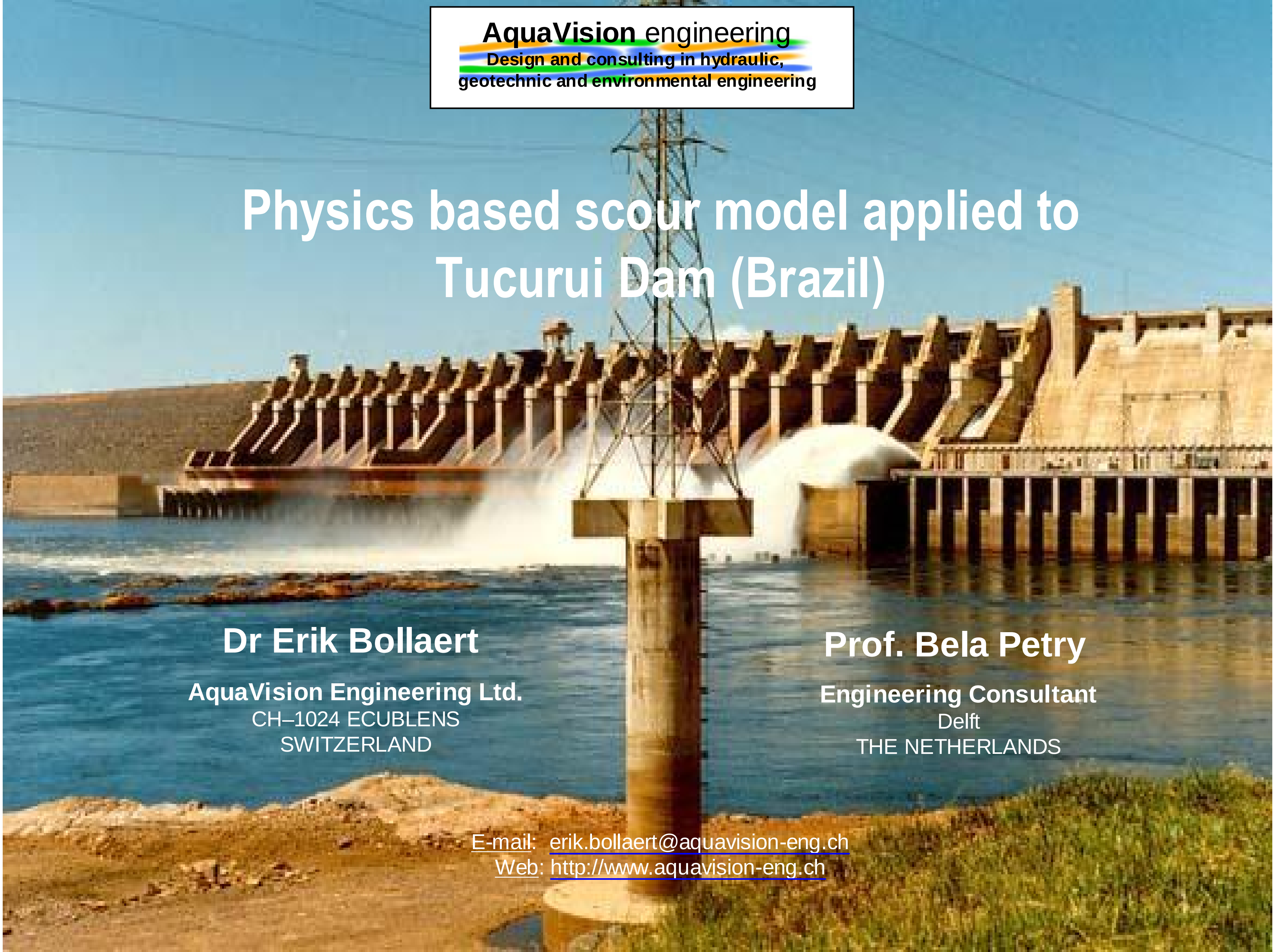

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Design and consulting in hydraulic, geotechnic and environmental engineering

Physics based scour model applied to Tucurui Dam (Brazil)

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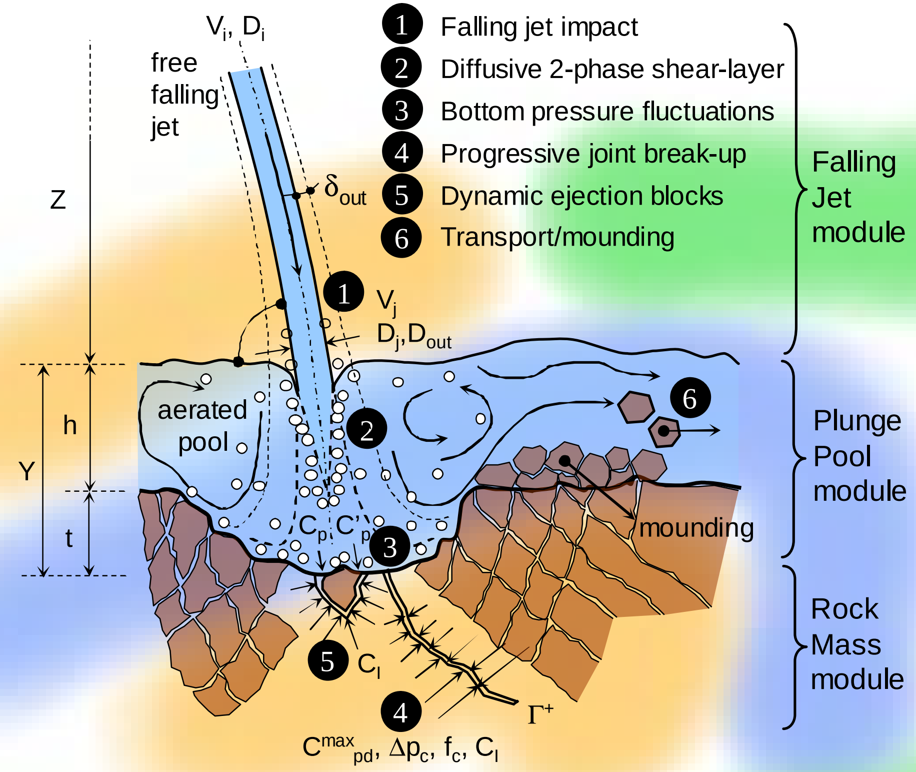
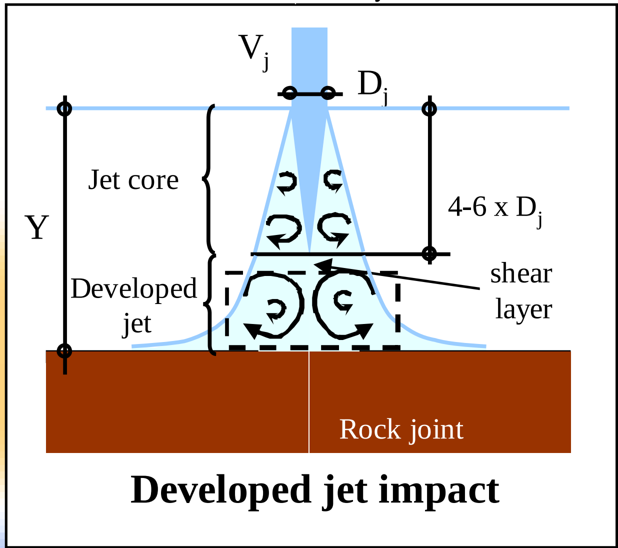
Physical processes of rock scour formation

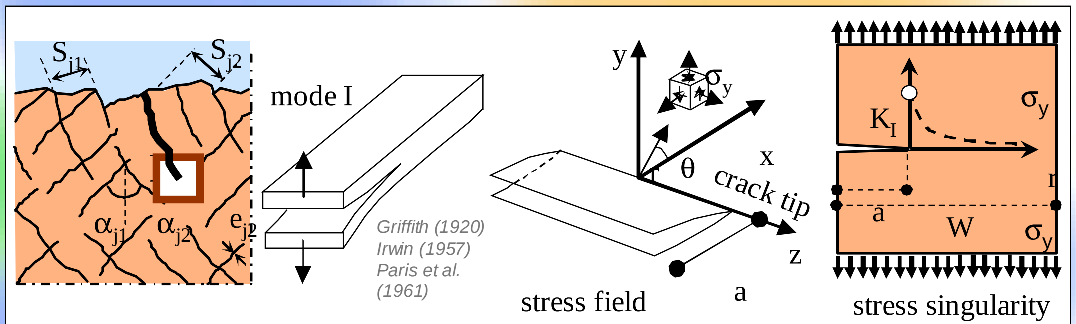
Physical-mechanical processes



Process 2. Diffusive shear layer: Jet module



Process 4. Progressive joint break-up by fatigue: LEFM model



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

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

$$\Delta a_c = \int_0^{t_f} \left(f \cdot C \cdot S^m_{max} \cdot S^n_a + \upsilon \cdot e^{bS}\right) \cdot dt$$

(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

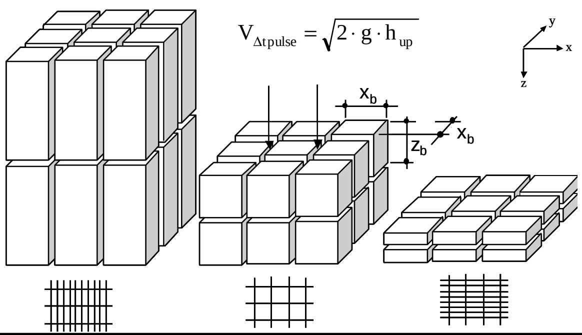
Grady & Kipp (1980)
Haimson & Zhao (1991)
Zhao & Li (2000)
Zhao (2000)
Zhang et al. (2000)

Process 5. Dynamic ejection blocks: Uplift model

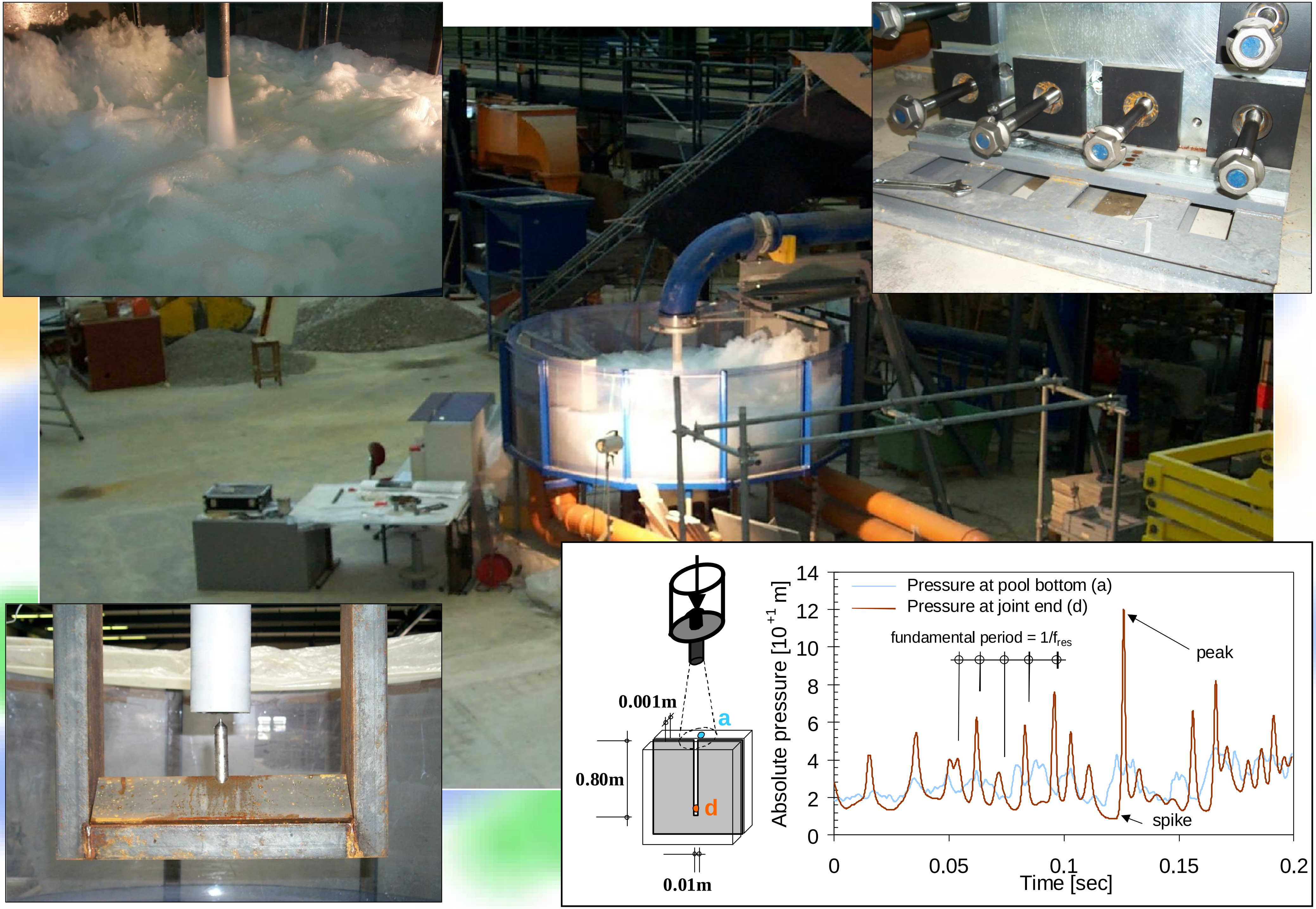
$$I_{\Delta tpulse} = \int_0^{\Delta tpulse} (F_u - F_o - G_b - F_{sh}) \cdot dt = m \cdot V_{\Delta tpulse}$$

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

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



Experimental facility at EPFL, Switzerland

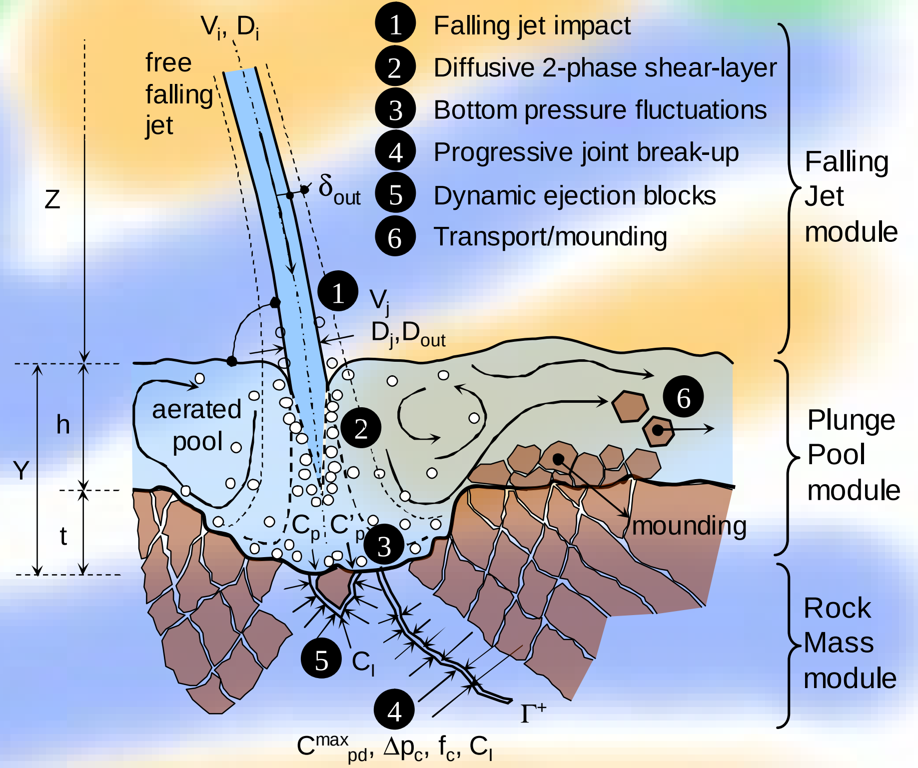


Experimental facility at EPFL, Switzerland

Comprehensive Scour Model (CSM) (Bollaert, 2002)

- use of dynamic pressures at plunge pool bottoms
- computation of transient pressures inside rock mass
- comparison with resistance of rock mass against fracturing
- computation of net uplift pressures on single rock blocks
- comparison with resistance of blocks against uplift

New engineering model
for evaluation of ultimate scour
and time evolution of scour formation



Modules:

1. falling jet
2. plunge pool
3. rock mass
   - hydrodynamic forces in rock
   - resistance criteria of fractured rock

Falling jet and plunge pool modules

Falling jet

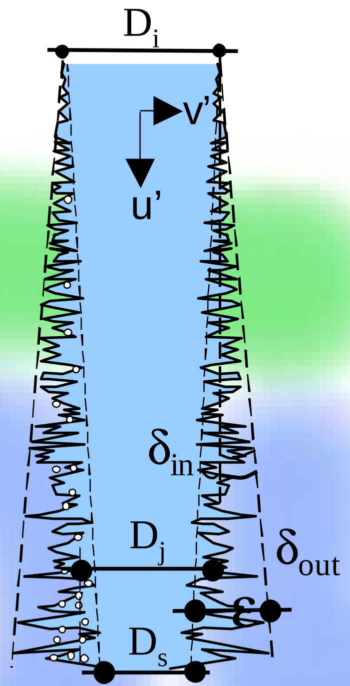
$$D_j = D_i \cdot \sqrt{\frac{V_i}{V_j}}$$

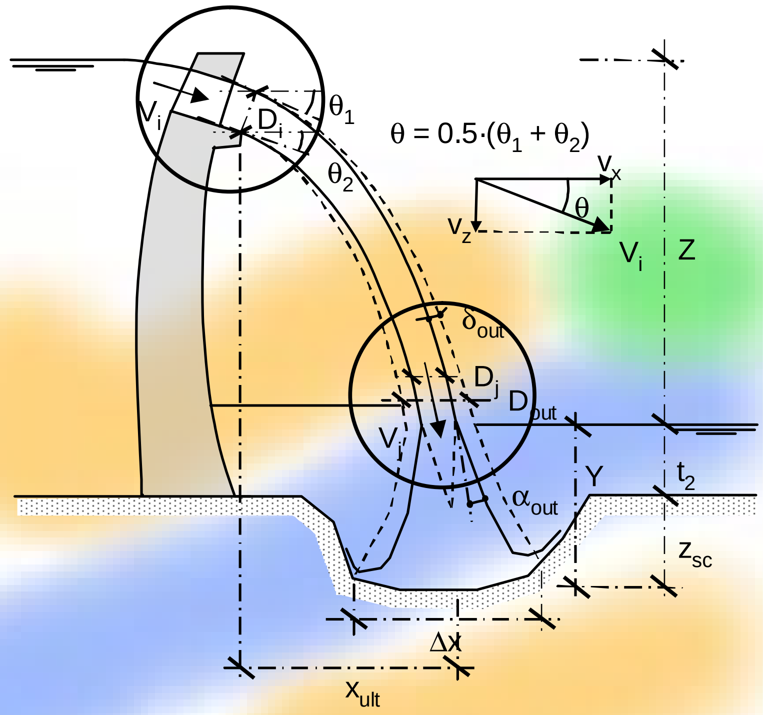
$$D_{out} = D_i + 2 \cdot \delta_{out} \cdot L$$

$$\delta_{in} = 0.5\text{–}1\ \%$$

$$\delta_{out} = 3\text{–}4\ \%$$

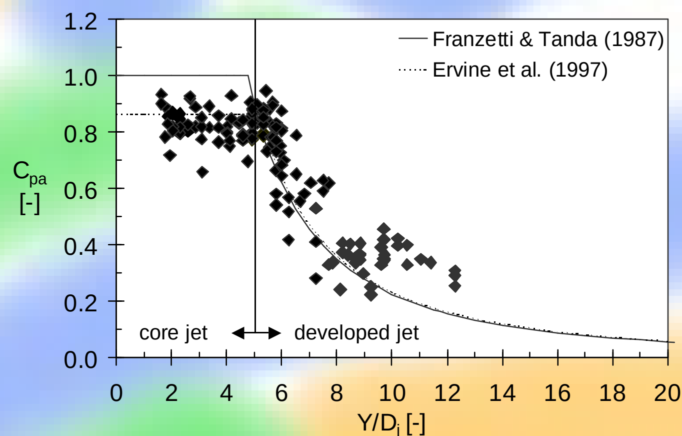
$$\delta_{out} \propto Tu$$

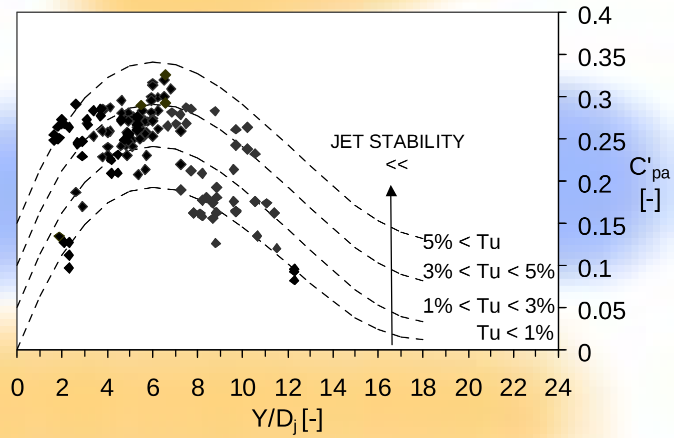




Plunge pool

- Y/D_j ratio
- centerline mean (C_{pa}) and fluctuating (C'_{pa}) dynamic pressures





$$C_{pa} = 38.4 \cdot (1 - \alpha_i) \cdot \left(\frac{D_j}{Y}\right)^2 \qquad \text{for } Y/D_j > 4\text{-}6$$

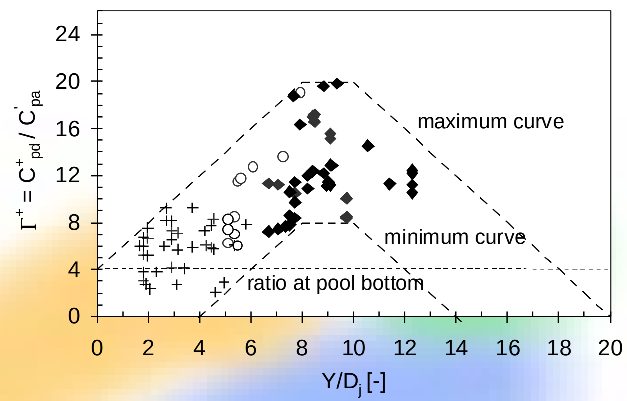
$$C_{pa} = 0.85 \qquad \text{for } Y/D_j < 4\text{-}6$$

$$C'_{pa} = 0.0022 \cdot \left(\frac{Y}{D_j}\right)^3 - 0.0079 \cdot \left(\frac{Y}{D_j}\right)^2 + 0.0716 \cdot \left(\frac{Y}{D_j}\right) + 0.0583$$

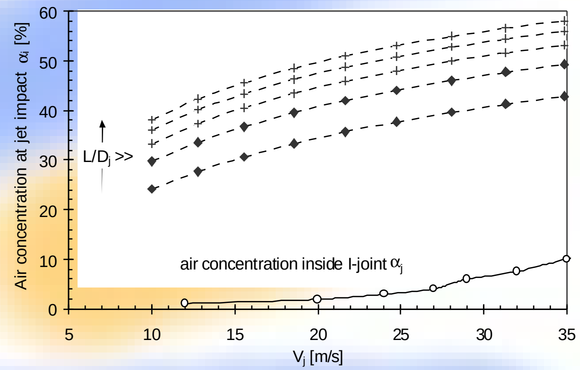
Rock mass module: Hydrodynamic forces

1.) Maximum dynamic pressure C^{max}_p in a closed-end joint

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



2.) Characteristic amplitude of pressures Δp_c in a closed-end joint



3.) Characteristic frequency of pressures f_c in a closed-end joint

c [m/s] = $4 \cdot L_j \cdot f_c$ ~ 100 – 200 f_c [Hz] ~ 10 – 100

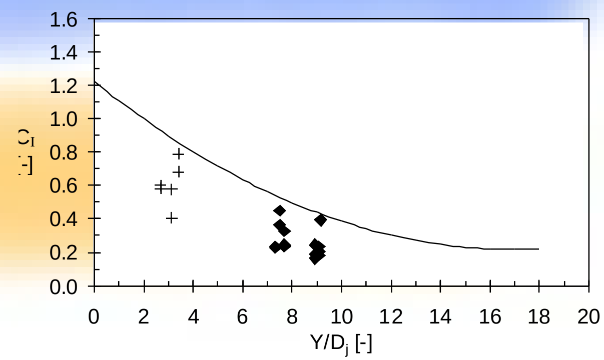
4.) Maximum dynamic impulsion C^{max}_I in an open-end joint

$p_{up} = C_{up} \cdot V^2/2g$

$\Delta t_{up} = T_{up} \cdot 2L/c$

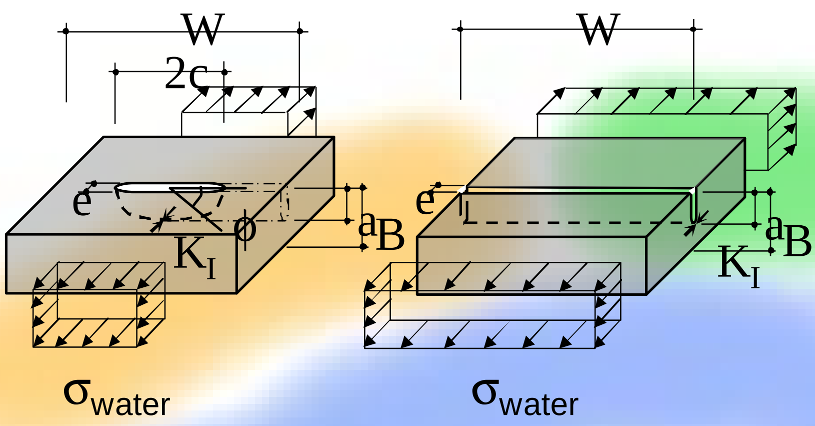
$I_{up} = p_{up} \cdot \Delta t_{up} = C_{up} \cdot T_{up} \cdot (V^2L/gc) = C_I \cdot (V^2L/gc)$ [m.s]

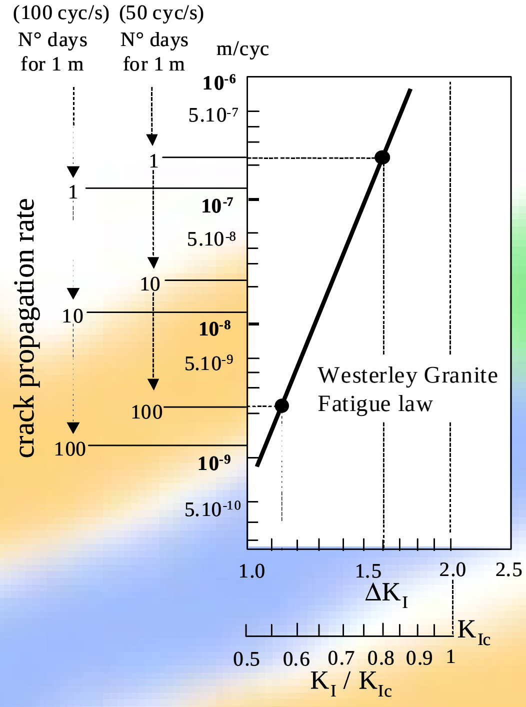
$$C_I = 0.0035 \cdot \left(\frac{Y}{D_j}\right)^2 - 0.119 \cdot \left(\frac{Y}{D_j}\right) + 1.22$$



Rock mass module: Fracture Mechanics Method

Semi-elliptical (EL) Single-edge (SE)





1. Stress Intensity at crack tip

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

2. Fracture toughness of rock

$$K_{I\ ins,T} = A \cdot (1.2\text{ to }1.5) \cdot T + (0.054 \cdot \sigma_c) + B$$

$$K_{I\ ins,UCS} = C \cdot (1.2\text{ to }1.5) \cdot UCS + (0.054 \cdot \sigma_c) + D$$

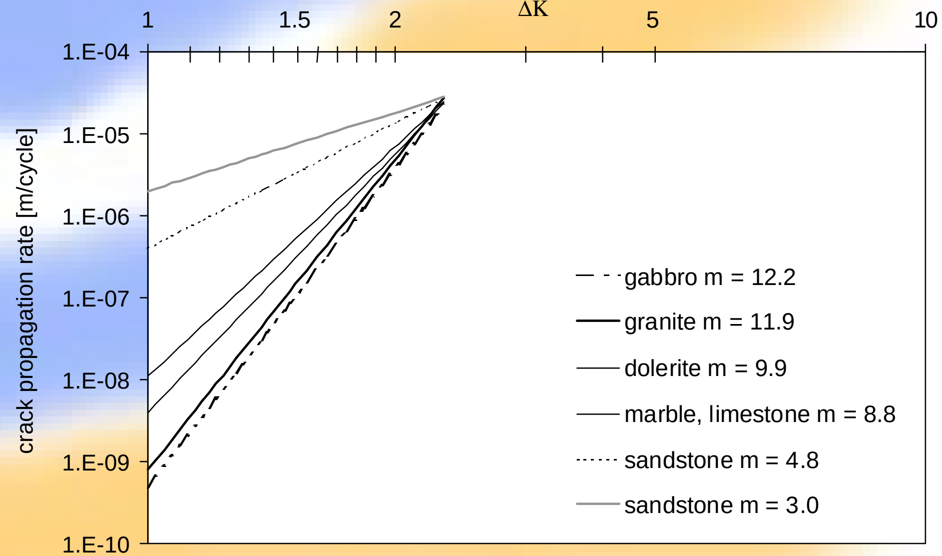
3. Instantaneous crack propagation (C^{max}_p)

$$K_I > K_{I\ ins}$$

4. Time-dependent crack propagation (Δp_c, f_c)

$$K_I < K_{I\ ins}$$

$$\frac{da}{dN} = C_r \cdot (\Delta K_I)^{m_r}$$



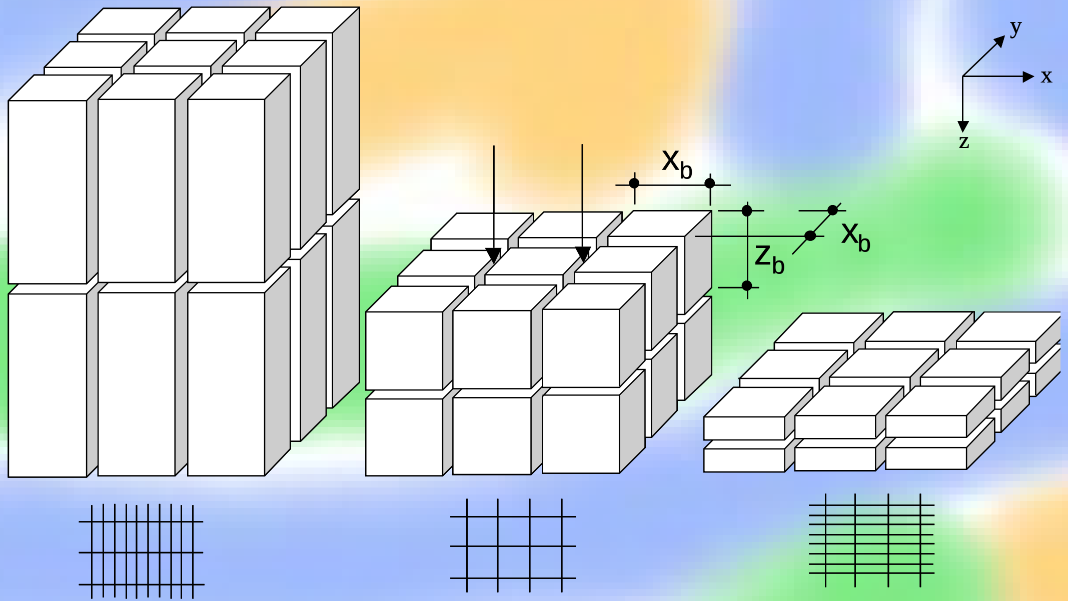
Rock mass module: Dynamic Impulsion Method

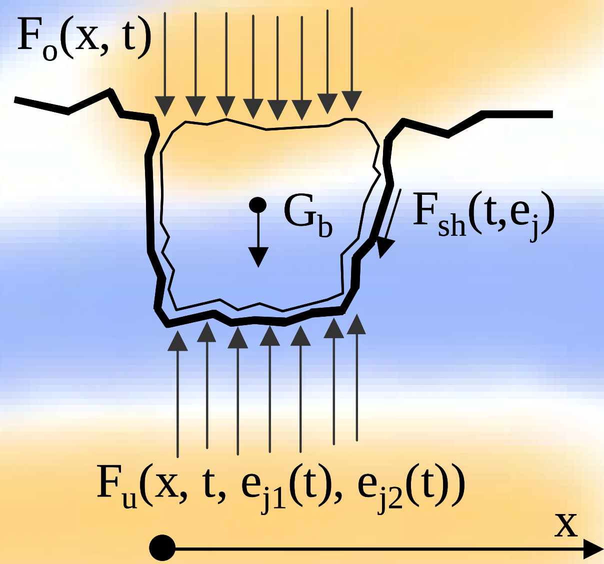
$$I_{\Delta tpulse} = \int_0^{\Delta tpulse} \left(F_u - F_o - G_b - F_{sh}\right) \cdot dt = m \cdot V_{\Delta tpulse}$$

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

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

F_u	=	underpressures
F_o	=	overpressures
G_b	=	weight of rock block
F_{sh}	=	shear and interlocking forces



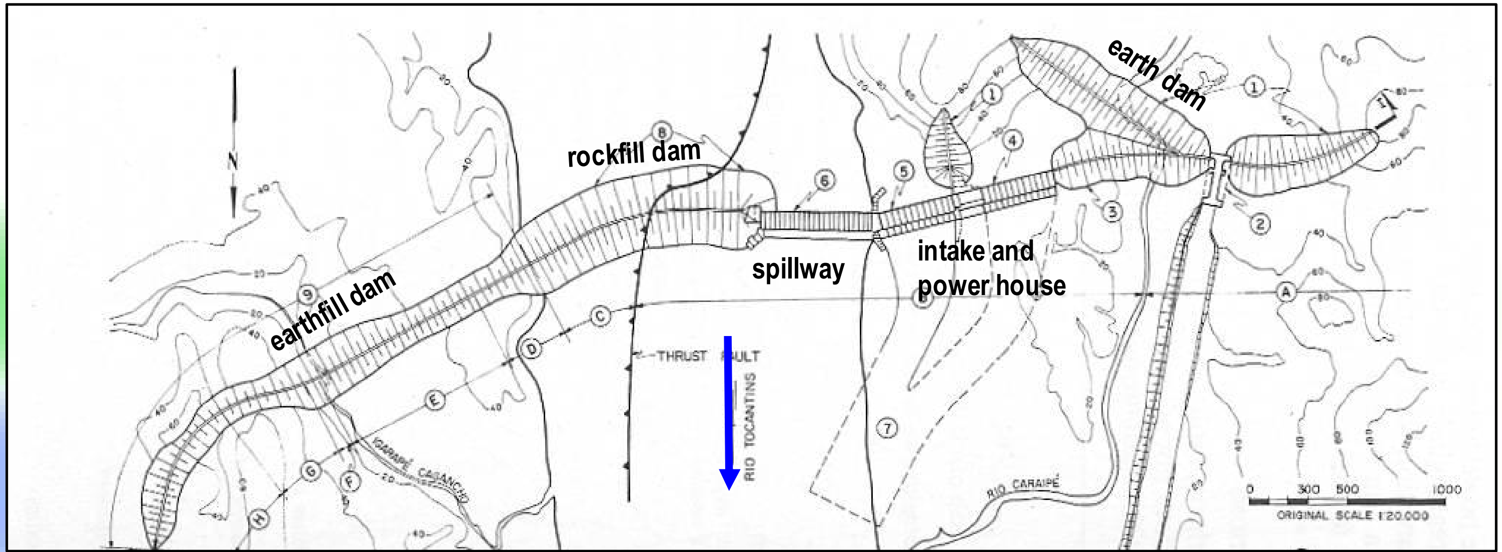


Tucurui Dam plunge pool (Brazil)

Tocantins-Araguaia basin

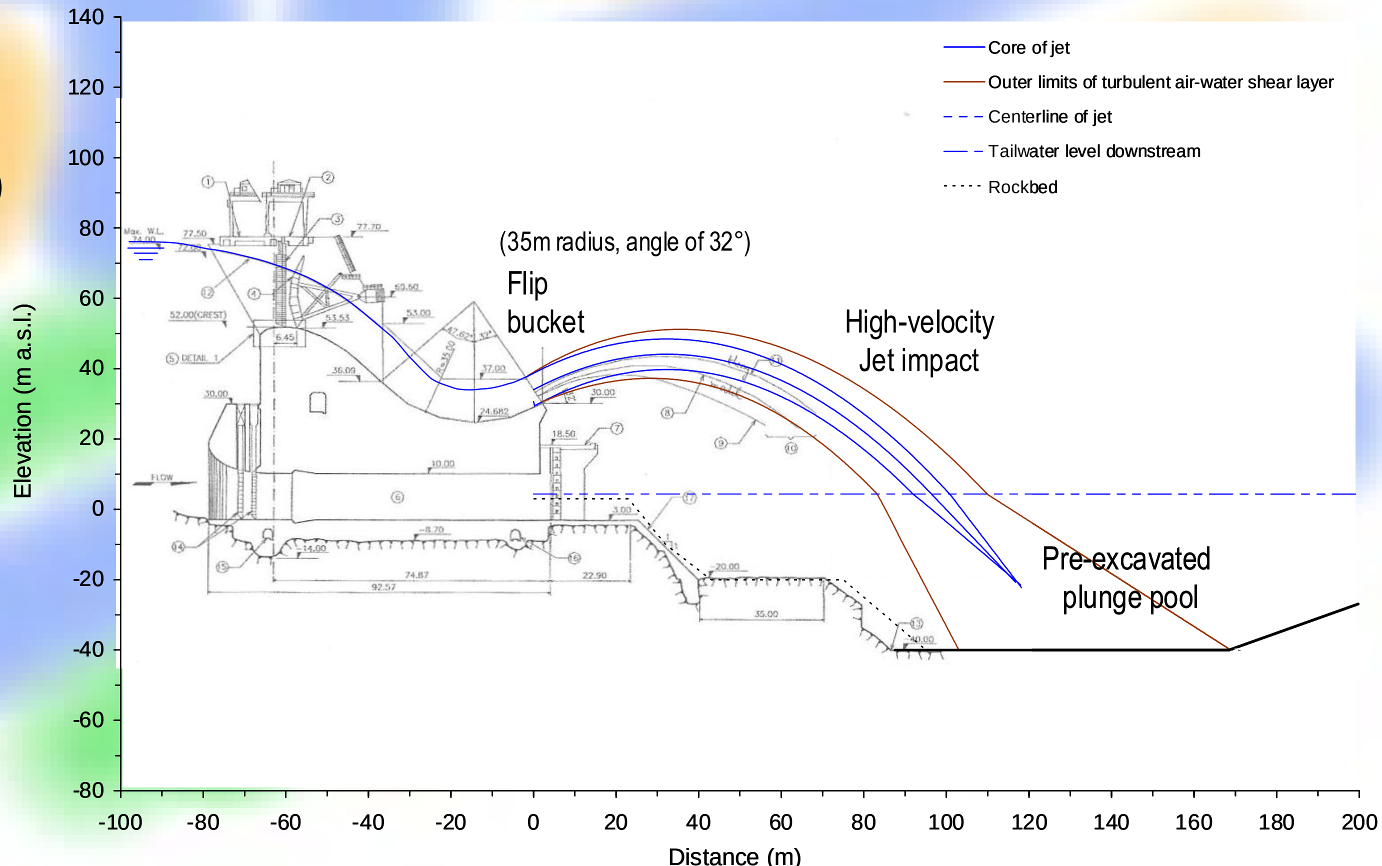
- catchment area Tocantins River 758'000 km^2 (7.5 % of land mass of Brazil)
- Tocantins River has a total length of 2'500 km
- average annual flow rate of 10'900 cms
- dry season in September-October
- peak flooding during February-April (average monthly flows of 50'000 cms)

Tucurui Dam plunge pool (Brazil)



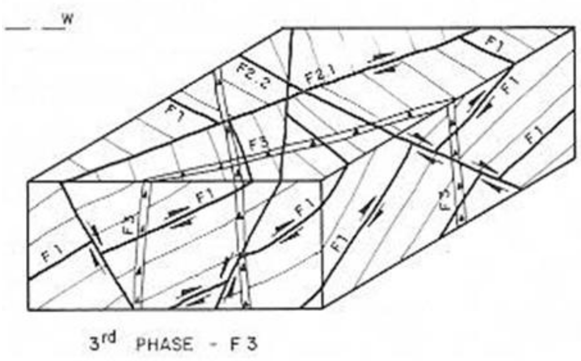
Tucurui Dam Complex

- 86 m high rockfill dam on Tocantins River
- 6’900 m long main dam wall
- meta-sedimentary rock at spillway
- 2nd largest spillway worldwide (110’000 m^3/s)
- pre-excavated plunge pool at – 40 m
- almost no scour since dam construction
- 23 rectangular gates 21 m x 20 m wide
- floods during 3 months / year (Feb-April)



Rock mass properties

Fault structures



F 1 Thrust faults parallel to bedding
Failles inverses parallèles à la stratification

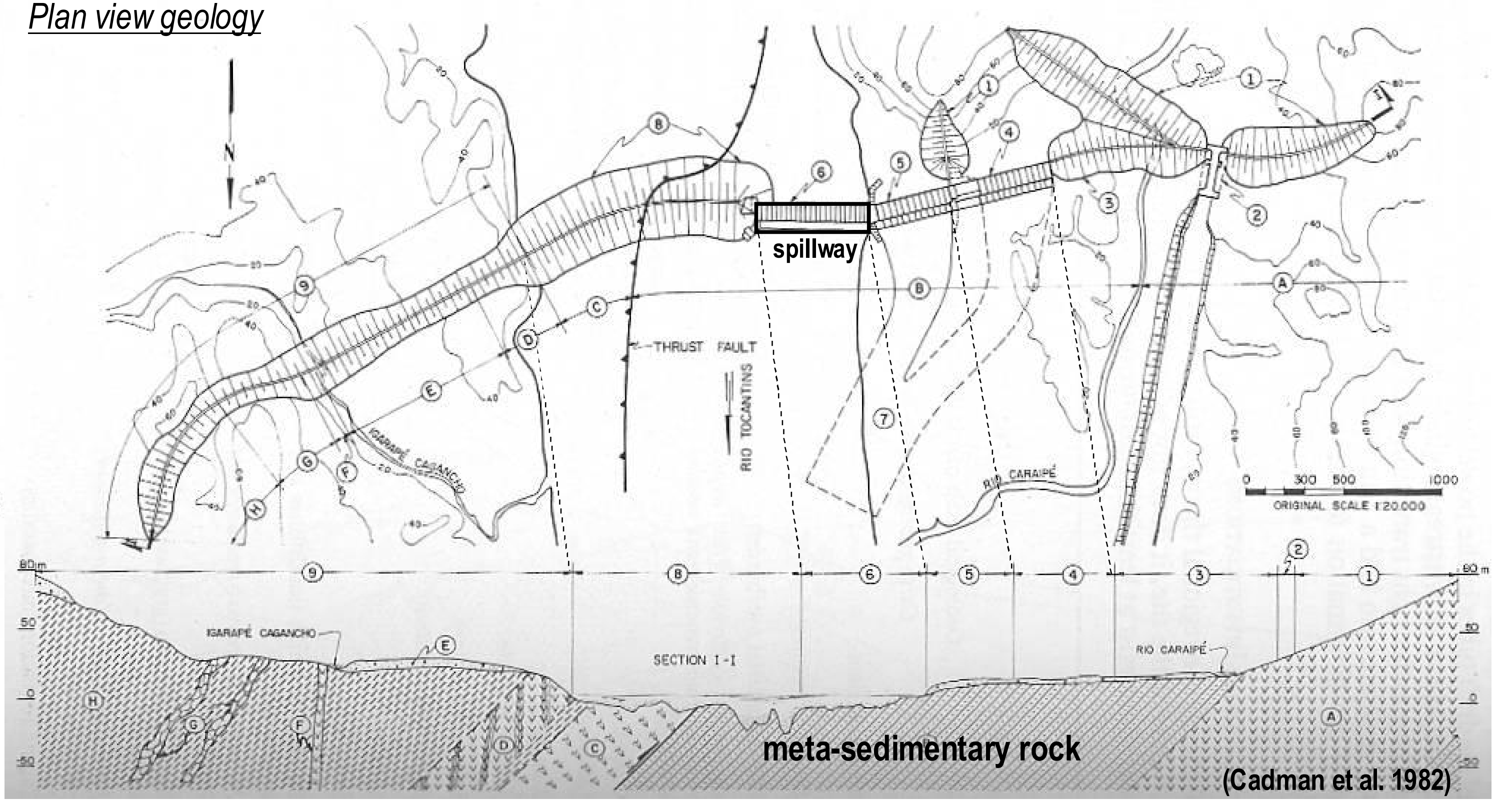
F 2.1 Normal faults dipping west
Failles normales plongeant vers l'ouest

F 2.2 Normal faults dipping south
Failles normales plongeant vers le sud

F 2.3 Normal faults dipping east
Failles normales plongeant vers l'est

F 3 Strike — slip subvertical faults
Failles transcourantes sub-verticales

Plan view geology

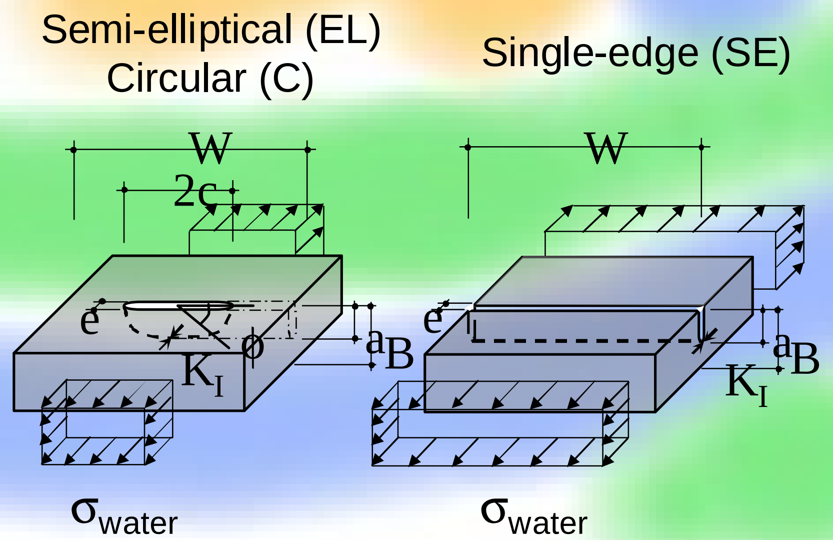


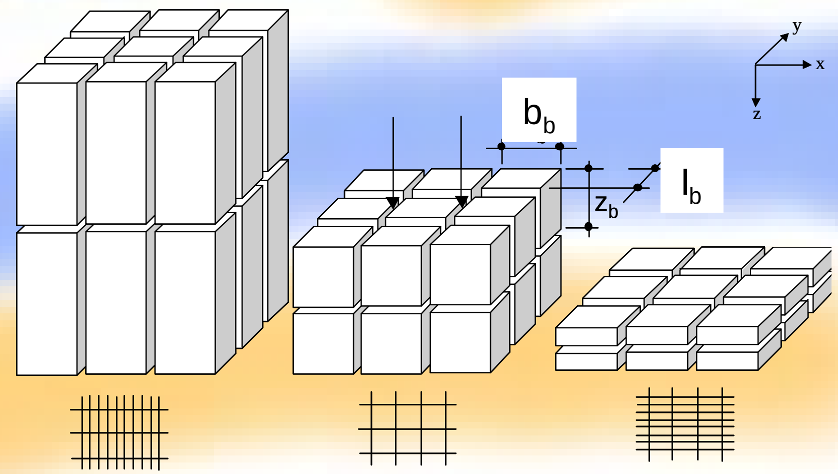
Meta-sedimentary rock

- Unconfined Compressive Strength of intact rock = ~ 125 MPa
- multiple families of faults, joints
- one major fault through the center of the riverbed
- very complex situation (lithology – tectonic structure – faults)
- near-horizontal bedding, sliding stability

Rock mass properties

Property	Symbol	CONSERV	AVERAGE	BENEF	Unity
Unconfined Compressive Strength	UCS	50	75	125	MPa
Density rock	γ_r	2600	2700	2800	kg/m3
Ratio horizontal/vertical stresses	K_0	2-3	2-3	2-3	-
Typical maximum joint length	L	1	1	1	m
Vertical persistence of joint	P	0.25	0.25	0.25	-
Form of rock joint	-	single-edge	elliptical	circular	-
Tightness of joints	-	tight	tight	tight	-
Total number of joint sets	N_j	3+	3	2+	-
Typical rock block length	l_b	1	1	1	m
Typical rock block width	b_b	1	1	1	m
Typical rock block height	z_b	0.5	0.75	1	m
Joint wave celerity	c	150	125	100	m/s
Fatigue sensibility	m	8	9	10	-
Fatigue coefficient	C	1.00E-07	1.00E-07	1.00E-07	-





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Flooding and bathymetric surveys (1969-2001)

Flooding survey (available since 1969)

- 1969 – 1980: statistical analysis based on Tucurui and Itupiranga about 175 km upstream, PMF = 90’000 cms
- 1978-1980: 3 major flood events during dam construction, up to 68’000 cms
- 1980-present: more detailed flood analysis, PMF = 110’000 cms, somewhat conservative, maximum peak since dam construction = 43’000 cms (Jan 1990)

Bathymetric survey

Survey 1 (1984)

Sedimentation along right hand side of plunge pool due to 3 yrs of river diversion during dam construction

Survey 2 (1985)

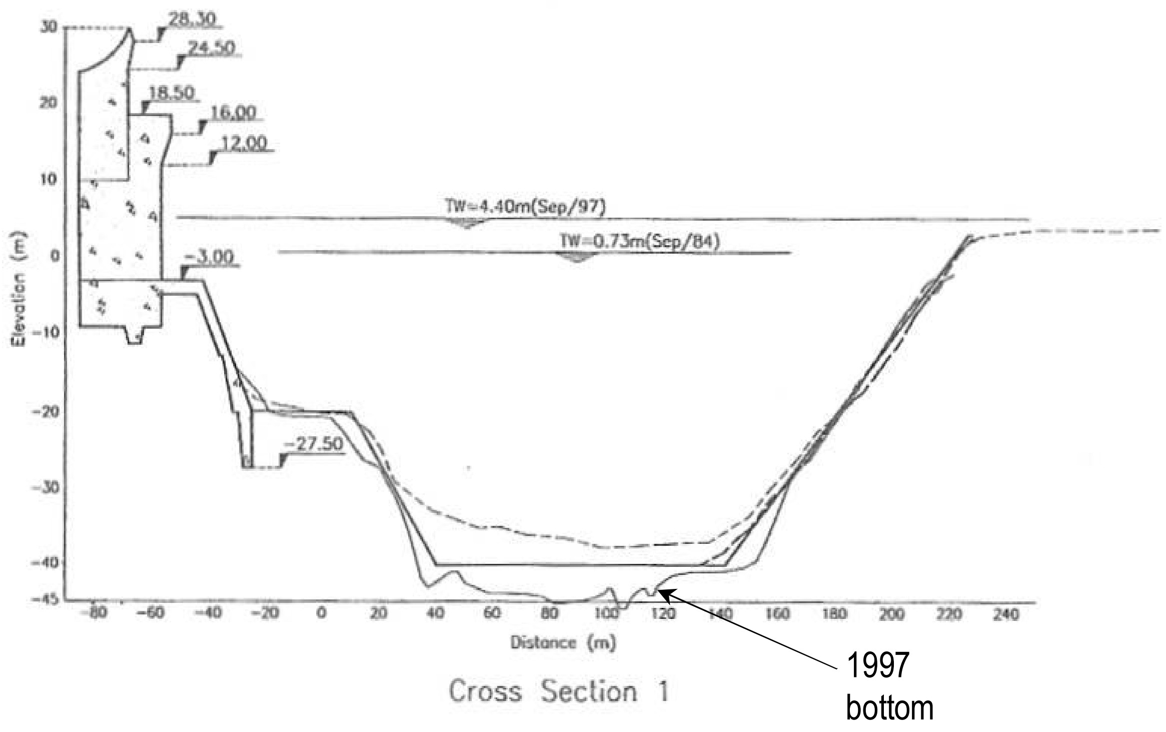
No specific issues, only left hand isde of basin has been surveyed due to strong turbulent vortices

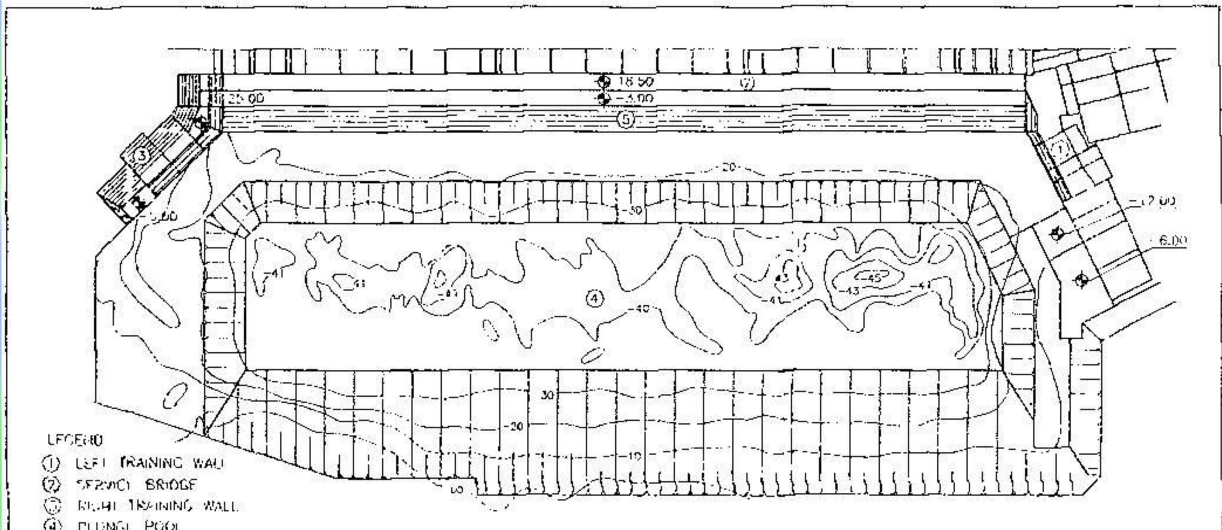
Survey 3 (1986)

Former sediment deposits washed away. Slight erosion (max. 5 m) along two local areas of plunge pool bottom and problaby related to removal of partially detached (blasting) rock blocks.

Survey 4 (1997)

Same erosion in same areas as found during the 1986 survey. No specific issues to notice.





Survey 1986 (ICOLD, 2002)

Laboratory model tests

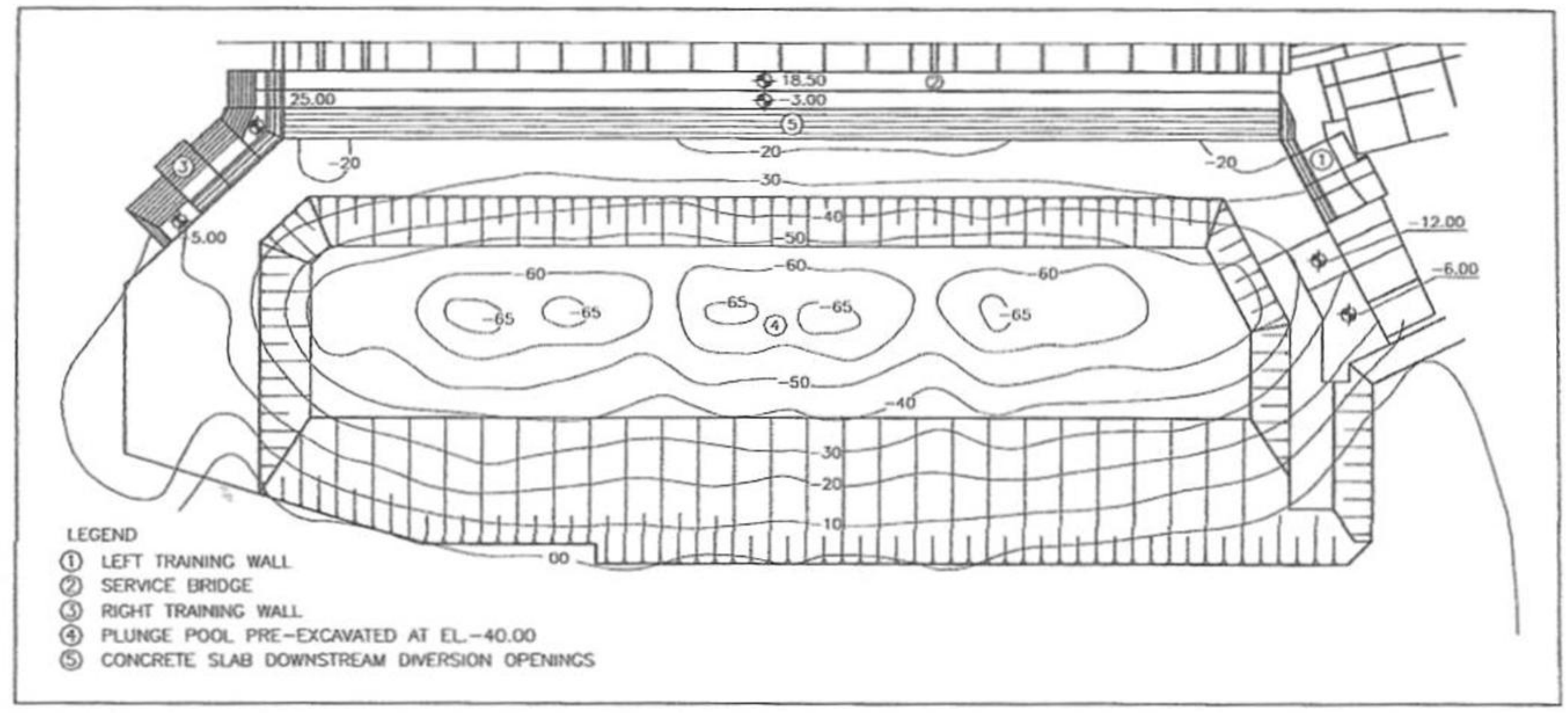


Figure 1.- Scour formation in plunge pool following laboratory test with gravel and 100’000 cms (Large Brazilian Spillways, ICOLD, Petry et al., 2002)

- discharges between 15’000 and 100’000 cms
- plunge pool bottoms at elevations of -15m, -25m, -40m
- pool at -40m: no erosion for discharges of up to 50’000 cms (calibration model)
  erosion until – 65m for discharge of 100’000 cms

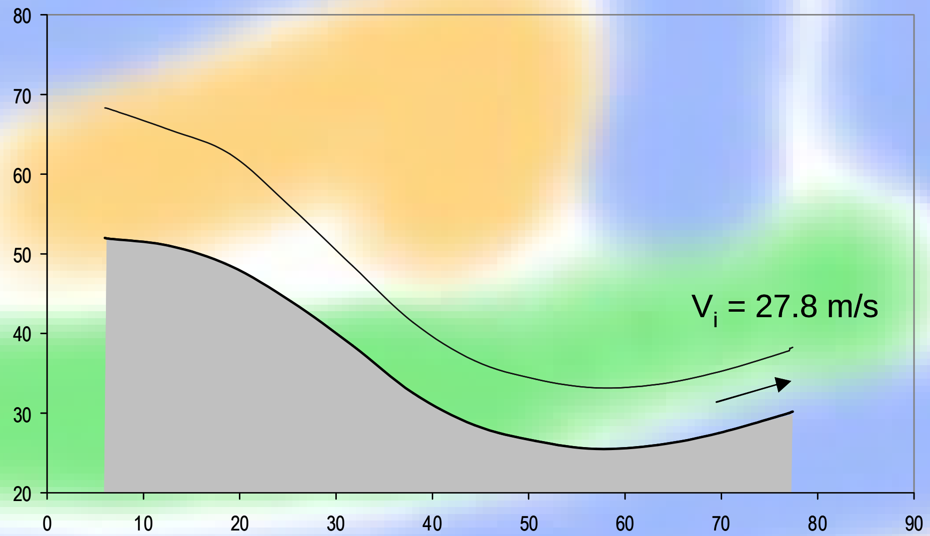
Application of Comprehensive Scour Model

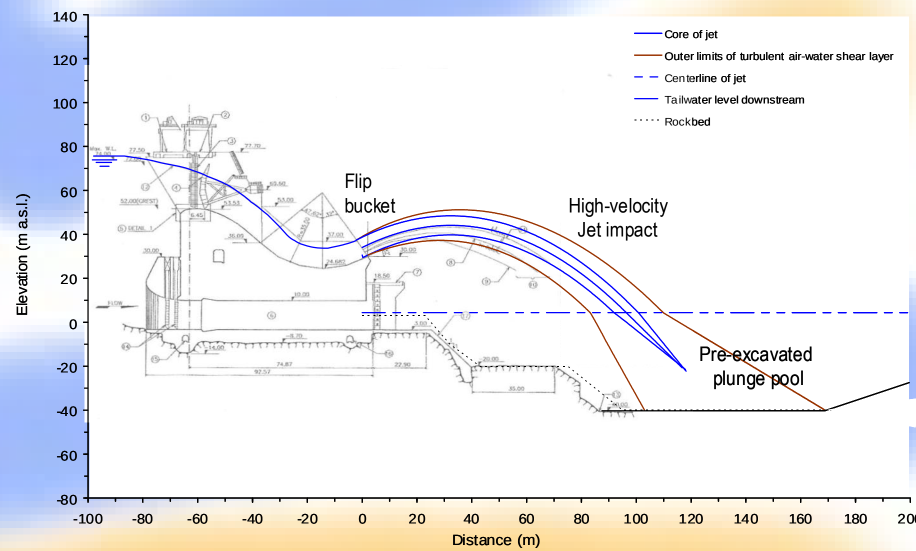
Falling jet at Tucurui Dam

The jet at Tucurui Dam is issuing from a chute with flip bucket. As such, numerical computations have first been performed of the air-water flow characteristics along the chute. The water surface line for a 110’000 m^3/s is presented in Figure 4.

The flow velocity at the lip of the flip bucket equals 27.8 m/s, for a total flow depth of about 8 m. The upstream water level is 75.3 m a.s.l. and the downstream plunge pool water level is at 4.4 m a.s.l. The jet is thus of rectangular shape with a width of 20m and an issuance thickness of 8m.

Second, the jet characteristics at impact in the tailwater depth have been defined based on ballistics accounting for air drag. As such, the jet velocity at impact has been computed at 37.9 m/s for an inner jet core diameter of about 6.9 m. Its turbulence intensity has been estimated at 8 % and its air concentration at impact at 40 %, corresponding to very turbulent air-water jets.





Plunge pool diffusion at Tucurui Dam

The diffusion of the jet through the pool water depth is presented in Figure 2. Significant spread of the jet is computed, with an outer jet diameter at impact in the pool of about 20m. The jet core vanishes before impacting the plunge pool bottom, corresponding to fully developed jet conditions.

Application of Comprehensive Scour Model

Results of computations

Table 2a.- Scour elevations as a function of time duration of flood following a 100’000 m^3/s flood event at Tucurui Dam (CSM model)

SCOUR ELEVATION COMPUTATIONS									
TIME				CFM			DI		
Hours	Days	Months	Years	BENEF	AVER	CONS	CONS	AVER	BENEF
96	4	0.1	0.01	-40.4	-53.6	-61.6	-93.9	-78.9	-63.2
192	8	0.3	0.02	-40.4	-53.6	-62.6	-93.9	-78.9	-63.2
720	30	1.0	0.08	-40.4	-54.3	-64.1	-93.9	-78.9	-63.2
1500	62.5	2.1	0.17	-40.4	-54.9	-65.0	-93.9	-78.9	-63.2
5760	240	8.0	0.67	-40.4	-56.4	-67.2	-93.9	-78.9	-63.2
57600	2400	80.0	6.67	-42.6	-59.2	-74.3	-93.9	-78.9	-63.2

Table 2b.- Scour elevations as a function of time duration of flood following a 50’000 m^3/s flood event at Tucurui Dam (CSM model)

SCOUR ELEVATION COMPUTATIONS									
TIME				CFM			DI		
Hours	Days	Months	Years	BENEF	AVER	CONS	CONS	AVER	BENEF
96	4	0.1	0.01	-40.6	-40.6	-40.6	-45.1	-40.0	-40.0
192	8	0.3	0.02	-40.6	-40.6	-40.6	-45.1	-40.0	-40.0
720	30	1.0	0.08	-40.6	-40.6	-40.6	-45.1	-40.0	-40.0
1500	62.5	2.1	0.17	-40.6	-40.6	-40.6	-45.1	-40.0	-40.0
5760	240	8.0	0.67	-40.6	-40.6	-40.6	-45.1	-40.0	-40.0
57600	2400	80.0	6.67	-40.6	-40.6	-40.6	-45.1	-40.0	-40.0

Conclusions

1. Almost no scour formation for 100’000 cms and under beneficial parametric assumptions
2. Small scour forms under average parametric assumptions and for 100’000 cms (10m of scour formation)
3. The laboratory model tests are probably somewhat on the conservative side (25m of socur formation)
4. For a completely broken up rock mass (detached blocks with depth), significant scour would form, however not plausible