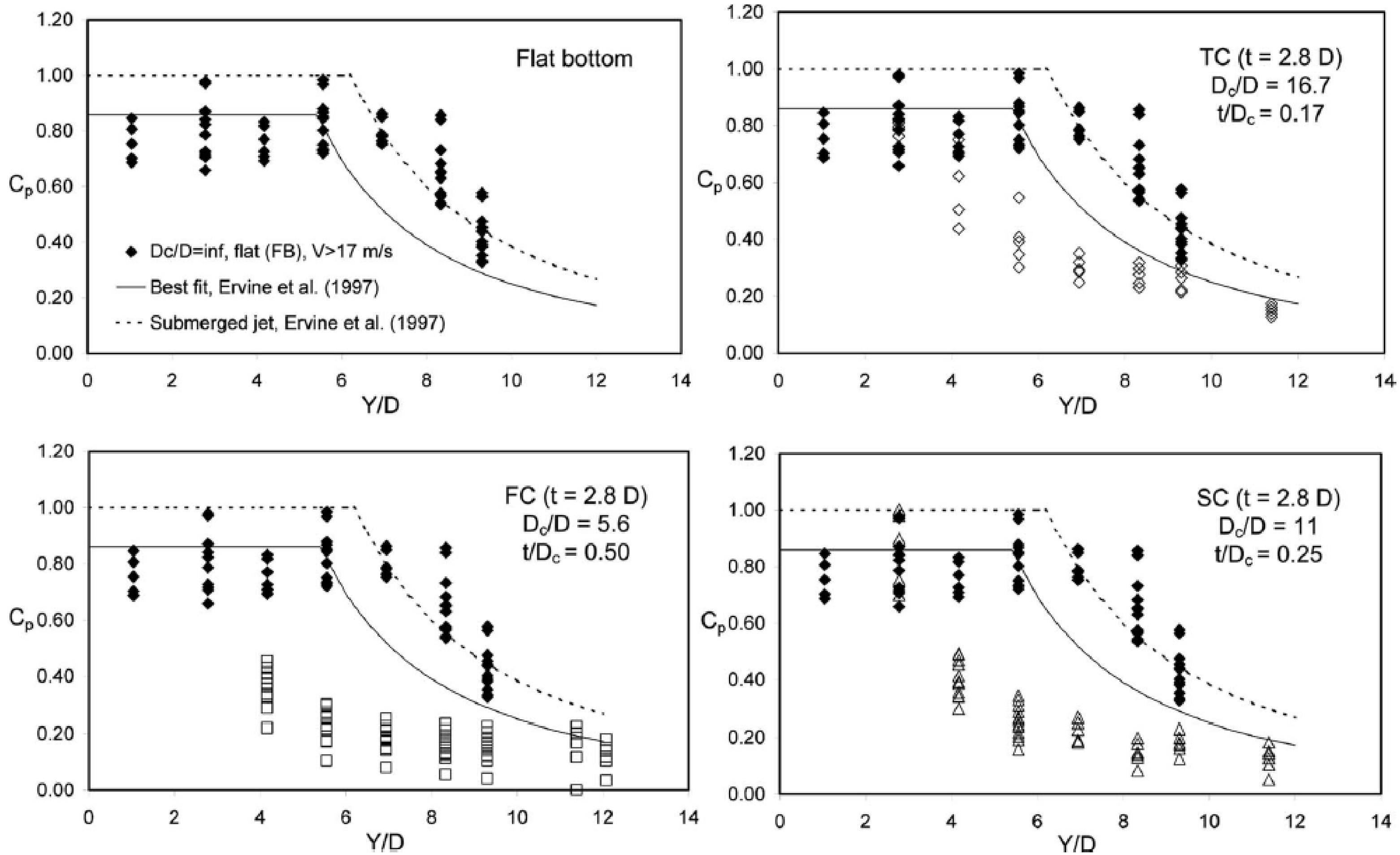


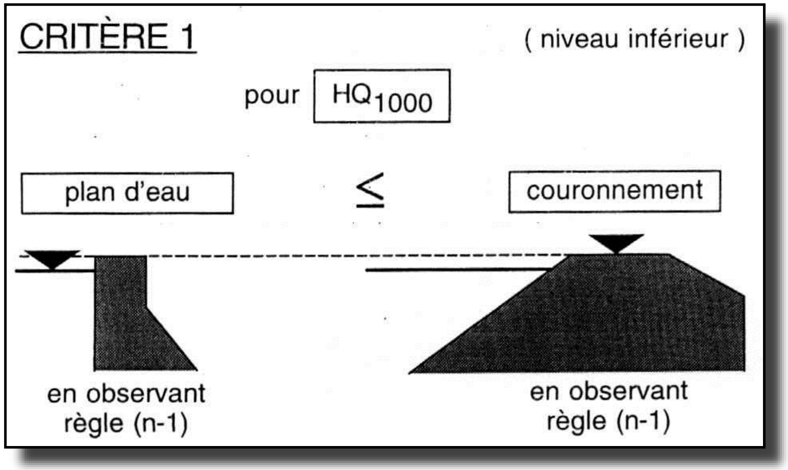
Fig. 7. Dimensionless mean dynamic pressure coefficient C_p close to the jet axis ($y/D=0.35$) as a function of Y/D, for laterally unconfined pools (FB ♦) and laterally confined pools (wide ◇, intermediate □, narrow △). Comparison with Ervine et al. (1997)'s best fit of data (continuous line) and submerged jet data (dotted line). All FC, SC, and TC geometry data for $t/D=2.8$ and $V>17$ m/s($F=20.5-35.1$).

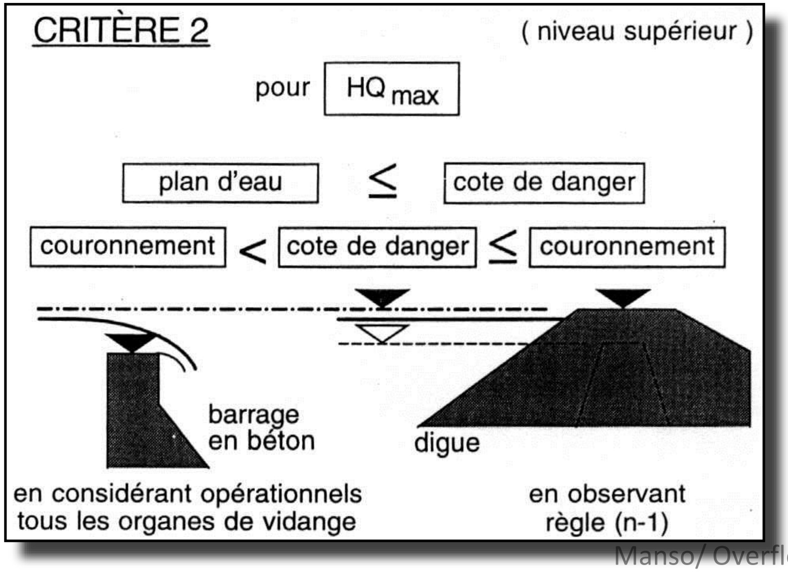
State-of-the-art practice

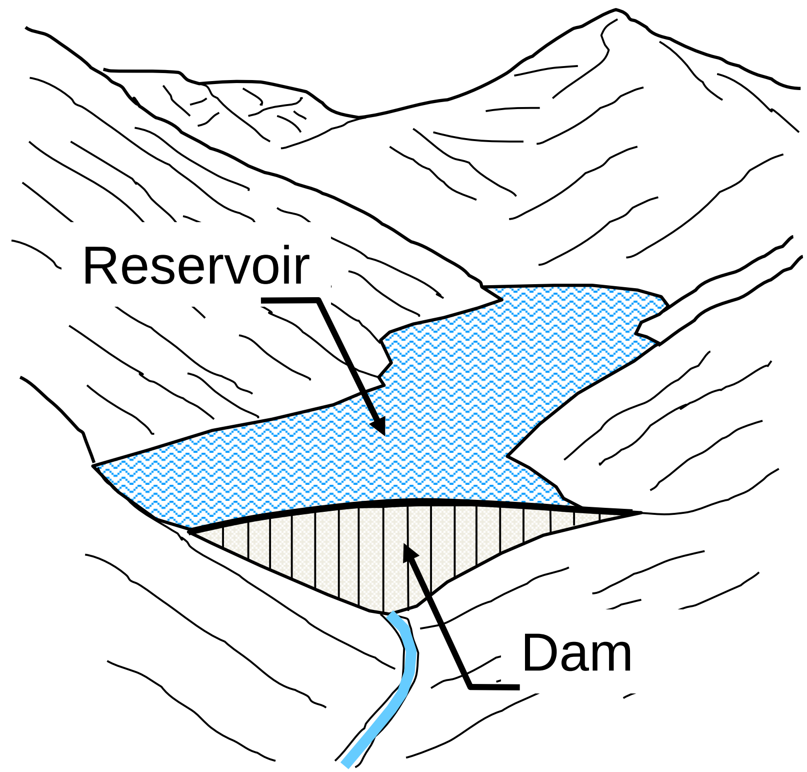
- No-overflow allowed in most countries
- Physical model tests for beyond safety-check Qs
- Empirical and semi-empirical formulations
- EPFL scour model
- Lessons from controlled spilling directly at concrete dam foundations

State-of-the-art practice

Dam safety regulations in Switzerland







State-of-the-art practice

- Scour control at concrete dam toe

Crest

- Clear of obstacles
- Hydrodynamic take off (thin nappes !)
- Splitters
- Partial overflow crest length

Fall

- Free fall (variable length)
- Guided (e.g. convergent)
- With/without nappe aerators

Impact

- Rock overlays / aprons/ plinth with joints
- Rock bolting / anchoring
- Scaling of weathered rock
- Mass concrete blocks with few joints
- Increased tailwater (sill with/without narrowing)

Dam

- Limit equilibrium at selected levels
- Increased uplift?
- Sliding resistance
- Drag effects?
- Overturning resistance

Open questions

- Engineering design issues or research?
- Residual risk management vs. underrated spillways
- Geometry effects
  - Convergent flows: when dissipative or erosive?
  - Effectiveness of d/s cushion?
  - Flaws, joints and faults
  - Arch vs. Gravity profiles
  - Vertical vs. horizontal splitters
- Time effects
  - Duration of overflow vs. abutment/foundation uplift pressures
  - Duration x power: can the total energy be used as KPI?
  - Exposed rock: protected today, weathered tomorrow
  - Long-duration overflow proxies (Cambambe)
  - Pool inertia

Missing design criteria

System scale

- Flood return period in cascades with routing capacity

Combined probabilities

- Reservoir backwater effects and extension of owner's liability

Dam site scale

- Arch dam crest design
- Cross-valley nappe aeration
- Gravity dam crest & d/s face design
- Criteria for d/s preventive works
- Overflow resistant concrete joints
- Armoured doors?
- Scour rates ?
- Impact of LWD?
- Engineering scour tool with large number of users

Acknowledgments

- FCT, Portugal
- FOEn Switzerland
- EPFL-LCH, Switzerland
- LAHE-Furnas, Brazil
- IPH-UFGRS, Brazil
- IST, Portugal
- University Trieste, Italy
- Stucky, Switzerland
- ENE, Angola
- CEHPAR, Brazil
- ODEBRECHT & ENGEVIX, Brazil
- All team members from various projects

Backcutting scour progress at Estreito dam, Rio Grande, Brazil
[source: CBDB, 2006]

pedro.manso@epfl.ch