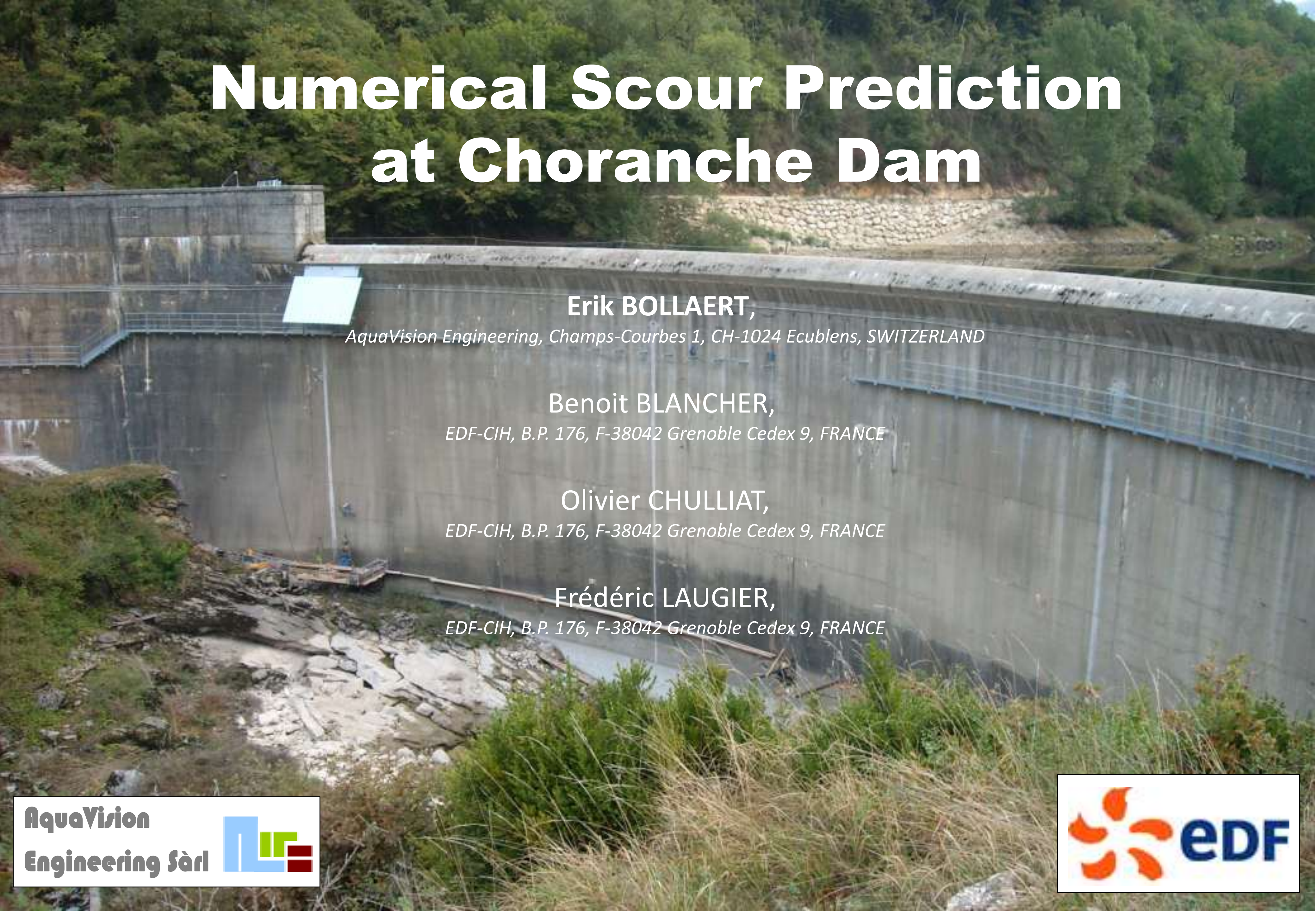

Numerical Scour Prediction at Choranche Dam

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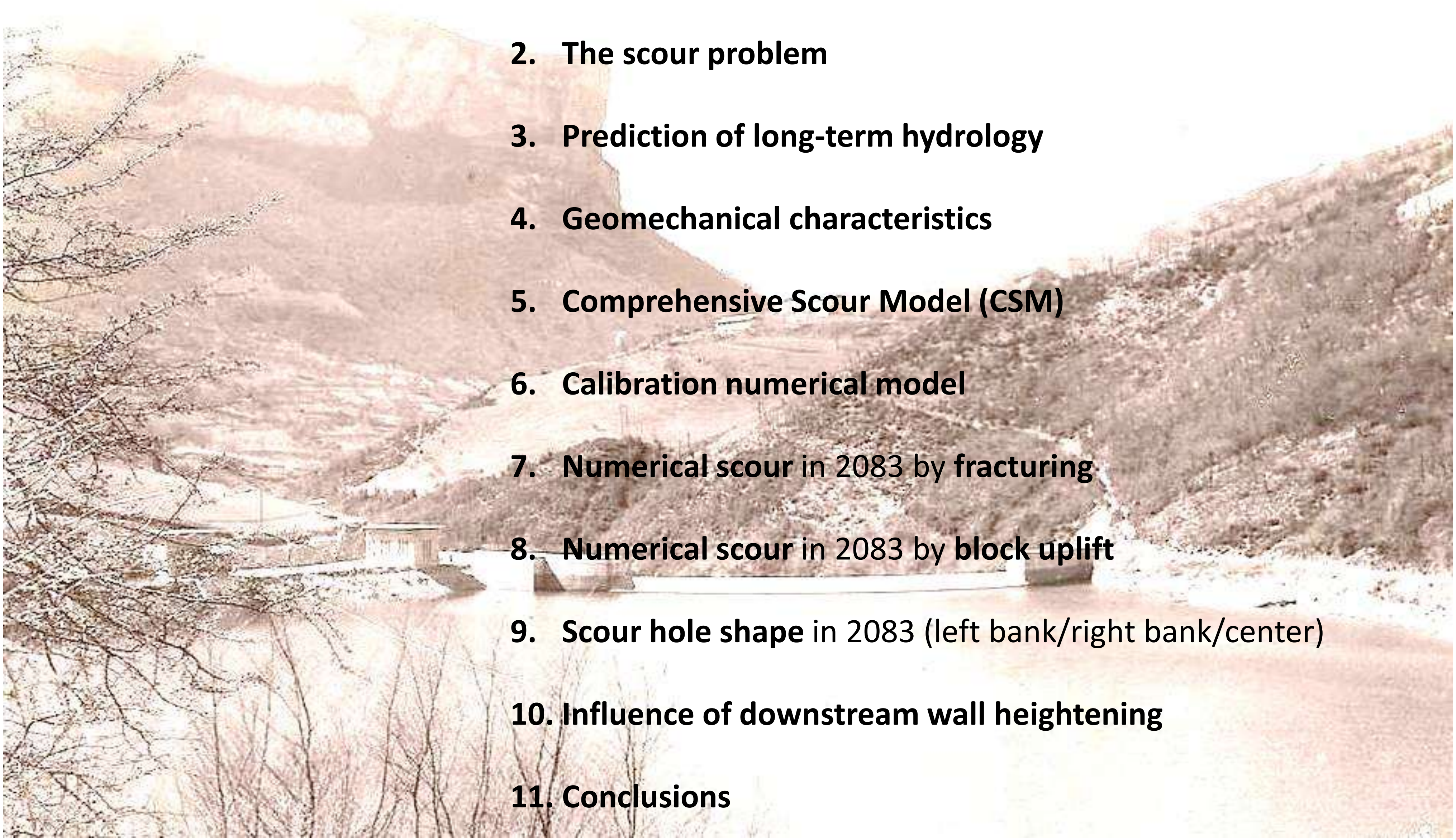
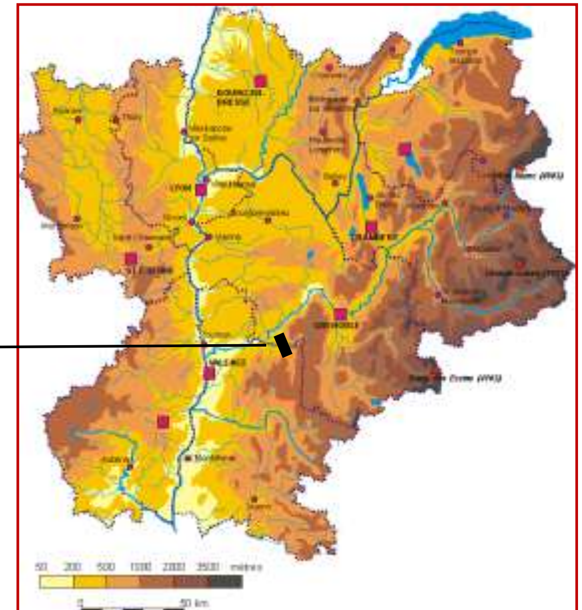


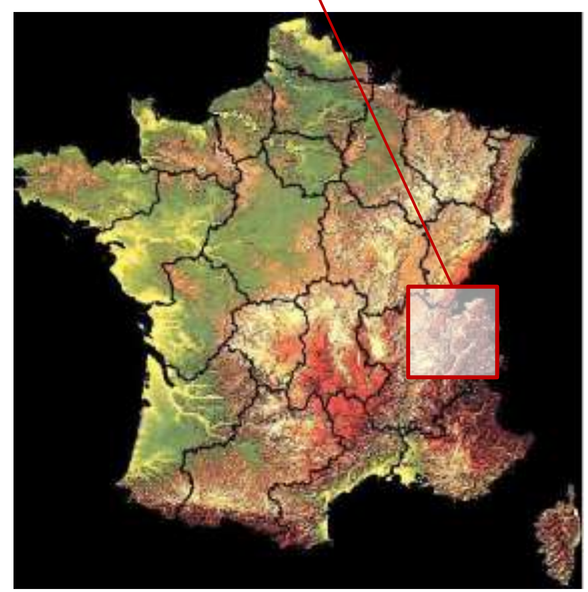
The dam site

Schéma de l'aménagement de Pont-en-Royans



Main characteristics

- 30 m high arch dam
- Bourne River (French Alps)
- Pont-en-Royans (between Valence and Grenoble)
- Constructed 1947-1950
- Operated by EDF
- Founded on limestone rock
- Central overflow spillway
- Catchment area 246-446 km2
- Karstic behavior during floods
- Original design flood 500 m3/s
- New design flood 720 m3/s



The scour problem

- since 1996 : several significant flood events in the catchment area
- Scour formation in plunge pool downstream
- Re-assessment of hydrology at the site since 1948

- **Assessment of scour potential for NEW DESIGN FLOOD AT THE DAM = 720 m3/s**

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Prediction of long term hydrology

- HISTORY = 1963 – 2003

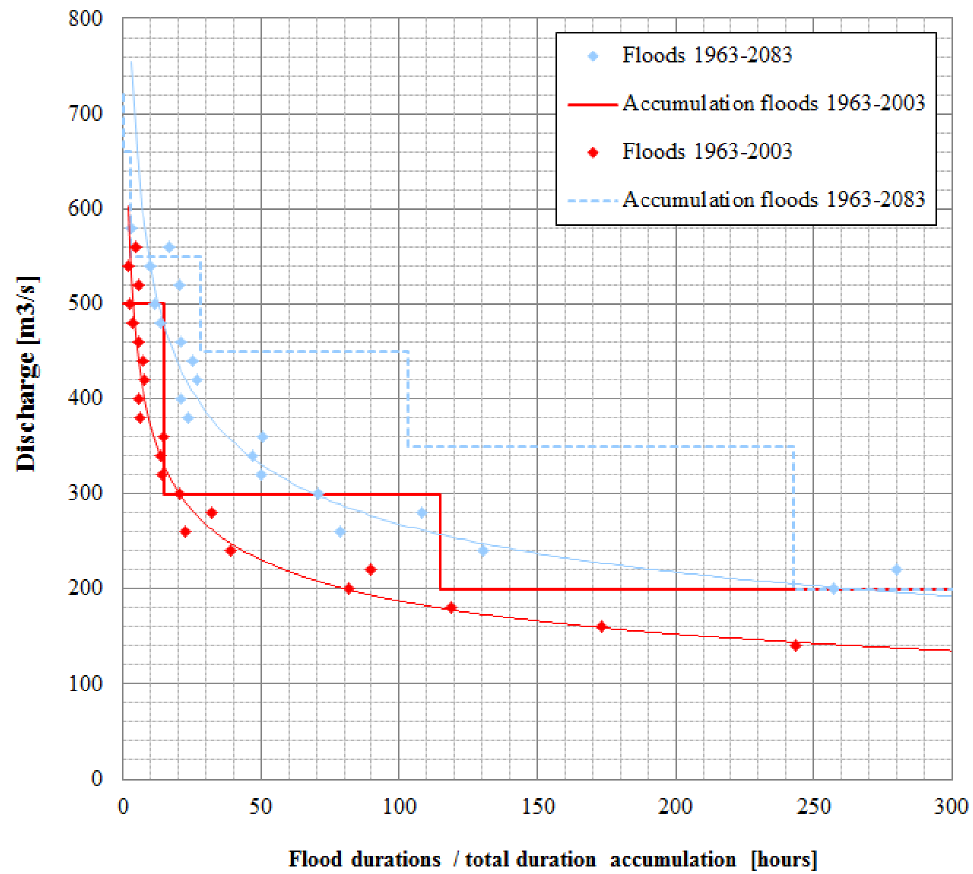
- separate reporting of historic peak values, GRADEX
- use of types of flood events recently recorded
- determination of shape /duration historic peak events
- accumulation of total flood durations
- total hours of overflow per discharge level

1963-2003		
Hours	**Cumul hours**	**Discharge**
-	-	720
-	-	660
5	0-5	550
20	5-25	450
42	25-67	350
103	67-170	250
210	170-380	200

- FUTURE = 1963 - 2083 (+ flood events)

- Double repetition of past 40 years of events
- Addition of several low probability events + design flood
- FUTURE total hours of overflow per discharge level

1963-2083		
Hours	**Cumul hours**	**Discharge**
0.4	0-0.4	720
2.6	0.4-3	660
25	3-28	550
75	28-103	450
140	103-243	350
340	243-583	250
660	583-1243	200



Geomechanical characteristics

RIGHT BANK SCOUR HOLE

- layering clearly visible but disturbed by scour
- complete fracturing of rock into large blocks
- angular/cubic shaped blocks ~ 0.5-1.0 m diameter
- progressive destabilization of bank
- rock mass is not resisting to overflows
- **clear signs of recent scour formation**

LEFT BANK SCOUR HOLE

- layering clearly visible
- dip towards upstream
- block thickness ~ 0.2-0.5 m
- block length ~ 1.0 m
- block width ~ 0.5-1.0 m
- rock fissures are mostly closed
- rock mass seems scour resistant
- **no signs of recent scour formation**

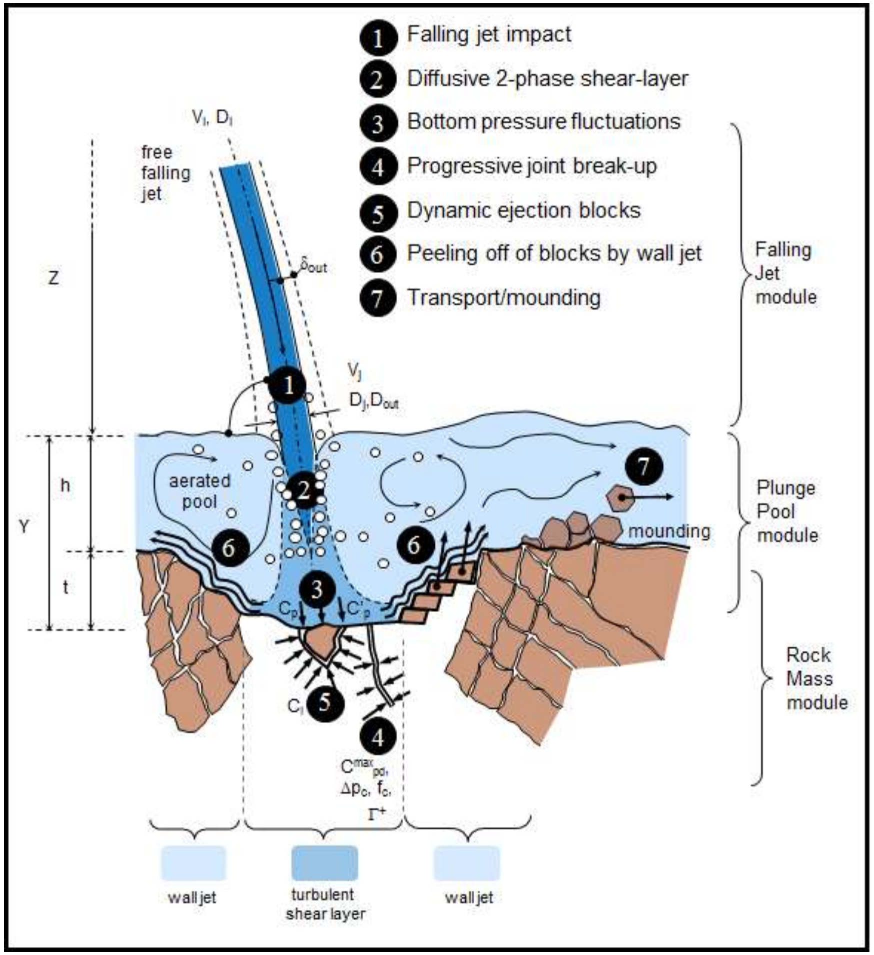
Geomechanical characteristics

- destruction of downstream tailpond dam along right bank
- impact rock blocks d ~ 50-100 cm
- directly related to recent scour formation along right bank
- most probably durign one of the major flood events 1996-2003

- use of dynamic pressures at plunge pool bottoms
- computation of transient pressures inside rock mass
- resistance of rock joints against fracturing
- computation of net uplift pressures on single rock blocks
- resistance of blocks against uplift and peeling off

Quasi-3D engineering model
for evaluation of ultimate scour depth
and time evolution of scour formation

Mechanism	Symbol	Functioning	Validity	Output
Comprehensive **F**racture **M**echanics	CFM	progressive break-up of existing rock joints due to jet impact	area of turbulent jet impingement	Time evolution of scour development
Dynamic **I**mpulsion	DI	sudden vertical ejection of rock blocks generated by pressure differences over and under the block	area of turbulent jet impingement	Ultimate scour depth
Quasi-**S**teady **I**mpulsion	QSI	peeling off of protruding rock plates due to wall jet generated by turbulent impingement	area between dam and location of turbulent jet impingement	Ultimate scour depth



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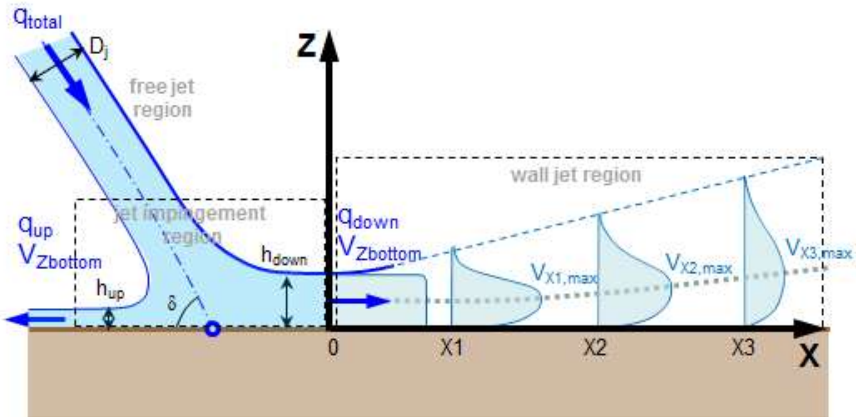
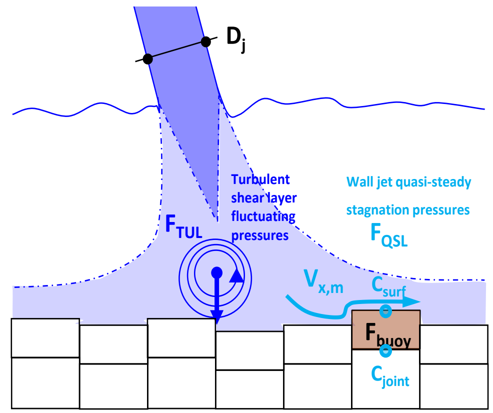
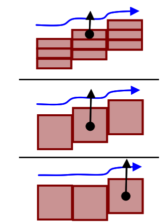
Rock break-up mechanisms

Quasi-steady ejection of blocks: Quasi-Steady Impulsion (QSI) model







Quasi-steady lift force F_{QSL}

$$F_{QSL} = \left(C_{joint} - C_{surf}\right) \cdot L_{block} \cdot \frac{V_{x,m}^2}{2g}$$

$$V_{x,m} = f\left(X, h_{down}, V_{Zbottom}\right)$$

$$h_{down} = D_j \cdot \frac{q_{down}}{q_{total}}$$

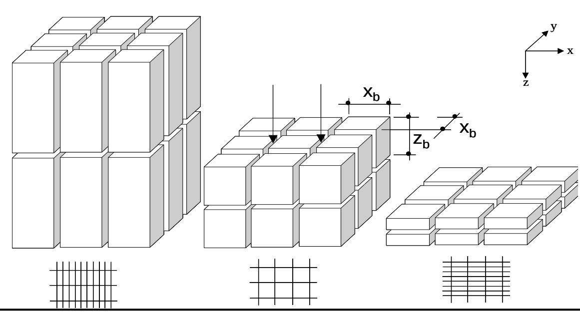
Dynamic ejection blocks: Dynamic Impulsion (DI) model

Impulsion on block $$I_{\Delta tpulse} = \int_0^{\Delta tpulse} \left(F_u - F_o - G_b - F_{sh}\right) \cdot dt = m \cdot V_{\Delta tpulse}$$

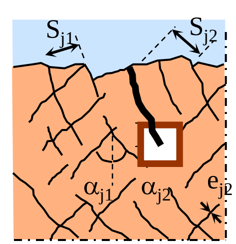
Submerged weight $$G_b = \forall \cdot \left(\gamma_r - \gamma_w\right) = x_b^2 \cdot z_b \cdot \left(\gamma_r - \gamma_w\right)$$

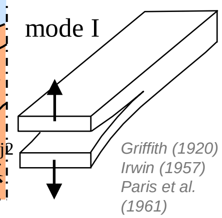
Uplift height of block after pulse $$h_{up} = V_{\Delta t,pulse} \cdot \Delta t + \frac{1}{2} \cdot g \cdot \Delta t^2$$

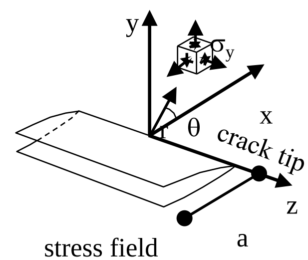
Max. possible uplift height of block after pulse $$V_{\Delta tpulse} = \sqrt{2 \cdot g \cdot h_{up}}$$

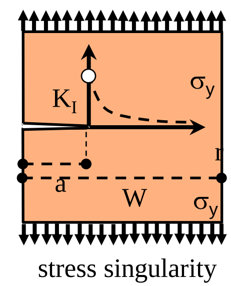


Progressive joint break-up by fatigue: Fracture Mechanics (CFM) model









$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} \cdot f_{ij}(\theta) \;\; + \text{higher order terms}$$

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

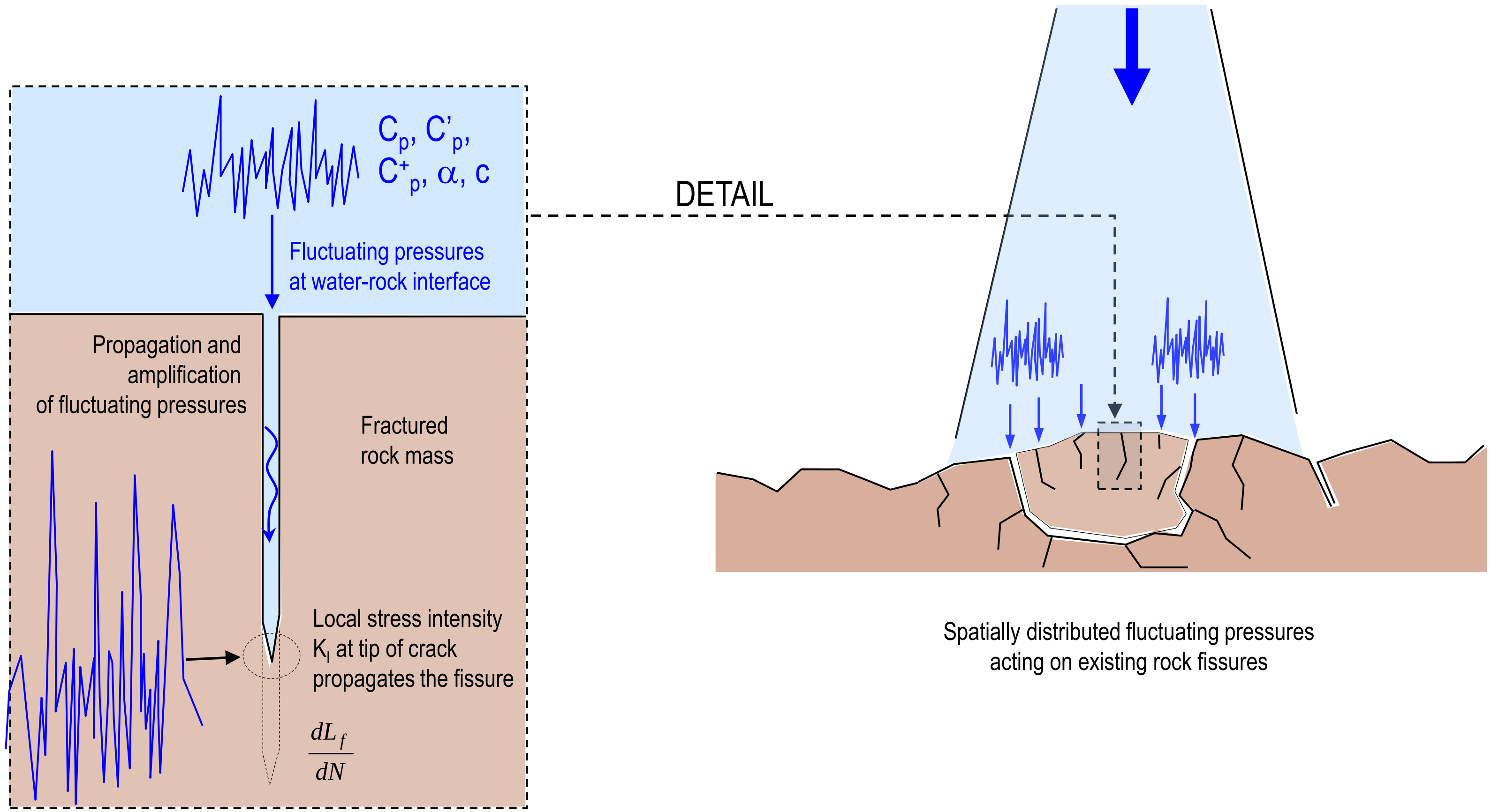
$$\Delta a_c = \int_0^{t_f} \left(f \cdot C \cdot S_{max}^m \cdot S_a^n + \upsilon \cdot e^{bS}\right) \cdot dt$$

(after Costin & Holcomb 1981)

- K_I = f (pressure distribution)
- K_I = f (in-situ stress field)
- K_{Idyn} = f (pressurization rate)
- f (a/W) = f (geometry fissure) planar, …
- K_{Ic} = fracture toughness value
  - literature
  - tests

Grady & Kipp (1980)
Haimson & Zhao (1991)
Zhao & Li (2000)
Zhao (2000)
Zhang et al. (2000)

Rock break-up mechanisms



C_p, …
$f_{res} = c / 4 \cdot L_f$

⇨

Number N of stress cycles at joint end $\quad N = 1/f_{res} \cdot \Delta t$

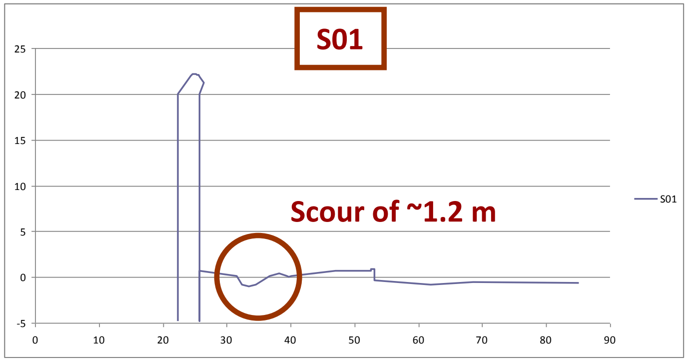
Stress intensity at joint end by water pressure $\quad \Delta K_I = \Delta P_{max} \cdot F \cdot \sqrt{\pi \cdot L_f}$

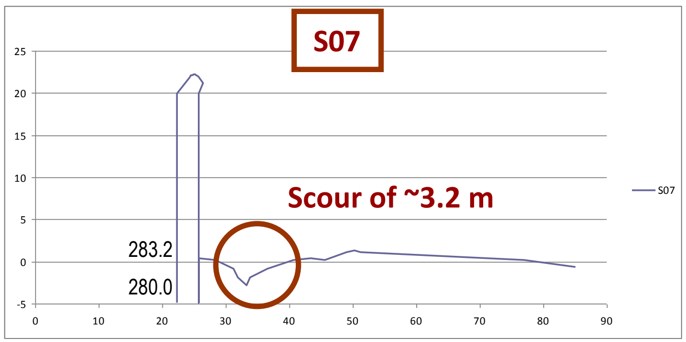
Fracture toughness of rock mass $\quad K_{Ic} = (0.008 \text{ to } 0.010) \cdot UCS + (0.054 \cdot \sigma_c) + 0.42$

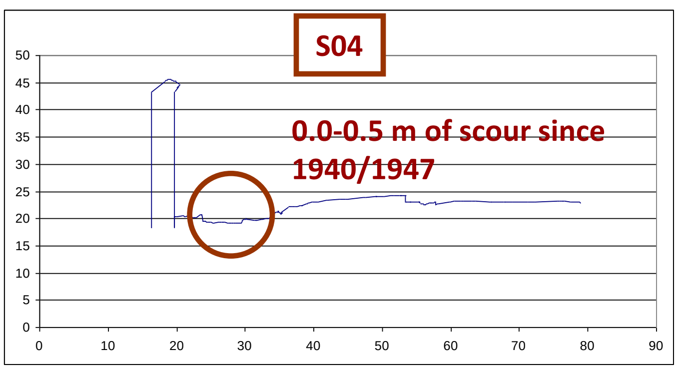
⇨

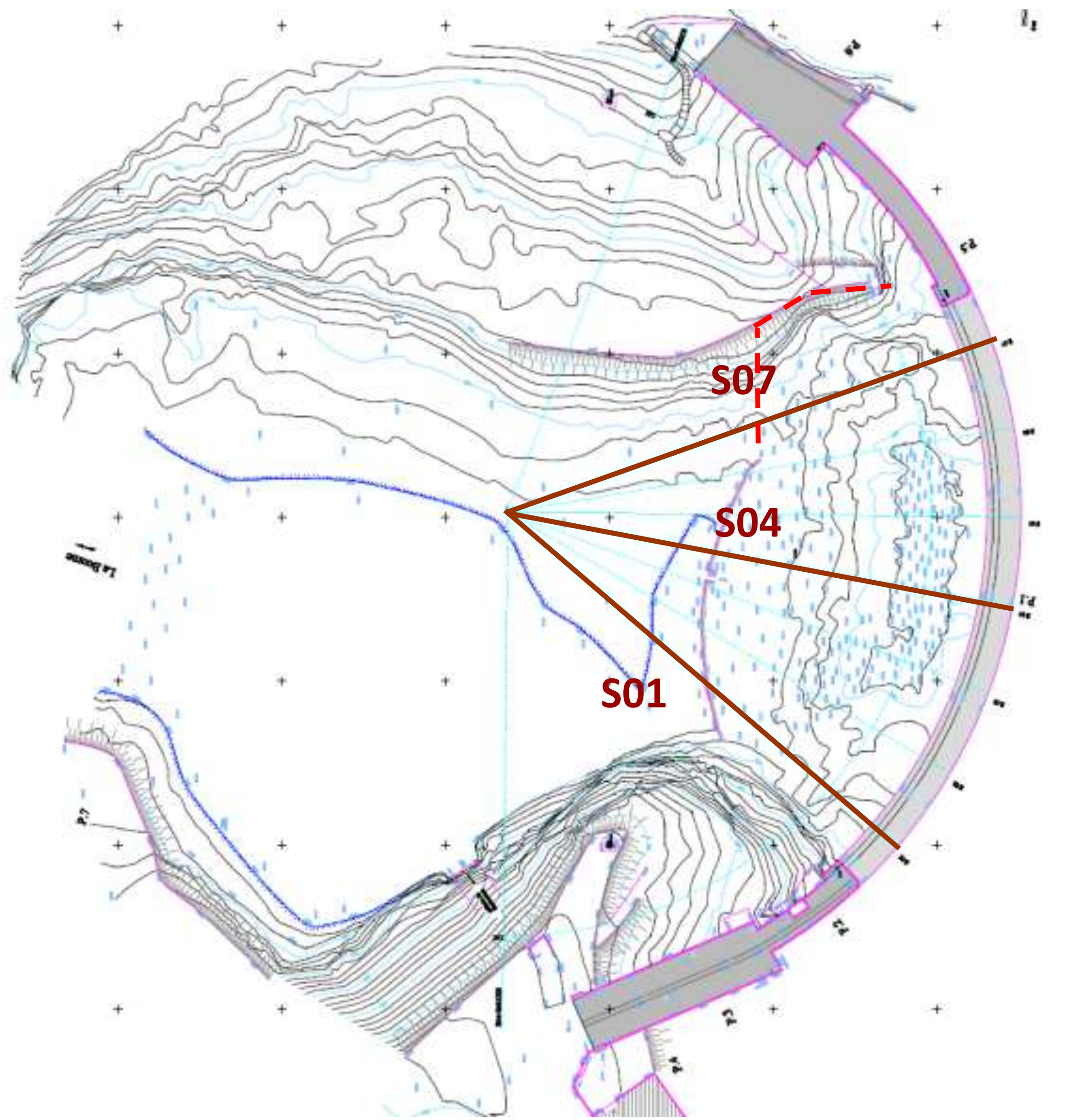
$$\frac{dL_f}{dN} = C_r \cdot (\Delta K_I / K_{Ic})^{m_r}$$

Model calibration

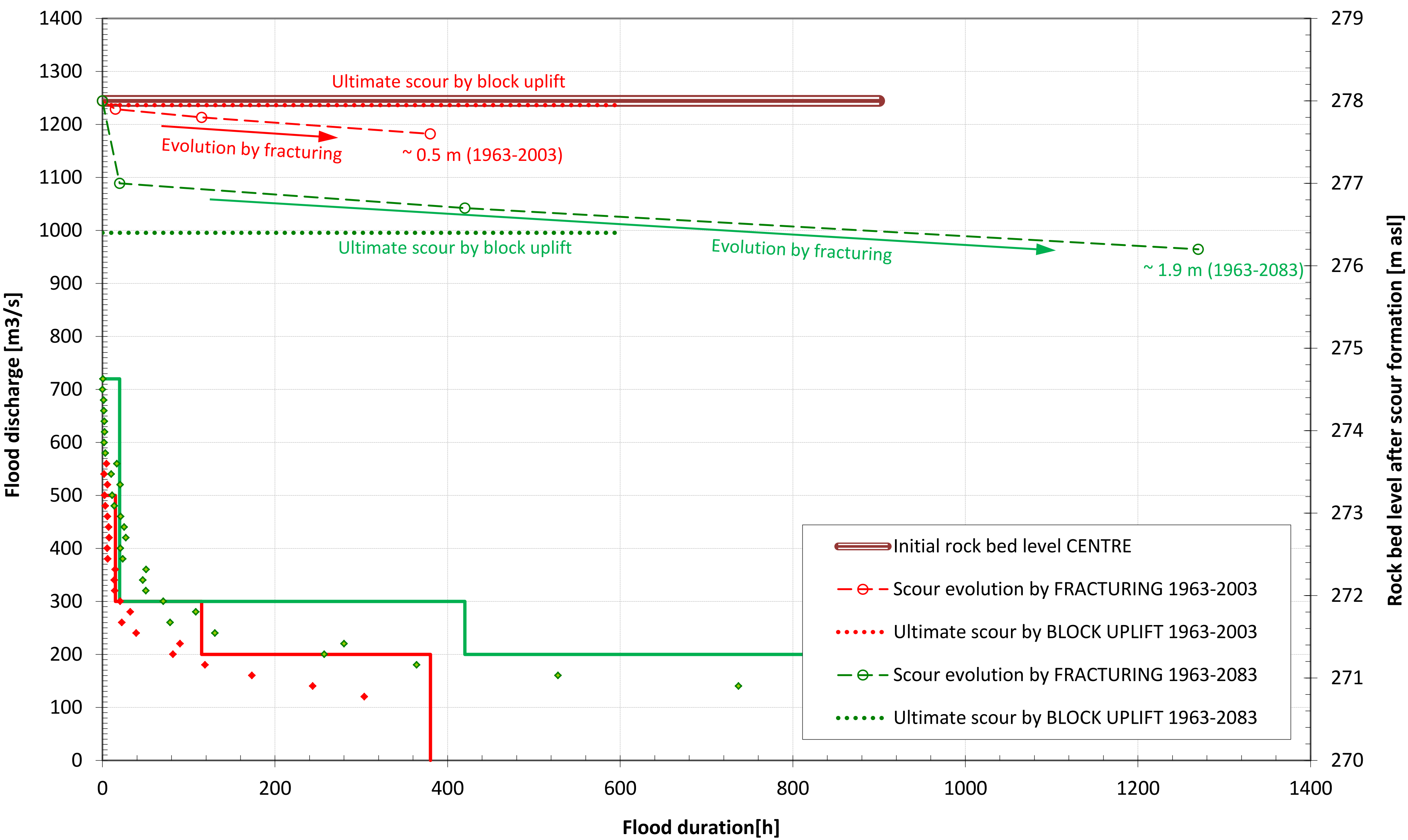








Model calibration



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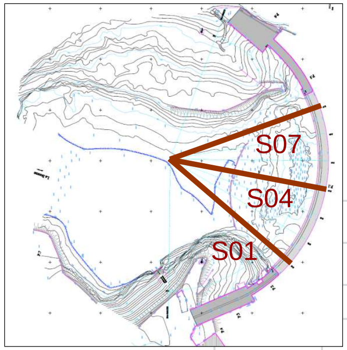
Numerical scour in 2083 (Fracturing)

EDF



ACTUAL POOL, floods 1963-2003

FUTURE POOL, floods 1963-2083

CALIBRATION based on LEFT BANK

		Q [m³/s]	Duration [h]	[h cumul]	AVER [m asl]	OPT [m asl]	CONS [m asl]
S01	1963-2003	-	0	0	283.2	283.2	283.2
		500	15	15	282.5	283.2	277.4
		300	100	115	281.6	283.2	277.4
		200	265	380	281.6	283.2	277.4
	1963-2083	-	0	0	283.2	283.2	283.2
		720	20	20	282.1	283.2	275.1
		300	400	420	281.4	283.2	275.0
		200	850	1270	281.4	283.2	274.9

-0.20 m

		Q [m³/s]	Duration [h]	[h cumul]	AVER [m asl]	[m asl]	[m asl]
S04	1963-2003	-	0	0	-	-	-
		500	15	15	-	-	-
		300	100	115	-	-	-
		200	265	380	-	-	-
	1963-2083	-	0	0	-	-	-
		720	20	20	-	-	-
		300	400	420	-	-	-
		200	850	1270	-	-	-

CALIBRATION based on CENTRE /RIGHT BANK

		Q [m³/s]	Duration [h]	[h cumul]	AVER [m asl]	OPT [m asl]	CONS [m asl]
S07	1963-2003	-	0	0	283.2	283.2	283.2
		500	15	15	278.8	283.0	264.2
		300	100	115	278.7	282.8	263.2
		200	265	380	278.5	282.6	261.1
	1963-2083	-	0	0	283.2	283.2	283.2
		720	20	20	277.0	282.9	260.2
		300	400	420	276.7	282.2	257.0
		200	850	1270	276.2	282.2	251.0

-2.30 m

		Q [m³/s]	Duration [h]	[h cumul]	AVER [m asl]	OPT [m asl]	[m asl]
S04	1963-2003	-	0	0	278.0	278.0	278.0
		500	15	15	277.9	278	264.1
		300	100	115	277.8	278	263.1
		200	265	380	277.6	277.9	257.2
	1963-2083	-	0	0	278.0	278.0	278.0
		720	20	20	277.0	278.0	260.2
		300	400	420	276.7	278.0	257.0
		200	850	1270	276.2	277.9	251.0

-1.40 m

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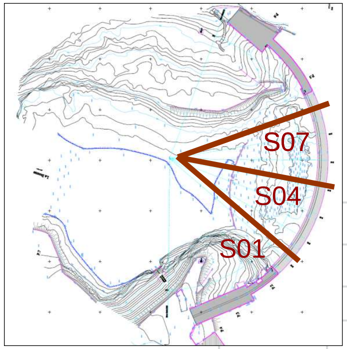
Numerical scour in 2083 (Block uplift)



ACTUAL POOL, floods 1963-2003

FUTURE POOL, floods 1963-2083

CALIBRATION based on LEFT BANK

		Q	Duration		AVER	OPT	CONS
		[m³/s]	[h]	[h cumul]	[m asl]	[m asl]	[m asl]
S01	1963-2003	-	0	0	283.2	283.2	283.2
		500	15	15	278.3	279.2	276.9
		300	100	115	278.3	279.2	276.9
		200	265	380	278.3	279.2	276.9
	1963-2083	-	0	0	283.2	283.2	283.2
		720	20	20	276.4	277.6	274.3
		300	400	420	276.4	277.6	274.3
		200	850	1270	276.4	277.6	274.3

-1.90 m

		Q	Duration		AVER		
		[m³/s]	[h]	[h cumul]	[m asl]	[m asl]	[m asl]
S04	1963-2003	-	0	0	-	-	-
		500	15	15	-	-	-
		300	100	115	-	-	-
		200	265	380	-	-	-
	1963-2083	-	0	0	-	-	-
		720	20	20	-	-	-
		300	400	420	-	-	-
		200	850	1270	-	-	-

CALIBRATION based on CENTRE /RIGHT BANK

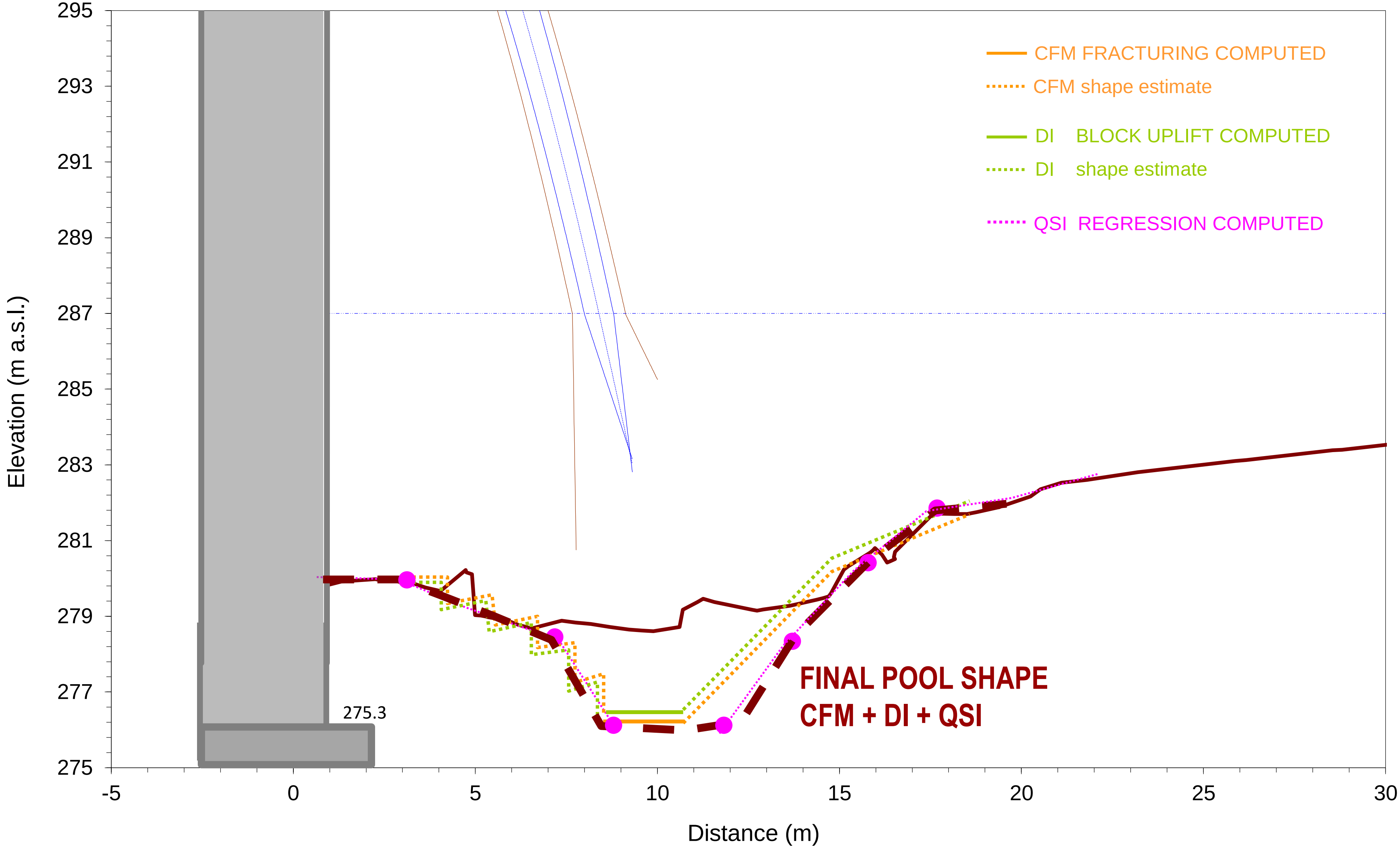
		Q	Duration		AVER	OPT	CONS
		[m³/s]	[h]	[h cumul]	[m asl]	[m asl]	[m asl]
S07	1963-2003	-	0	0	283.2	283.2	283.2
		500	15	15	278.3	279.2	276.9
		300	100	115	278.3	279.2	276.9
		200	265	380	278.3	279.2	276.9
	1963-2083	-	0	0	283.2	283.2	283.2
		720	20	20	276.4	277.6	274.3
		300	400	420	276.4	277.6	274.3
		200	850	1270	276.4	277.6	274.3

-1.90 m

		Q	Duration		AVER	OPT	
		[m³/s]	[h]	[h cumul]	[m asl]	[m asl]	[m asl]
S04	1963-2003	-	0	0	278	278	278
		500	15	15	278	278	276.9
		300	100	115	278	278	276.9
		200	265	380	278	278	276.9
	1963-2083	-	0	0	278	278	278
		720	20	20	276.4	277.6	274.3
		300	400	420	276.4	277.6	274.3
		200	850	1270	276.4	277.6	274.3

-1.60 m

Scour hole shape in 2083 (centre/right bank)



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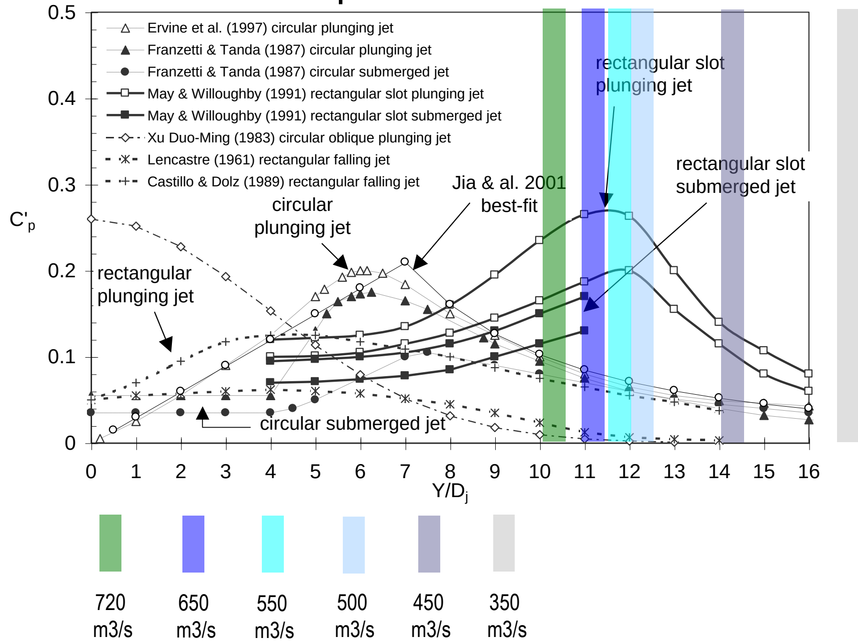
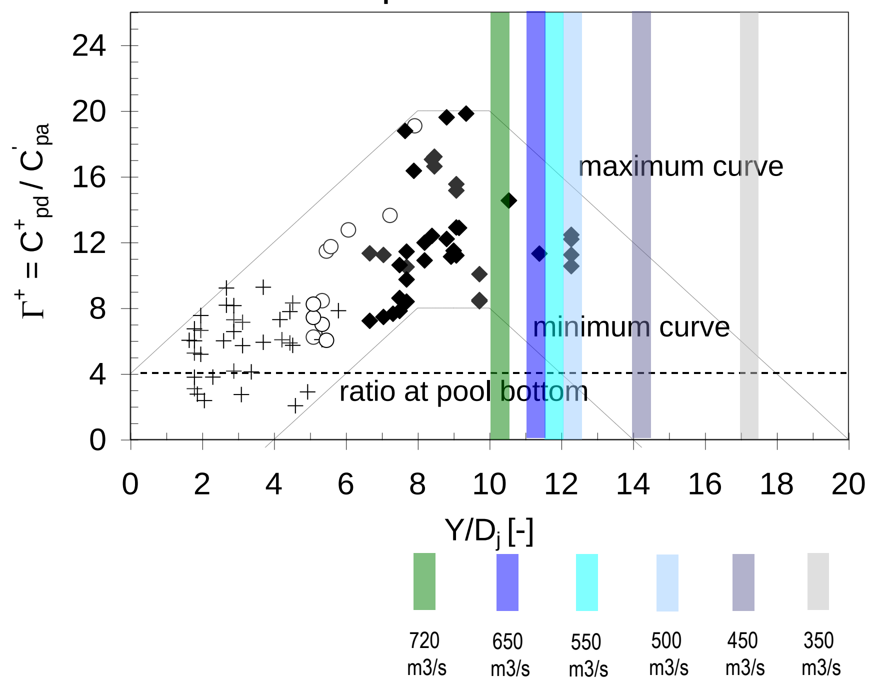
Influence of downstream wall heightening

Actual wall

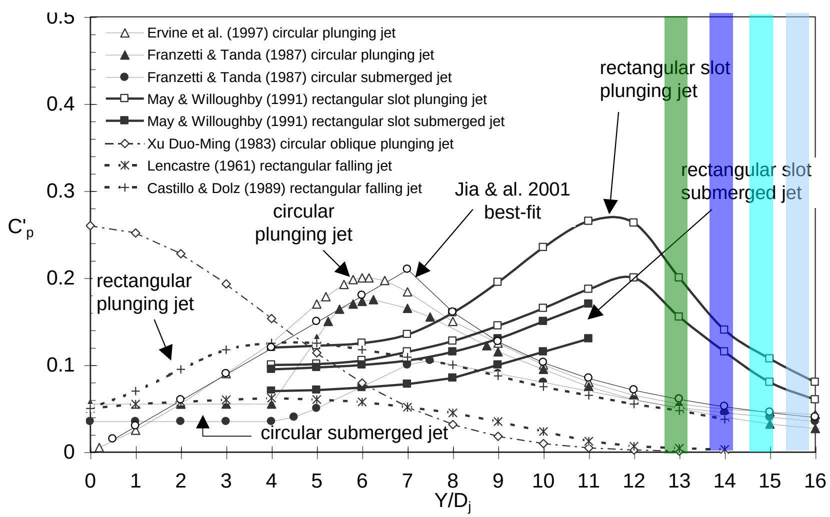
RMS pressure fluctuations

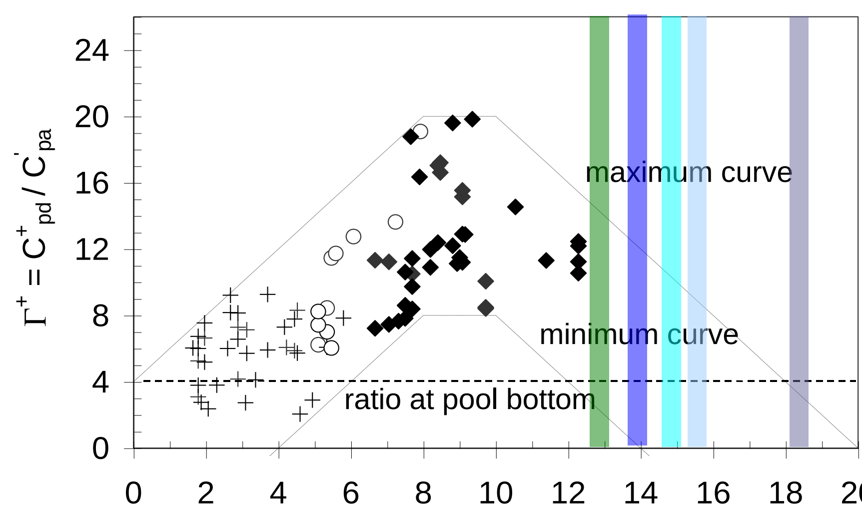


Pressure amplification in fissures



Actual wall + 2m





Conclusions

- Quasi no scour formation in center of pool since 1947
- Along left bank, local scour by 1.0-1.5 m
- Along right bank, scour by several metres, scour process still very active
- Left bank rock mass more resistant than right bank rock mass
- In general, relatively moderate ultimate scour depths
- Ultimate scour following calibration along left bank:

  0.0 – 0.2 m (fracturing)

  1.6 – 1.9 m (uplift)
- Ultimate scour following calibration along center/right bank:

  1.4 – 2.3 m (fracturing)

  1.6 – 1.9 m (uplift)
- Scour is valid for decreasing hydrology (computed period starts with design discharge)
- Scour by fracturing is 15-20% less when inversing hydrology; scour by uplift is not affected by inversion of hydrology
- Refinement of hydrological period does not increase ultimate scour depth
- A priori no direct danger to dam stability by scour regression on the long term at Choranche Dam