LABORATOIRE DE CONSTRUCTIONS HYDRAULIQUES

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

The challenge of scour management at high head and high capacity spillways of concrete dams

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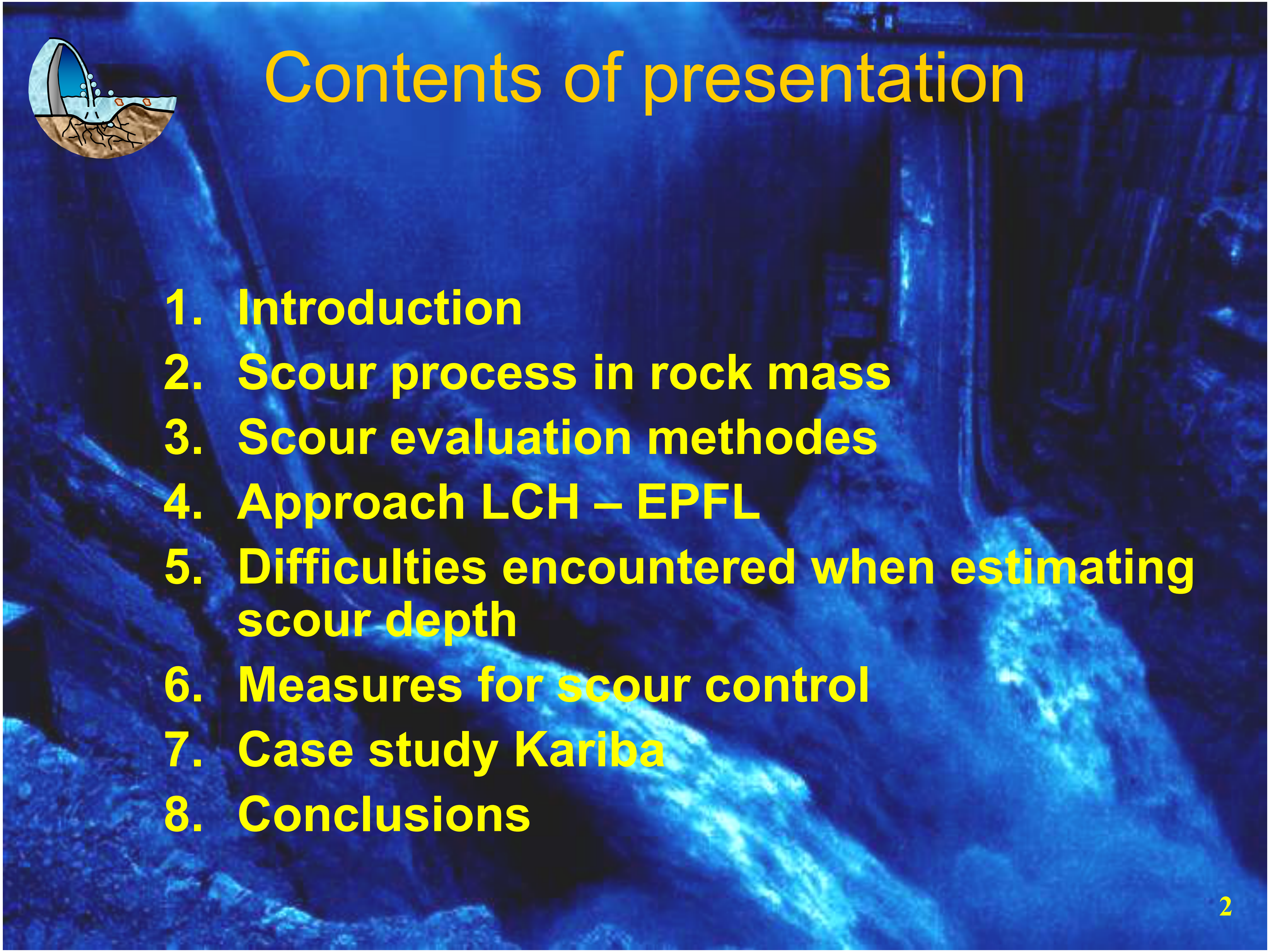
International Workshop on overflowing erosion of dams and dikes
11 – 14th December 2017 - AUSSOIS, FRANCE



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2. Scour process in rock mass
3. Scour evaluation methodes
4. Approach LCH – EPFL
5. Difficulties encountered when estimating scour depth
6. Measures for scour control
7. Case study Kariba
8. Conclusions

1.Introduction

Safety of dams during flood events

Design criteria

☐ Project flood: typically 1’000-years flood
☐ Safety check flood: 10’000 years flood or PMF

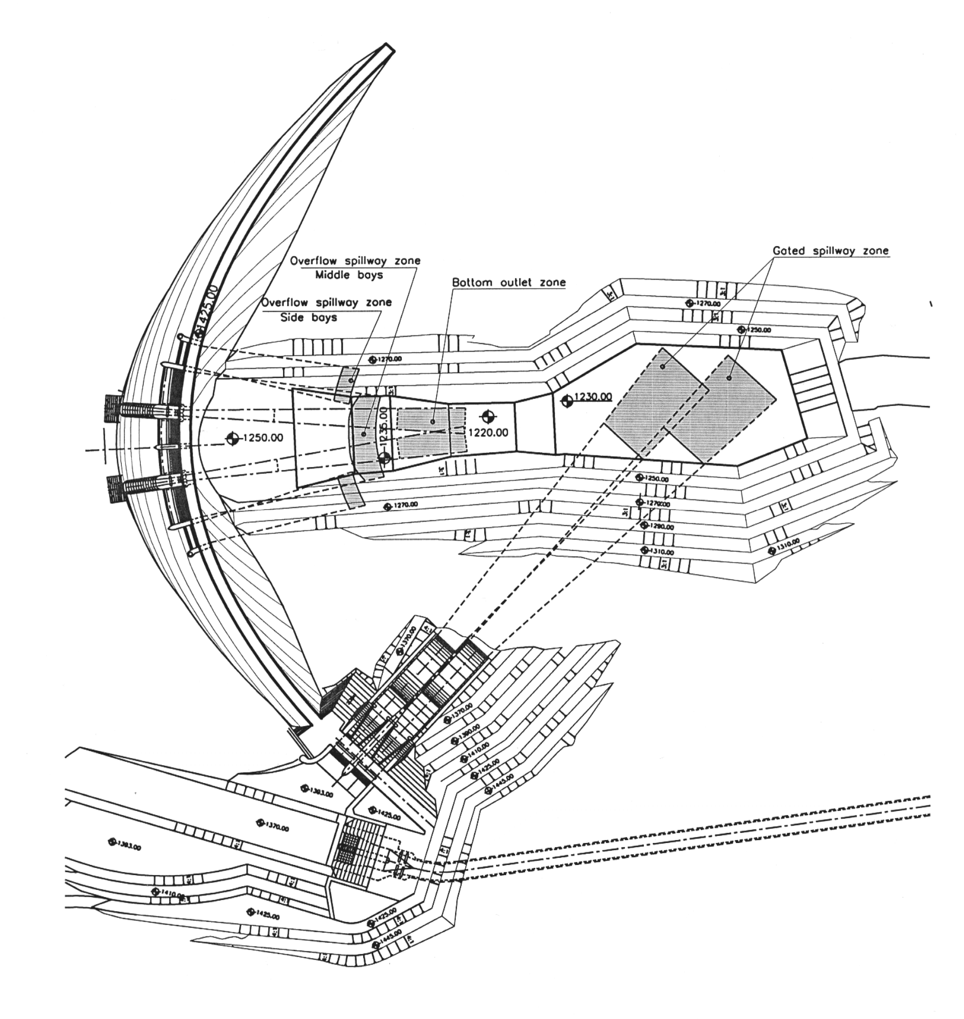
High-velocity jets and scouring

- at concrete dams where spillways are combined with the dam structure
- Gated or ungated crest spillways (arch dams only)
- Chute spillways followed by a ski-jump
- Orifice spillways

1. Introduction

High scour potential at high concrete arch dams in narrow valleys

Example of Khersan III Dam Project in Iran



Spillway facilities:

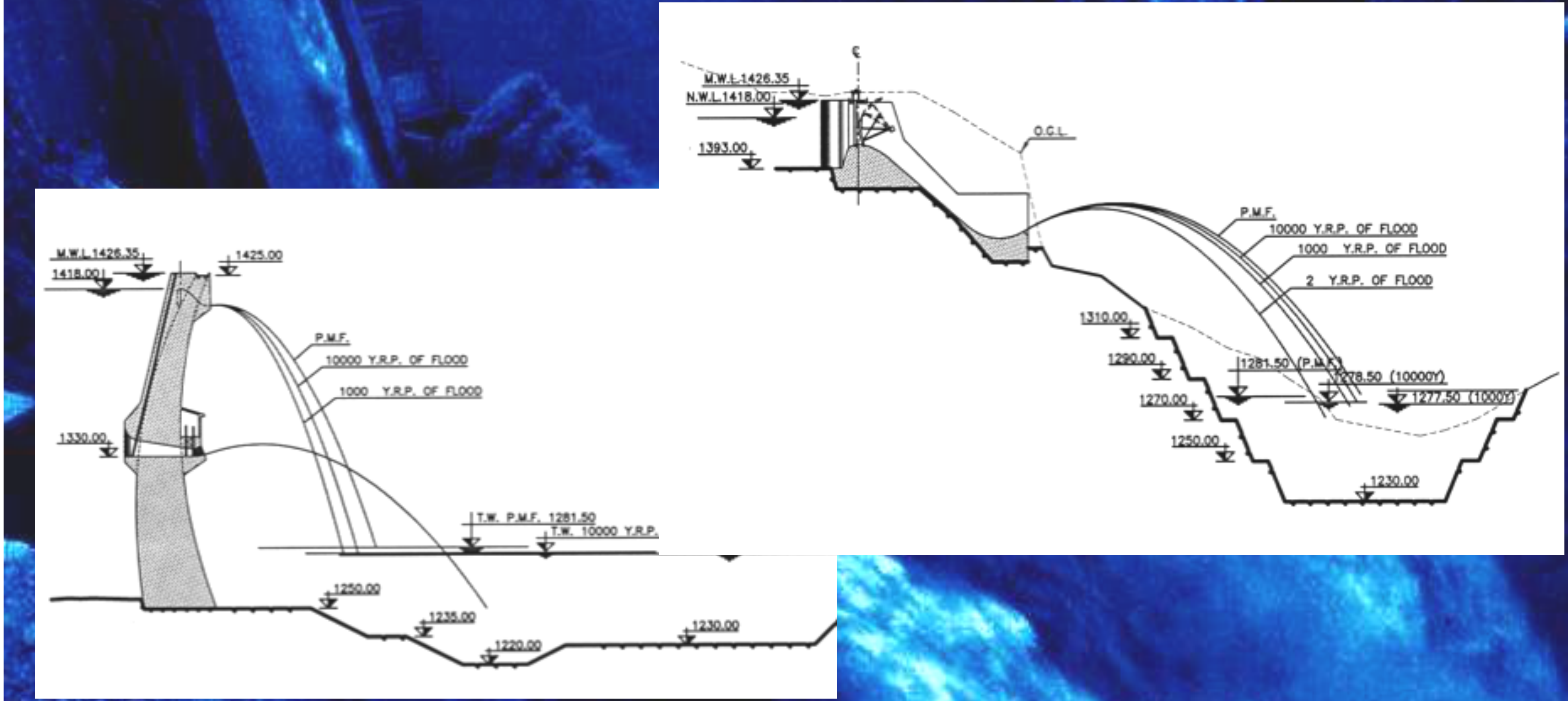
- Two-bay chute flip bucket spillway 4’240 m^3/s (at PMF Flood El. 1426.30)
- Uncontrolled crest spillway 3’360 m^3/s (at PMF Flood El. 1426.30)
- Two bottom outlets 395 m^3/s (at PMF flood El. 1426.30)

TOTAL PMF ~ 8’000 m^3/s

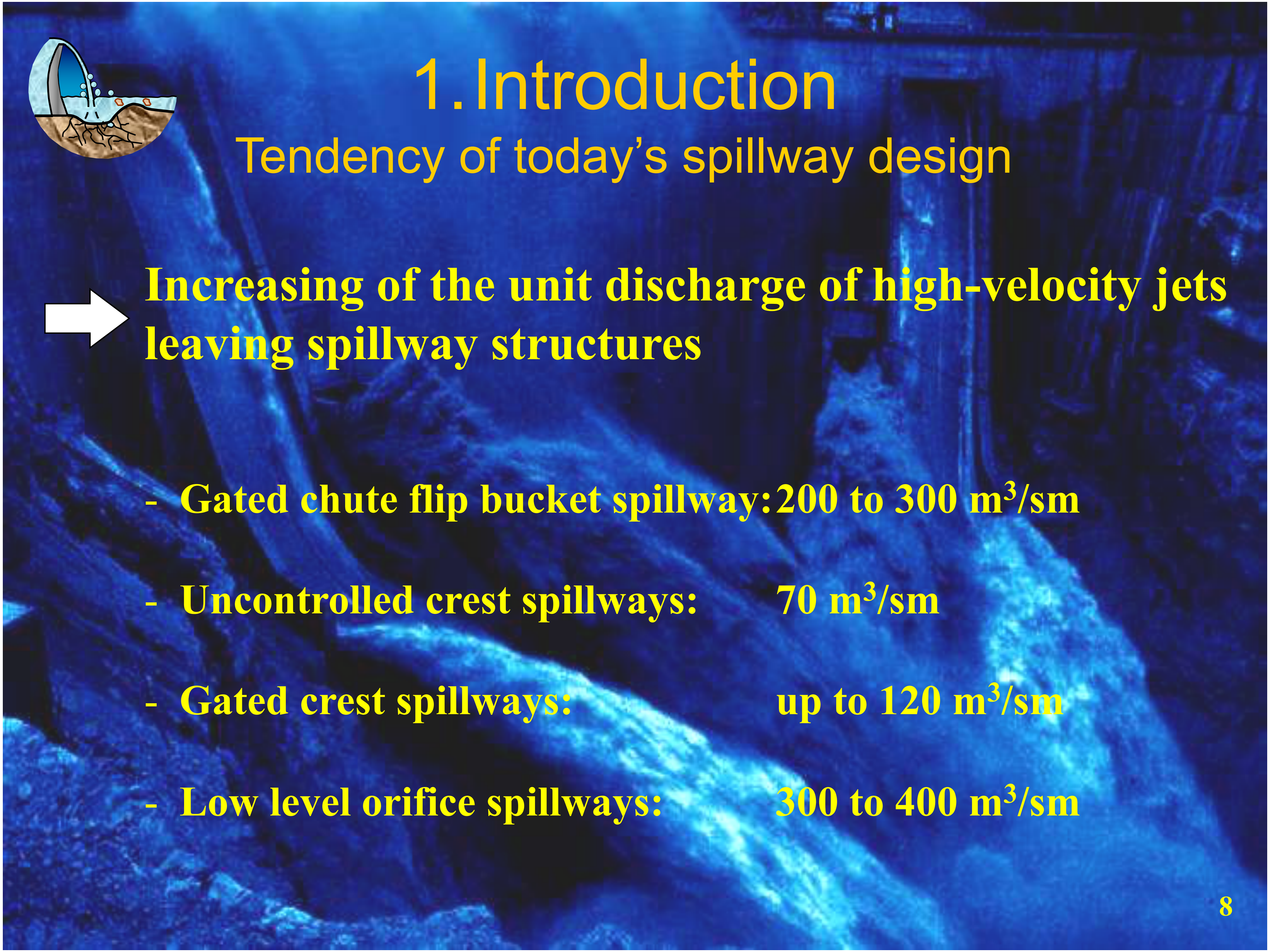
1. Introduction

High scour potential at high concrete arch dams in narrow valleys

Example of Khersan III Dam Project in Iran



Karun III, 205 m, Iran



1. Introduction

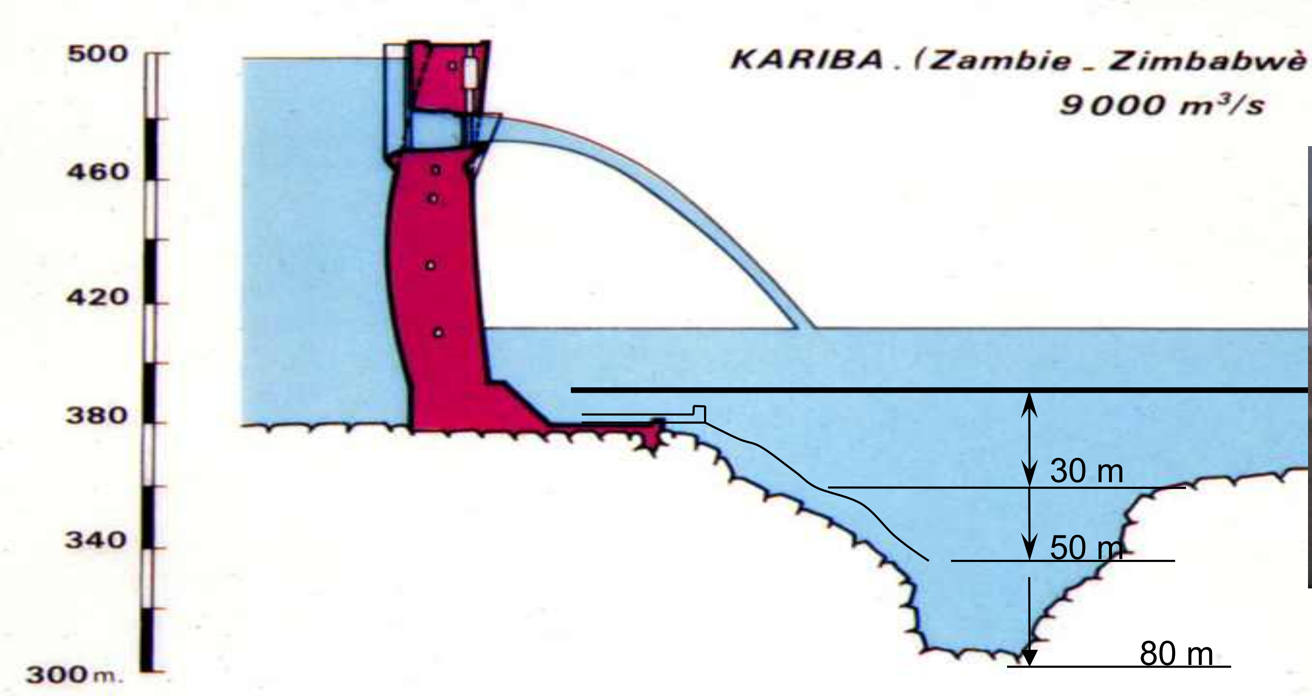
Tendency of today's spillway design

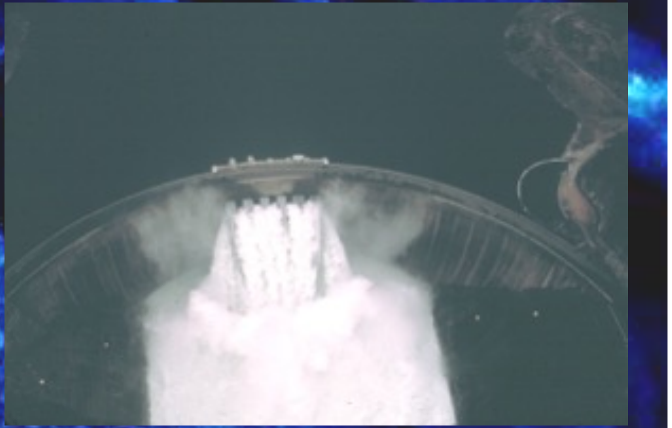
⇨ **Increasing of the unit discharge of high-velocity jets leaving spillway structures**

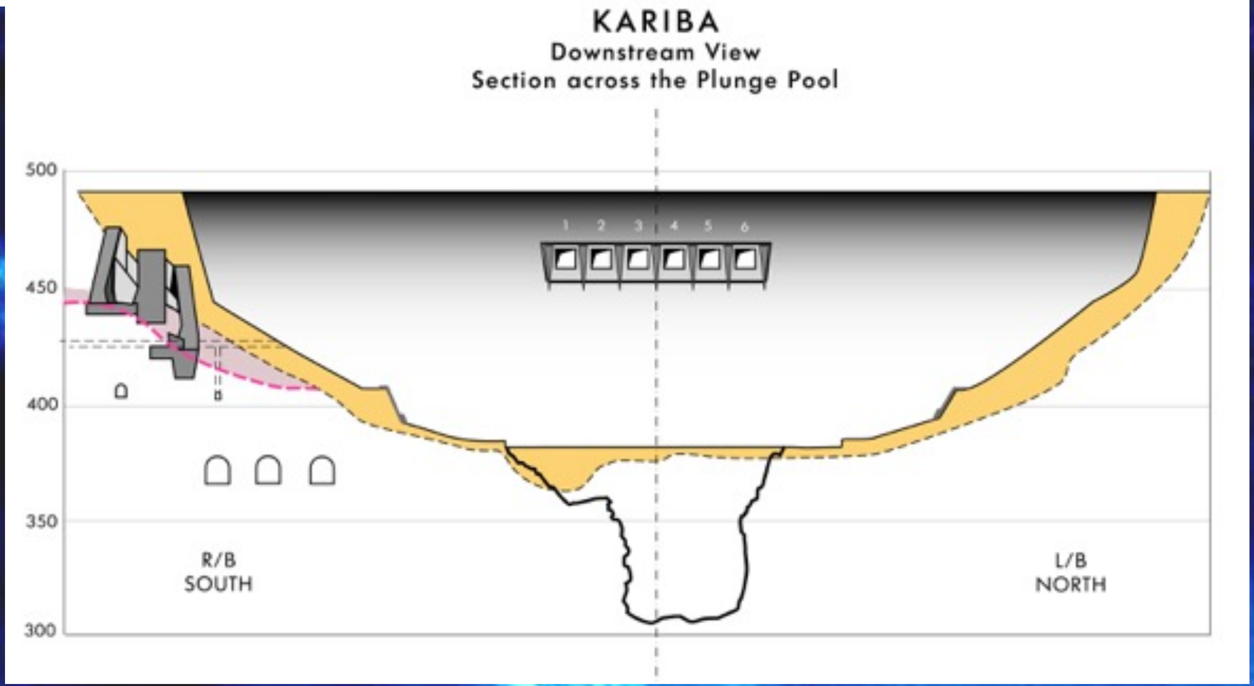
- **Gated chute flip bucket spillway: 200 to 300 m^3/sm**
- **Uncontrolled crest spillways: 70 m^3/sm**
- **Gated crest spillways: up to 120 m^3/sm**
- **Low level orifice spillways: 300 to 400 m^3/sm**

Kariba on Sambezi, 140 m

25/04/2010


KARIBA . (Zambie _ Zimbabwè)
9000 m³/s
500
460
420
380
340
300 m.
30 m
50 m
80 m




KARIBA
Downstream View
Section across the Plunge Pool
500
450
400
350
300
1
2
3
4
5
6
R/B
SOUTH
L/B
NORTH

1. Introduction

The challenge of dam designers

Practical design questions:

- What will be the evolution and extent of scour downstream of the dam at the jet impact zone?
- Are the stability of the valley slopes and the foundation of the dam itself endangered?
- Is a tailpond dam required to create a water cushion and how does it affect the scour depth?
- Is a pre-excavation of the rocky river bed required and/or has the plunge pool to be lined?

- Is the powerhouse operation influenced by scour formation?

2. The scour process

Physical processes in rock scour formation

① **free falling jet behavior in the air and aerated jet impingement**

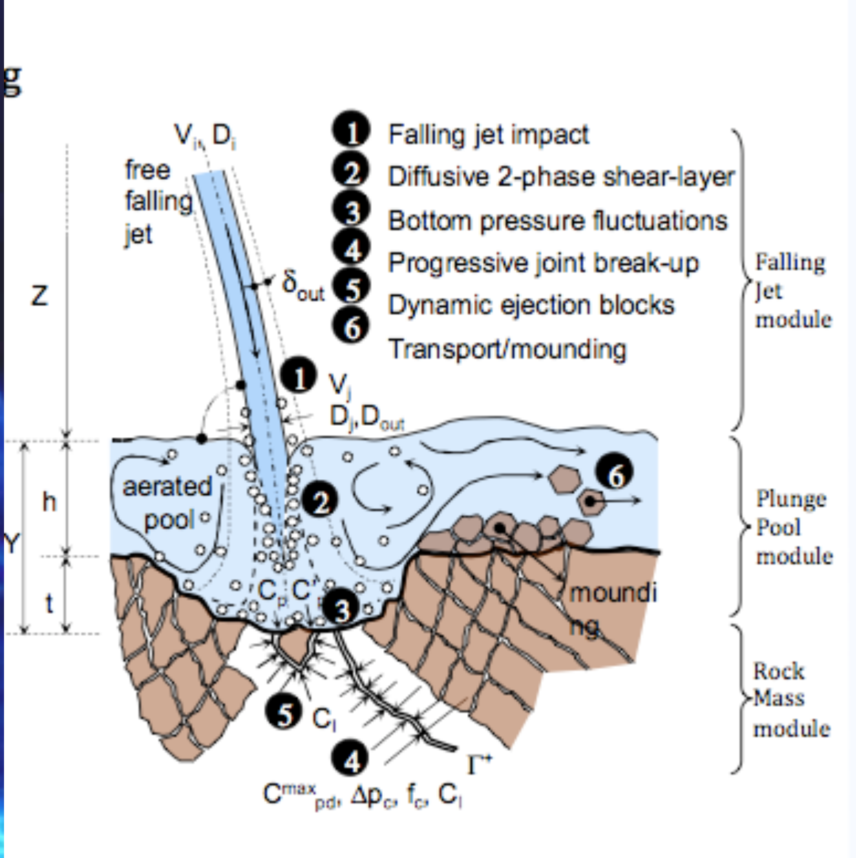
② **plunging jet behavior and turbulent flow in the plunge pool**

③ **pressure fluctuation at the water-rock interface propagation of dynamic water pressures into rock joints**

④ **hydrodynamic fracturing of closed end rock joints and splitting of rock in rock blocks**

⑤ **ejection of the so formed rock blocks by dynamic uplift into the plunge pool break-up of the rock blocks by the ball milling effect of the turbulent flow in the plunge pool**

⑥ **formation of a downstream mound and displacement of the scoured materials by sediment transport**



(Bollaert, 2002)

2. The scour process

Jet behavior in the air

Jet trajectory

- Location of jet impingement

Ballistic equations for ideal jet

Prototype jets

- Air drag
- Disintegration of the jet in the air
- Initial flow aeration in long chutes
- Spread of the jet during fall

Hydraulic model tests Karun III

2. The scour process

Jet behavior in the plunge pool and pressure fluctuations

- **air entrainment when jet plunges into the pool (40 to 60 % at 30 m/s)**

- **high-velocity, two-phase turbulent shear layer flow and macroturbulent flow**

- **shear layer flow produces severe pressure fluctuations at the water-rock interface**

- **dynamic pressures are different for developed jet impact (more severe) and core jet impact**

⇨ **not every water cushion has a retarding effect on the scour formation**

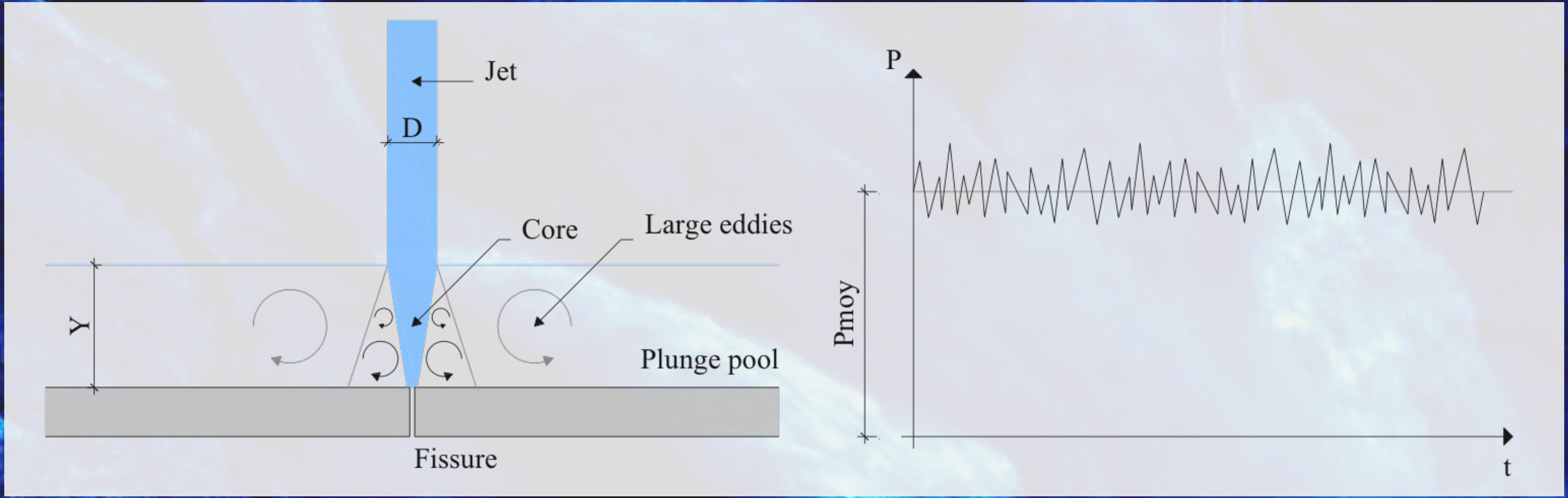
Hydraulic model tests Karun III

2. The scour process

Physical processes in scour formation

Impact jet types

- ***Core jet impact*: Y/D < 4 ÷ 6**
- ***Developed jet impact*: Y/D > 4 ÷ 6**



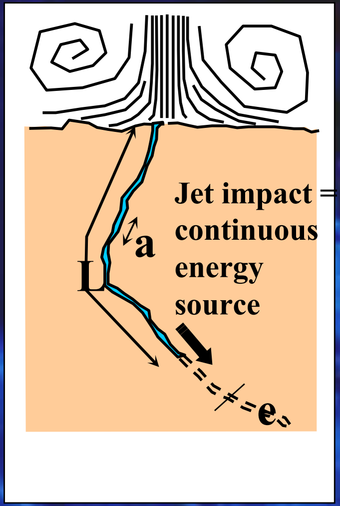
2. The scour process

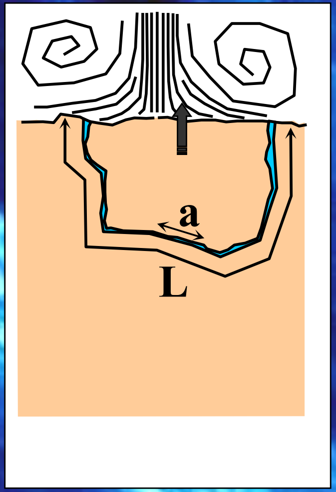
Propagation of dynamic water pressures into rock joints, hydrodynamic fracturing and uplift

- transient flow in joints is governed by the propagation of pressure waves

- closed-end rock joints
  - reflection and superposition of pressure waves
  - hydrodynamic loading at the tip of the joint

- open-end rock joints
  - pressure waves will break up the remaining rock bridges
  - dynamic uplift will eject the rock blocks into the macro-turbulent plunge pool flow





Hydraulic model tests
Karun III

2. The scour process

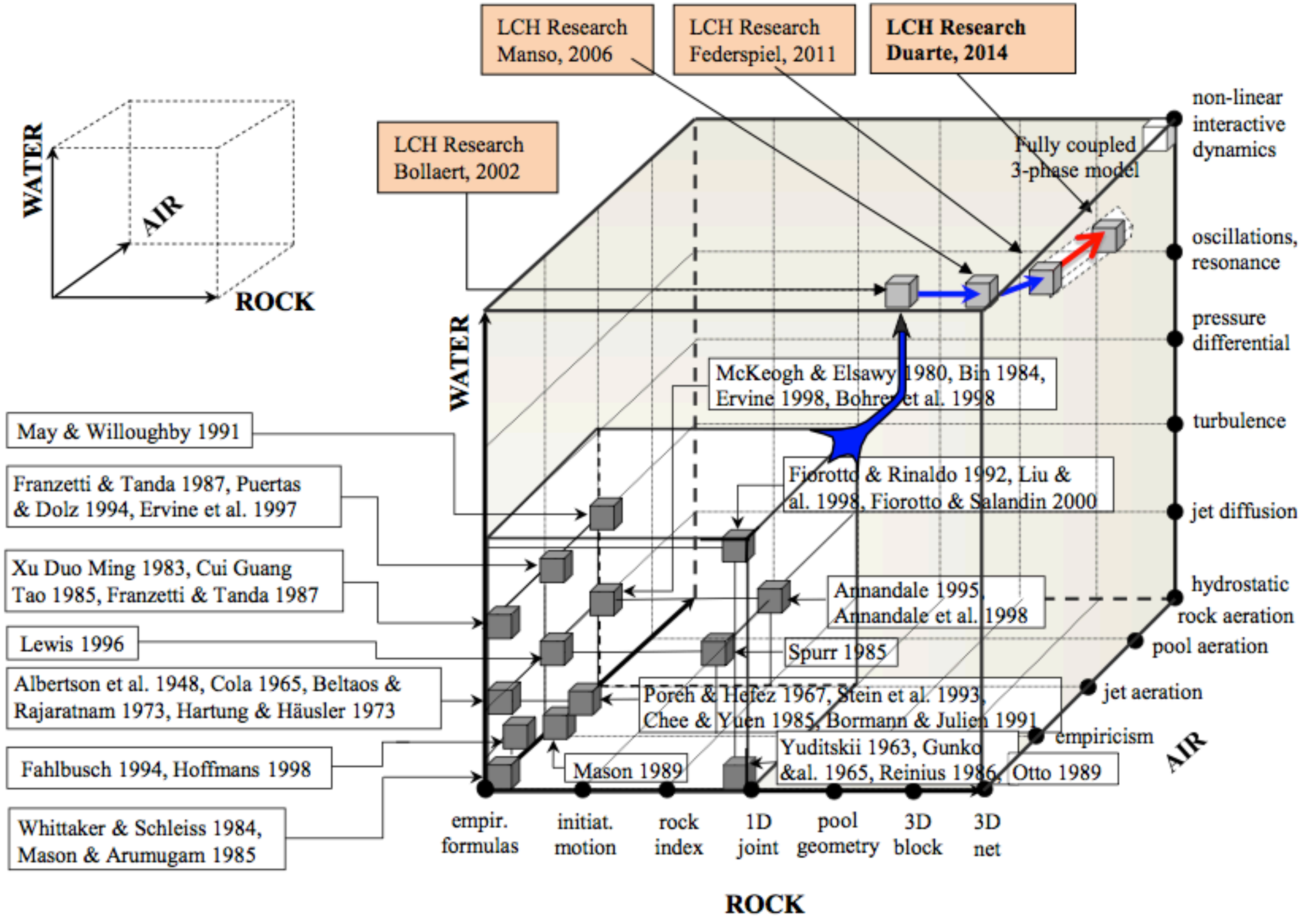
Ball milling effect of the turbulent flow in the plunge pool and formation of a downstream mound

- rock blocks taken up by the macroturbulent eddies
- further break-up by the ball-milling effect
- downstream displacement by flow
- deposited on the mound or carried away by sediment transport
- mound may limit scour depth but also raise the tailwater level

Hydraulic model tests Karun III

3. Scour evaluation methods

General overview



LCH Research Manso, 2006

LCH Research Federspiel, 2011

LCH Research Duarte, 2014

LCH Research Bollaert, 2002

McKeogh & Elsawy 1980, Bin 1984, Ervine 1998, Bohrer et al. 1998

Fiorotto & Rinaldo 1992, Liu & al. 1998, Fiorotto & Salandin 2000

Annandale 1995, Annandale et al. 1998

Spurr 1985

Poreh & Hefez 1967, Stein et al. 1993, Chee & Yuen 1985, Bormann & Julien 1991

Yuditskii 1963, Gunko &al. 1965, Reinius 1986, Otto 1989

Mason 1989

May & Willoughby 1991

Franzetti & Tanda 1987, Puertas & Dolz 1994, Ervine et al. 1997

Xu Duo Ming 1983, Cui Guang Tao 1985, Franzetti & Tanda 1987

Lewis 1996

Albertson et al. 1948, Cola 1965, Beltaos & Rajaratnam 1973, Hartung & Häusler 1973

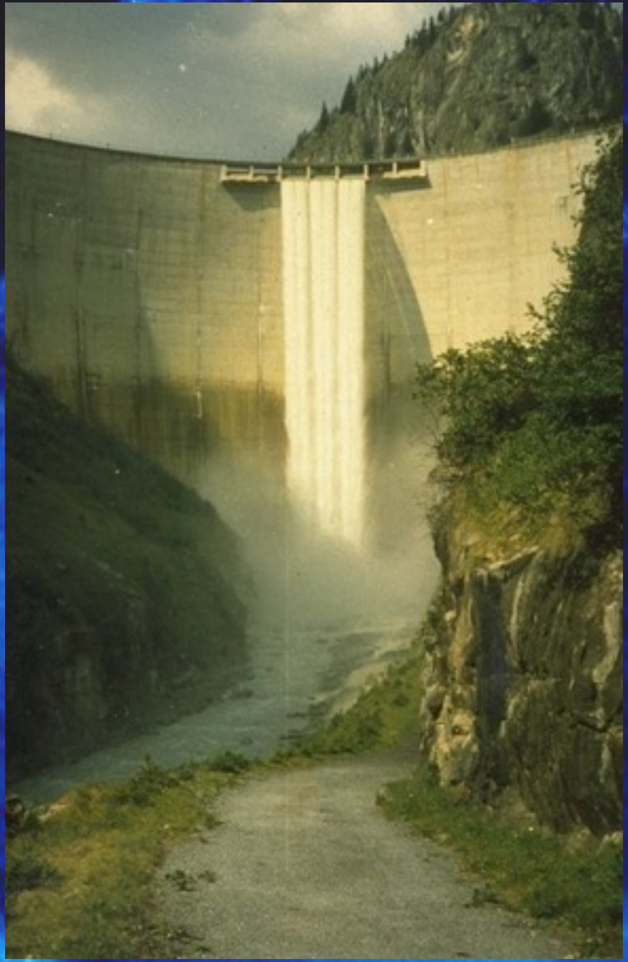
Fahlbusch 1994, Hoffmans 1998

Whittaker & Schleiss 1984, Mason & Arumugam 1985

3. Scour evaluation methods

Existing scour evaluation methods

- ⓐ - **Empirical approaches based on laboratory and field observations**
- ⓑ - **Analytical-empirical methods combining laboratory and field observations with some physics**
- ⓒ - **Approaches based on extreme values of fluctuating pressures at the plunge pool bottom**
- ⓓ - **Techniques based on time-mean and instantaneous pressure differences and accounting for rock characteristics**
- ⓔ - **Scour model based on fully transient water pressures in rock joints**



3. Scour evaluation methods

Empirical formulae

Mason & Arumugam (1985)

$$Y = t + h = K \cdot \frac{H^{y} \cdot q^{x} \cdot h^{w}}{g^{v} \cdot d_{m}^{z}}$$

26 sets from prototype data

47 from model tests

$K = (6.42 – 3.10H^{0.10})$
$v = 0.30$
$w = 0.15$
$x = (0.60 – H/300)$
$y = (0.15 – H/200)$
$z = 0.10$

where:

t = scour depth below initial bed level
K = constant
q = specific discharge
H = fall height
h = tailwater depth (measured from initial bed level)
d_m = characteristic sediment size or rock block diameter d

3. Scour evaluation methods

Semi-empirical equations

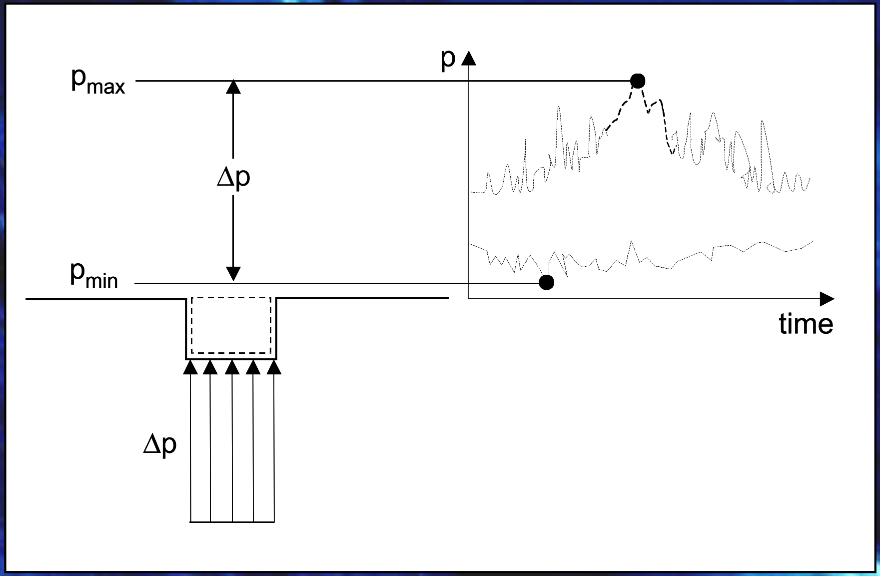
Laboratory and field observations are combined with some physics:

- initiation of motion of the bed material by shear stress
- energy conservation equations
- geomechanical characteristics
- angle of impingement of the jet
- steady-state two-dimensional jet diffusion theory
- aeration effects

Hydrodynamic and geomechanical characteristics are combined in Annandale's Erodibility Index Method

3. Scour evaluation methods

Approaches based on extreme values of fluctuating pressures at the plunge pool bottom



Maximum pressure differences of 1.50 – 1.75 times the incoming kinetic jet energy

3. Scour evaluation methods

Techniques based on time-mean and instantaneous pressure differences and accounting for rock characteristics

Instead of maximum pressure differences, time-averaged or instantaneous pressure differences are considered

Fluctuating pressures have to be known at the plunge pool bottom but also inside the rock joints

Pressure field underneath the concrete slabs or rock blocks is assumed constant over the surface of the element and equal to the pressure at the entrance of the joints, i.e. at the surface

3. LCH-EPFL approach

Scour model based on fully transient water pressures in rock joints

Transient water pressures in rock joints due to high-velocity jet impact (Bollaert, 2002):

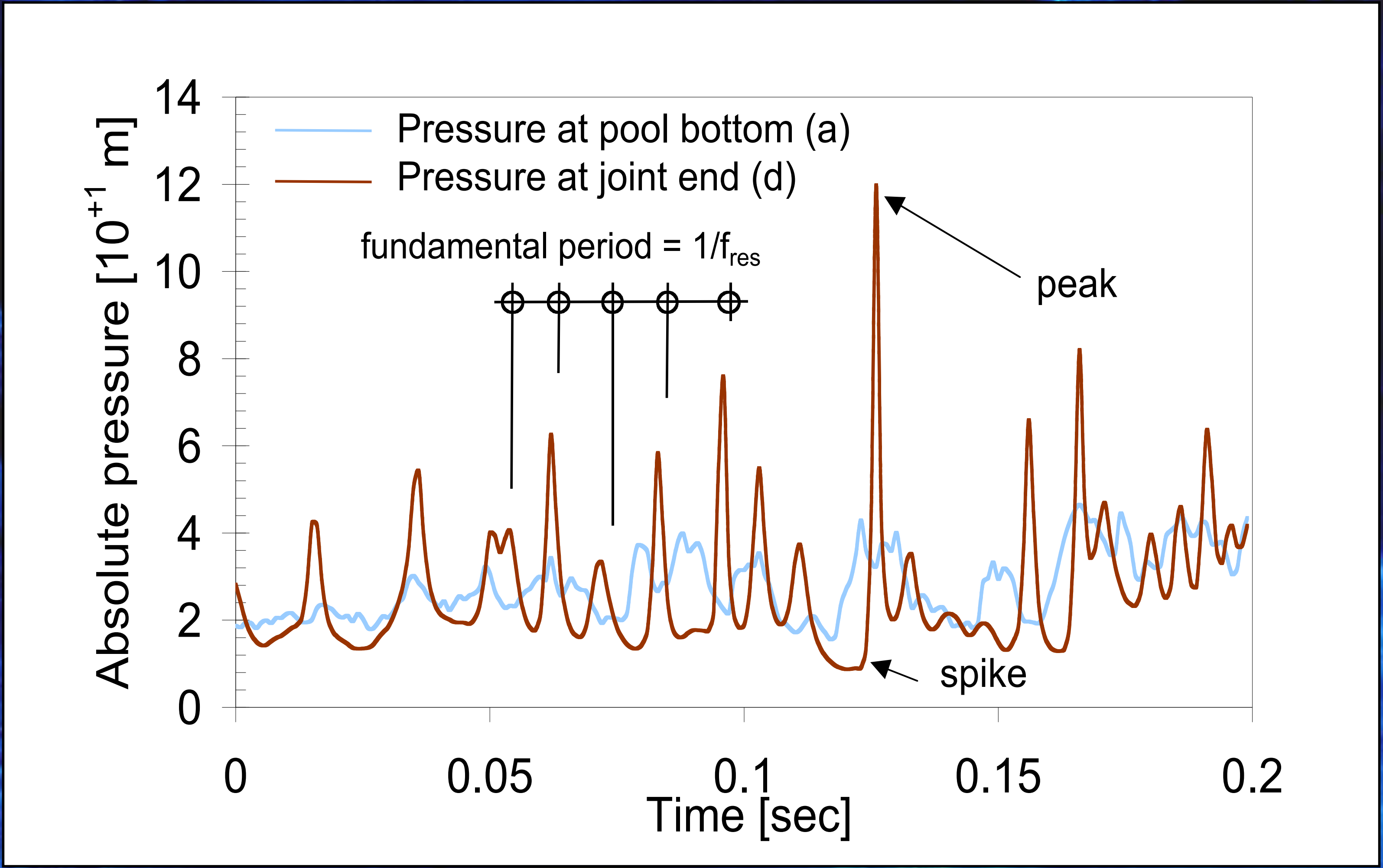
- **reflection and superposition of pressure waves**
- **resonance pressures**
- **quasi-instantaneous air release and re-solution due to pressure drops**
- **pressure wave celerity highly influenced by free air bubbles in the joints**
- **net uplift pressures of 0.8 to 1.6 times the incoming kinetic energy**

Comprehensive Scour Method

4. New LCH-EPFL approach

Comprehensive Scour Method

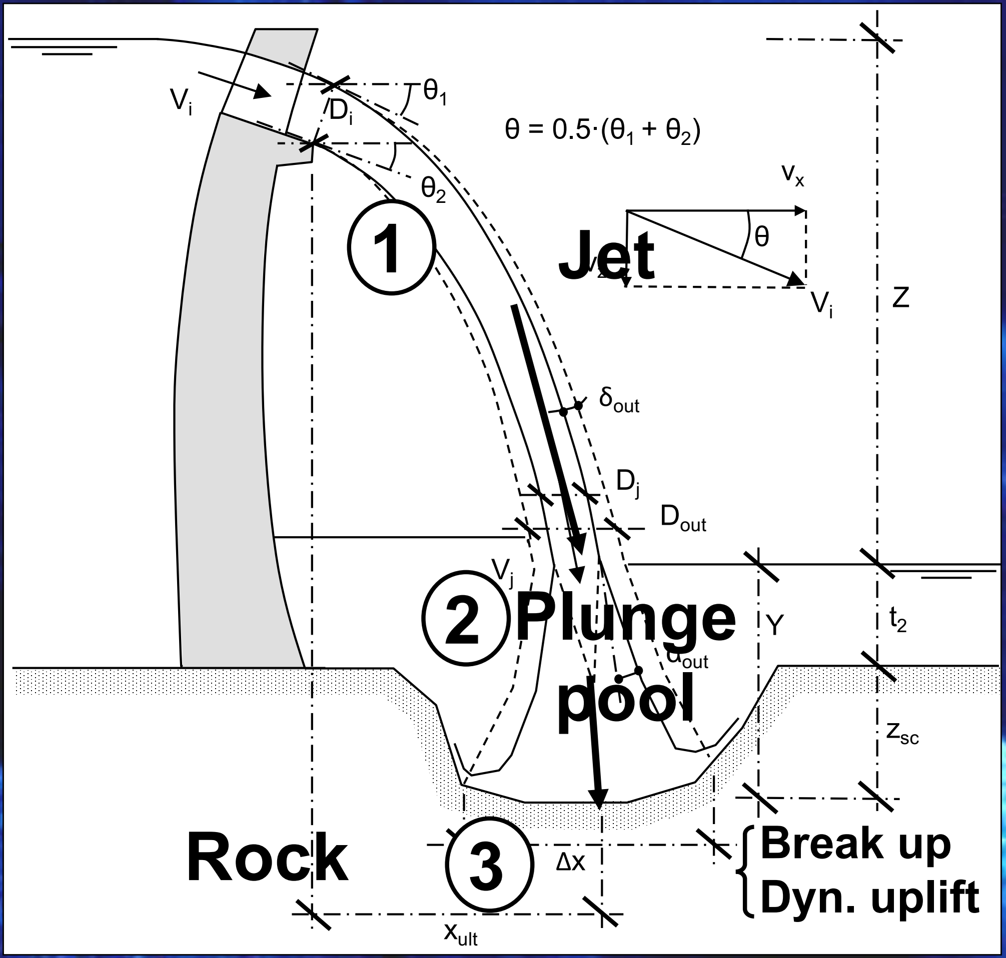
Dynamic water pressures in rock joints

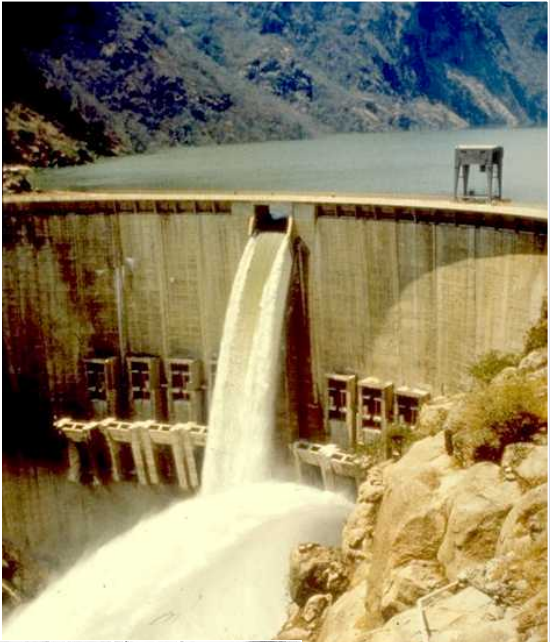


4. New LCH-EPFL approach

Comprehensive Scour Method

Modules of the approach





4. New LCH-EPFL approach

Comprehensive Scour Method

$$D_j = D_i \cdot \sqrt{\frac{V_i}{V_j}}$$

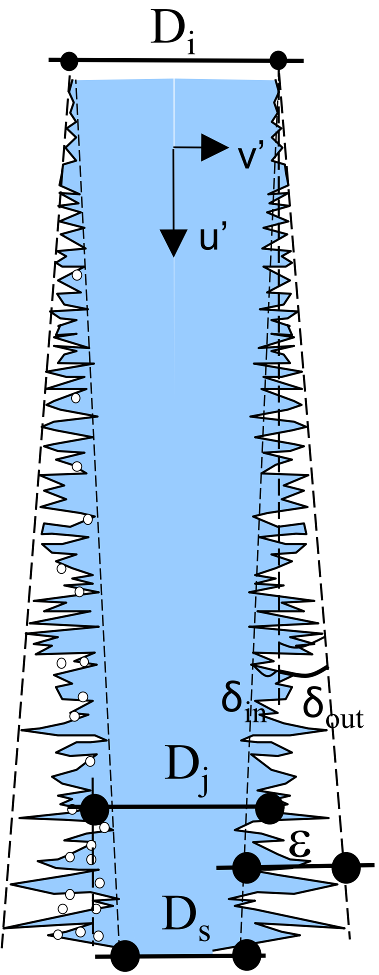
$$D_{out} = D_i + 2 \cdot \delta_{out} \cdot L$$

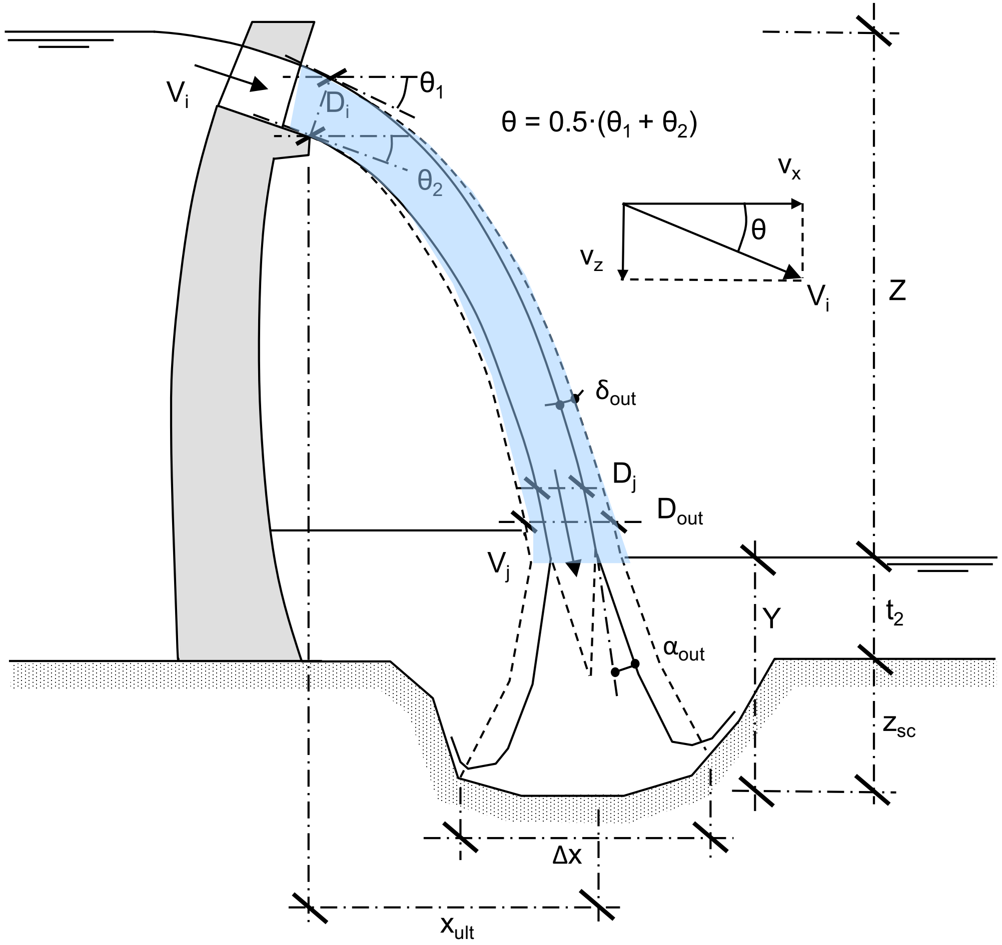
Modul « falling jet »

$$\delta_{in} = 0.5–1\ \%$$

$$\delta_{out} = 3–4\ \%$$

$$\delta_{out} = f\,(Tu)$$



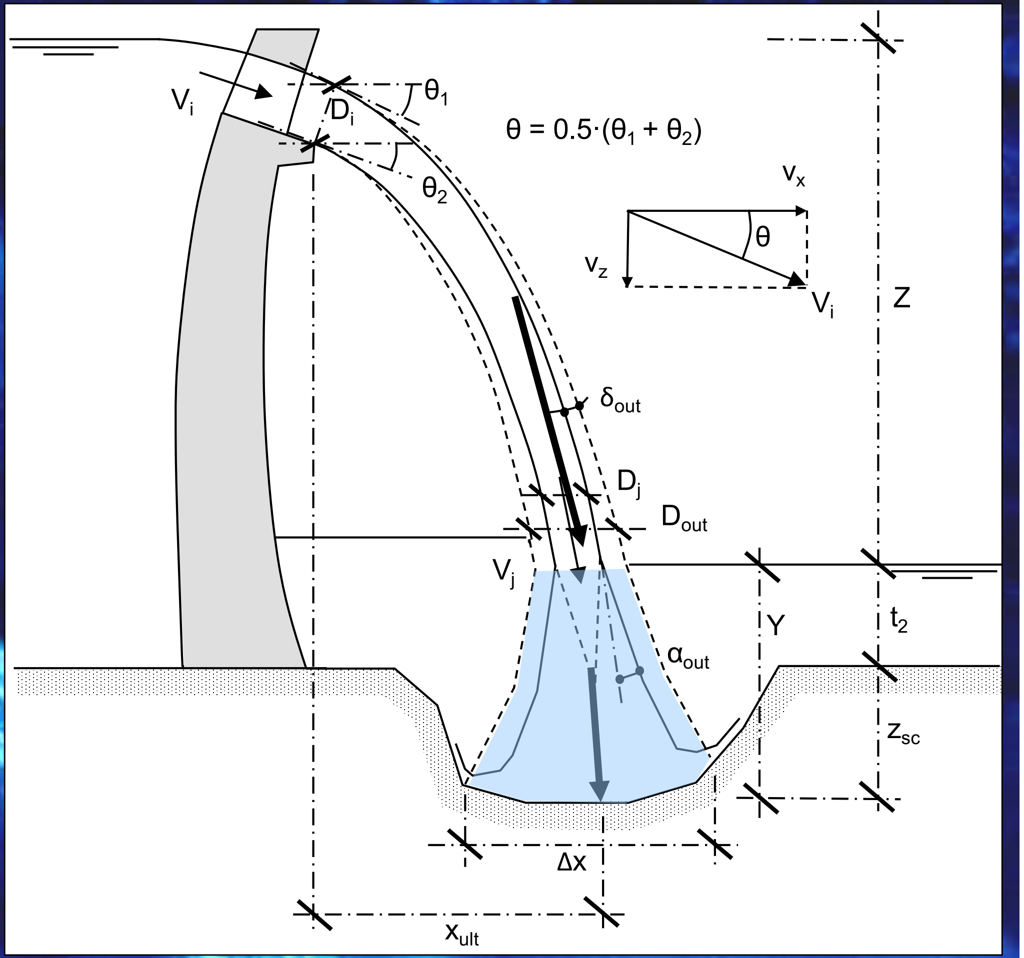


4. New LCH-EPFL approach

Comprehensive Scour Method

Parameters of « plunge pool « module

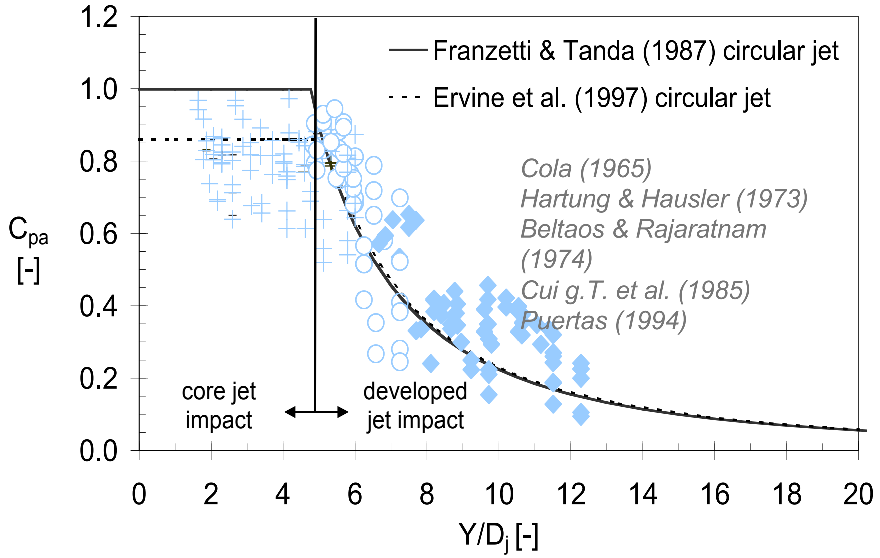
- **Y/D_j (diffusion of jet in the water)**
- **mean dynamic pressure coefficient (C_{pa}) in jet axis**
- **dynamic pressure fluctuation (C'_{pa}) in jet axis**
- **mean dynamic pressure coefficient (C_{pa}) in radial direction**
- **dynamic pressure fluctuation (C'_{pa}) in radial direction**
- **influence zone Δx of dynamic pressure fluctuation**



The plunge pool module
Mean dynamic water pressures

Mean dynamic pressure coefficient C_{pa} :

$$C_{pa} = \frac{\frac{p^{mean}}{\gamma}}{\frac{V^2}{2g}}$$



$$\begin{cases} C_{pa} = 38.4 \cdot (1-\alpha_i) \cdot \left(\frac{D_j}{Y}\right)^2 & \text{for } Y/D_j > 4 - 6 \\ C_{pa} = 0.85 & \text{for } Y/D_j < 4 - 6 \end{cases}$$

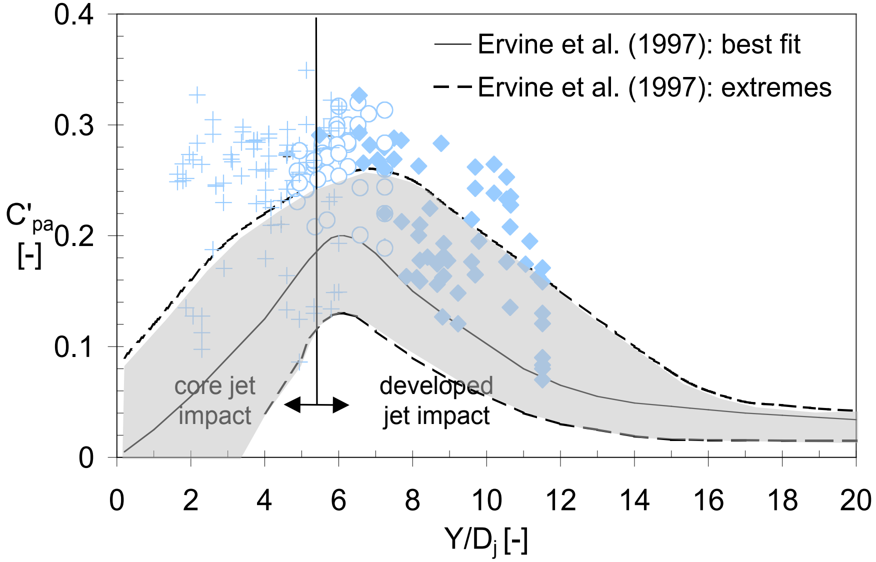
$$\alpha_i = \frac{\beta}{1+\beta}, \quad \beta = \text{volumetric air-to-water ratio}$$

The plunge pool module

Fluctuation of dynamic water pressures

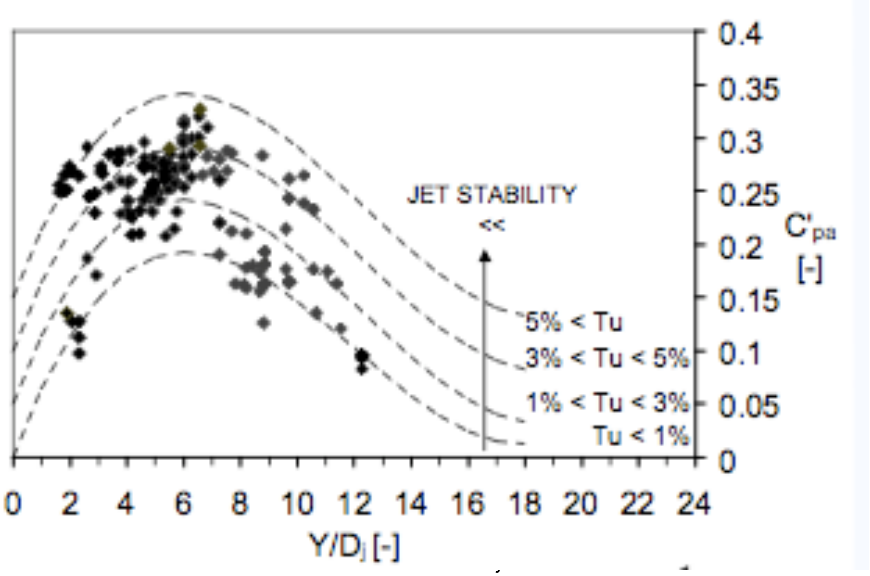
RMS value of pressure fluctuation C'_{pa} :

$$C'_{pa} = \frac{\frac{RMS}{\gamma}}{\frac{V^2}{2g}}$$



$$C'_{pa} = a_1 \cdot \left(\frac{Y}{D_j}\right)^3 + a_2 \cdot \left(\frac{Y}{D_j}\right)^2 + a_3 \cdot \left(\frac{Y}{D_j}\right) + a_4$$

N°	Tu (%)	a_1	a_2	a_3	a_4
4	< 1	0.000220	-0.0079	0.0716	0.000
3	1-3	0.000215	-0.0079	0.0716	0.050
2	**3-5**	**0.000215**	**-0.0079**	**0.0716**	**0.100**
1	> 5	0.000215	-0.0079	0.0716	0.150



The rock module

Main parameters

Hydrodynamic parameters

1.) Maximum dynamic pressure coefficient C^{max}_p (closed end fissures)
2.) Characteristc amplitude of pressure cycles Δp_c (closed end fissures)
3.) Characteritic frequency of pressure cycles f_c (closed end fissures)

CFM

4.) Maximum dynamic impulsion C^{max}_I on rock blocks (open end fissures)

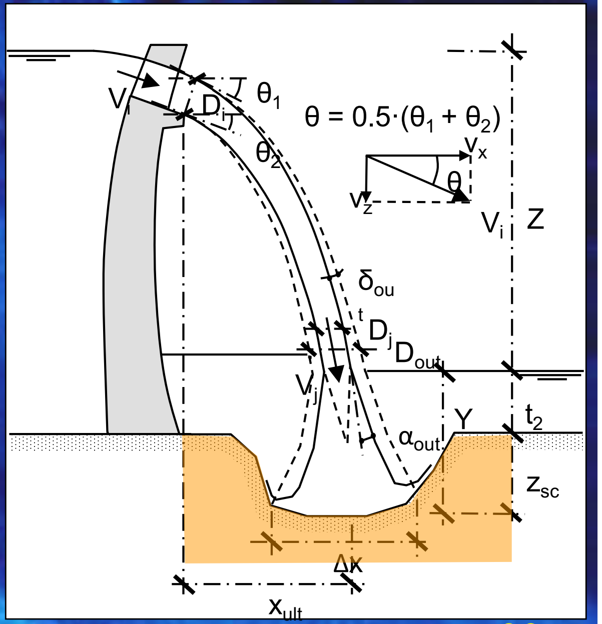
DIM

Geomechanical parameters

1.) Properties of rock joints

2.) Rock type and strength (compression and tensile strength, fracture persistence and toughness, permeability, density,..)

3.) In-situ conditions (natural stresses, geometry of valley, geology,…)



The rock module
Hydrodynamic pressure peaks inside rock fissures

1.) Maximum dynamic pressure C^{max}_{pd} at the end of a closed fissure

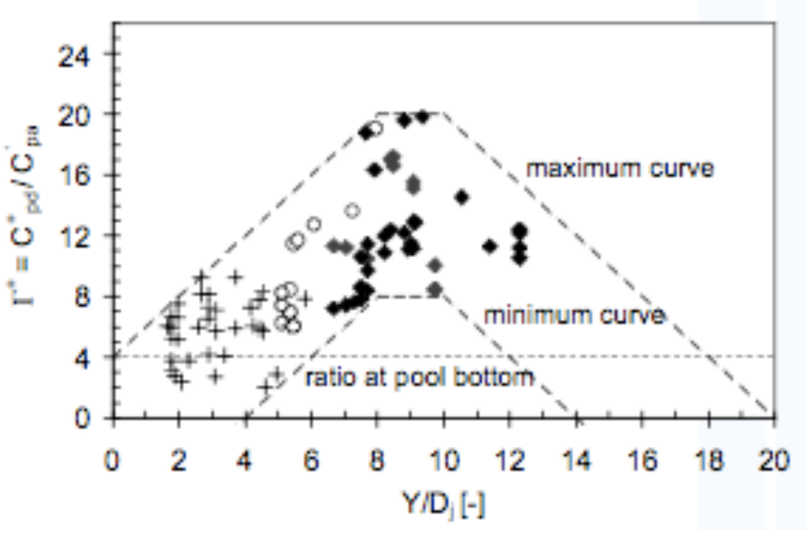
$$P_{max}[Pa] = \gamma \cdot C^{max}_{pd} \cdot \frac{\phi \cdot V_j^2}{2g} = \gamma \cdot \left(C_{pa} + \underbrace{\Gamma^{+} \cdot C'_{pa}}_{C^{+}_{pd}}\right) \cdot \frac{\phi \cdot V_j^2}{2g}$$

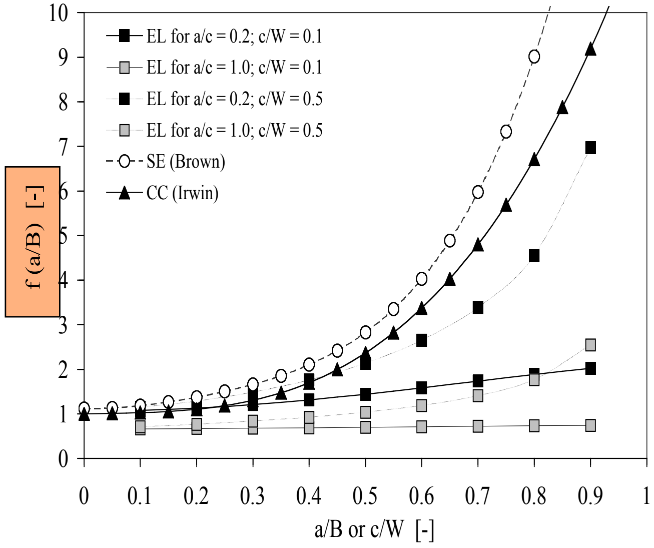
$\Gamma^{+} = 4 + 2\square Y/D_j$ for $Y/D_j < 8$
$\Gamma^{+} = 20$ for $8 \leq Y/D_j \leq 10$
$\Gamma^{+} = 40 - 2\square Y/D_j$ for $10 < Y/D_j$

$\Gamma^{+} = -8 + 2\square Y/D_j$ for $Y/Dj < 8$
$\Gamma^{+} = 8$ for $8 \leq Y/D_j \leq 10$
$\Gamma^{+} = 28 - 2\square Y/D_j$ for $10 < Y/D_j$

Stress intensity factor

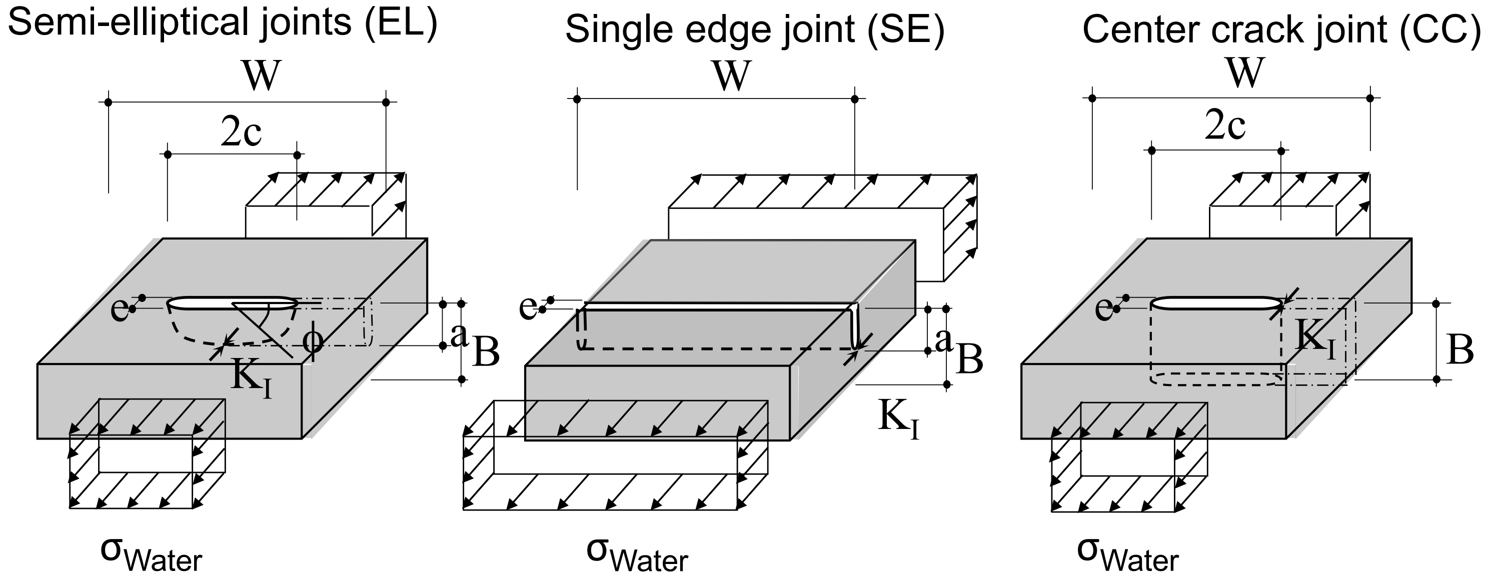
$$K_I = P_{max} \sqrt{\pi \cdot a} \cdot f\left(\frac{a}{W}\right)$$





The rock module

Comprehensive Fracture Mechanics(CFM)



Brittle fracture (C^{max}_p):

$K_I > \boxed{K_{I\ ins}}$ (fracture toughness)

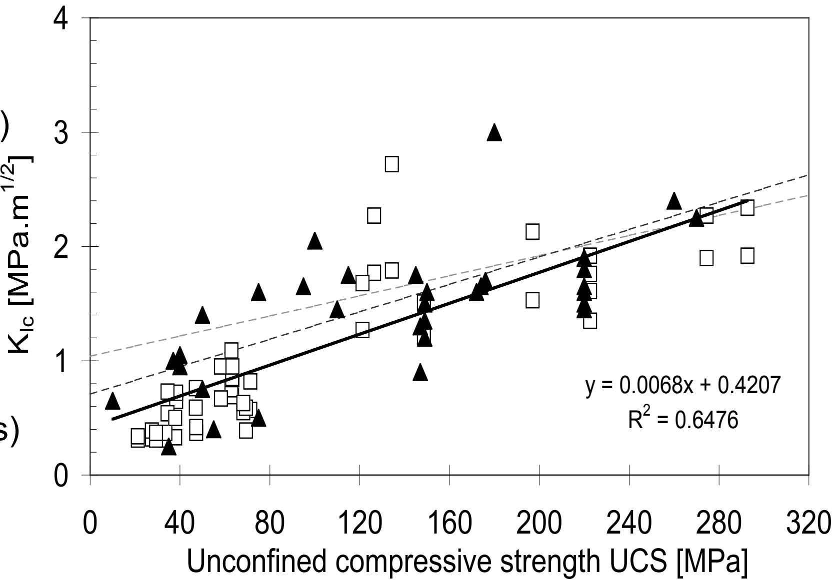
$K_{I,T}$ = (0.105 to 0.132)T+(0.054σ_c)+ 0.5276

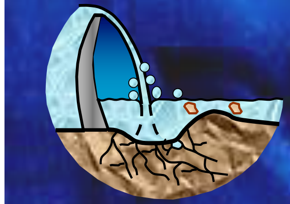
$K_{I,UCS}$= (0.008 to 0.010)UCS+(0.054σ_c)+ 0.42

Crack propagation by fatigue (Δp_c, f_c)):

$K_I < \boxed{K_{I\ ins}}$ (fracture toughness)

$$\frac{dL_f}{dN} = C_r \cdot \left(\Delta K_I / K_{Ic}\right)^{m_r}$$





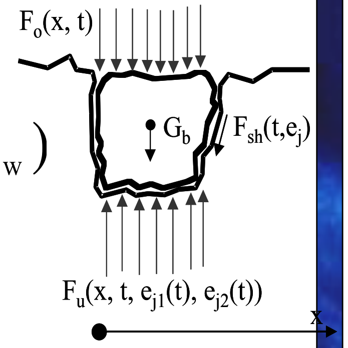
The rock module

Dynamic uplift pressures acting on rock blocks - Dynamic Impulsion (DI)

$$I_{\Delta tpulse} = \int_{0}^{\Delta tpulse} \left(F_u - F_o - G_b - F_{sh}\right) \cdot dt = m \cdot V_{\Delta tpulse}$$

$$G_b = \forall \cdot \left(\gamma_r - \gamma_w\right) = x_b^2 \cdot z_b \cdot \left(\gamma_r - \gamma_w\right)$$

$$V_{\Delta tpulse} = \sqrt{2 \cdot g \cdot h_{up}}$$



F_u and F_o: forces acting in upward and downward direction

G_b: immerged block weight

F_{sh}: shear forces along the joint

$$\left.\begin{aligned} \Delta t_{up} &= T_{up} \cdot 2L_f/c \\ p_{up} &= C_{up} \cdot V^2/2g \end{aligned}\right\}$$

$V^2/2g$: incoming kinetic energy

L_f: Length of fissure

c: water hammer velocity 100-200 m/s

Maximum net impulsion:

$$\mathbf{I_{up}} = p_{up} \cdot \Delta t_{up} = C_{up} \cdot T_{up} \cdot (V^2 L_f/gc) = \boxed{\mathbf{C_I}} \cdot \mathbf{(V^2 L_f/gc)} \text{ [m.s]}$$

C_{up}: net uplift pressure coefficient (close to 0.35)

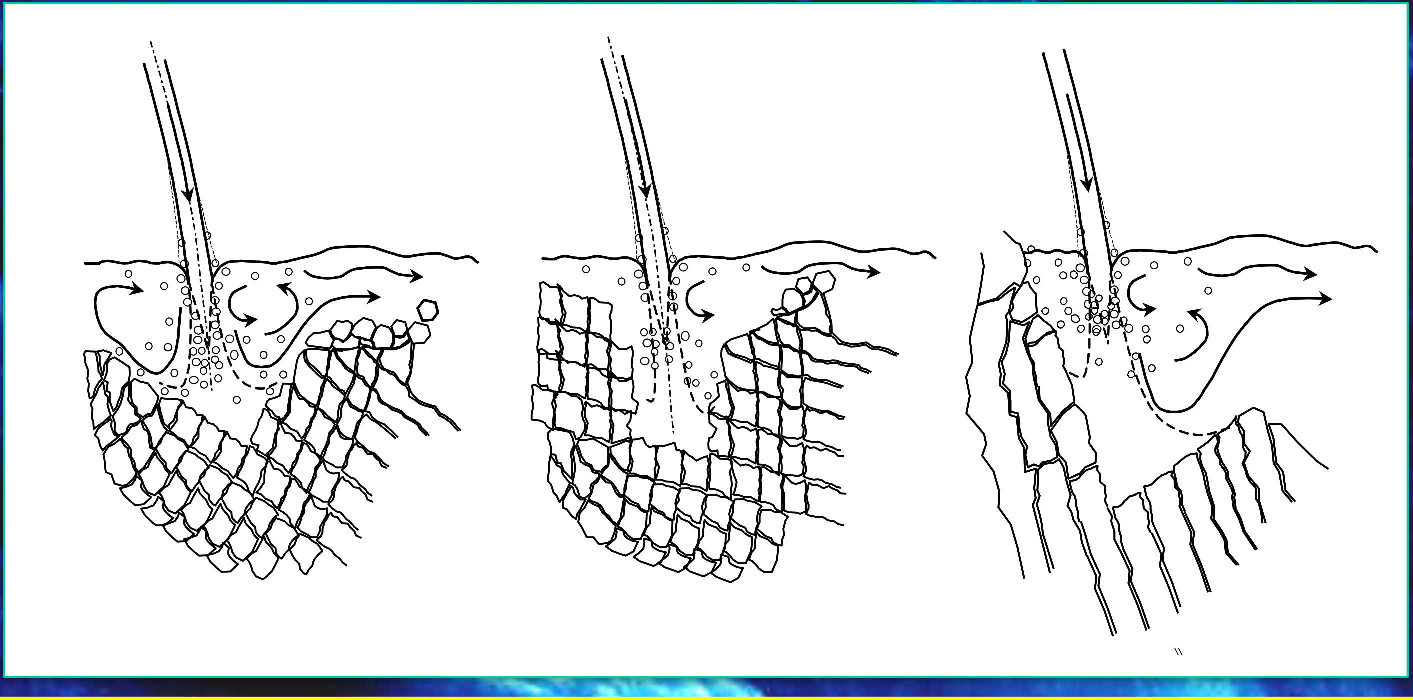
T_{up} : Time coefficient

$$C_I = 0.0035 \cdot \left(\frac{Y}{D_j}\right)^2 - 0.119 \cdot \left(\frac{Y}{D_j}\right) + 1.22$$

4. New LCH-EPFL approach

Scour model based on fully transient water pressures in rock joints

Influence of the scour hole geometry – lateral confinement of water jet (Manso, 2006):



Real scour geometry

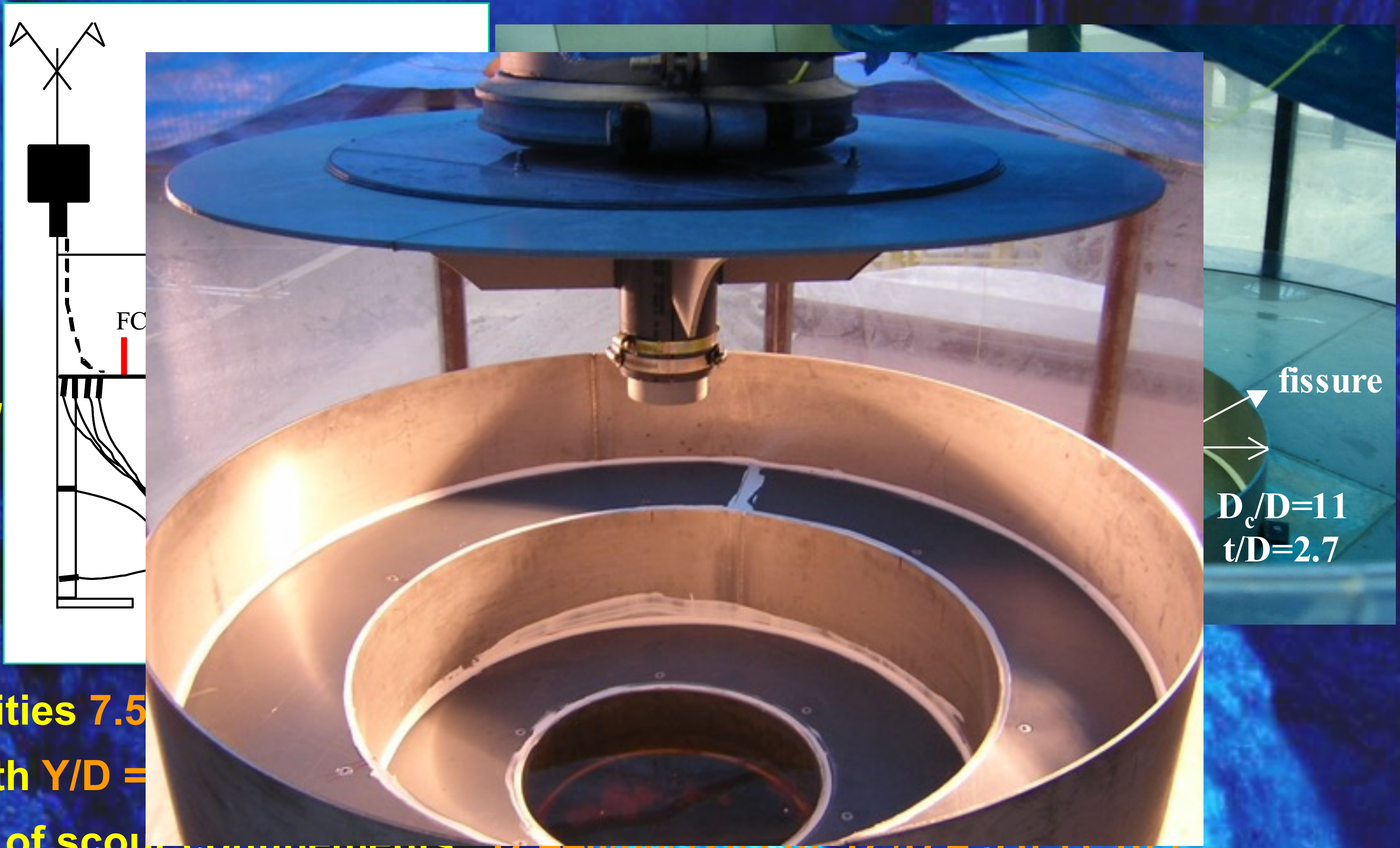
Goal: Interaction between scour geometry and dynamic pressure fluctuations at the rock surface

Influence of the scour hole geometry – lateral confinement of water jet (Manso, 2006):

Jet

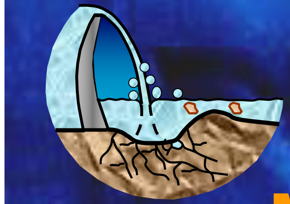
Pool

Fissured rock mass



Parameters

- Jet velocities 7.5
- Pool depth Y/D =
- Diameter of scour confinements : D_c=40/80/120 cm; D_c/D = 5.6, 11, 16.7
- Depth of scour steps : h_e=20/40/60 cm; t/D ~ 2.8, 5.6, 8.3

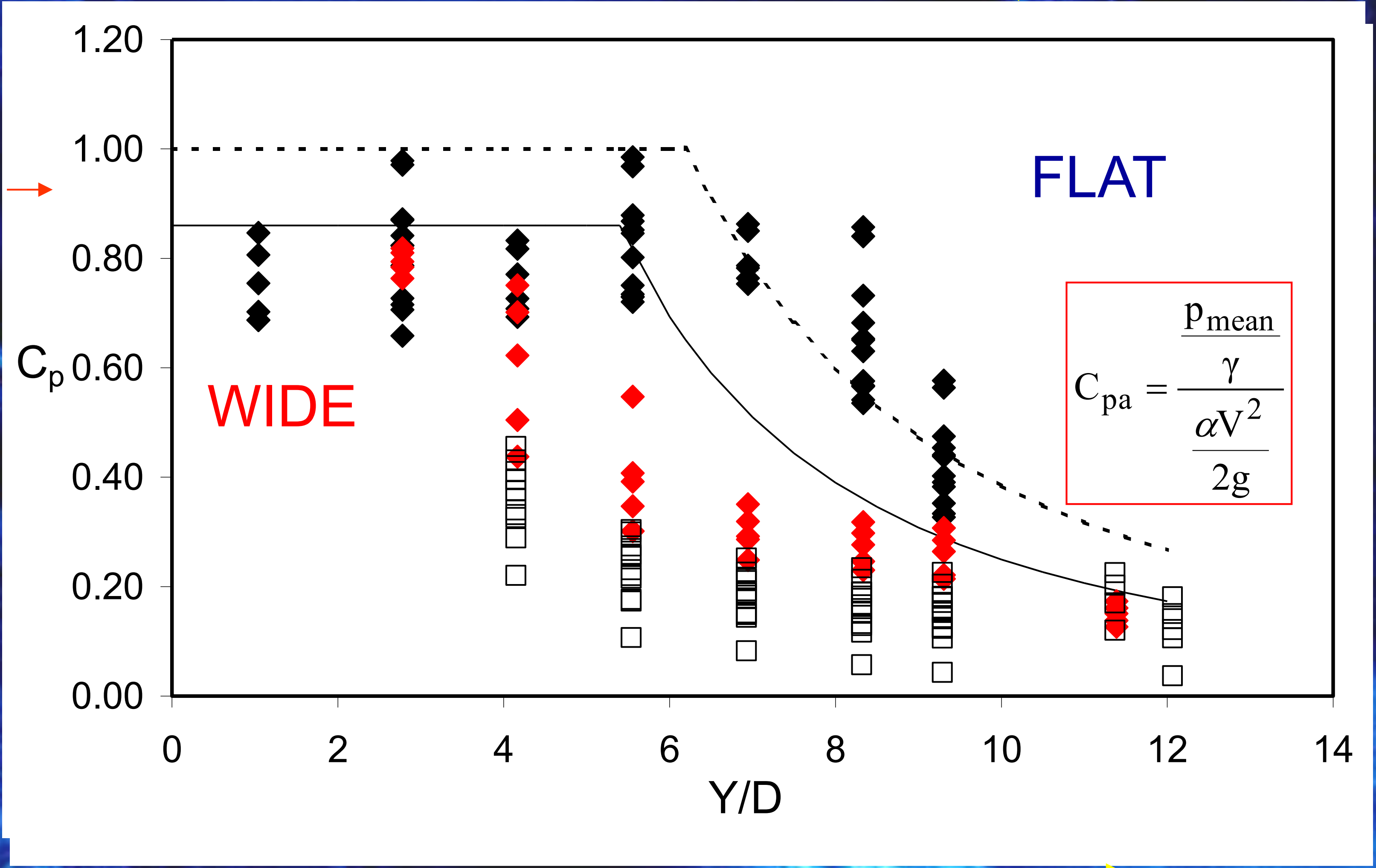


Influence of the scour hole geometry – lateral confinement of water jet (Manso, 2006):

Mean pressure coefficent Cp

At pool bottom, below jet axis
t/D = 2.8, V > 17 m/s

$$\frac{\alpha V^2}{2g}$$



$$C_{pa} = \frac{\frac{p_{mean}}{\gamma}}{\frac{\alpha V^2}{2g}}$$

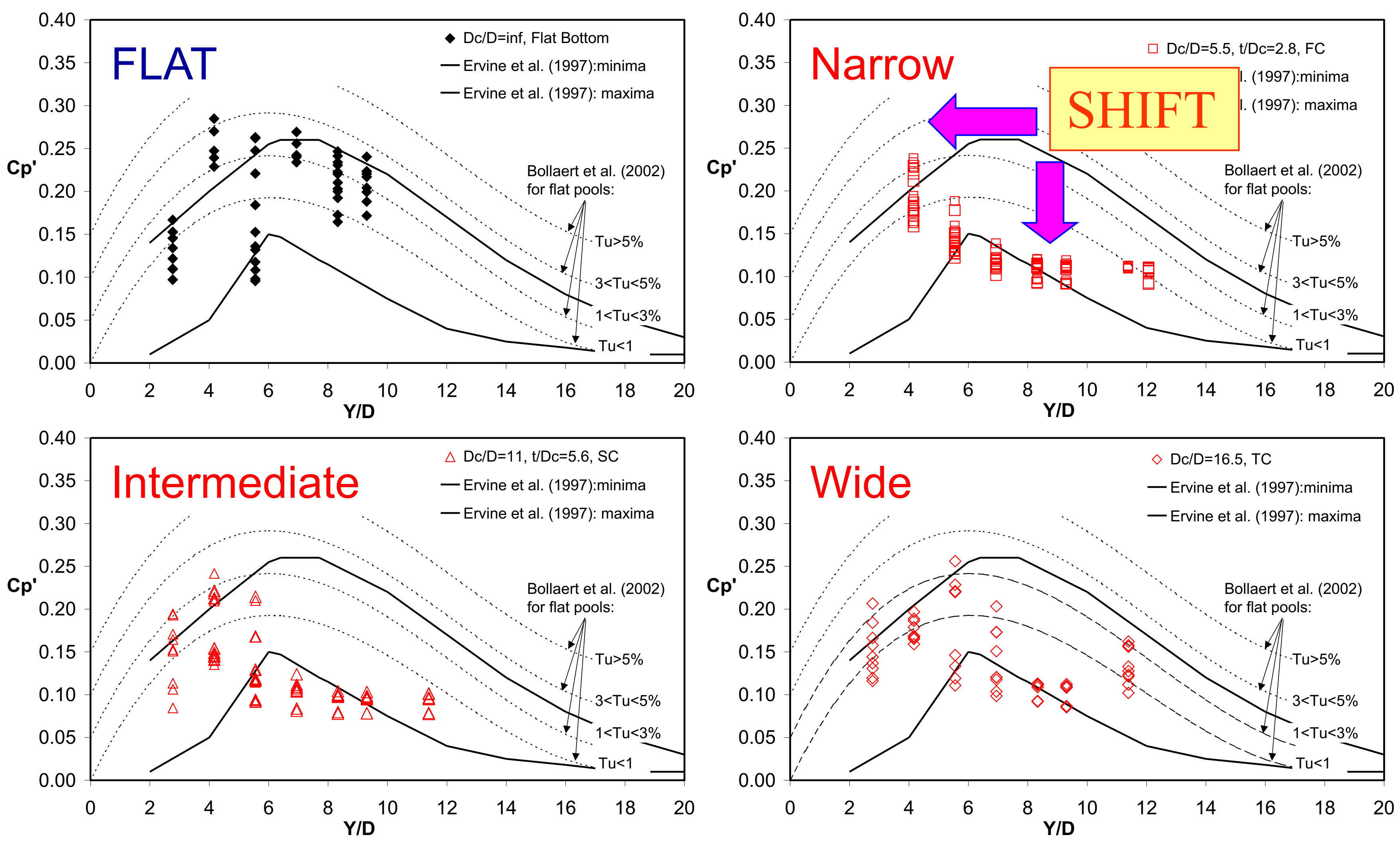
Shallow pools → Deep pools

Influence of the scour hole geometry – lateral confinement of water jet (Manso, 2006):

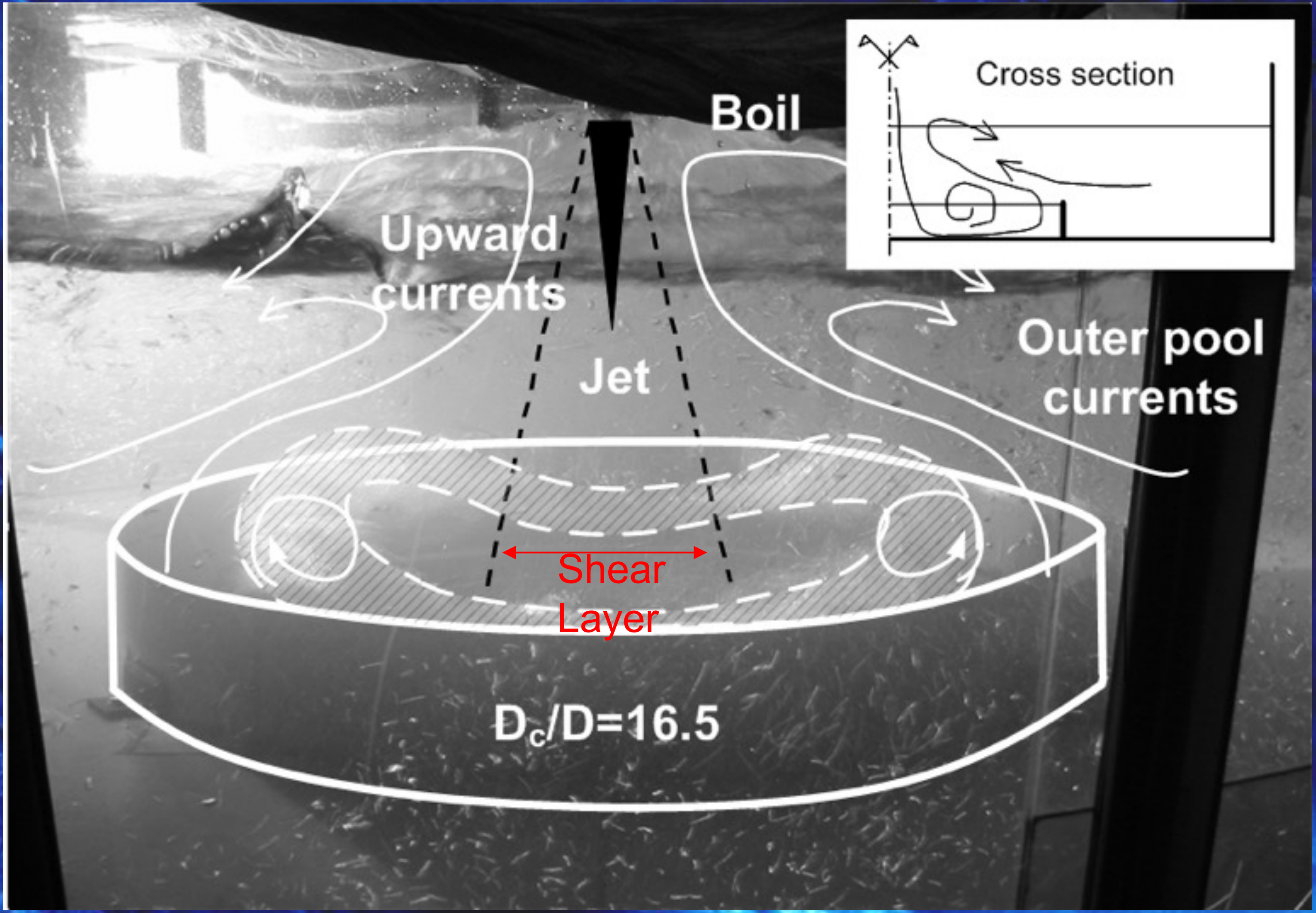
Pressure fluctuations: lateral evolution of scour

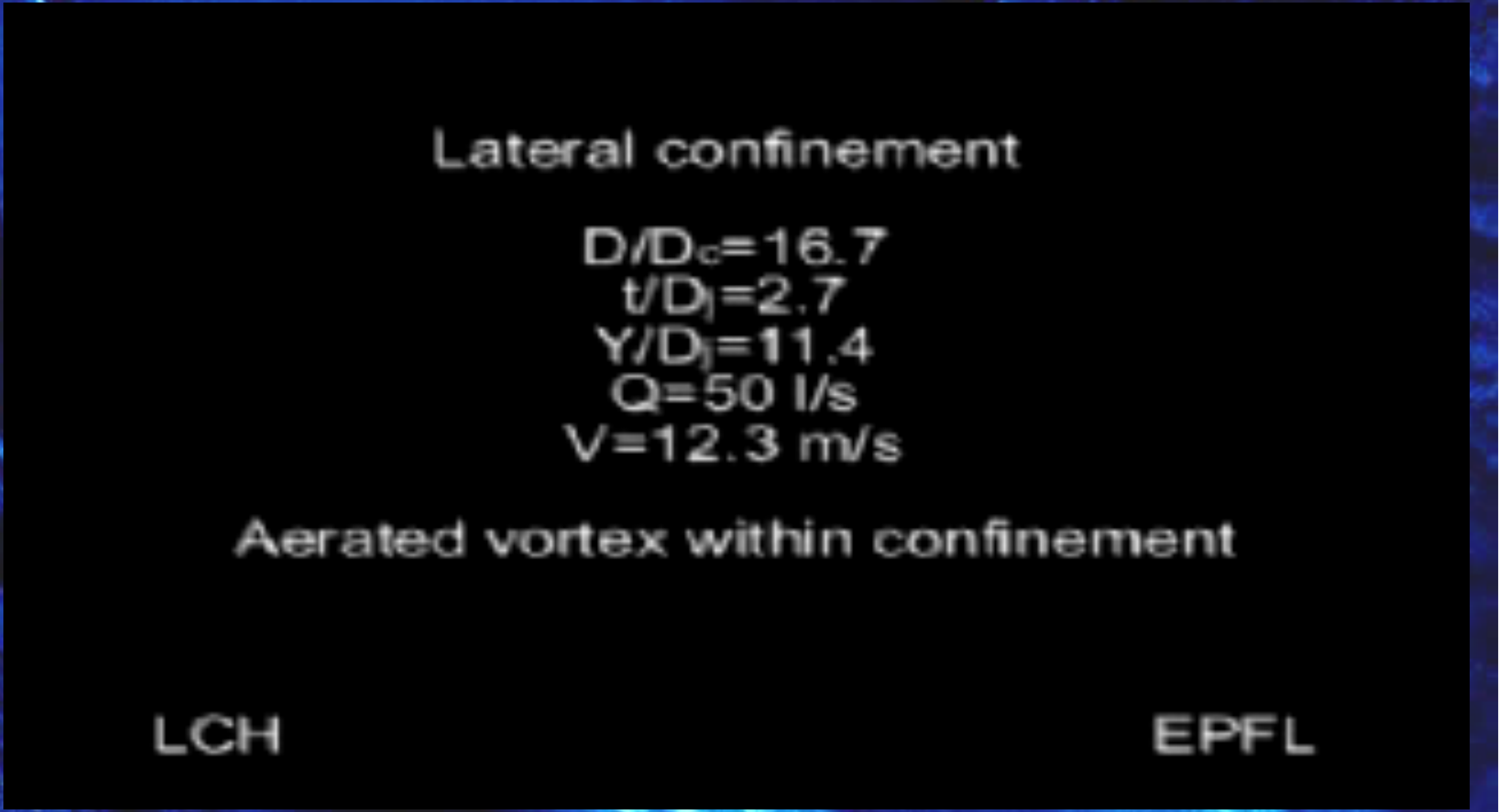
At pool bottom, below jet axis t/D = 2.8

$$C'_{pa} = \frac{\dfrac{RMS}{\gamma}}{\dfrac{\alpha V^2}{2g}}$$



Ring vortex (shear eddy cell) - WIDE





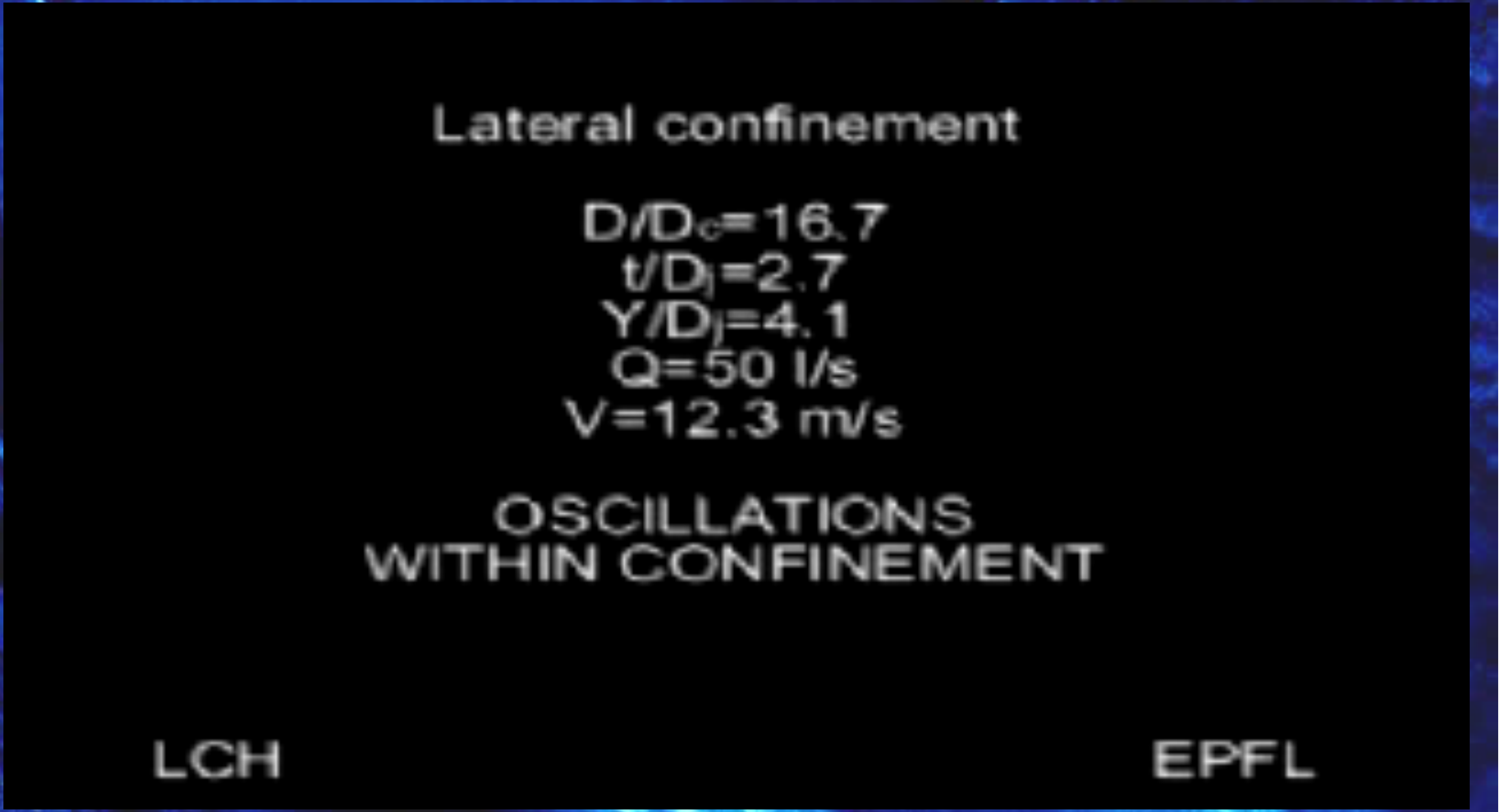
Lateral confinement

$D/D_c=16.7$
$t/D_j=2.7$
$Y/D_j=11.4$
$Q=50$ l/s
$V=12.3$ m/s

Aerated vortex within confinement

LCH

EPFL



Lateral confinement

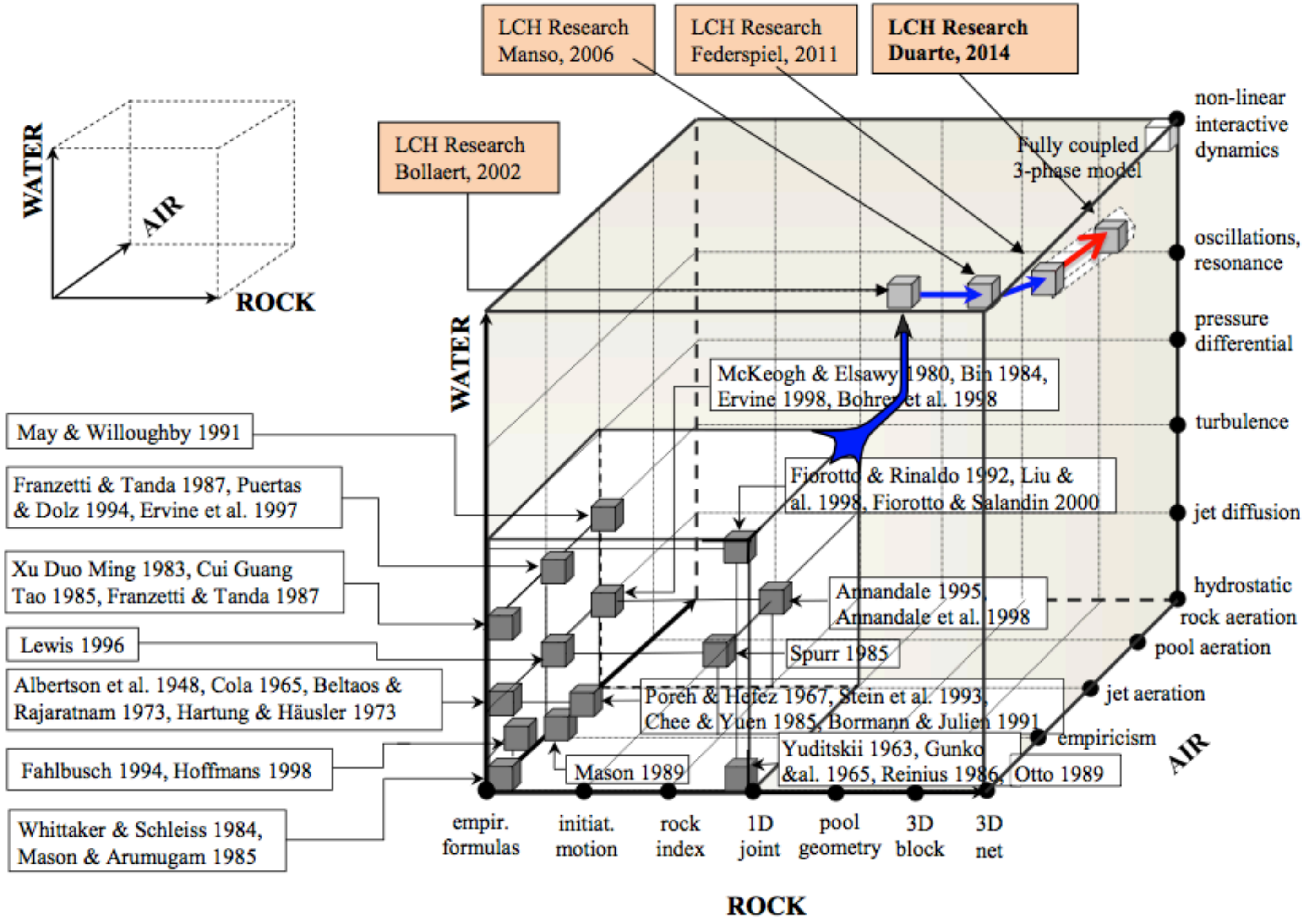
$D/D_c=16.7$
$t/D_j=2.7$
$Y/D_j=4.1$
$Q=50$ l/s
$V=12.3$ m/s

OSCILLATIONS
WITHIN CONFINEMENT

LCH EPFL

3. Scour evaluation methods

General overview



LCH Research
Manso, 2006

LCH Research
Federspiel, 2011

LCH Research
Duarte, 2014

LCH Research
Bollaert, 2002

Fully coupled
3-phase model

non-linear
interactive
dynamics

oscillations,
resonance

pressure
differential

turbulence

jet diffusion

hydrostatic

rock aeration

pool aeration

jet aeration

empiricism

McKeogh & Elsawy 1980, Bin 1984,
Ervine 1998, Bohrer et al. 1998

May & Willoughby 1991

Franzetti & Tanda 1987, Puertas
& Dolz 1994, Ervine et al. 1997

Fiorotto & Rinaldo 1992, Liu &
al. 1998, Fiorotto & Salandin 2000

Xu Duo Ming 1983, Cui Guang
Tao 1985, Franzetti & Tanda 1987

Annandale 1995,
Annandale et al. 1998

Lewis 1996

Spurr 1985

Albertson et al. 1948, Cola 1965, Beltaos &
Rajaratnam 1973, Hartung & Häusler 1973

Poreh & Hefez 1967, Stein et al. 1993,
Chee & Yuen 1985, Bormann & Julien 1991

Fahlbusch 1994, Hoffmans 1998

Mason 1989

Yuditskii 1963, Gunko
&al. 1965, Reinius 1986

Otto 1989

Whittaker & Schleiss 1984,
Mason & Arumugam 1985

empir.
formulas

initiat.
motion

rock
index

1D
joint

pool
geometry

3D
block

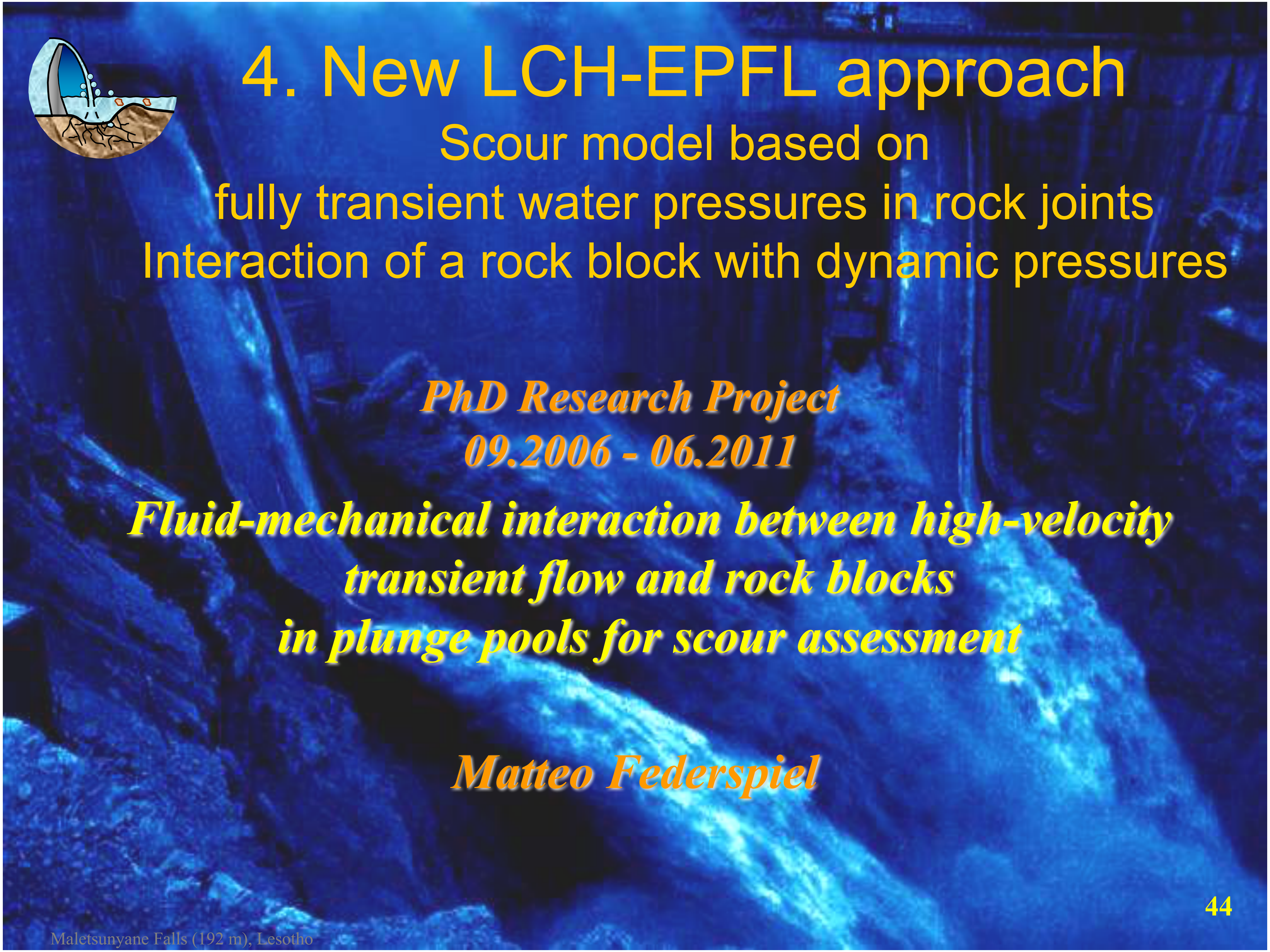
3D
net

ROCK

4. New LCH-EPFL approach

Scour model based on fully transient water pressures in rock joints

Interaction of a rock block with dynamic pressures



Maletsunyane Falls (192 m), Lesotho

PhD Research Project

09.2006 - 06.2011

Fluid-mechanical interaction between high-velocity transient flow and rock blocks in plunge pools for scour assessment

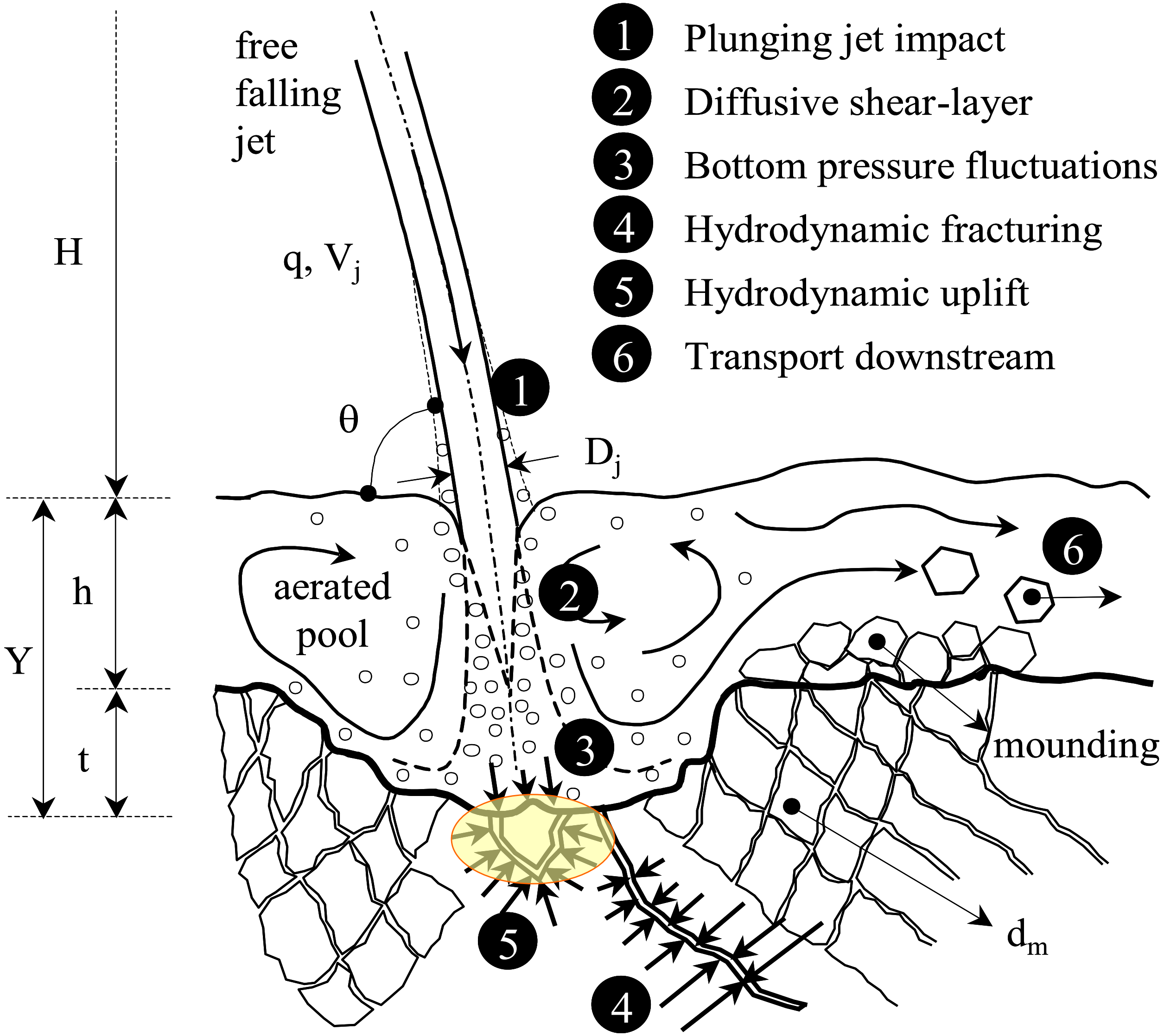
Matteo Federspiel

4. New LCH-EPFL approach

Interaction with a rock block

Verzasca Dam, Switzerland

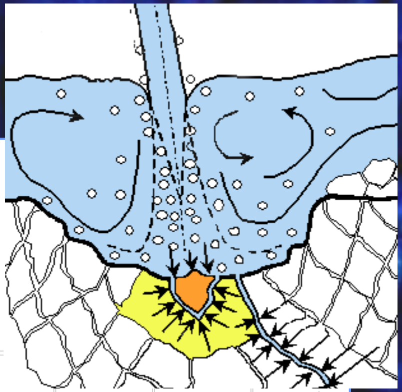
Angel Falls, Venezuela

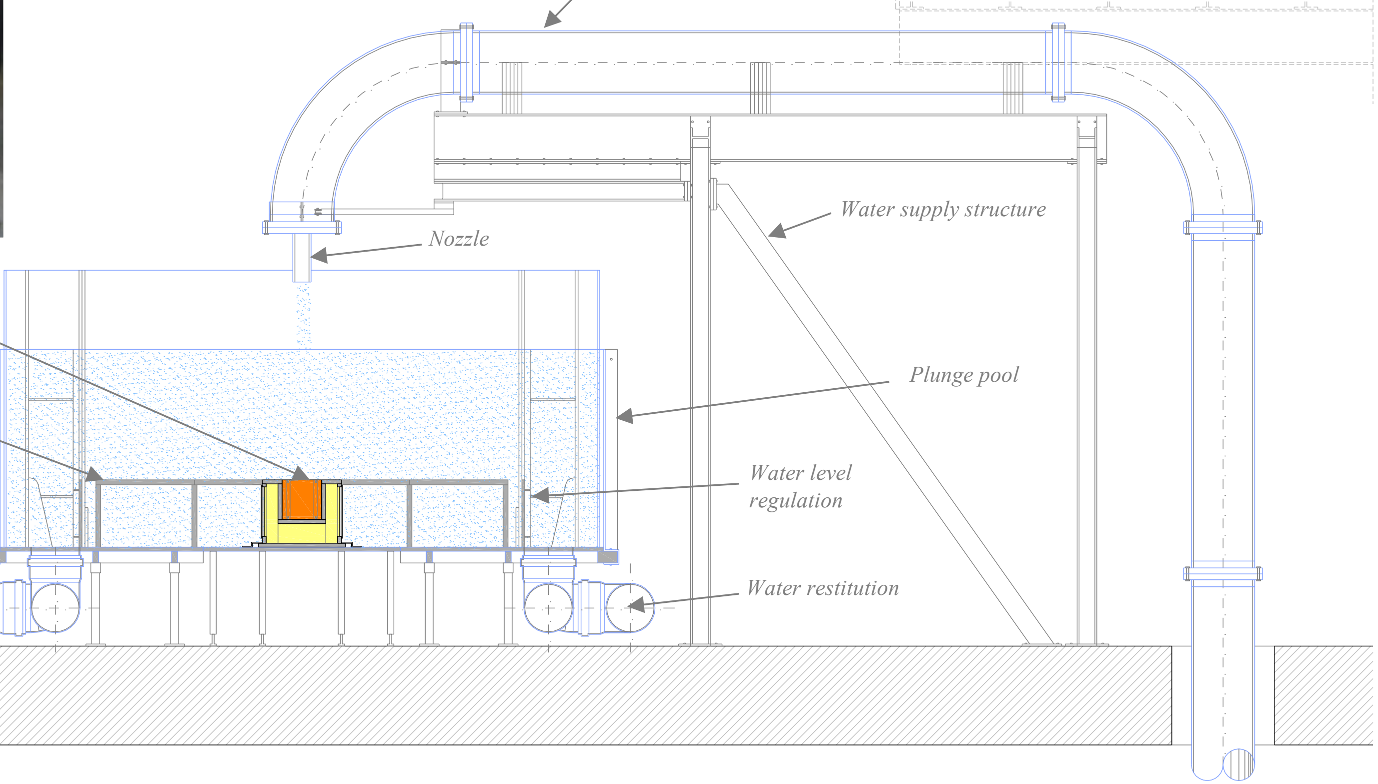


- ❶ Plunging jet impact
- ❷ Diffusive shear-layer
- ❸ Bottom pressure fluctuations
- ❹ Hydrodynamic fracturing
- ❺ Hydrodynamic uplift
- ❻ Transport downstream

Bollaert & Schleiss, 2002

Experimental facility of Federspiel





Water supply

Water supply structure

Nozzle

New experimental facility
Yellow: "measurement box"
Orange: "intelligent block"

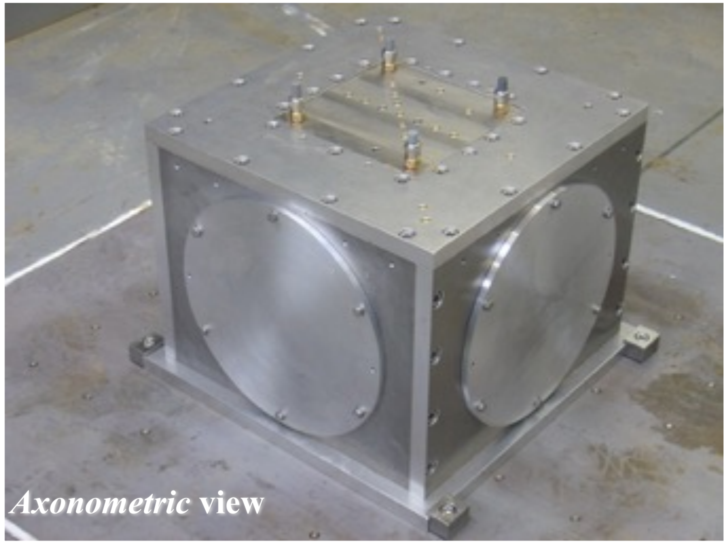
New level of the plunge pool bottom

Plunge pool

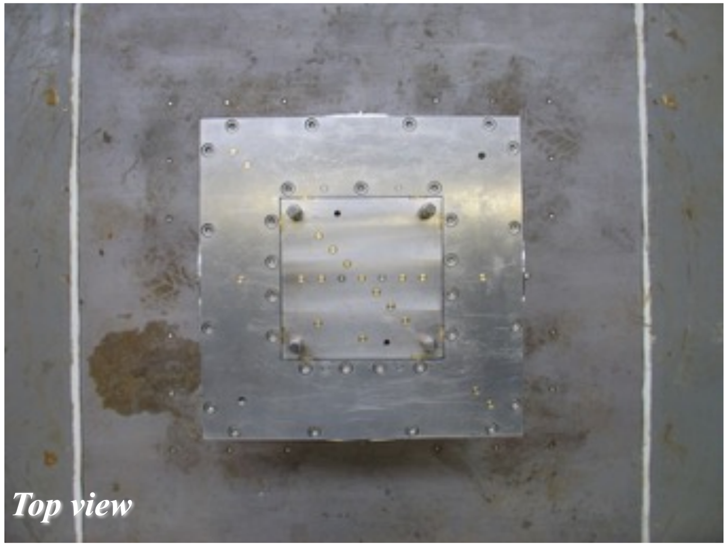
Water level regulation

Water restitution

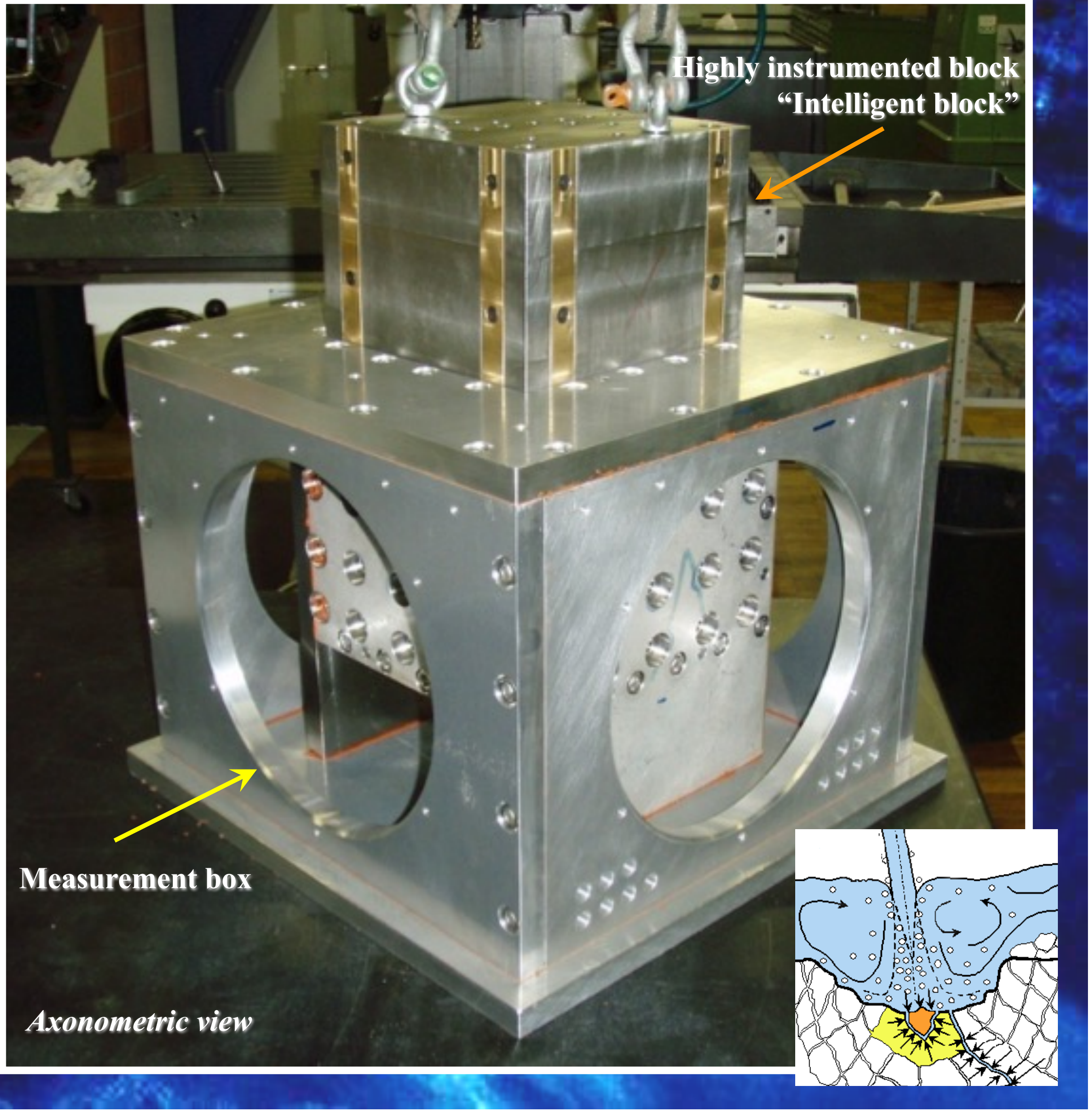
New experimental facility
Measurement box and highly instrumented block
("Intelligent block")



Axonometric view



Top view



Highly instrumented block
"Intelligent block"

Measurement box

Axonometric view

New experimental facility
Measurement box and highly instrumented block ("Intelligent block")

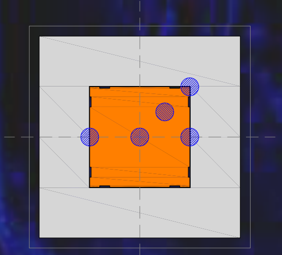
Y = 0.0 m and V = 9.2 m/s

4. New LCH-EPFL approach

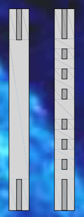
Interaction with a rock block

Configurations:

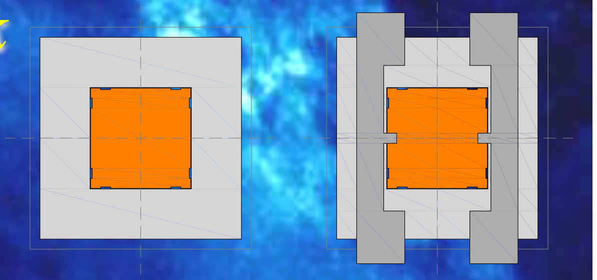
- ***Jet impact position on the intelligent block***
  Centered, on the vertical fissure axis: left side and right side, on the corner and radial



- ***The intelligent block lateral movement guidance***
  Two contact points or eight contact points



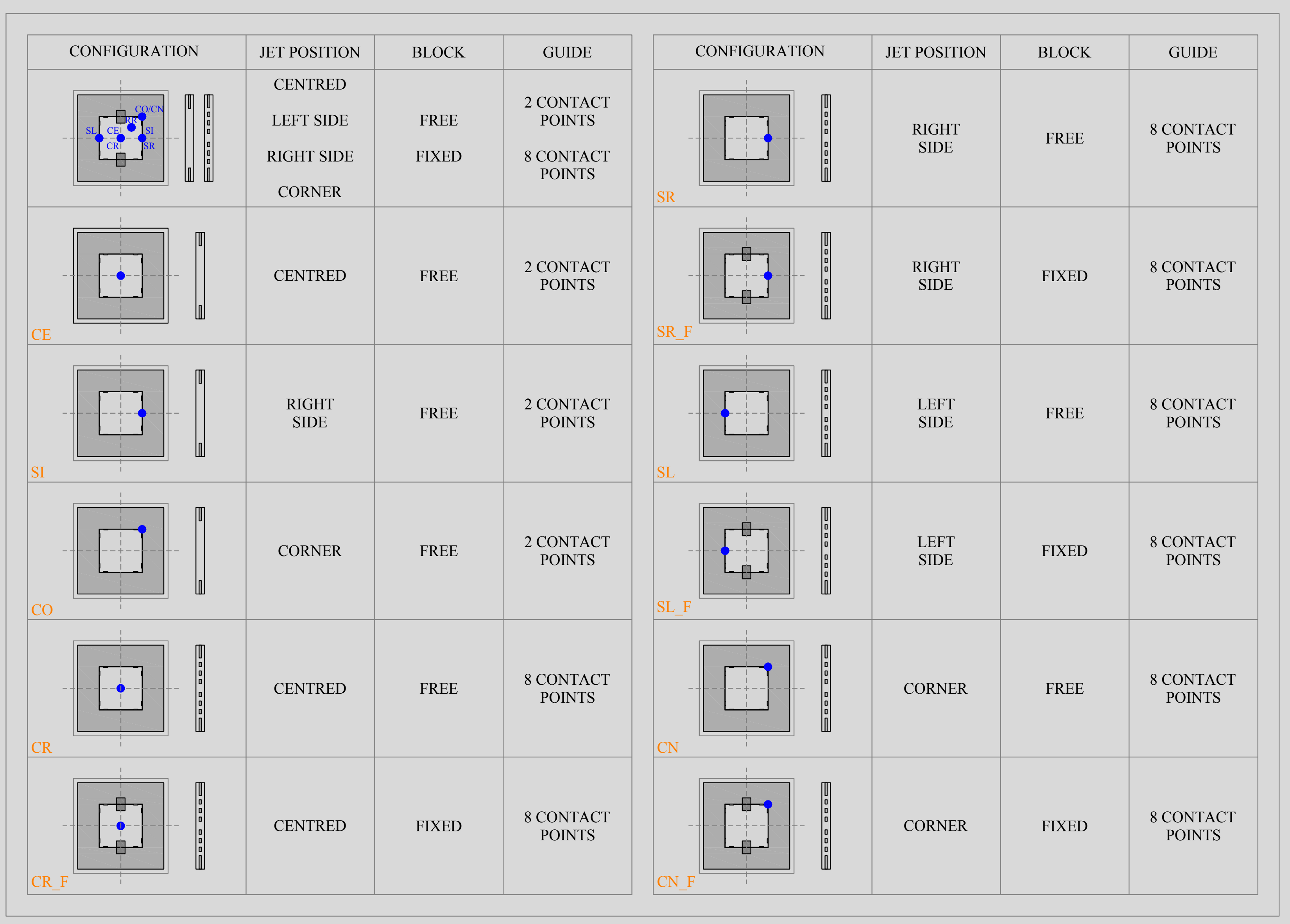
- ***The degree of freedom of the intelligent block***
  Free or fixed



Total configuration tested: 13

4. New LCH-EPFL approach

Interaction with a rock block



CONFIGURATION	JET POSITION	BLOCK	GUIDE
	CENTRED LEFT SIDE RIGHT SIDE CORNER	FREE FIXED	2 CONTACT POINTS 8 CONTACT POINTS
CE	CENTRED	FREE	2 CONTACT POINTS
SI	RIGHT SIDE	FREE	2 CONTACT POINTS
CO	CORNER	FREE	2 CONTACT POINTS
CR	CENTRED	FREE	8 CONTACT POINTS
CR_F	CENTRED	FIXED	8 CONTACT POINTS
SR	RIGHT SIDE	FREE	8 CONTACT POINTS
SR_F	RIGHT SIDE	FIXED	8 CONTACT POINTS
SL	LEFT SIDE	FREE	8 CONTACT POINTS
SL_F	LEFT SIDE	FIXED	8 CONTACT POINTS
CN	CORNER	FREE	8 CONTACT POINTS
CN_F	CORNER	FIXED	8 CONTACT POINTS

4. New LCH-EPFL approach

Interaction with a rock block

Test parameters

- ***Water level in the plunge pool***

  Ratio Y/D where Y is the water level and D is the nozzle outlet diameter - Y variable between 0.0 m and 0.7 m to generate core jet (Y/D < 4), transition jet (4< Y/D < 6) and developed jet (Y/D > 6)

- ***Nozzle outlet diameter***

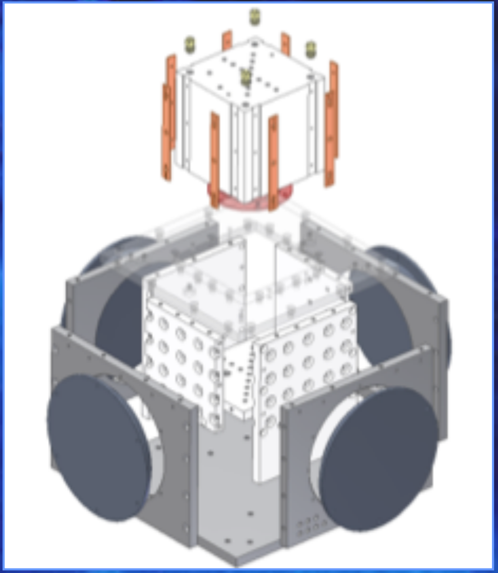
  D equal to 57 or 72 mm

- ***Velocity of the vertically impacting jet***

  Vmax 30 m/s or Qmax 120 l/s

- ***Position of the transducers***

  Pressure: 95 / Displacement: 2 / Acceleration: 1

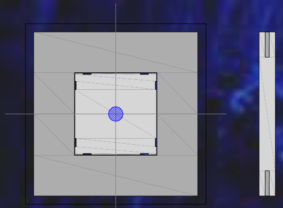


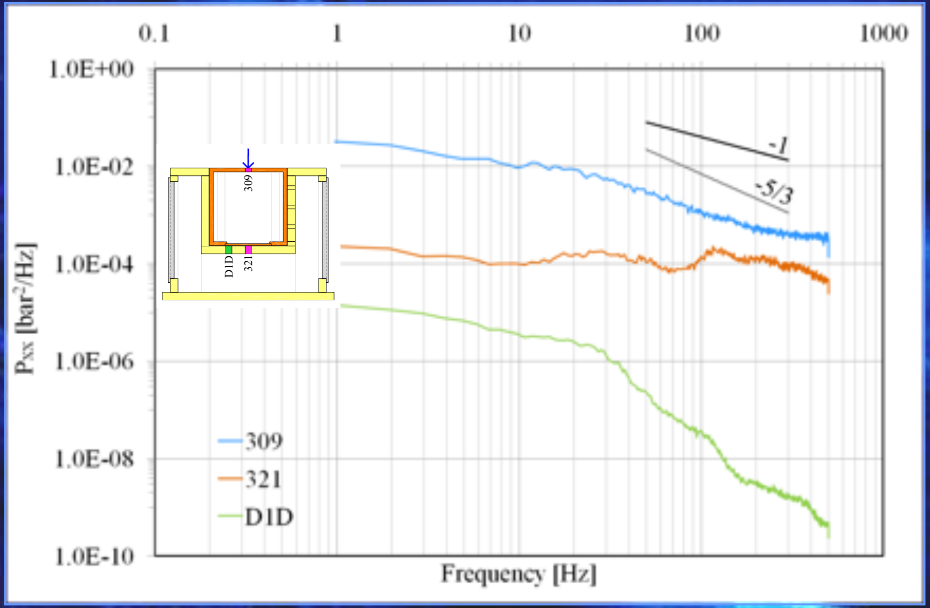
4. New LCH-EPFL approach

Interaction with a rock block

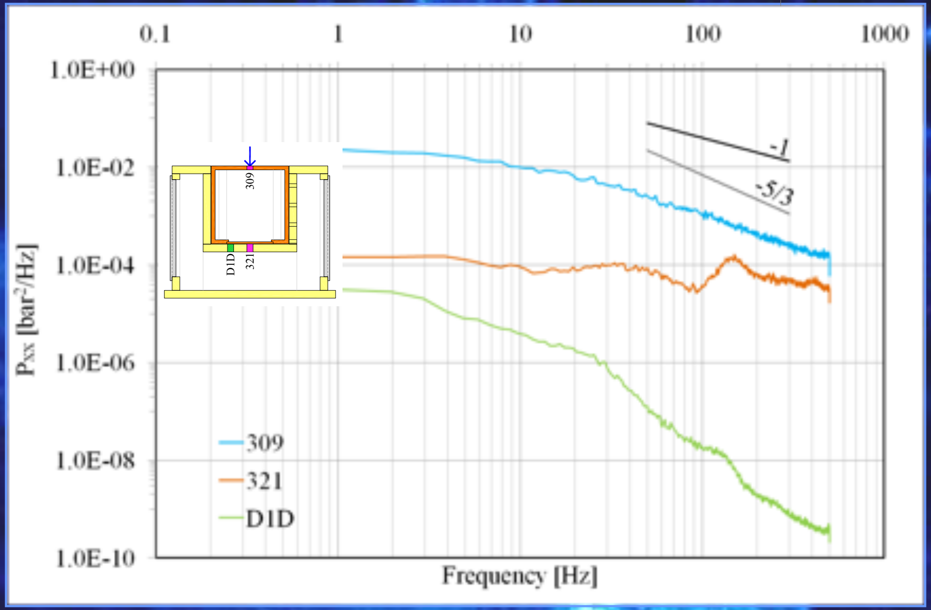
PSD_Power Spectral Density

FB_CE with jet velocity V = 27.0 m/s





Core jet: Y = 0.10 m and V = 27 m/s (Y/D = 1.39)



Developed jet: Y = 0.60 m and V = 27 m/s (Y/D = 8.33)

Two zones of increased PSD have been detected (10-100 Hz and 100-200 Hz), which might be related to the eigen frequencies of the travelling pressure wave in the joint and to the block inertia.

4. New LCH-EPFL approach

Scour model based on
fully transient water pressures in rock joints
Interaction of a rock block with dynamic pressures

PhD Research Project
04.2014 - 04.2014

Influence of air entrainment on rock scour development and block stability in plunge pools

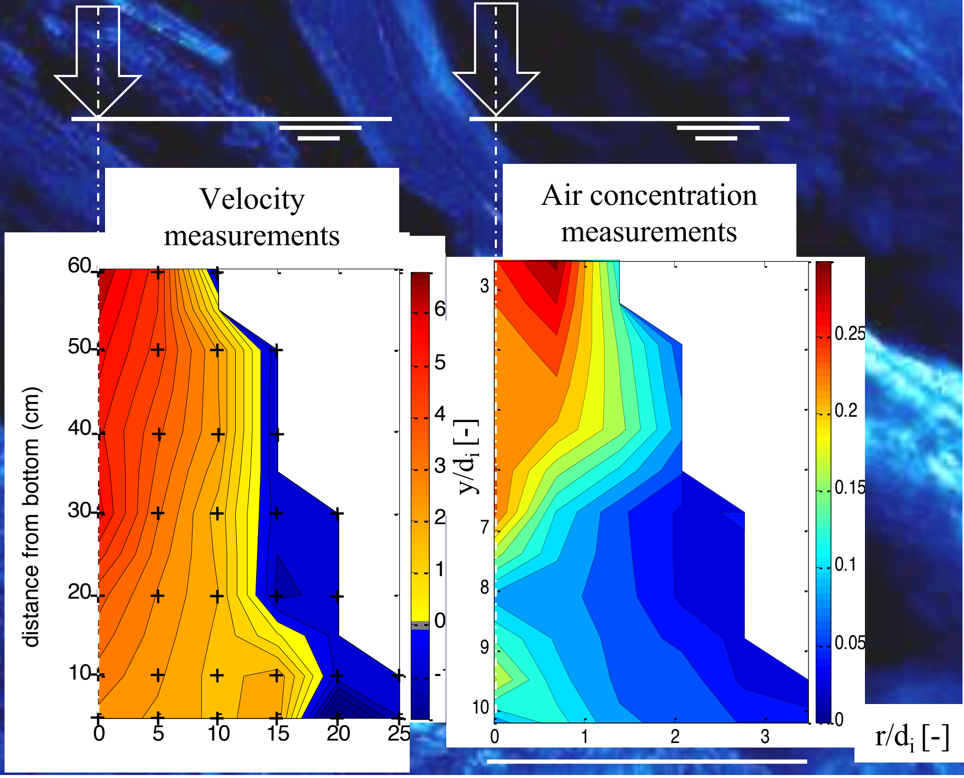
Rafael Duarte

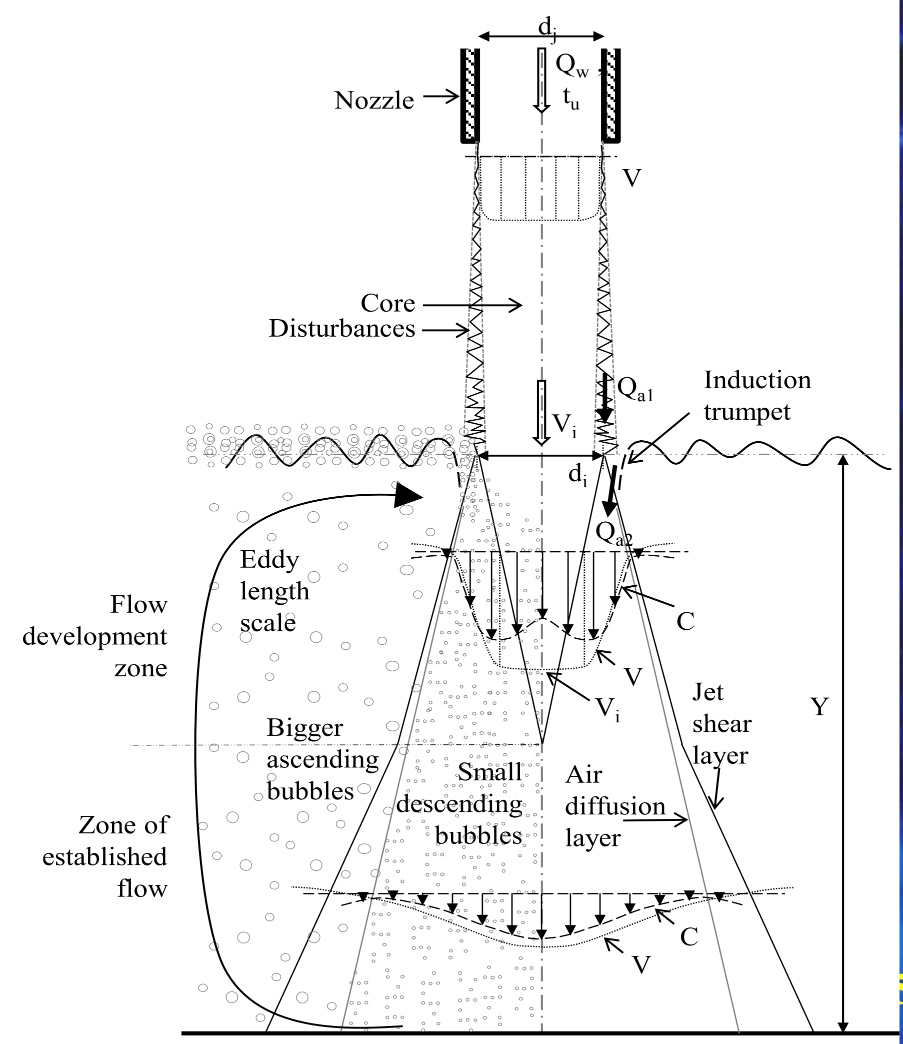
Maletsunyane Falls (192 m), Lesotho

Influence of jet aeration on rock scour

Research questions

- Air bubble dissipation features in receiving pool
- Influence of jet aeration on dynamic pressures in pool bottom





Influence of jet aeration on rock scour

Influence of air concentration

The mean density ρ_{aw} of the air-water jet inside the pool is with ρ_a and ρ_w as air and water densities

- $$\rho_{aw} = \frac{1}{1+\beta}\rho_w + \frac{\beta}{1+\beta}\rho_a$$

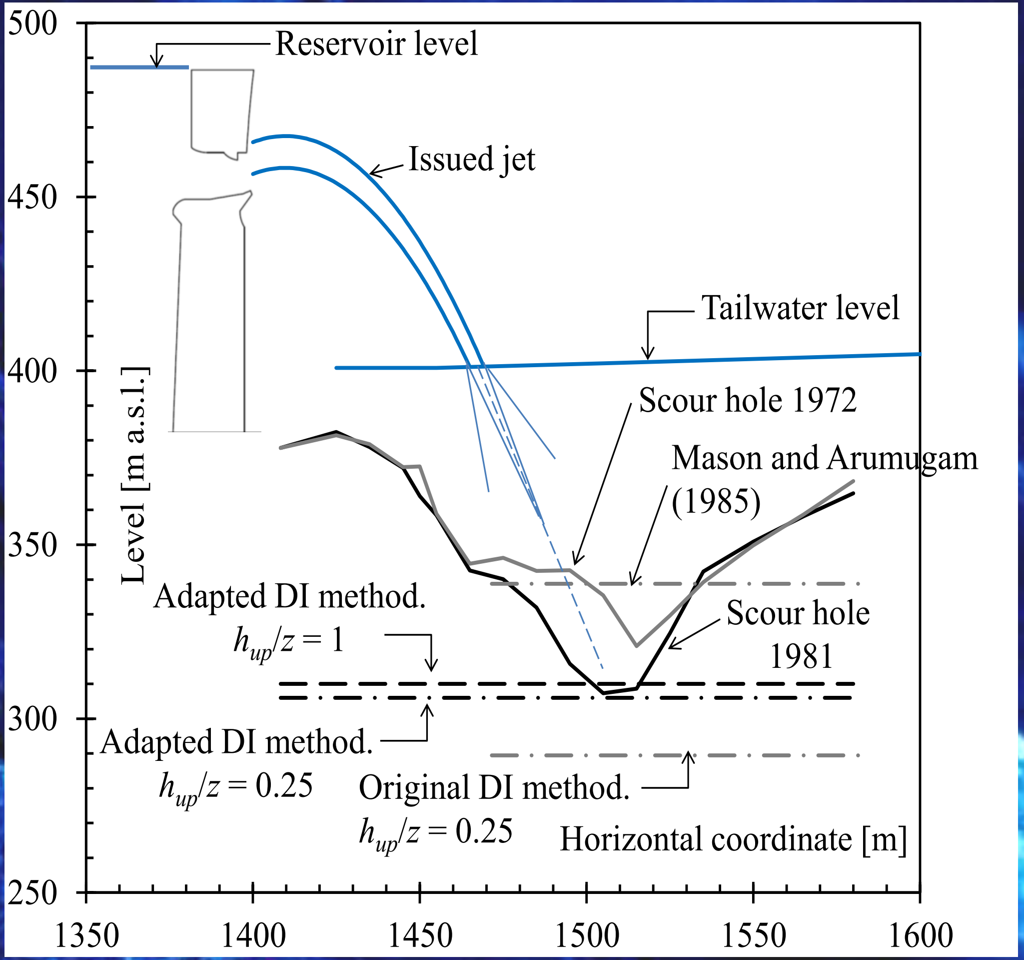
Kinetic energy per unit volume of the air-water jet at the plunge section

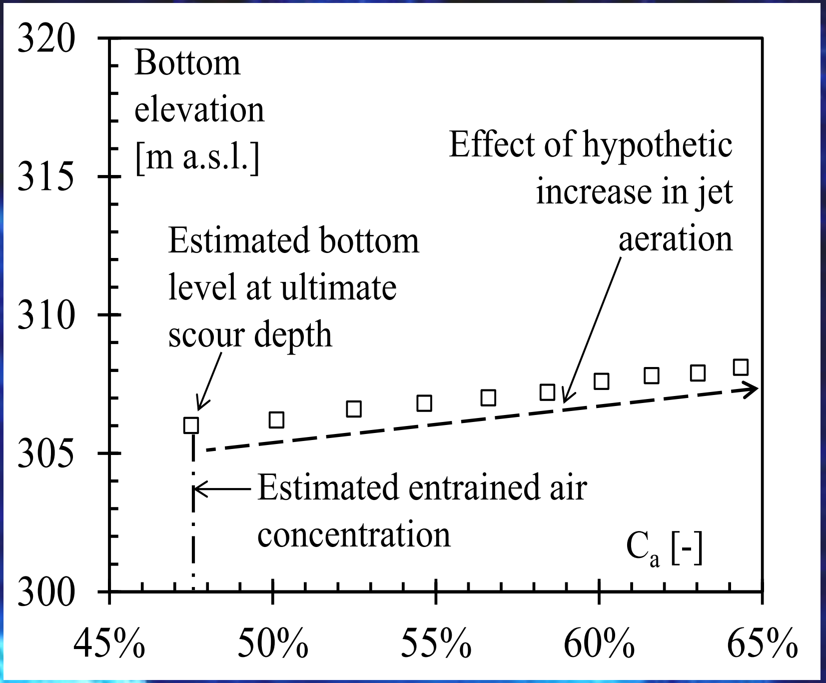
- $$E_k = \frac{1}{2}\rho_{aw}V_i^2$$

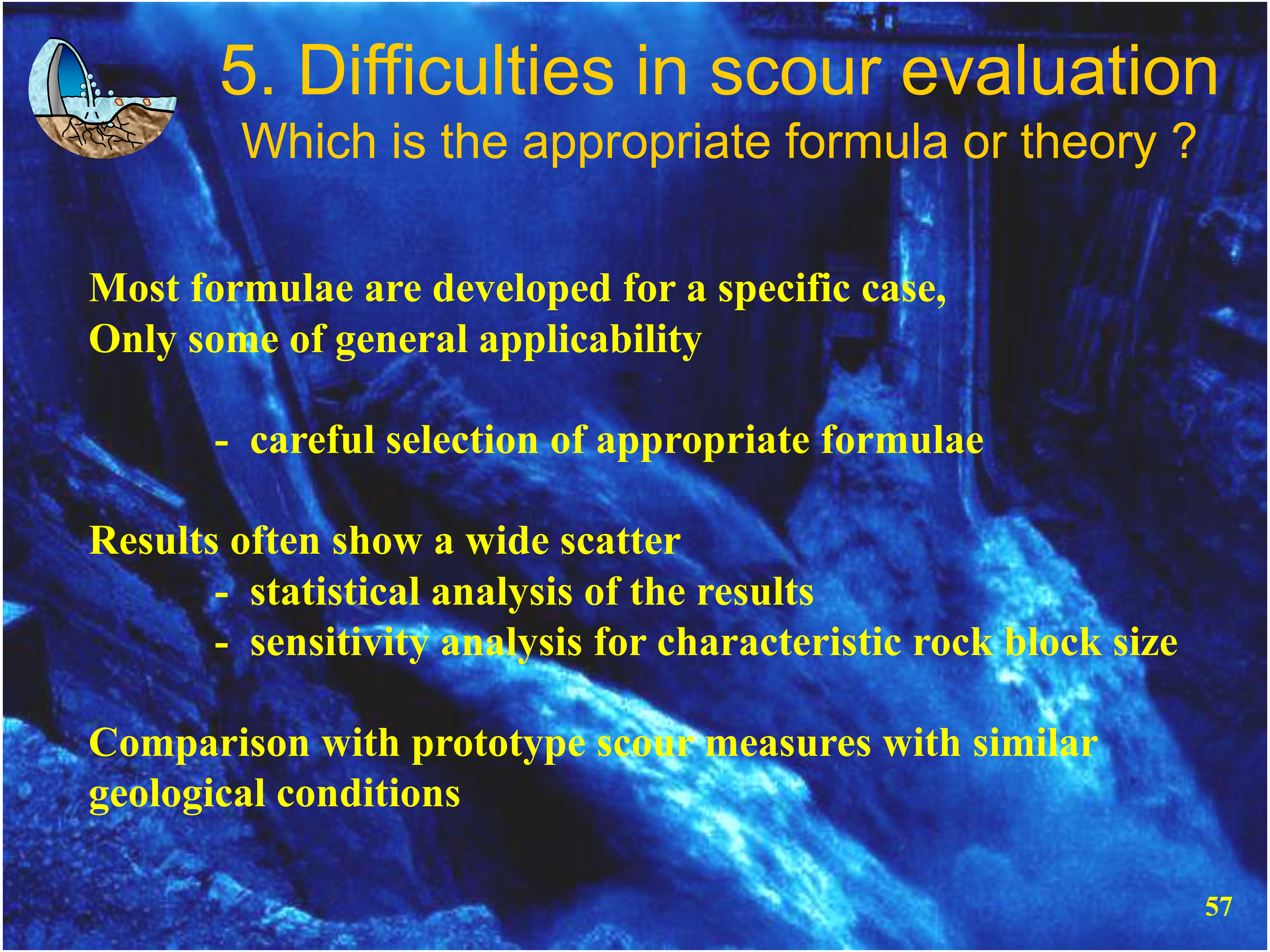
Time-averaged pressure coefficient

- $$\frac{C_p^a}{C_p} = 1 + 0.4\beta$$

Influence of jet aeration on rock scour – Case study Kariba (Rafael Duarte)







5. Difficulties in scour evaluation

Which is the appropriate formula or theory ?

Most formulae are developed for a specific case,
Only some of general applicability

- **careful selection of appropriate formulae**

Results often show a wide scatter

- **statistical analysis of the results**
- **sensitivity analysis for characteristic rock block size**

Comparison with prototype scour measures with similar geological conditions

5. Difficulties

How model tests should they be performed and interpreted ?

Three difficulties:

- a) appropriate choice of a material that will behave dynamically in the model as fissured rock does in the prototype
- b) grain size effects
- c) aeration effects

Hydraulic model tests at LCH for Ostour dam in Iran

5. Difficulties

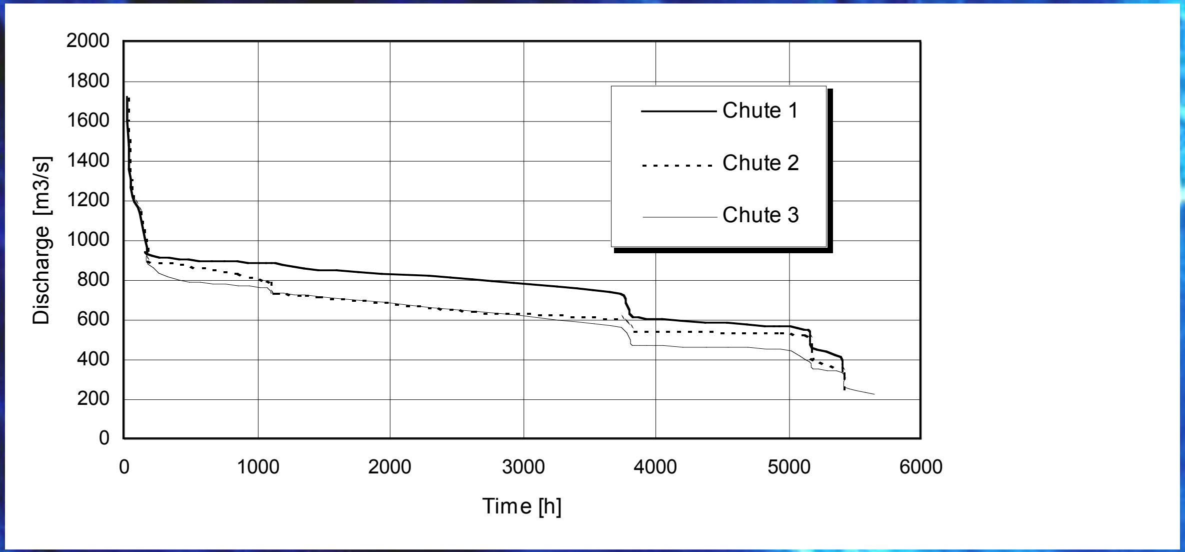
How to analyze prototype observations properly ?

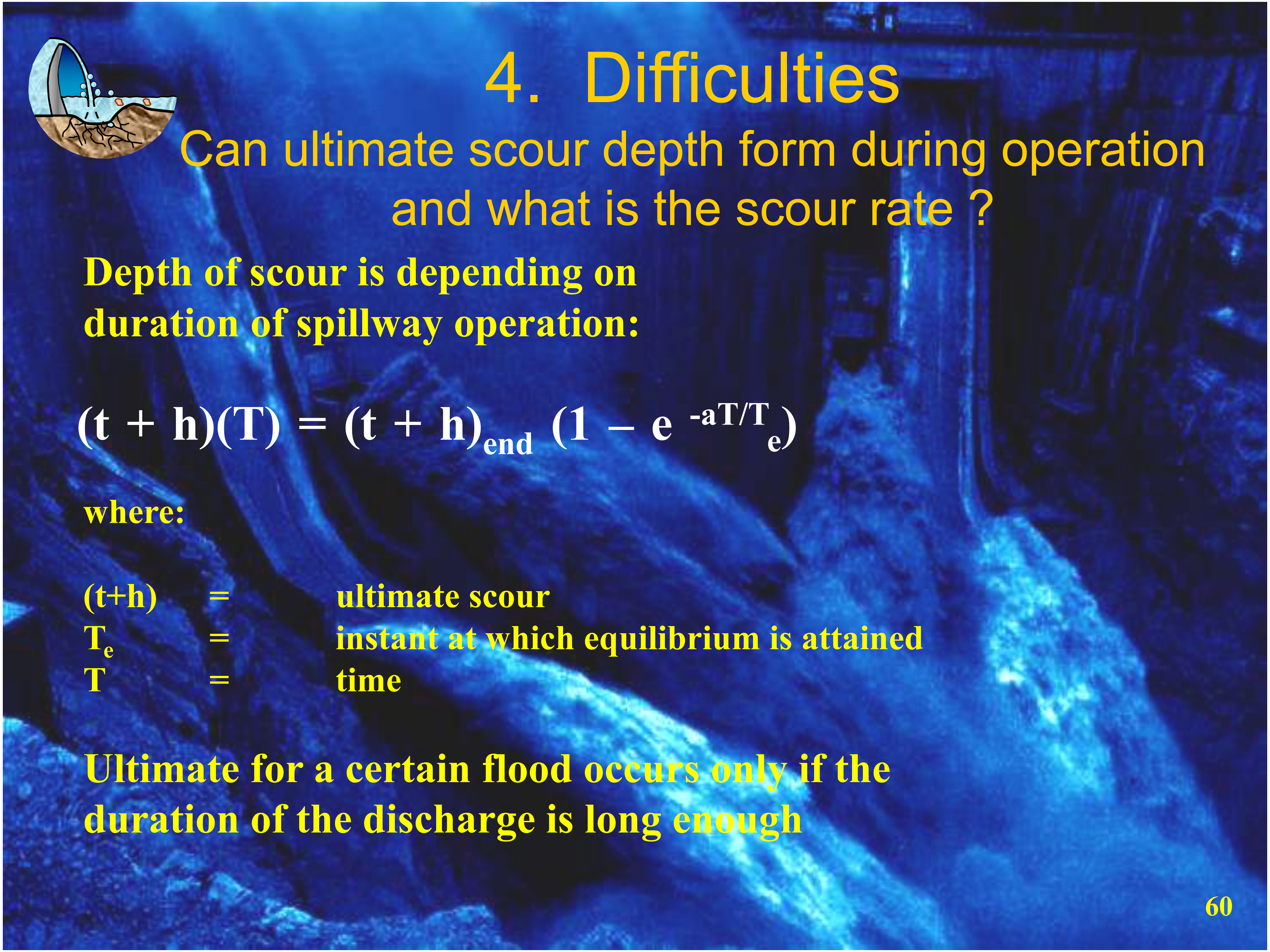
Questions to be answered:

1. What was the duration of the operation of the spillway for different specific discharges (discharge-duration curve)?
   An example of discharge-duration curve of a spillway is given in Figure below.

2. Which was the prevailing, specific discharge which formed the scour depth?

3. Was the duration of this specific discharge long enough to create ultimate scour depth?





4. Difficulties

Can ultimate scour depth form during operation and what is the scour rate ?

Depth of scour is depending on duration of spillway operation:

$$(t + h)(T) = (t + h)_{end} \; (1 - e^{-aT/T_e})$$

where:

$(t+h)$ = ultimate scour
T_e = instant at which equilibrium is attained
T = time

Ultimate for a certain flood occurs only if the duration of the discharge is long enough

5. Difficulties

Which will be the prevailing discharge for scour formation during a flood event ?

Determination of scour

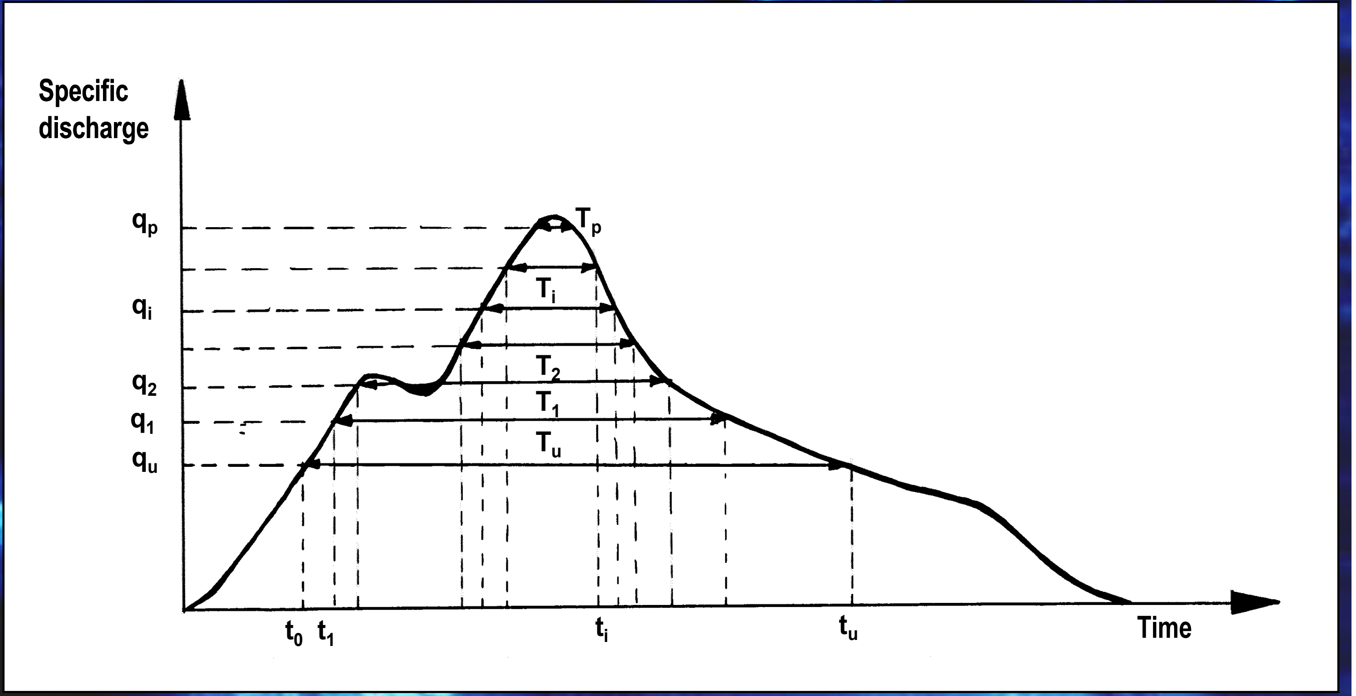
q_e $(T = T_e)$

q_1 $(T_1 < T_e)$

q_2 $(T_2 < T_1 < T_e)$

……..

q_{peak} $(T_{peak} < T_i < T_e)$



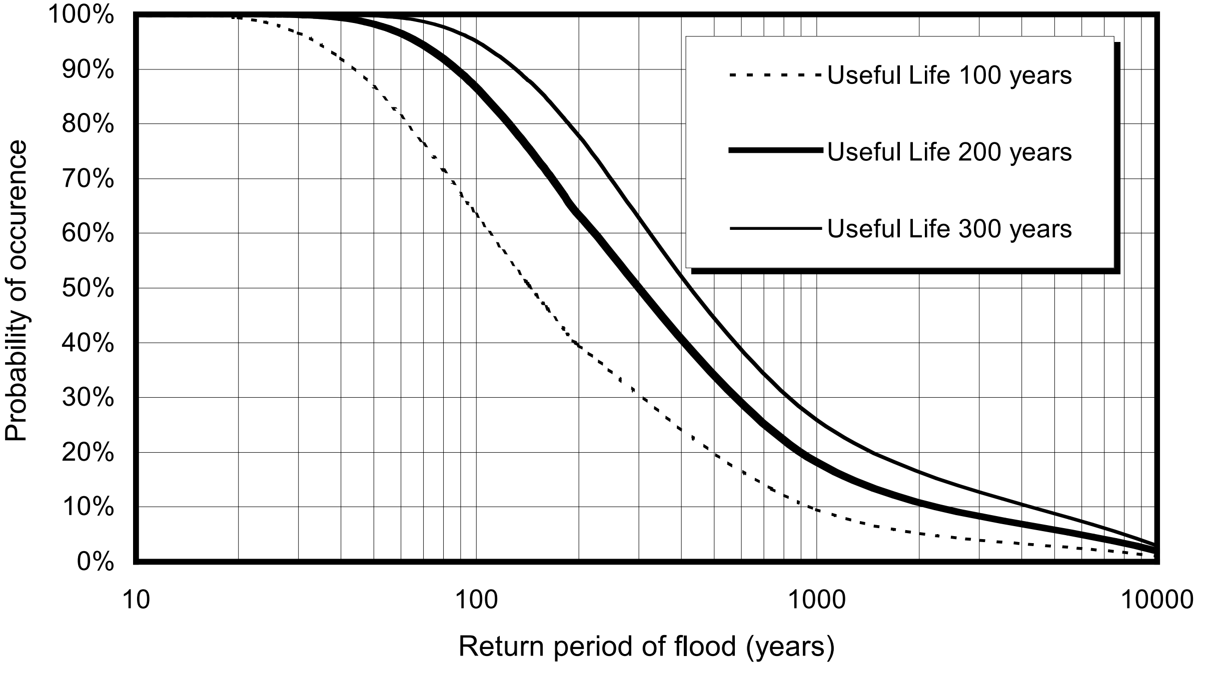
Discharge which gives the deepest scour is the prevailing discharge

5. Design discharge

Spillway design discharge and scour evaluation

Designing scour mitigation measures for the project or safety check flood is too conservative!

Design discharge with a probability of occurrence of 50 % during the useful lifetime of a dam is reasonable



Gated spillways can release « artificial »floods

6. Measures for scour control

Overview of measures for scour control

Active measures

- **Avoid scour formation completely**
  - Lined plunge pools
- **Limit the extent of the scour**
  - Limitation of the specific spillway discharge
  - Forced aeration and splitting of jets
  - Increasing tailwater depth by tailpond dam
  - Pre-excavation of the plunge pool
- **Influence the location of the scour**
  - Type and design of spillway

Passive measures: Protecting dam abutments with anchors

6. Measures for scour control

Concrete lined plunge pools

Thickness of the lining is limited by construction and economical reasons

High tension or pre-stressed rock anchors are required to ensure the lining stability regarding dynamic loading

Surface of the lining has to be protected against abrasion

Construction joints have to be carefully sealed (double waterstops)

A drainage system can reduce static uplift during dewatering and dynamic uplift during operation

In the case of cracks in the lining the response of the drainage system has to be considered, i.e. dynamic uplift can not be excluded

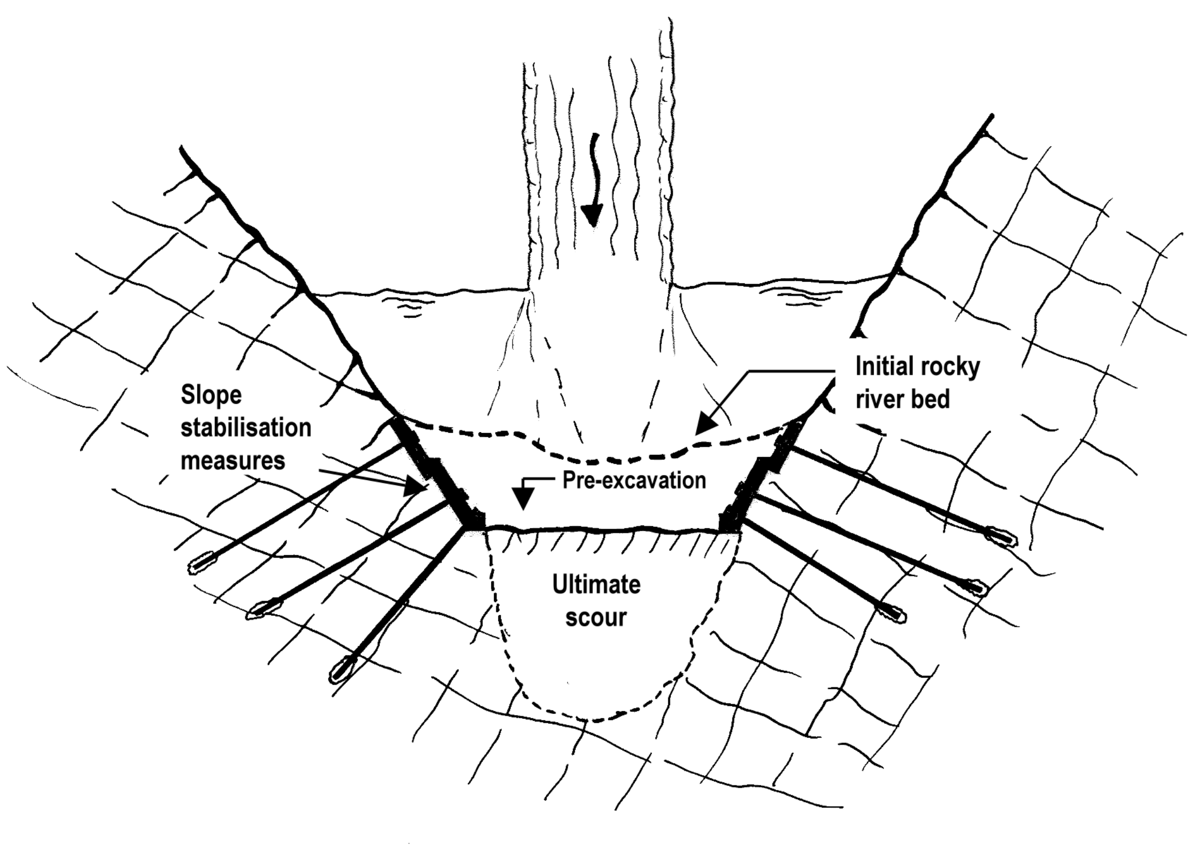
6. Measures for scour control

Pre-excavation and anchoring

Passive measures:

Anchoring of rock slope

Protection against toe scouring



7. Case study Kariba in Sambia - Simbabwe

KARIBA

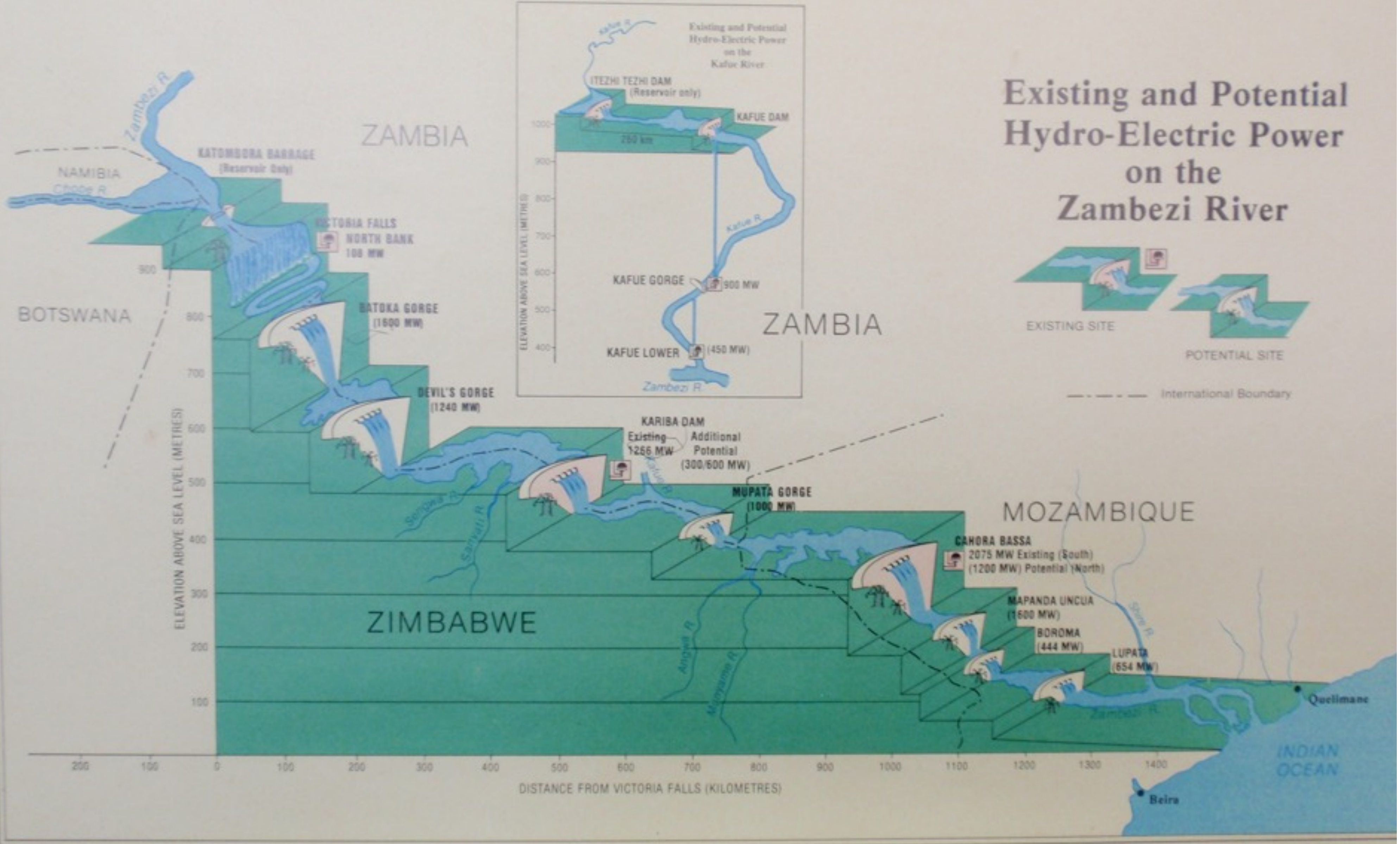
H 128 m

L 617 m

C 181 km^3

Zambezi River Authority

Existing and Potential Hydro-Electric Power on the Zambezi River



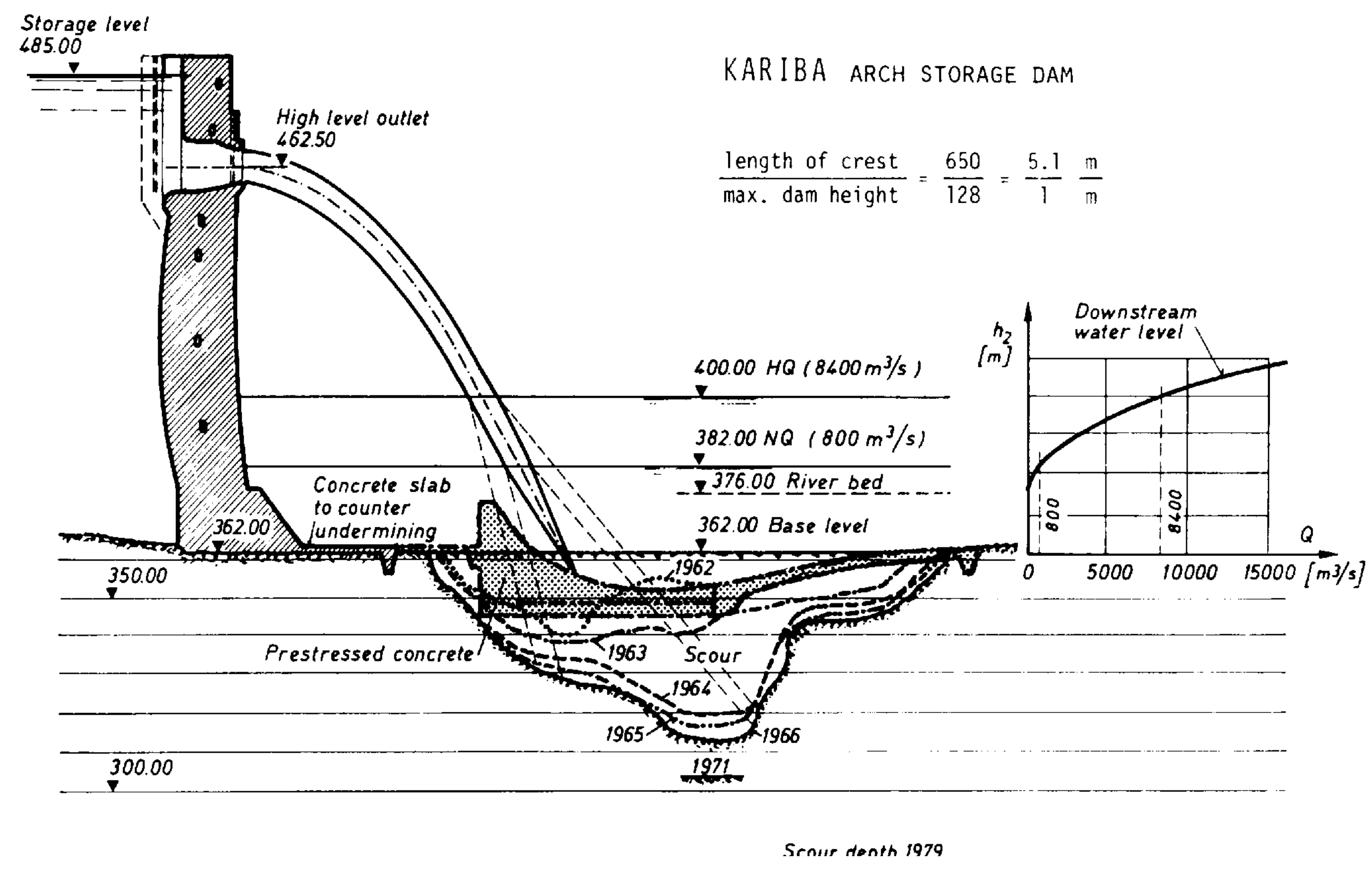
REVISION 'A'


AEROS
AEROS
BATOKA SKY
ZAMBIA

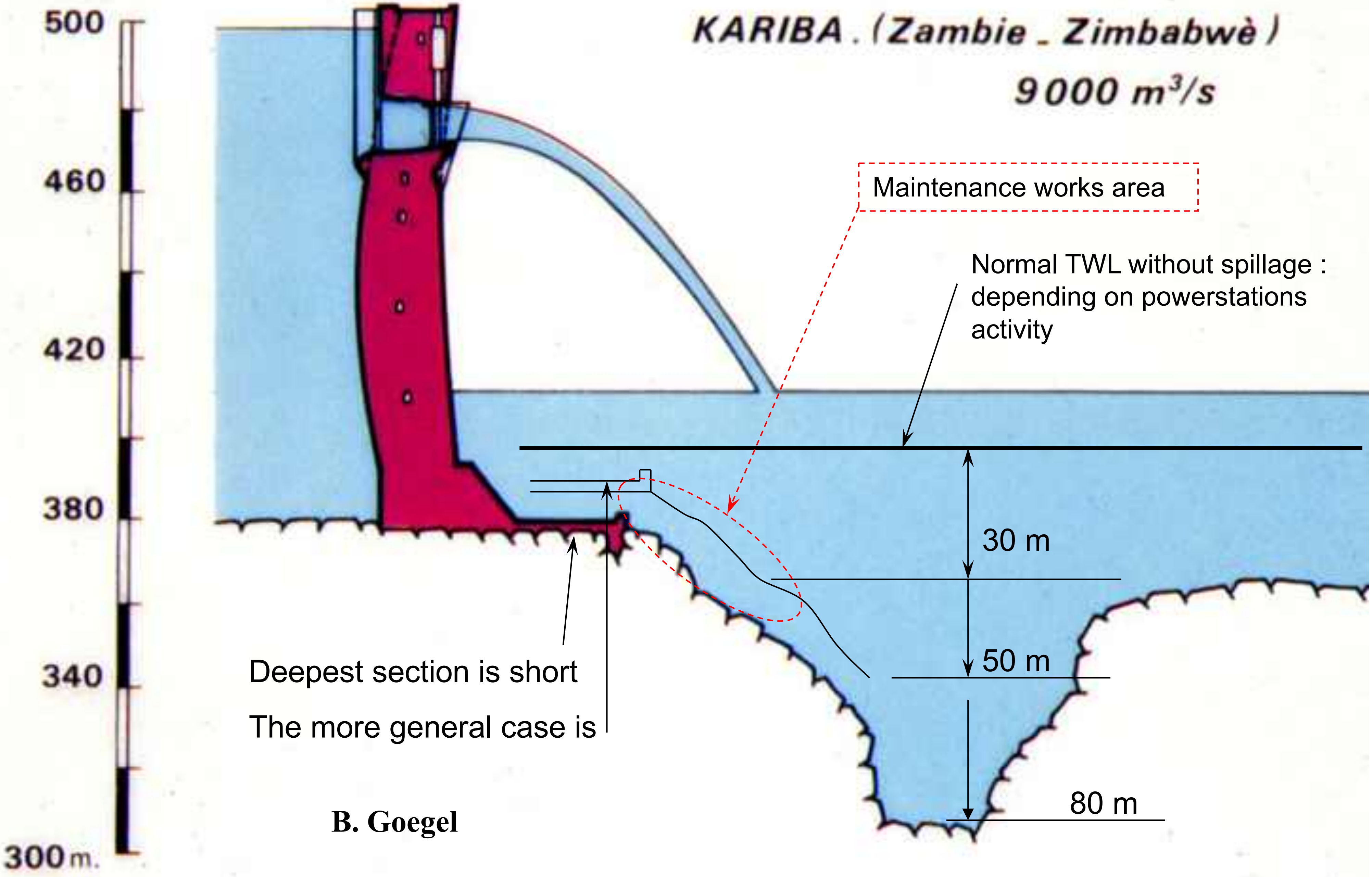

AEROS
AEROS
BATOKA SKY
ZAMBIA


AEROS
AEROS
COBRA
BATOKA SKY
ZAMBIA

7. Case study Kariba in Sambia - Simbabwe

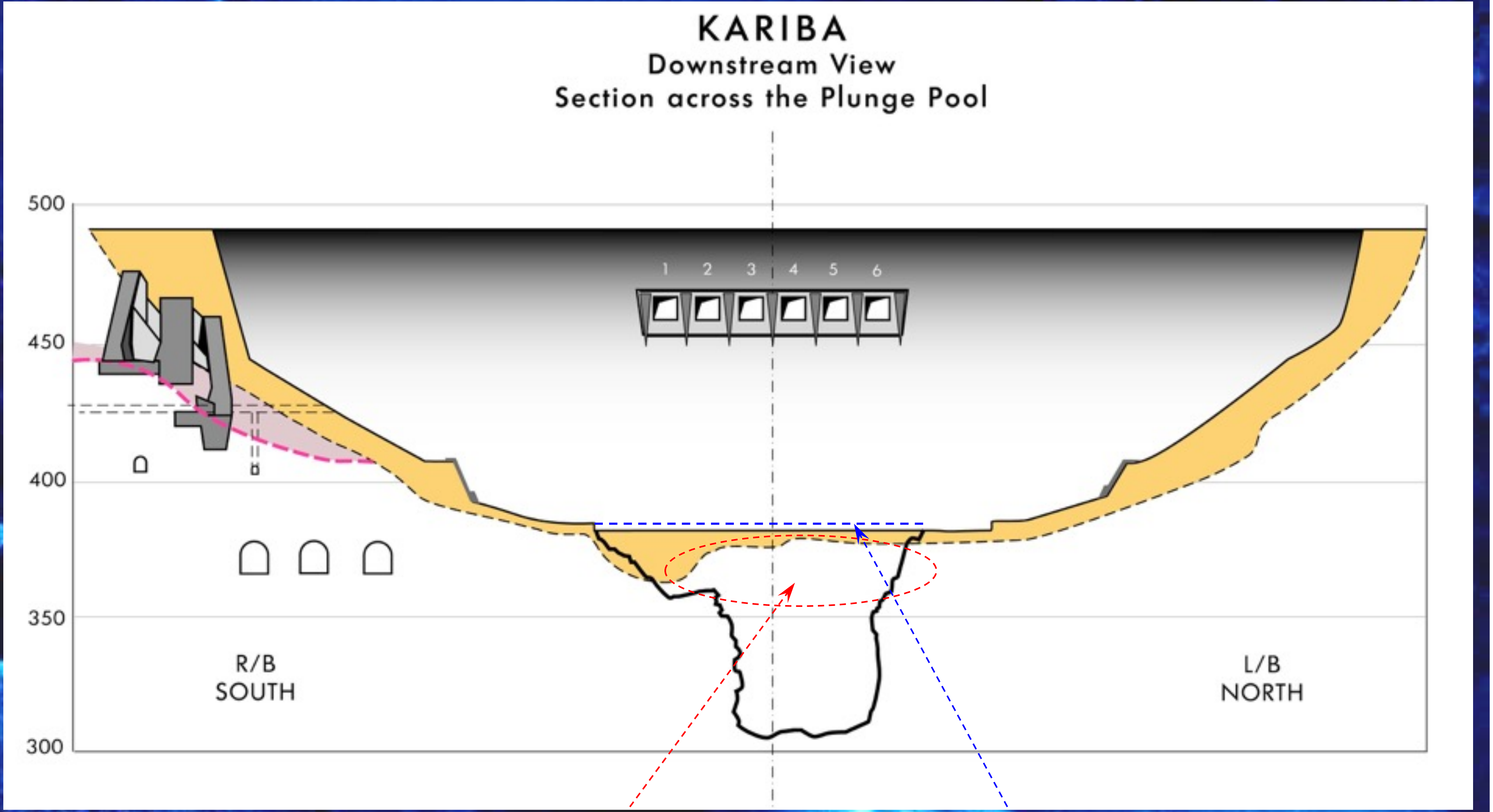


7. Case study Kariba in Sambia - Simbabwe



B. Goegel

7. Case study Kariba in Sambia - Simbabwe

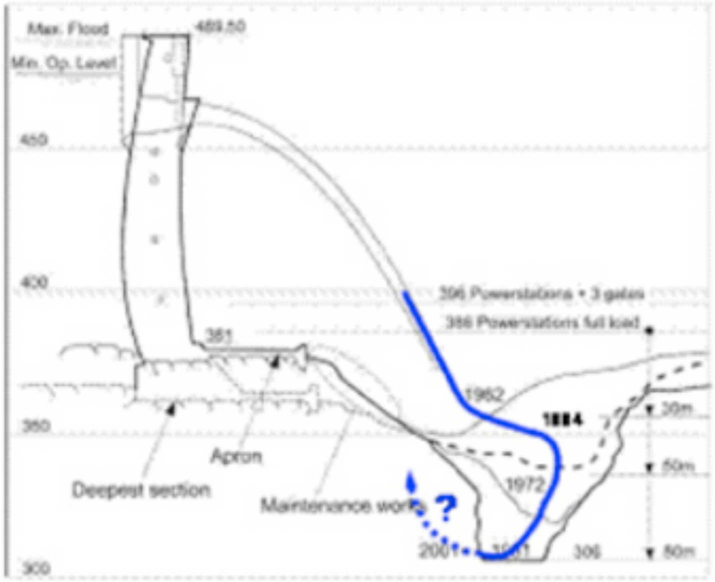


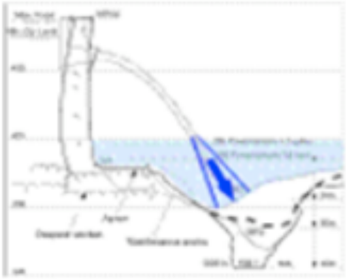
B. Goegel

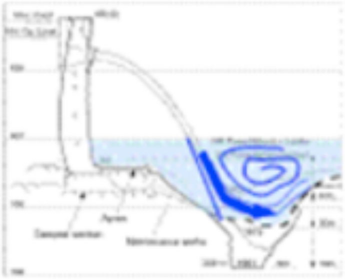
Maintenance works area

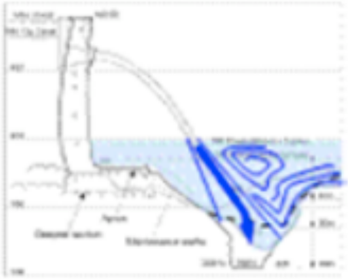
Normal TWL without spillage : depending on powerstations activity

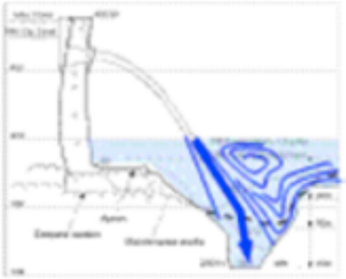
6. Fallbeispiel Kariba in Sambia - Simbabwe

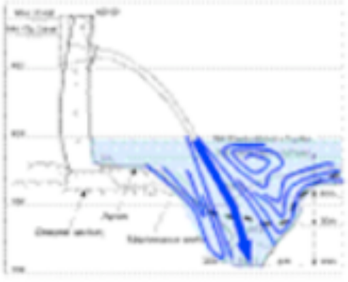



1962


1964


1972


1981


20xx?

7. Case study Kariba in Sambia - Simbabwe

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H 128 m

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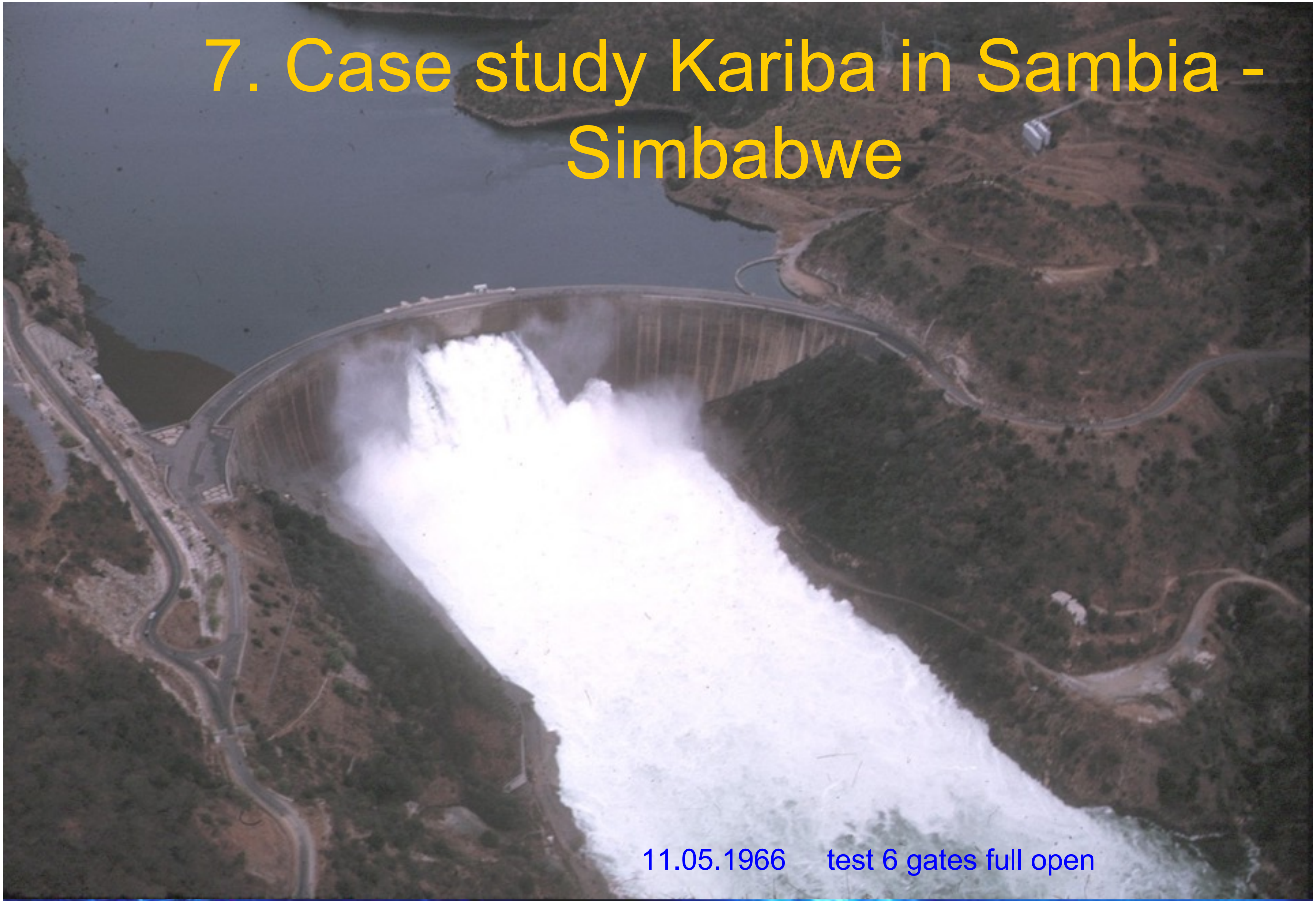
7. Case study Kariba in Sambia - Simbabwe

11.05.1966 test 6 gates full open

7. Case study Kariba in Sambia - Simbabwe



11.05.1966 test 6 gates full open

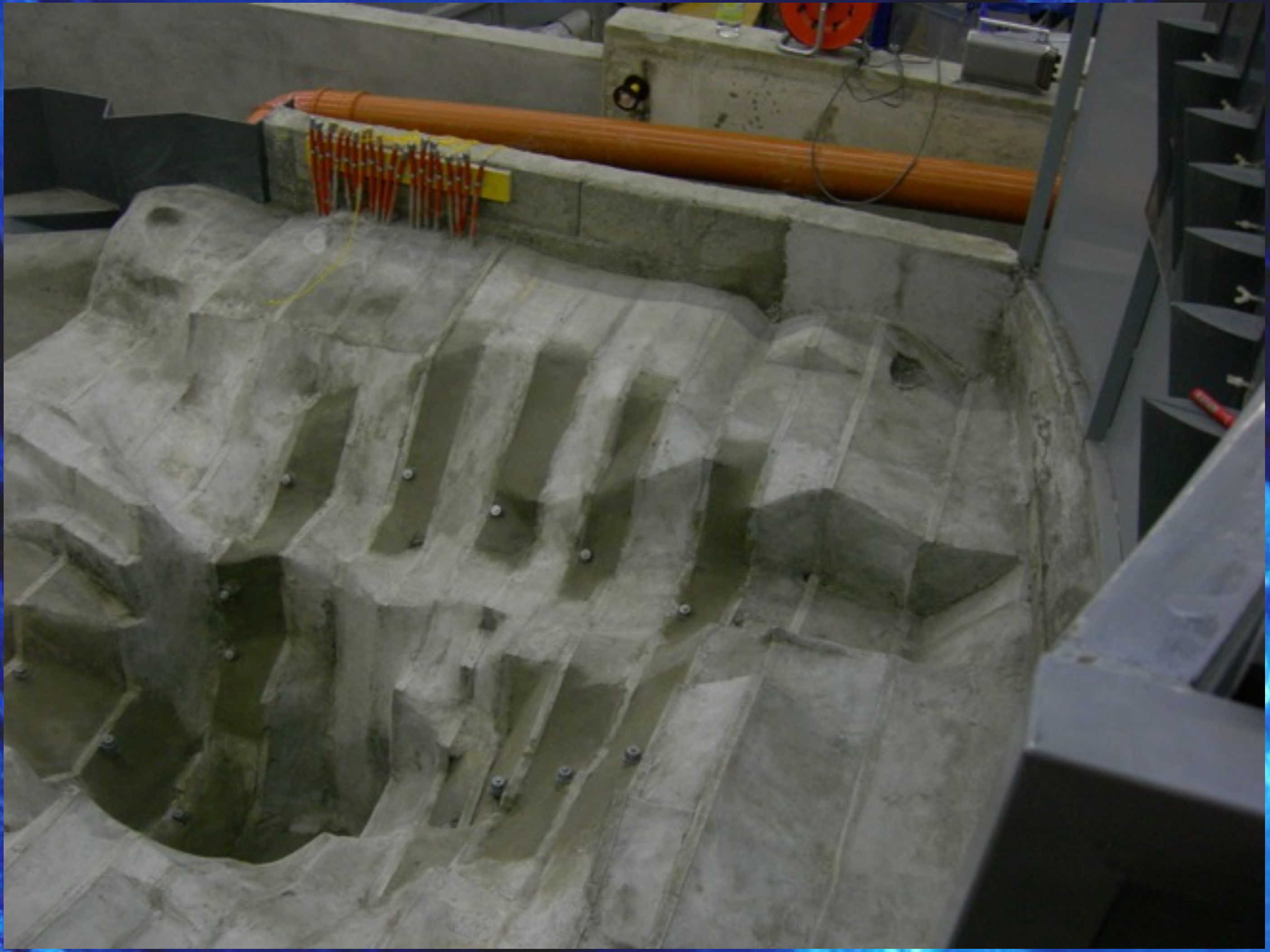
7. Case study Kariba in Sambia - Simbabwe

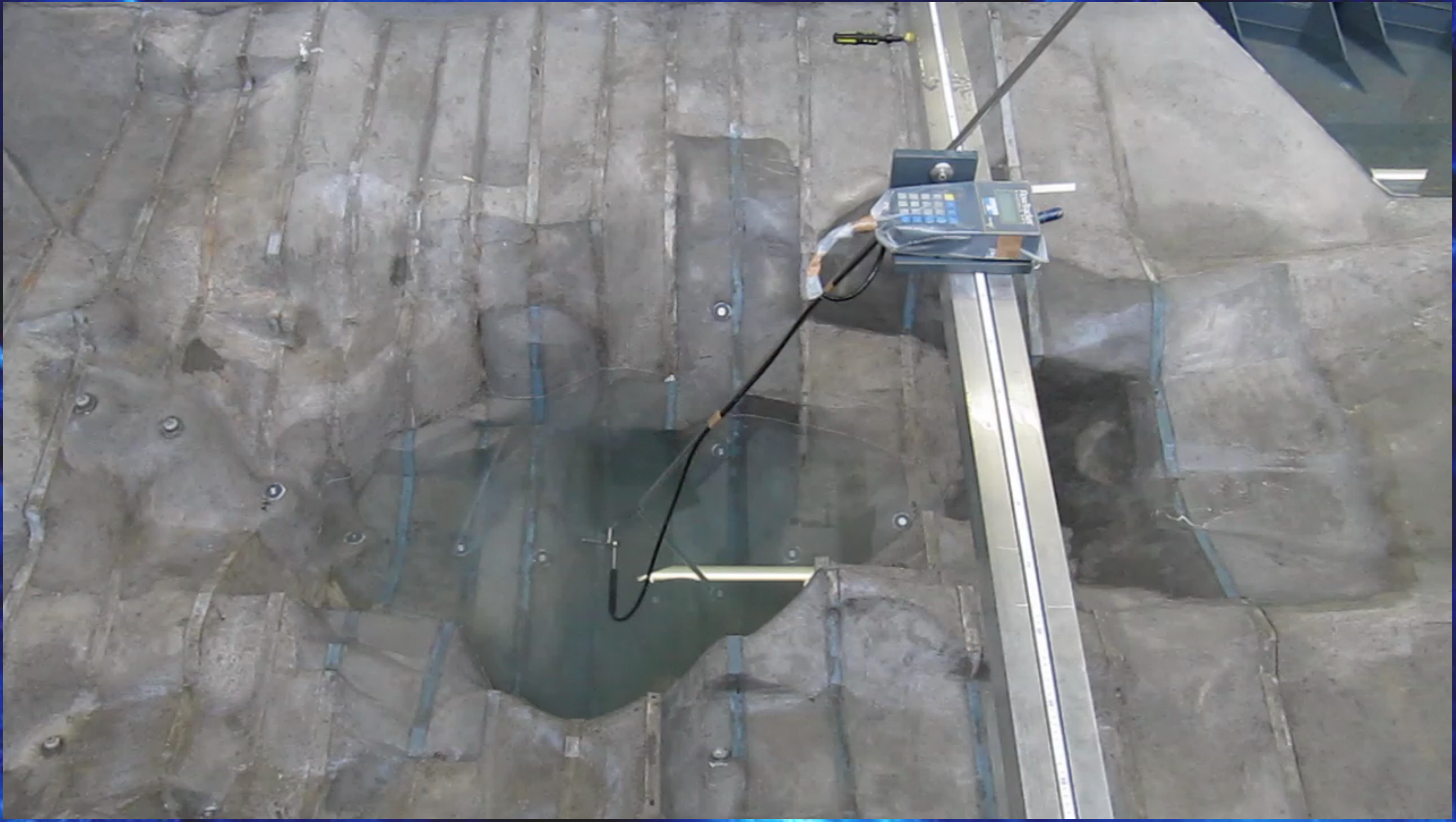
11.05.1966 test 6 gates full open

7. Case study Kariba in Sambia - Simbabwe

7. Case study Kariba hydraulic model tests

7. Case study Kariba hydraulic model tests





7. Case study Kariba hydraulic model tests

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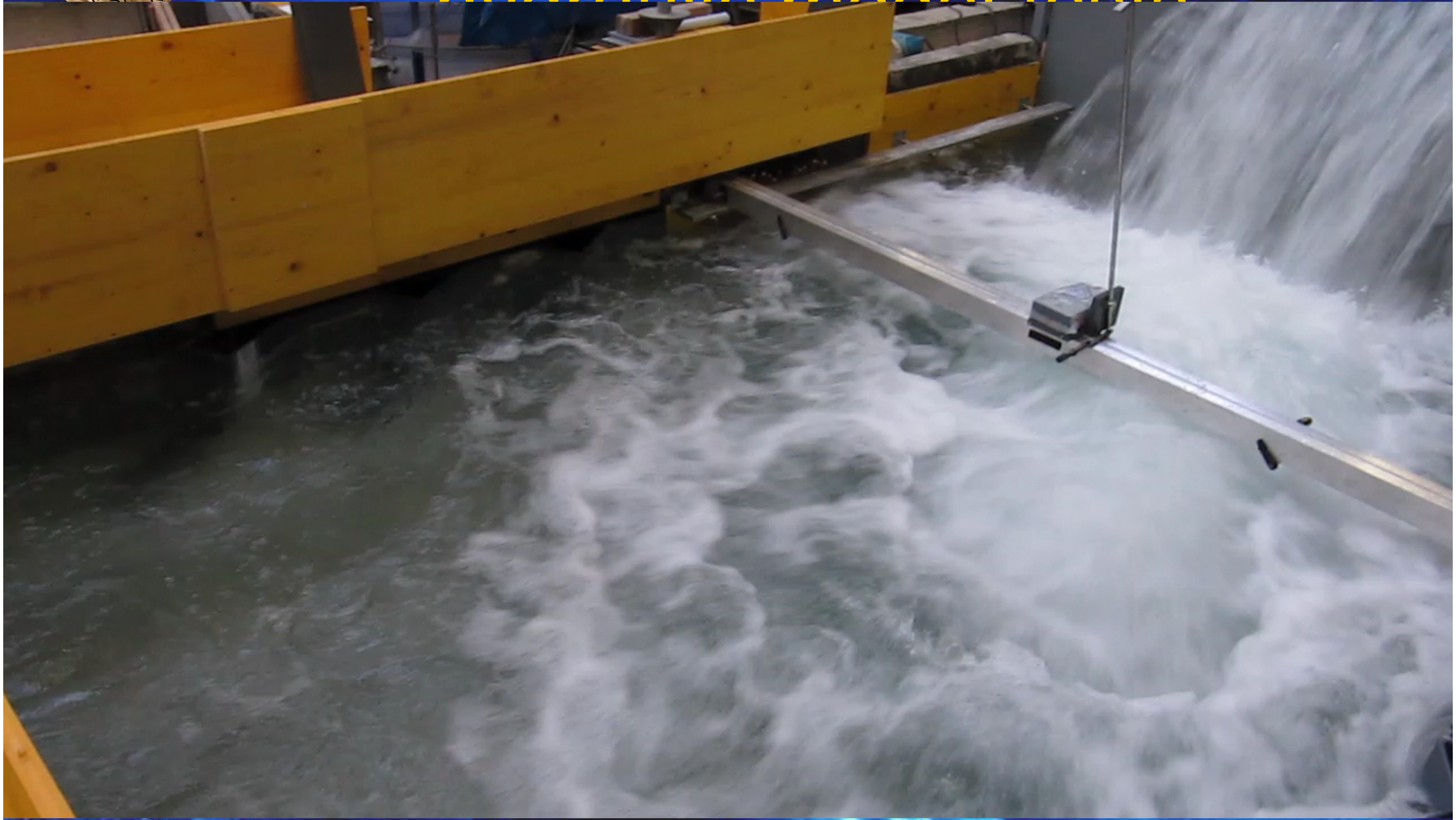
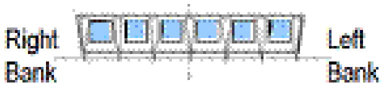
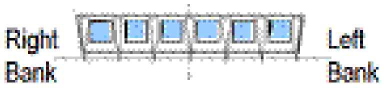
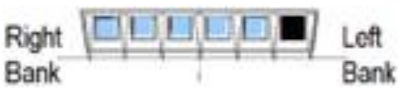


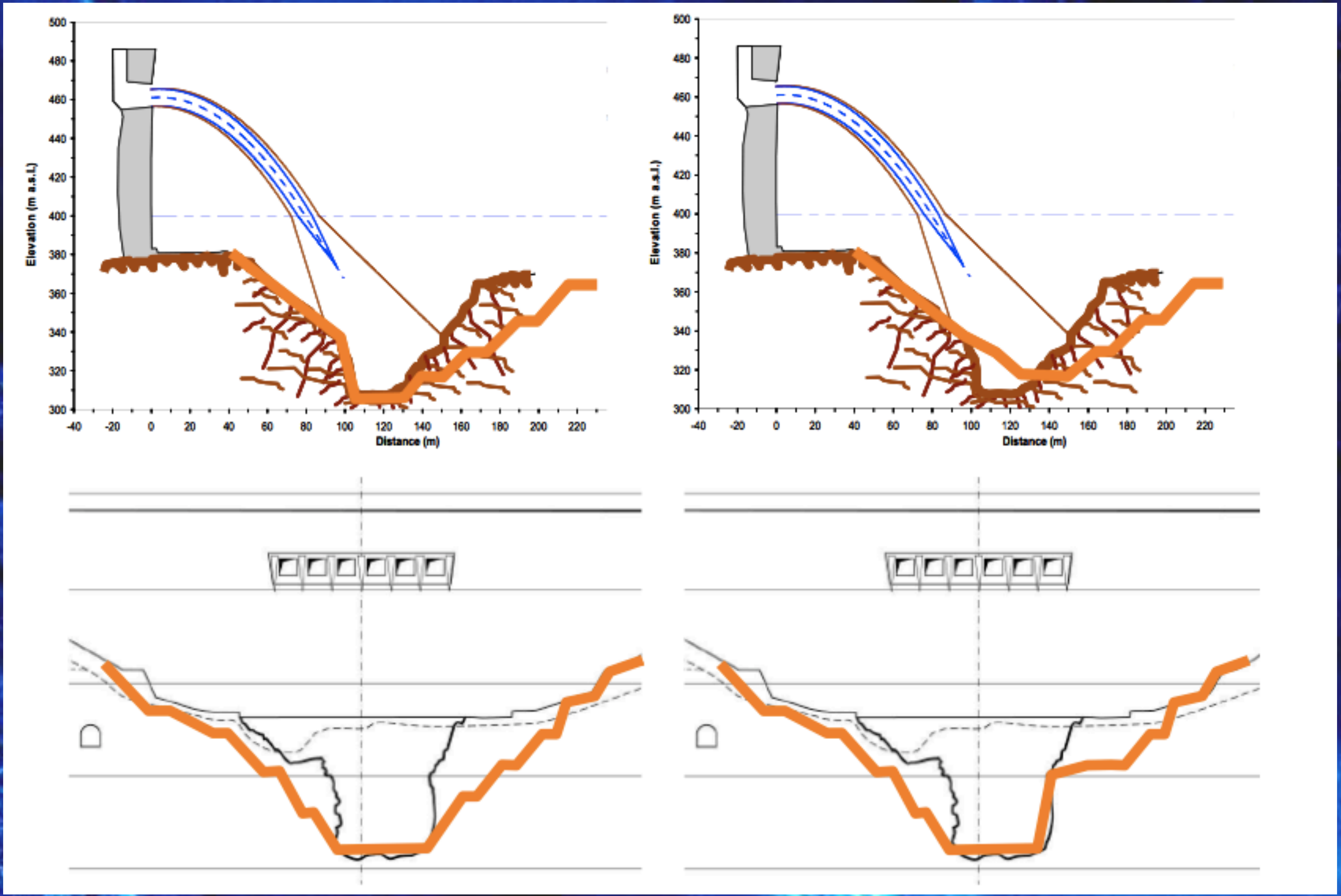
7. Case study Kariba hydraulic model tests

7. Case study Kariba hydraulic model tests

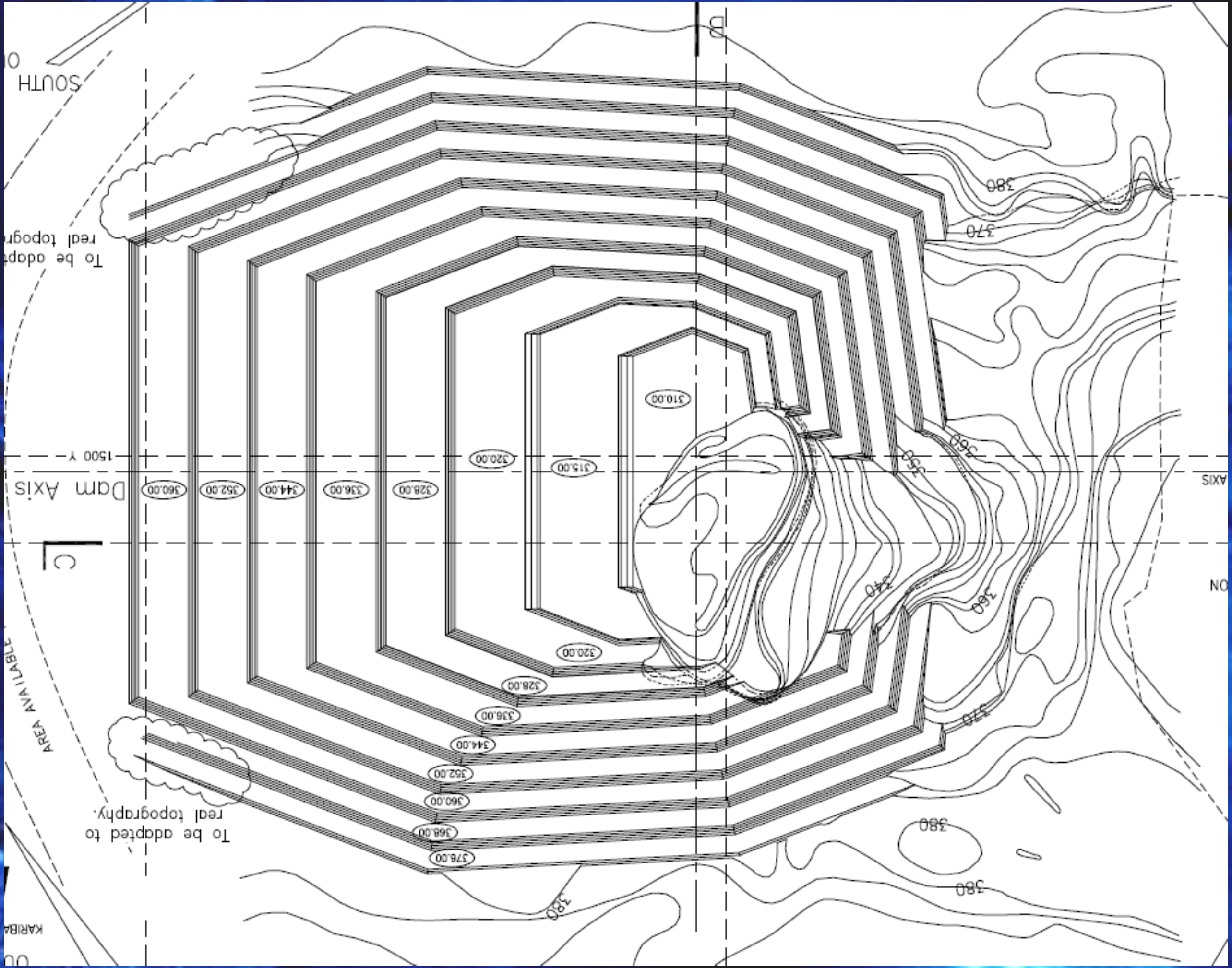
Test configurations

N°	Gate	N° Gates (-)	Gate opening (%)	Spillway discharge (m^3/s)	Powerhouses discharge (m^3/s)	Tailwater level (m)	Velocity measurements
1		3 non adjacent gates	100	≈4,500	≈1,400	ZRA curve	No
3		2x2 adjacent gates	100	≈6,000	≈1,400	ZRA curve	No
5		6 adjacent gates	100	≈9,000	≈1,400	ZRA curve	Yes
7		6 adjacent gates	100	≈9,000	0	ZRA curve	No
8		5 adjacent gates	100	≈7,500	≈1,400	ZRA curve	Yes

7. Case study Kariba in Sambia - Simbabwe



Physical modeling

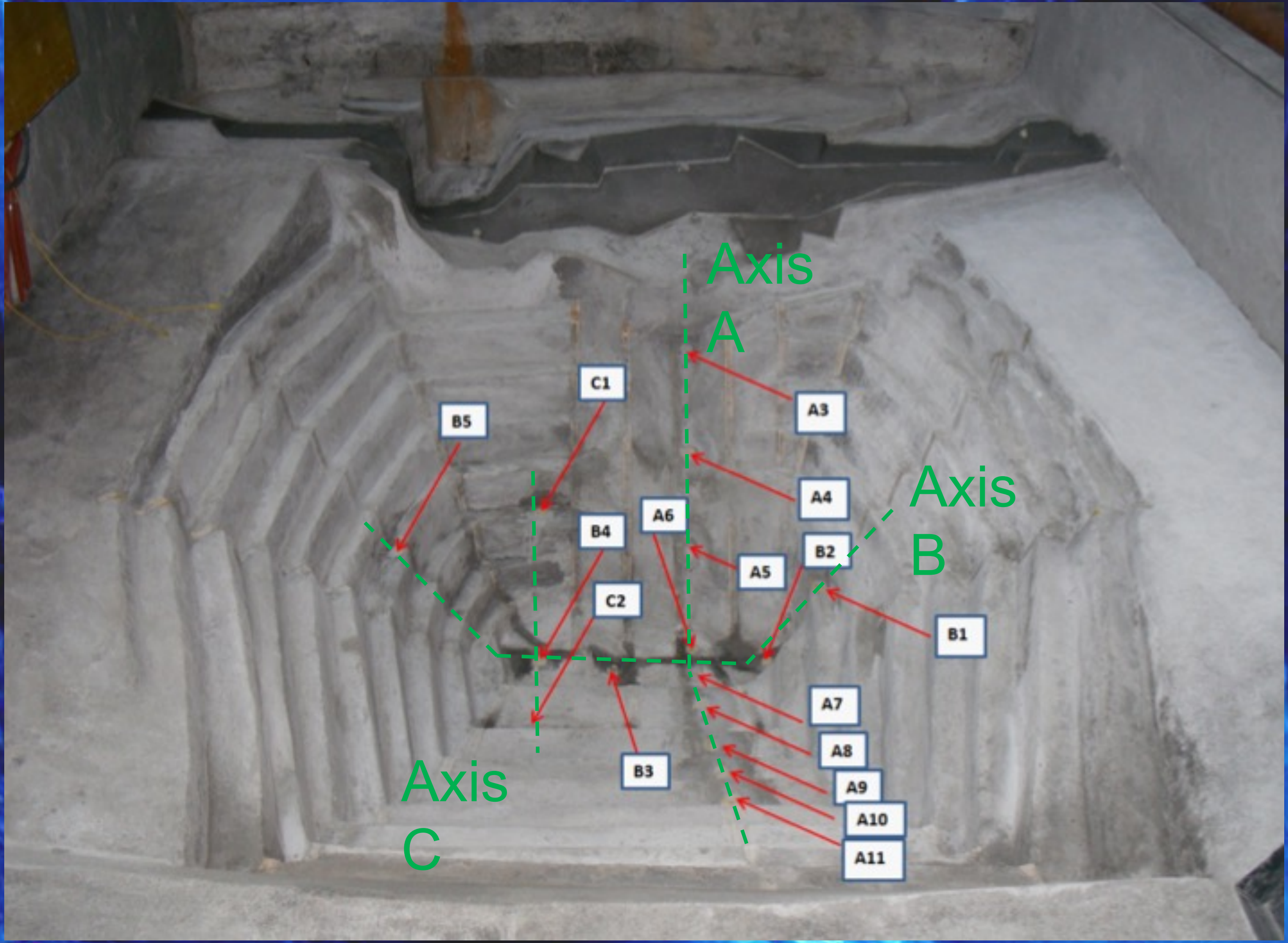


Reshaped geometry no 1

Left: reshaped geometry no 2

7. Case study Kariba hydraulic model tests

Physical modeling



Pressure measurement positions

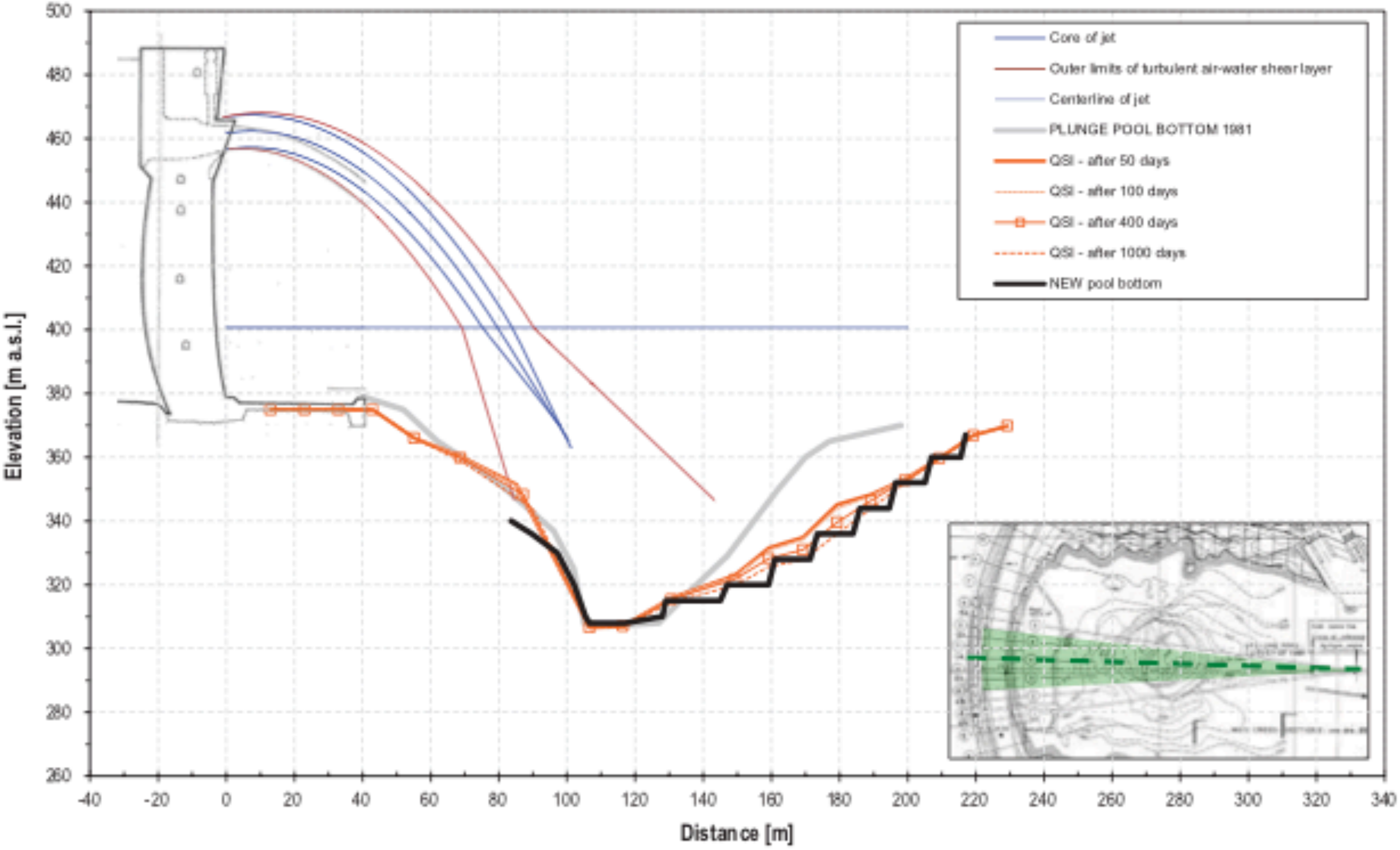
Physical modeling

1st reshaped Geometry

2nd reshaped Geometry

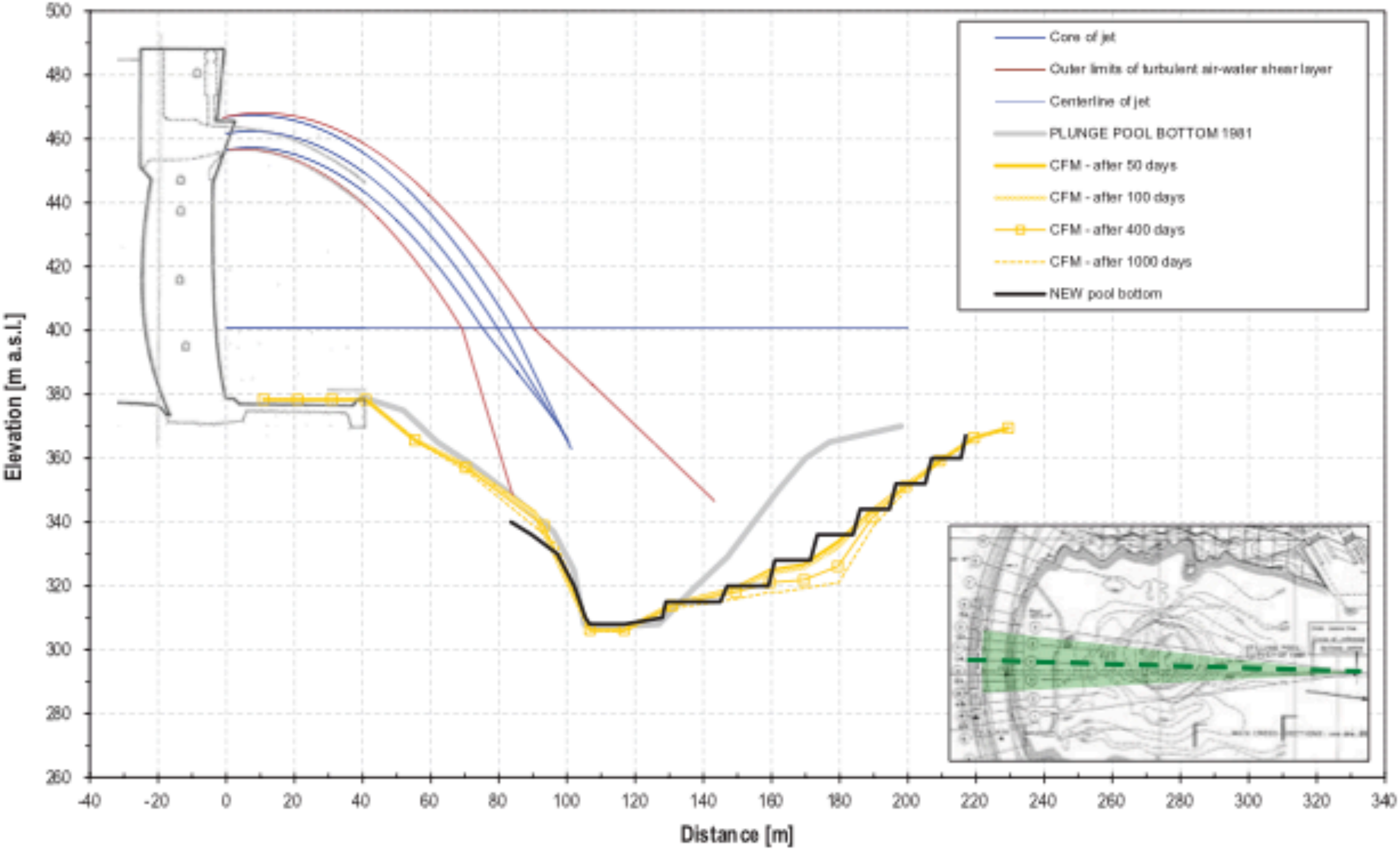
ZAMBEZI RIVER AUTHORITY

4.1 Evolution following measured pressures of NEW POOL (A sensors)



ZAMBEZI RIVER AUTHORITY

4.1 Evolution following measured pressures of NEW POOL (A sensors)



8. Conclusions

- **The physical understanding of the scouring process has been strongly improved over the last 15 years**
- **Theoretical models are available which take into account the interaction between dynamic pressure fluctuations and fissured rock mass (Comprehensive Scour Method).**
- **The LCH-EPFL model considers the essential physical processes but the rock mass characteristics have to be known and have to be used with engineering judgement**
- **Prototype data with complete historical record of spillway discharge data which created the scour are helpful for further improvement of comprehensive scour model**

Scour evaluation in space and time still remains a challenge for dam designers

Selected LCH references

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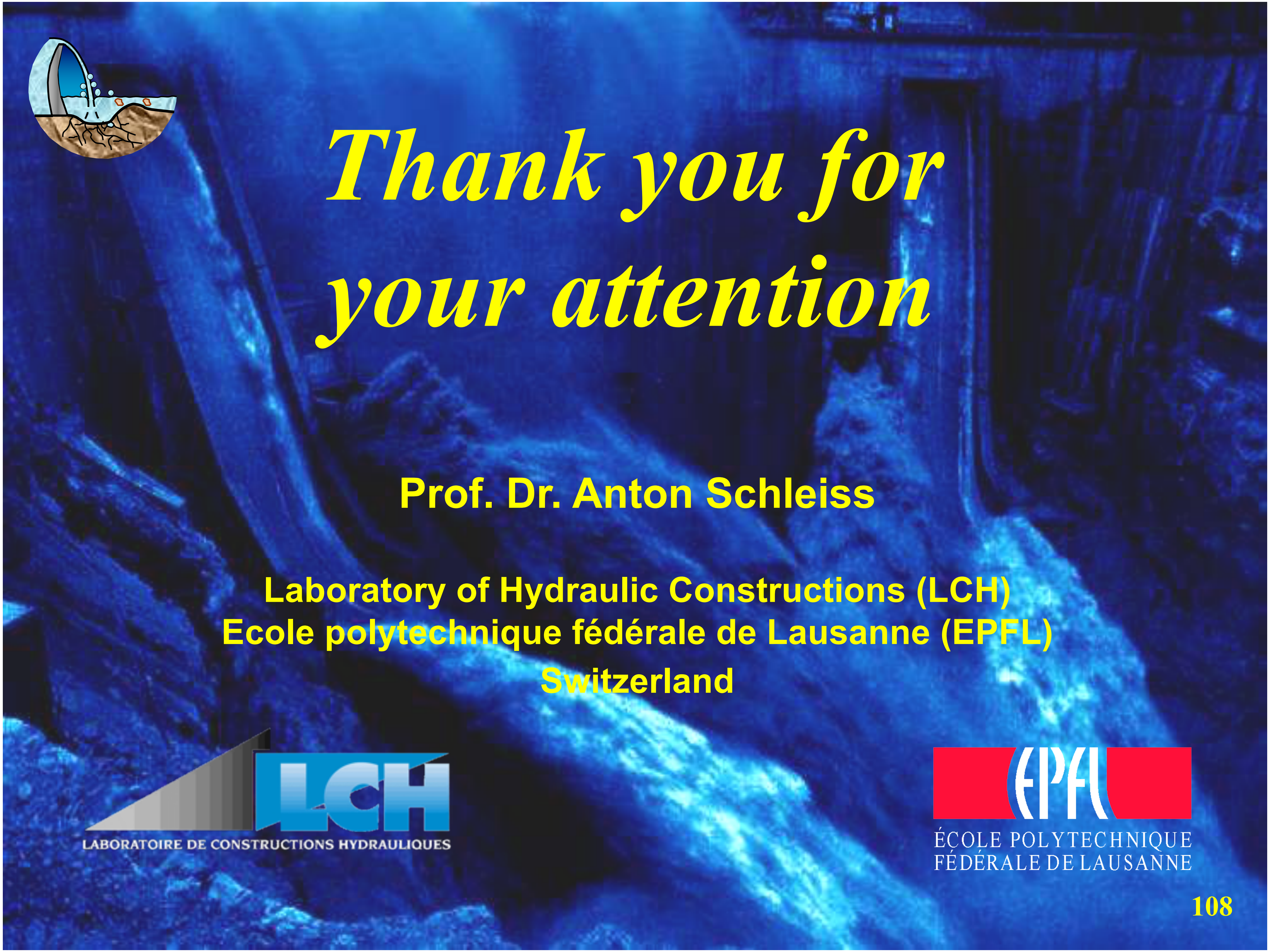

Thank you for your attention

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