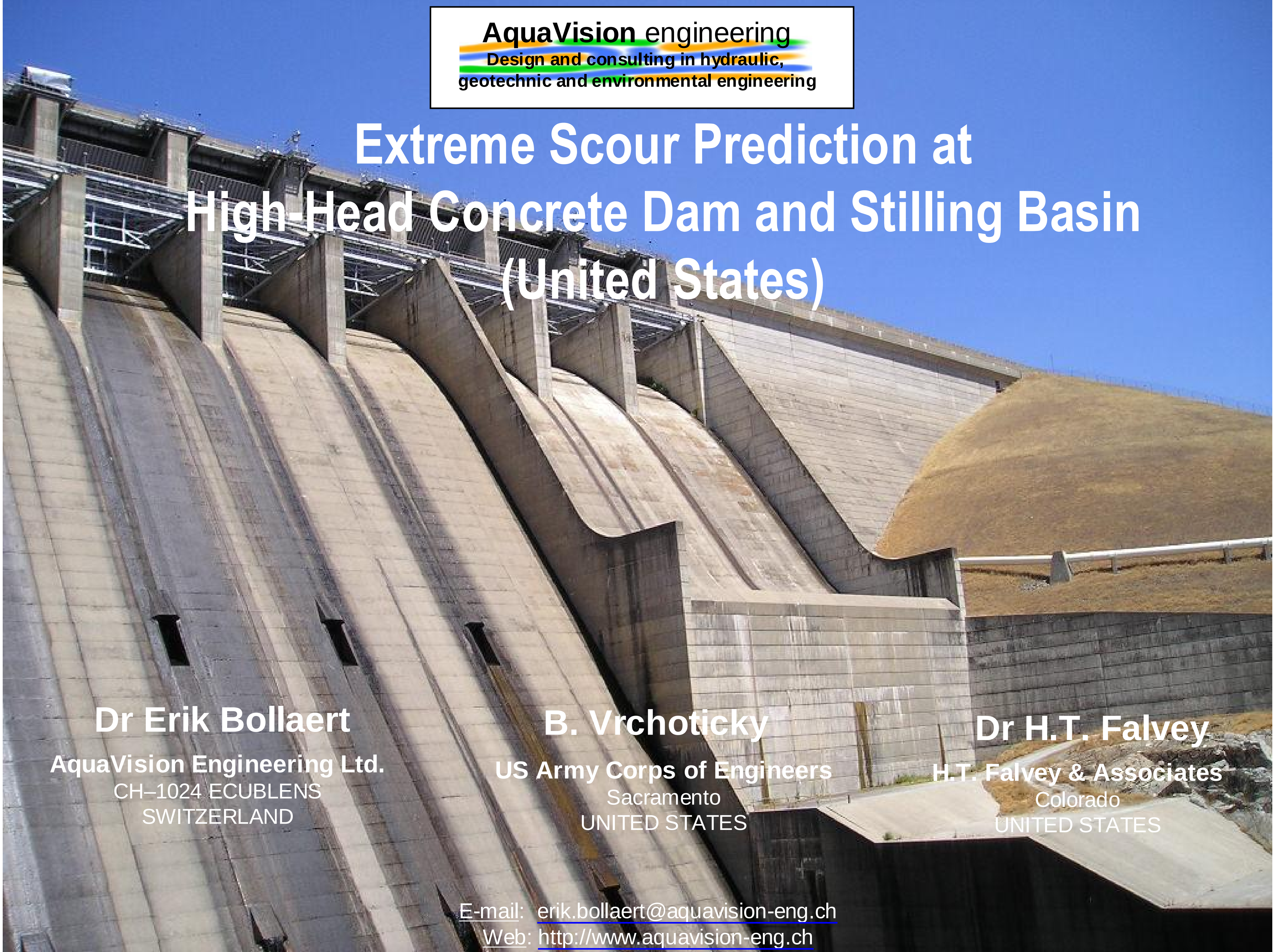

AquaVision engineering
Design and consulting in hydraulic, geotechnic and environmental engineering

Extreme Scour Prediction at High-Head Concrete Dam and Stilling Basin (United States)

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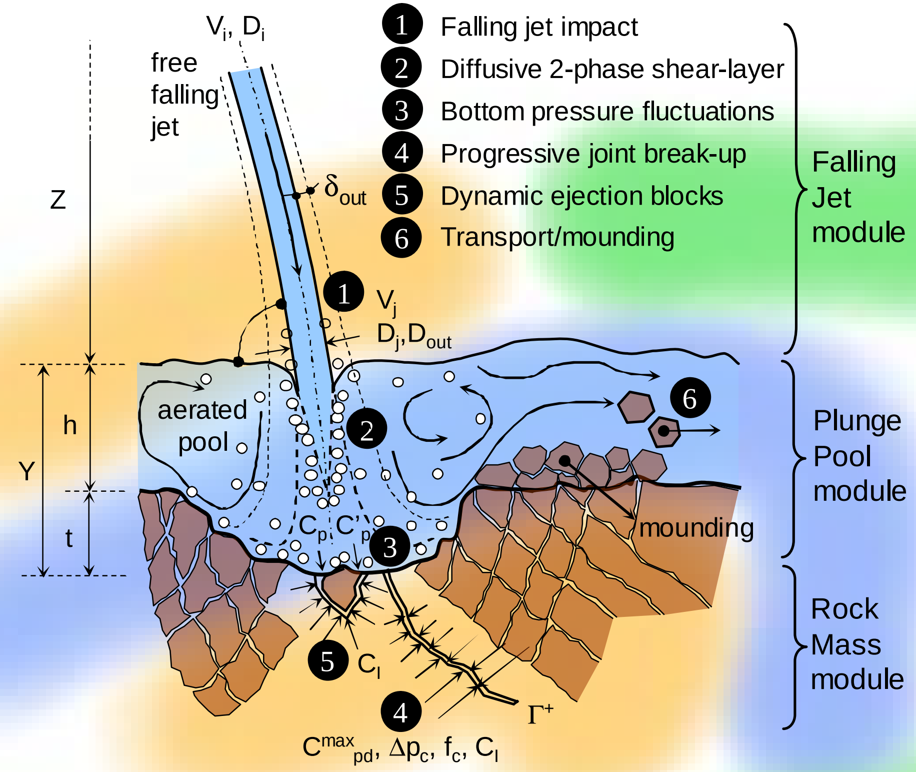
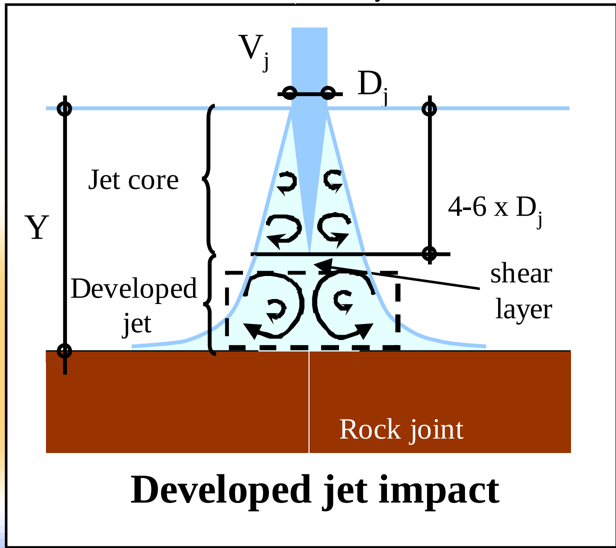
Physical processes of rock scour formation

Physical-mechanical processes



Process 2. Diffusive shear layer: Jet module

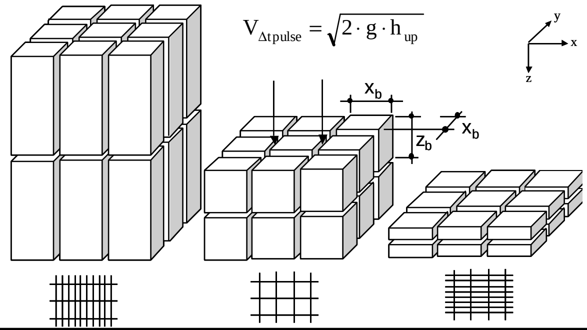


Process 5. Dynamic ejection blocks: Uplift model

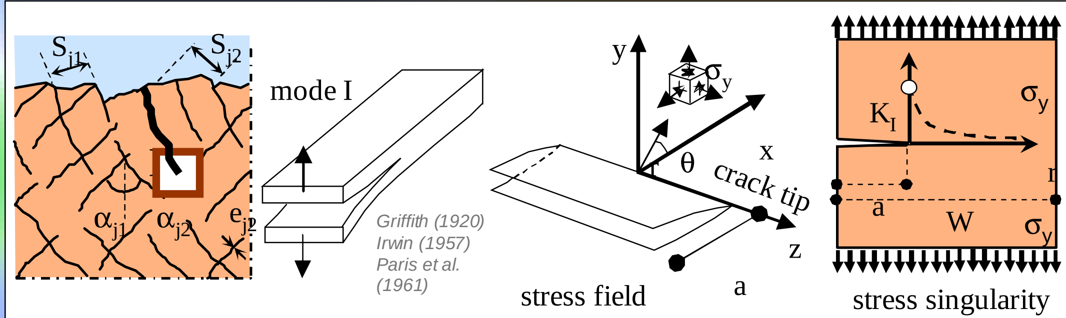
$$I_{\Delta tpulse} = \int_0^{\Delta tpulse} (F_u - F_o - G_b - F_{sh})\cdot dt = m\cdot V_{\Delta tpulse}$$

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

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



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



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

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

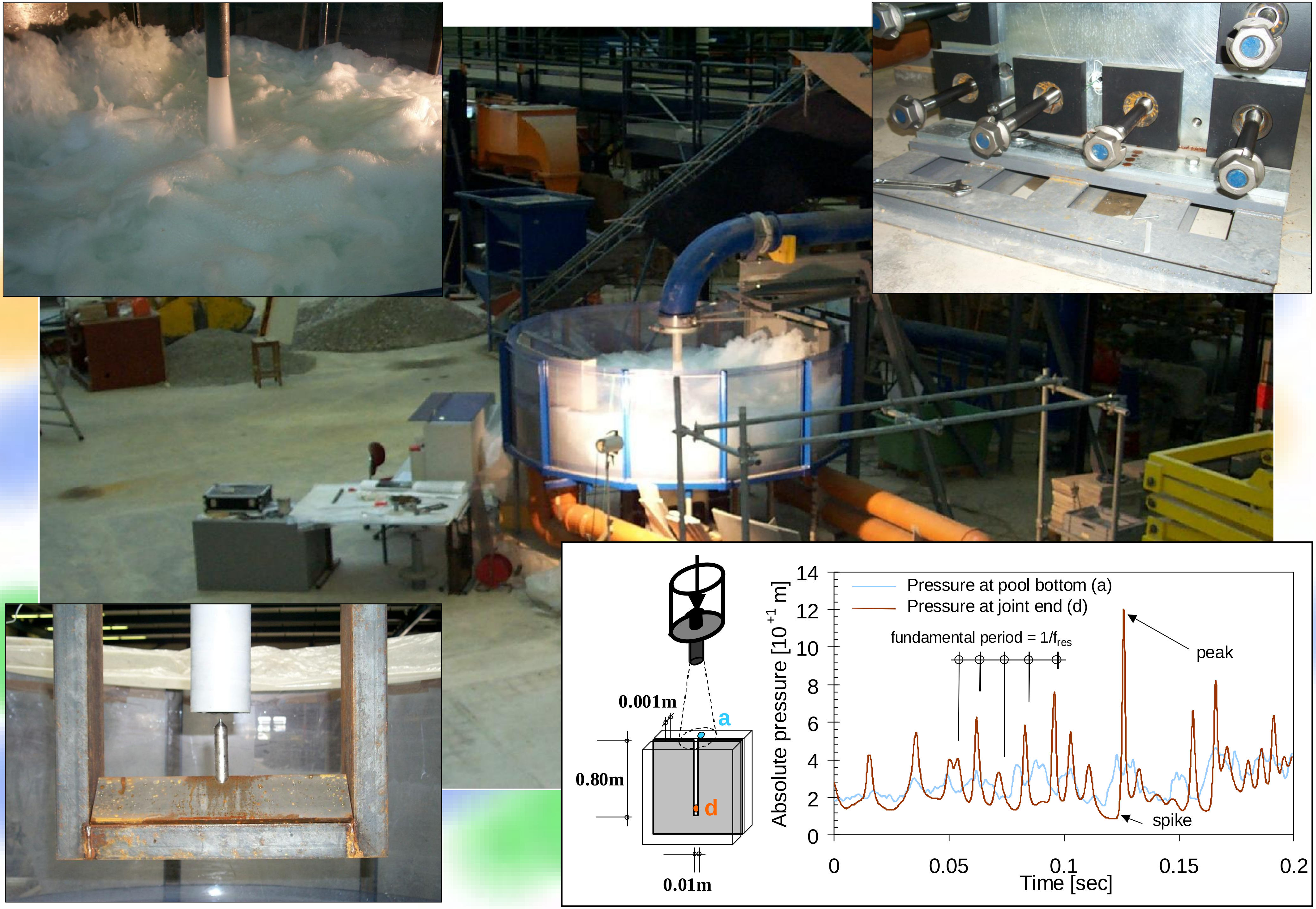
$$\Delta a_c = \int_0^{t_f}\left(f\cdot C\cdot S_{max}^m \cdot S_a^n + \upsilon\cdot e^{bS}\right)\cdot dt$$

(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)

Experimental facility at EPFL, Switzerland

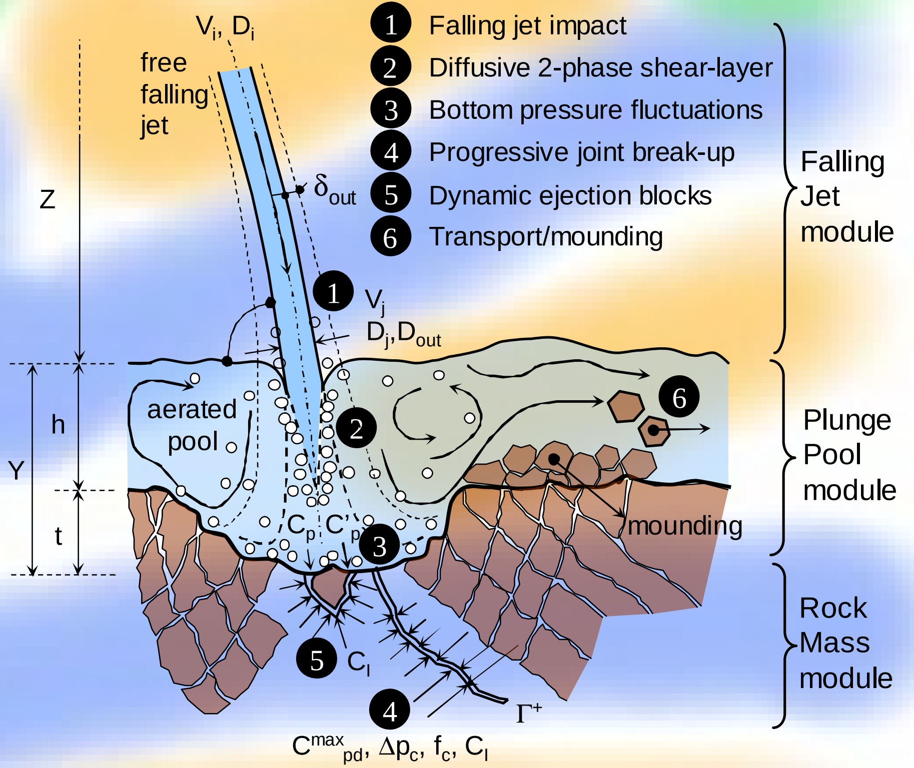


Experimental facility at EPFL, Switzerland

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

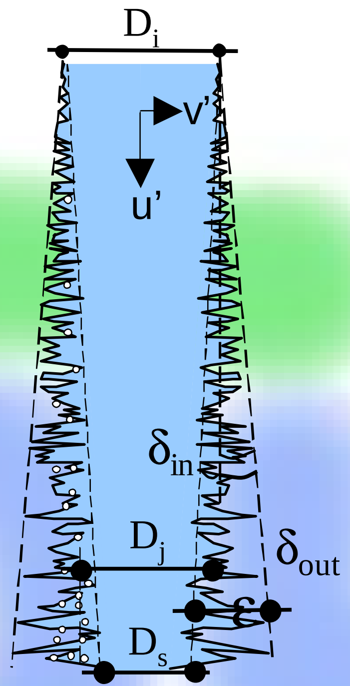
$$D_j = D_i \cdot \sqrt{\frac{V_i}{V_j}}$$

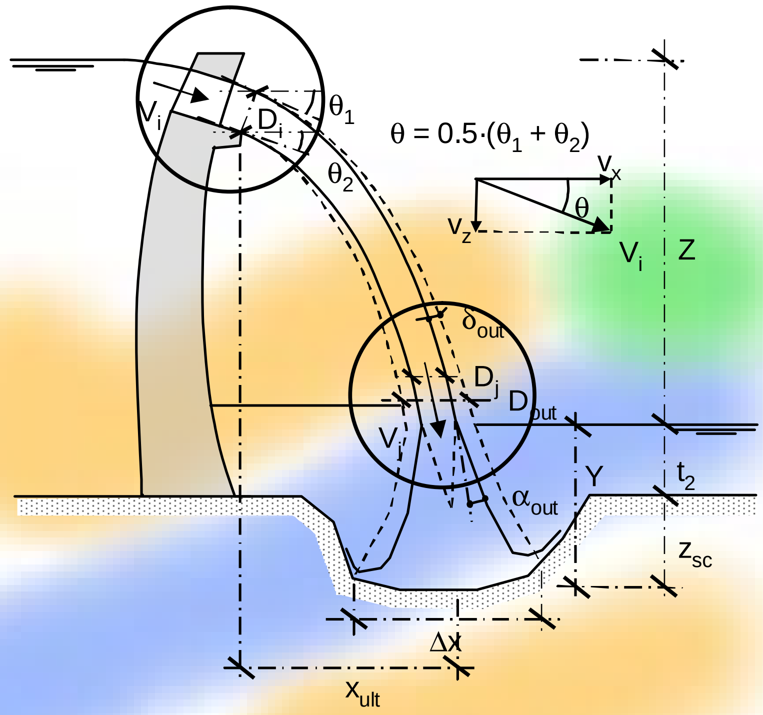
$$D_{out} = D_i + 2 \cdot \delta_{out} \cdot L$$

$$\delta_{in} = 0.5\text{–}1\ \%$$

$$\delta_{out} = 3\text{–}4\ \%$$

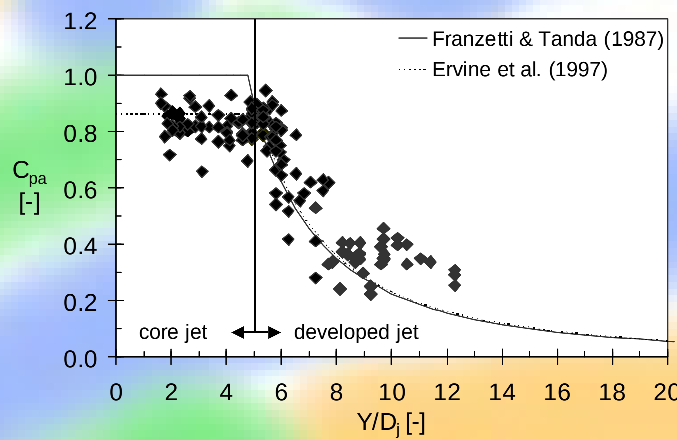
$$\delta_{out} \propto Tu$$

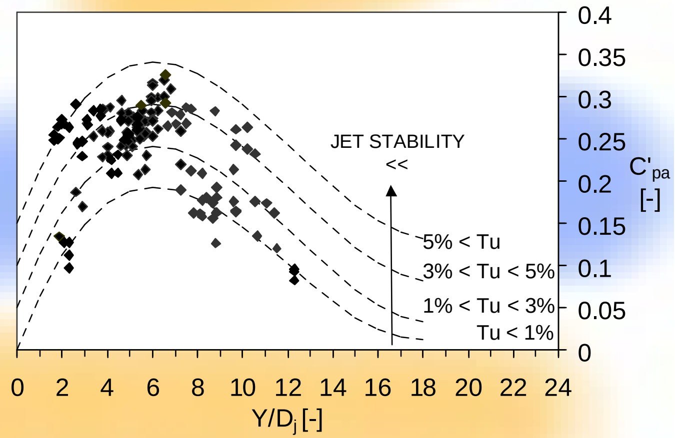




Plunge pool

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





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

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

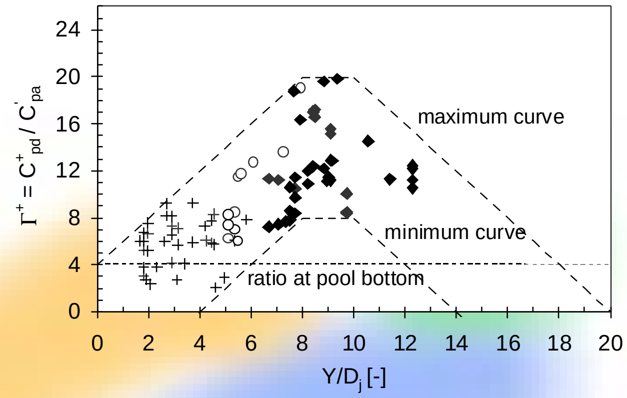
$$C'_{pa} = 0.0022 \cdot \left(\frac{Y}{D_j}\right)^3 - 0.0079 \cdot \left(\frac{Y}{D_j}\right)^2 + 0.0716 \cdot \left(\frac{Y}{D_j}\right) + 0.0583$$

Rock mass module: Hydrodynamic forces

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

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

Bollaert (2002)

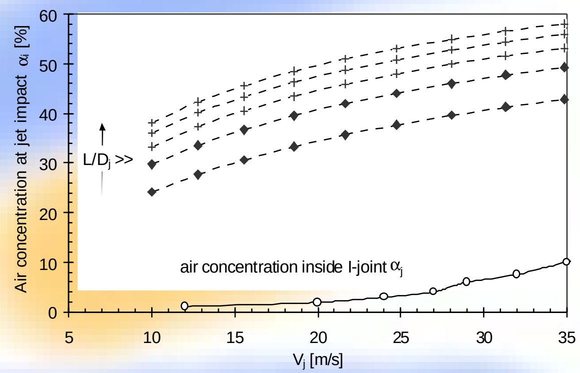


2.) Characteristic amplitude of pressures Δp_c in a closed-end joint

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



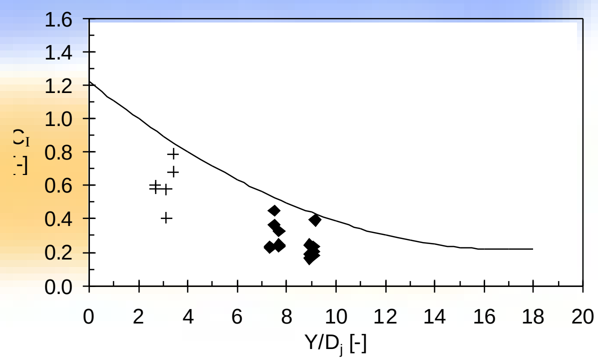
4.) Maximum dynamic impulsion C^{max}_I in an open-end joint

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

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

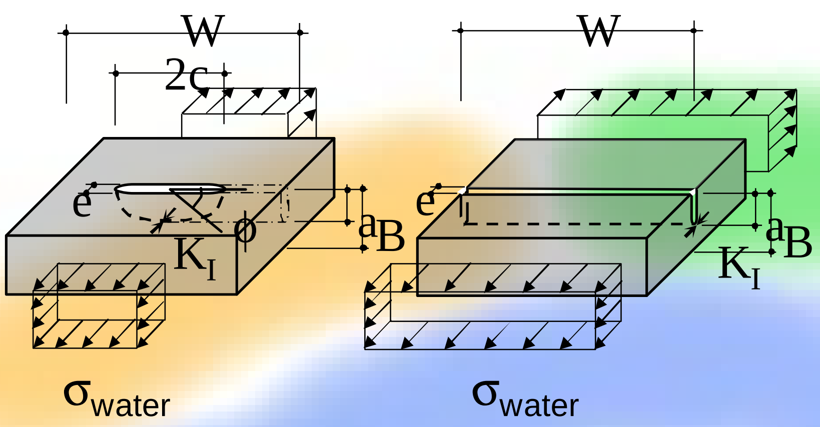
$I_{up} = p_{up} \cdot \Delta t_{up} = C_{up} \cdot T_{up} \cdot (V^2L/gc) = C_I \cdot (V^2L/gc)$ [m.s]

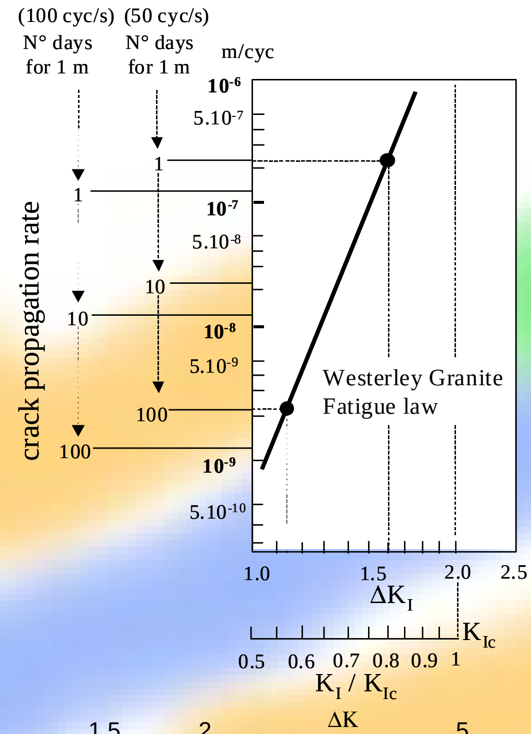
$$C_I = 0.0035 \cdot \left(\frac{Y}{D_j}\right)^2 - 0.119 \cdot \left(\frac{Y}{D_j}\right) + 1.22$$



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

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

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

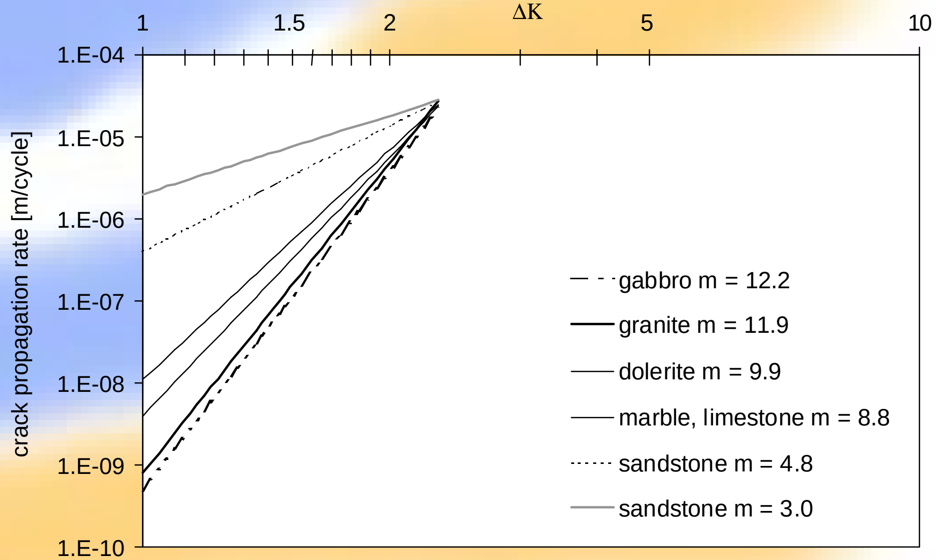
3. Instantaneous crack propagation (C^{max}_p)

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

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

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

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

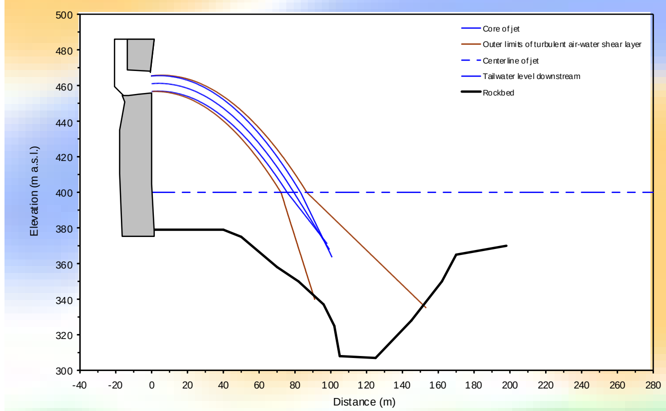


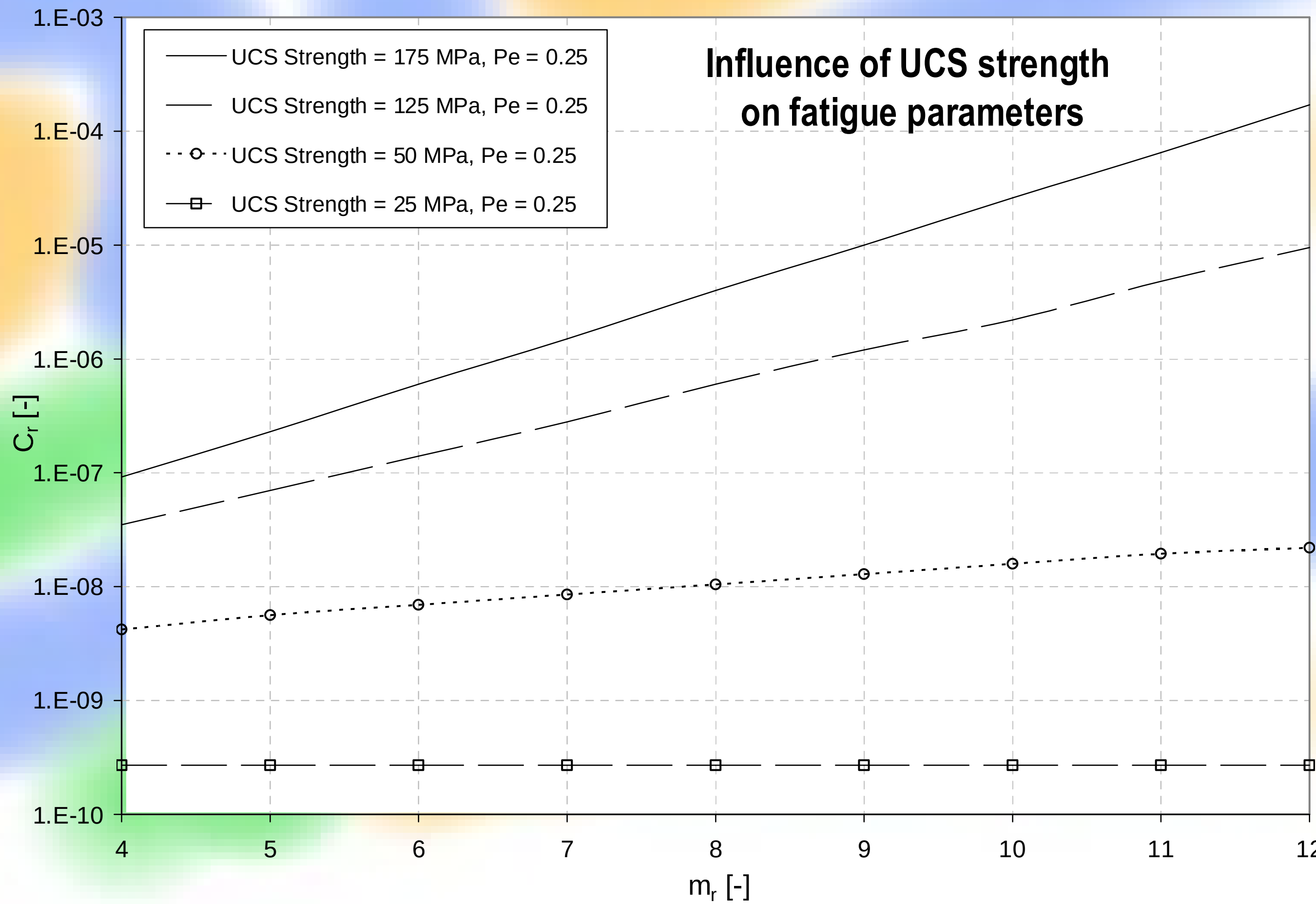
Rock mass module: Fracture Mechanics Method

Most relevant model parameters for practice:

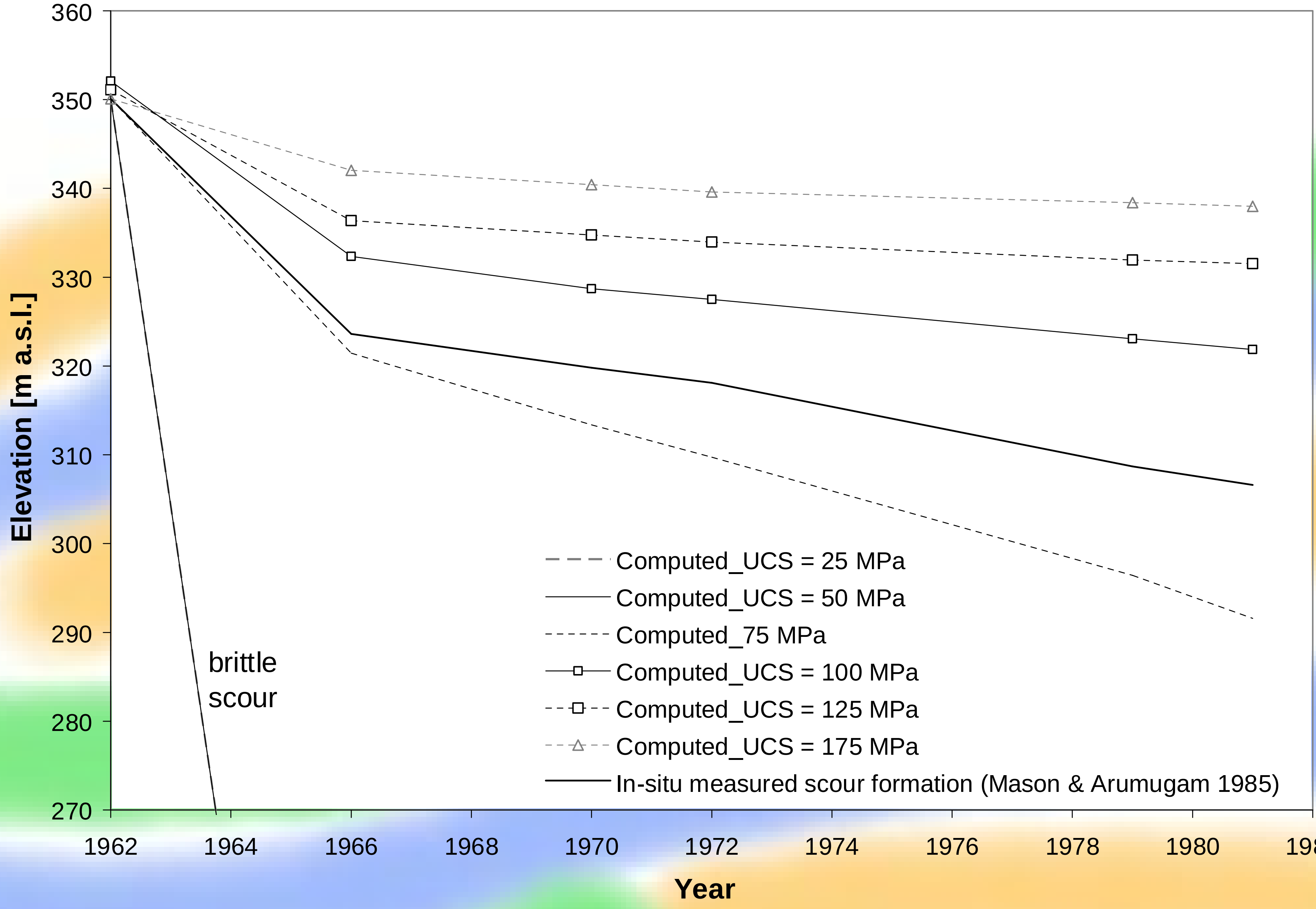
1. UCS strength of rock mass
2. Initial degree of fracturing of rock mass
3. Flood durations
4. Amplification factor Γ^+ (air/tightness)
5. Initial jet turbulence and break-up jet (RMS)

Application to **Kariba Dam** (Bollaert, 2005):





Rock mass module: Fracture Mechanics Method



Complete parametric analysis can be found in :

Bollaert (2005): « The Influence of Geomechanic and Hydrologic Uncertainties on Scour at Large Dams: Case Study of Kariba Dam », 73rd Annual Meeting of ICOLD, Teheran, Iran

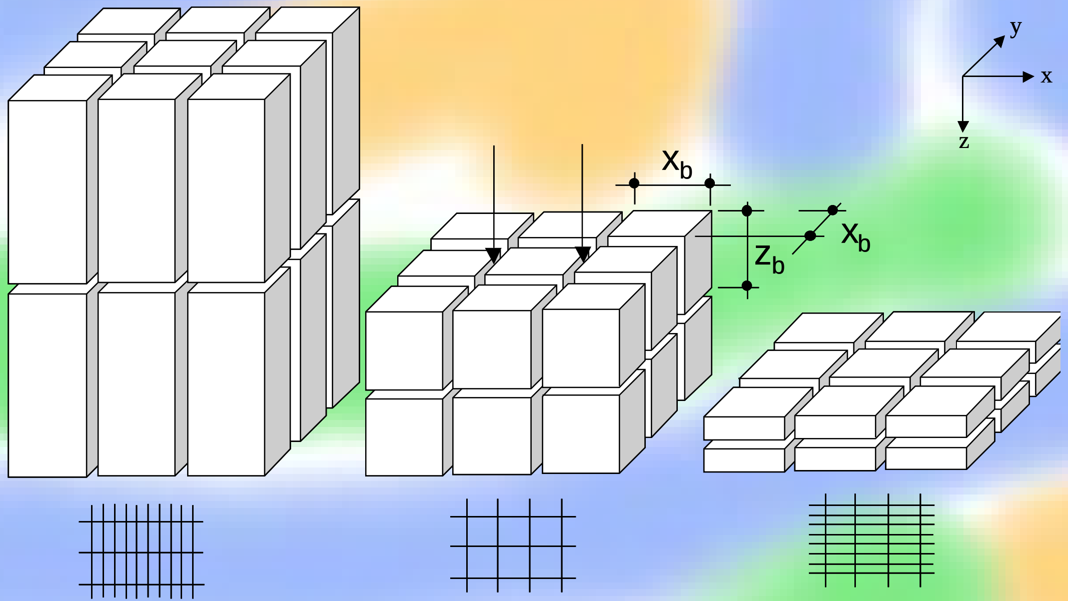
Rock mass module: Dynamic Impulsion Method

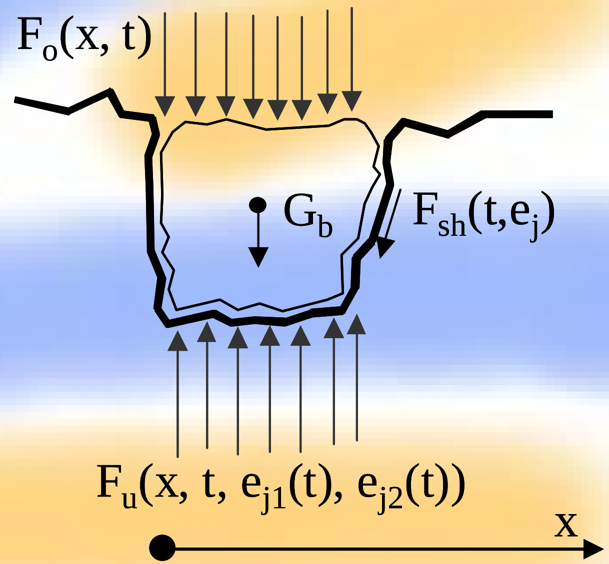
$$I_{\Delta tpulse} = \int_0^{\Delta tpulse} \left(F_u - F_o - G_b - F_{sh}\right) \cdot dt = m \cdot V_{\Delta tpulse}$$

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

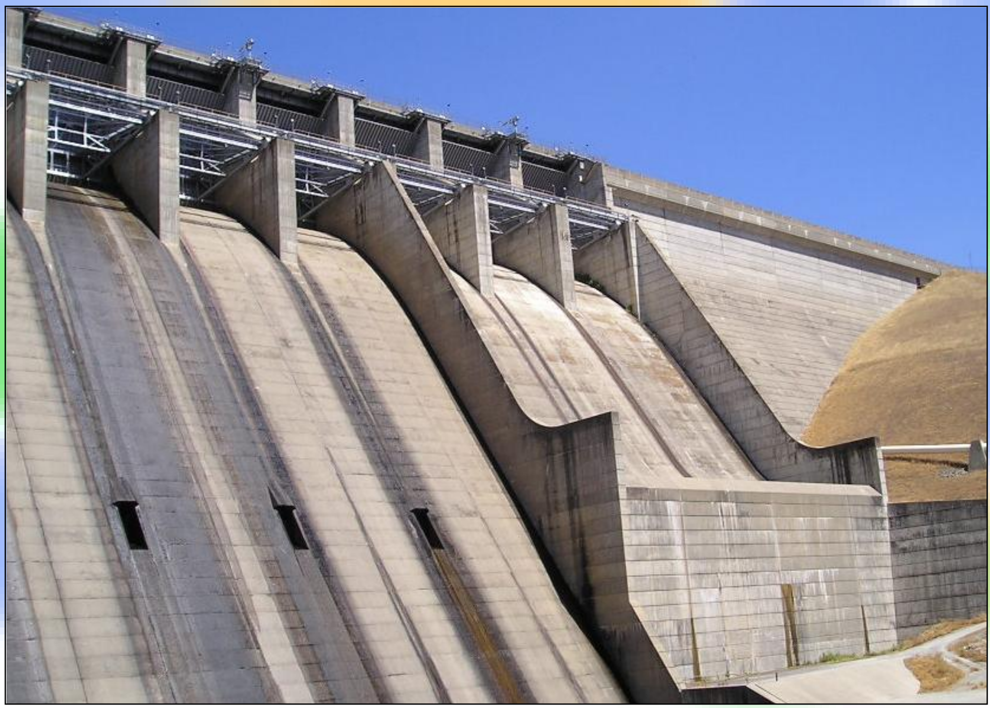
$$V_{\Delta tpulse} = \sqrt{2 \cdot g \cdot h_{up}}$$

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





Application: High-Head Concrete Dam



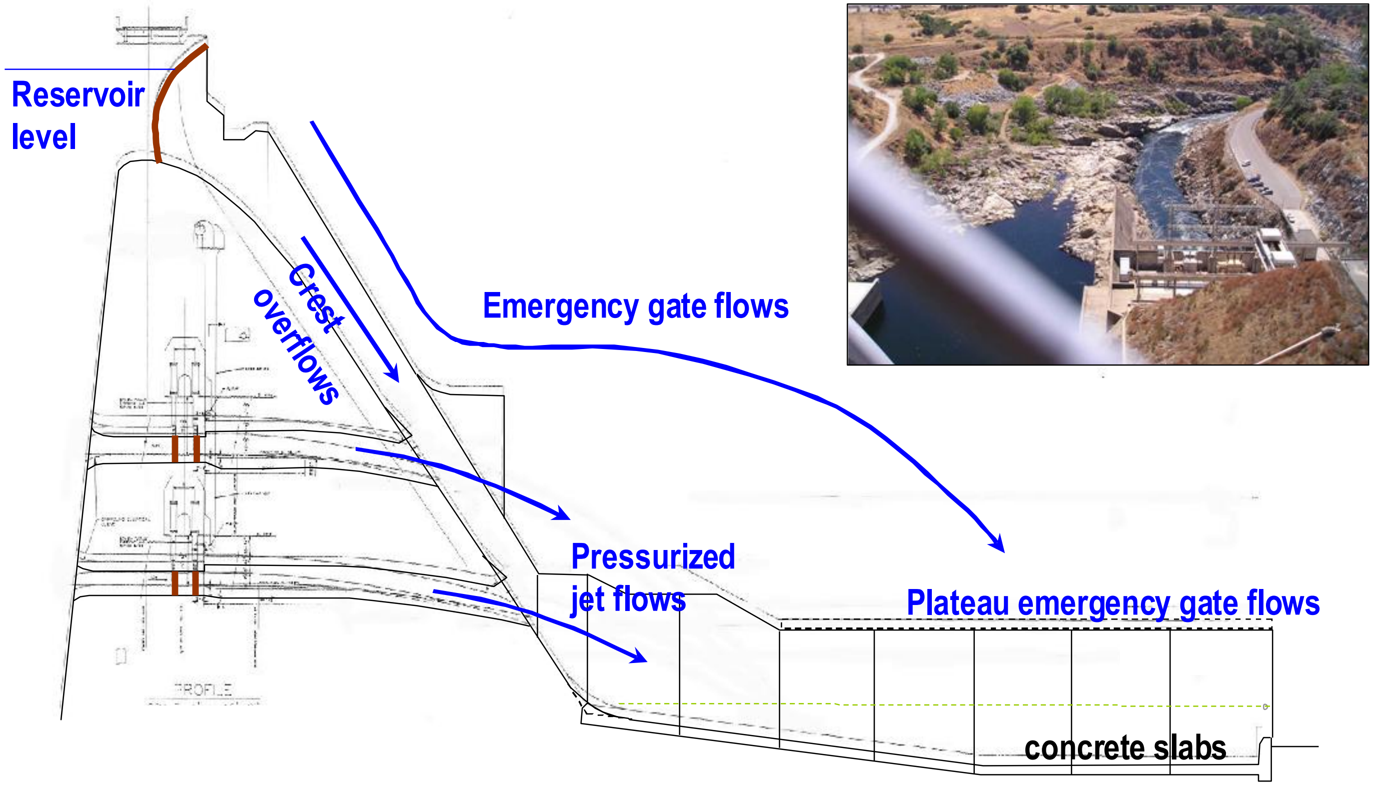
High-Head Dam

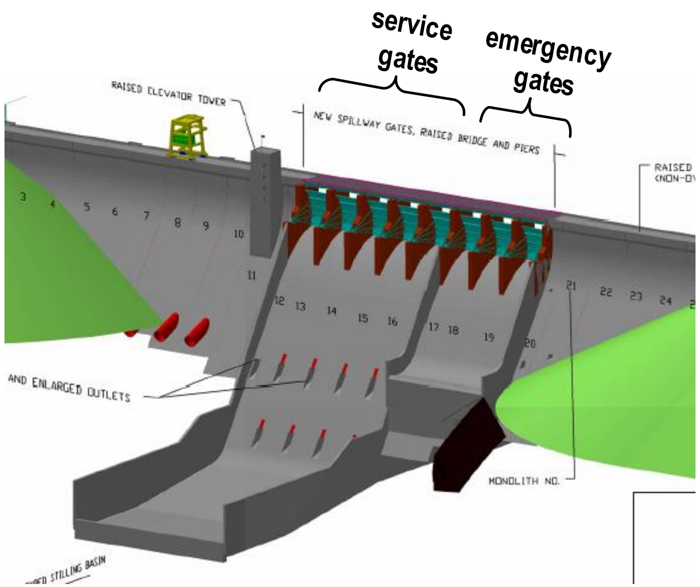
- 100 m high concrete gravity dam
- 5 service spillway gates
- 3 emergency spillway gates
- 10 intermediate outlet works (3m x 4.5m)
- combination of crest flows + jet flows
- concrete lined stilling basin floor
  110 m long by 75 m wide, with end sill

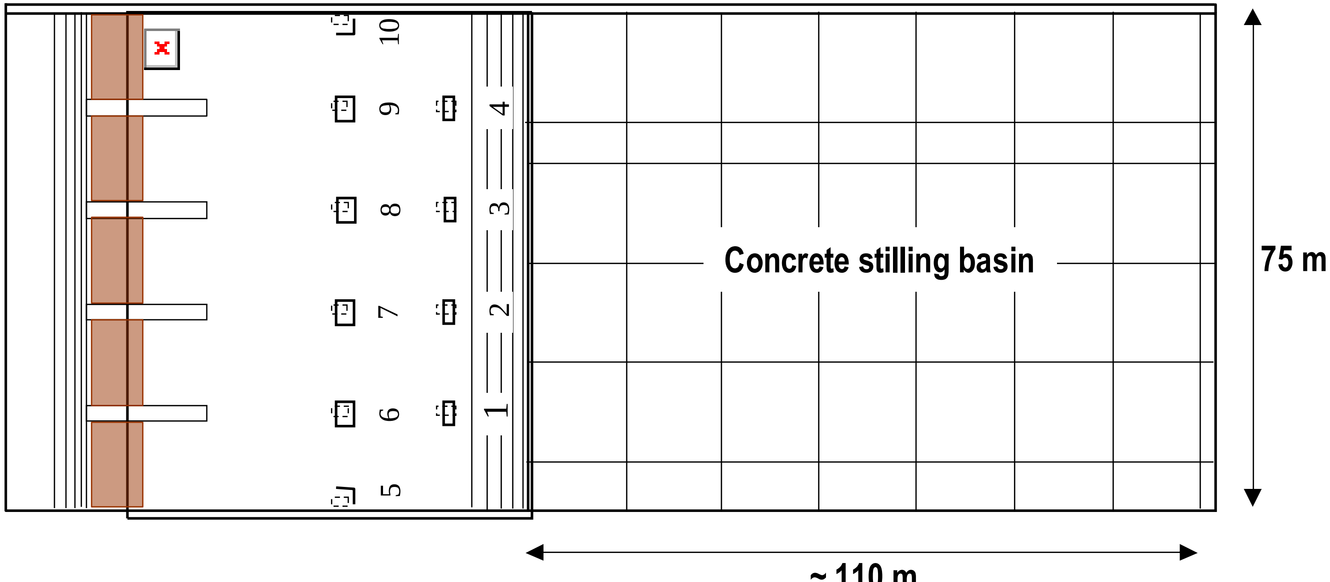
Stilling Basin

Stilling Basin

- concrete lined stilling basin floor 110 m long by 75 m wide, with end sill
- concrete slabs 15m x 15m, 1.5m thickness



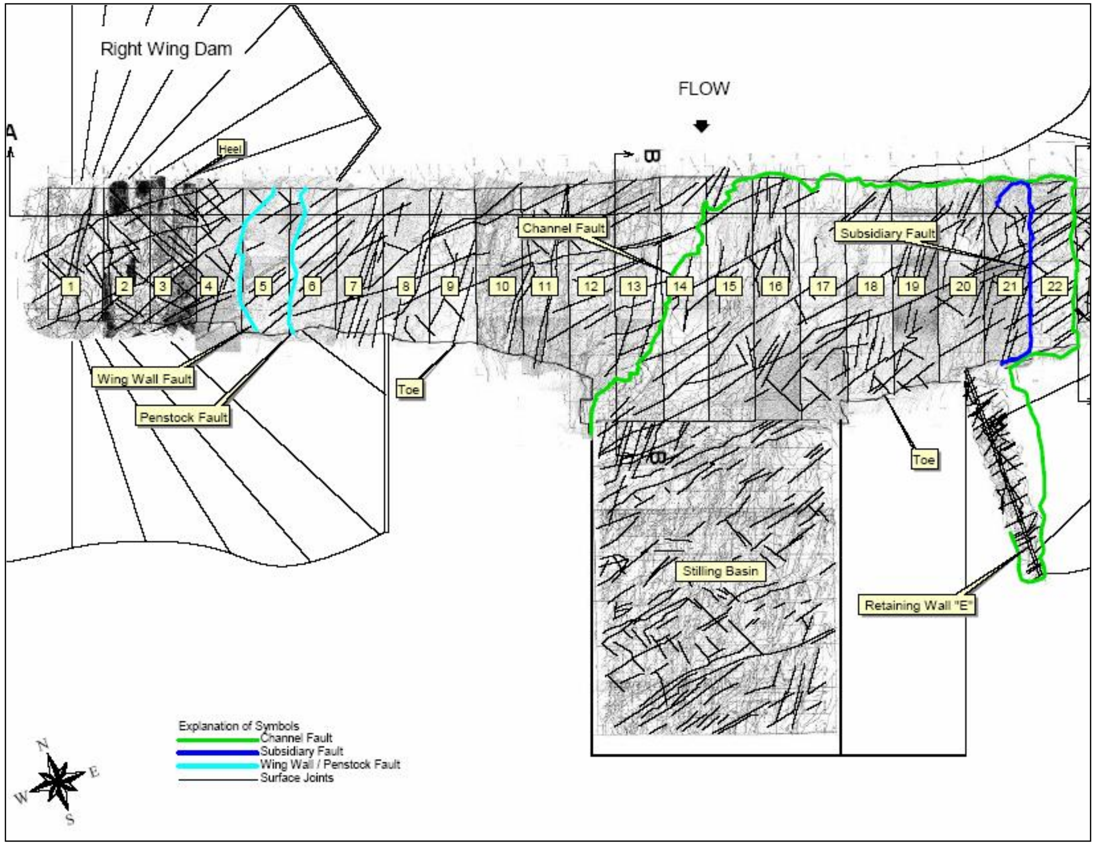


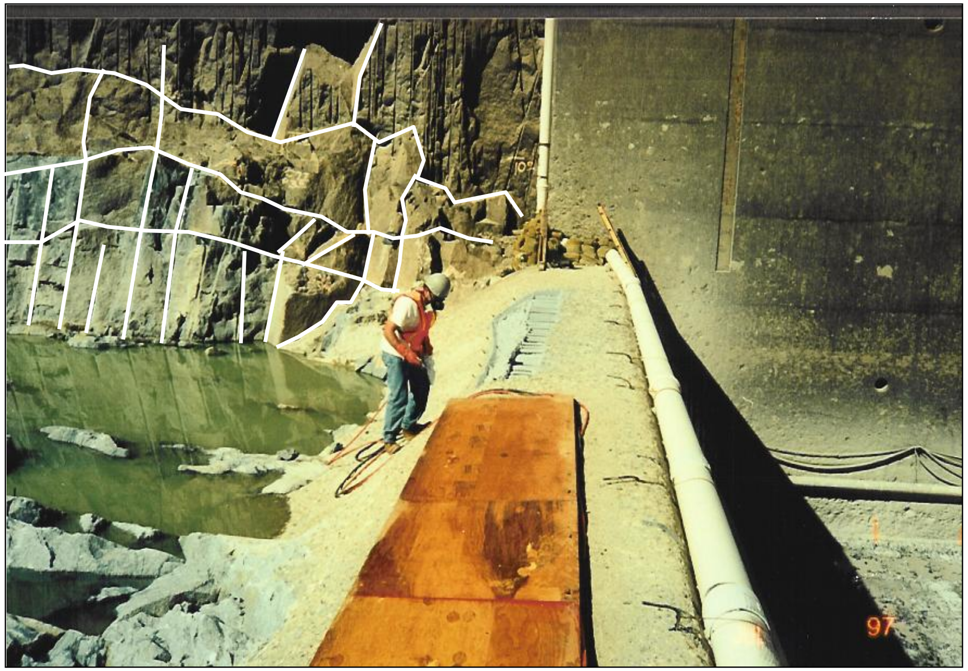


Rock mass properties (in-situ)

	Joint Set 1 (JS 1)	Joint Set 2 (JS 2)	Joint Set 3 (JS 3)
Orientation • Strike • Dip	 N38-55E 37 to 55 NW	 N71-90E 64-87 SE	 N30-80W 60-80NE
Spacing	10' to 40'	About 1'	About 1'
Persistance	100' plus	5' to 40'	3' to 30'
Termination	N/A	JS1	JS1 and JS2
Waviness	Planar to wavy	Planar to wavy	Planar to stepped
Smoothness	Smooth to slightly rough	Smooth to rough	Smooth to very rough
Aperture	Tight to very tight	Tight to very tight	Tight to very tight
Infilling	Quartz, minor iron oxide, sand, some grout	Occasional iron oxide, sand clay, some grout	Occasional iron oxide, some grout
Wall rock alteration	None	None	None

(after URS, 2001)





(Courtesy of J. Darling, USACE 1997)

Sierra granite / quartz diorite

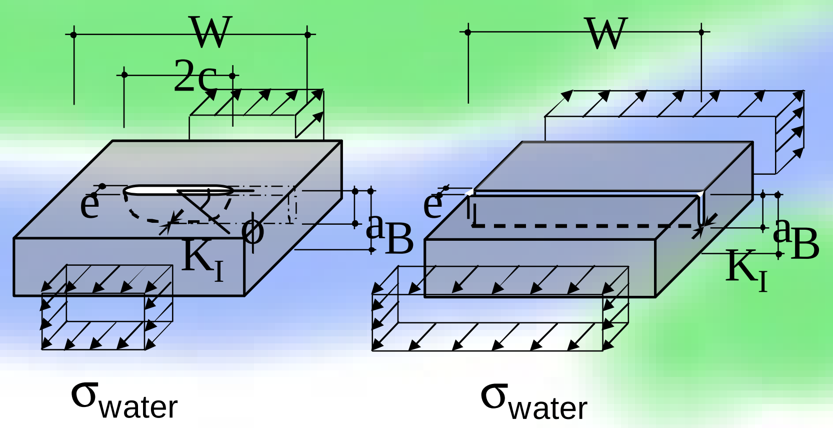
- Unconfined Compressive Strength ~ 130 MPa
- erosion resistant competent rock
- 3 main joint sets
- surface weathering of the rock
- faults and near-vertical shear zones of > 1m thickness
- blocky shape, height > side length

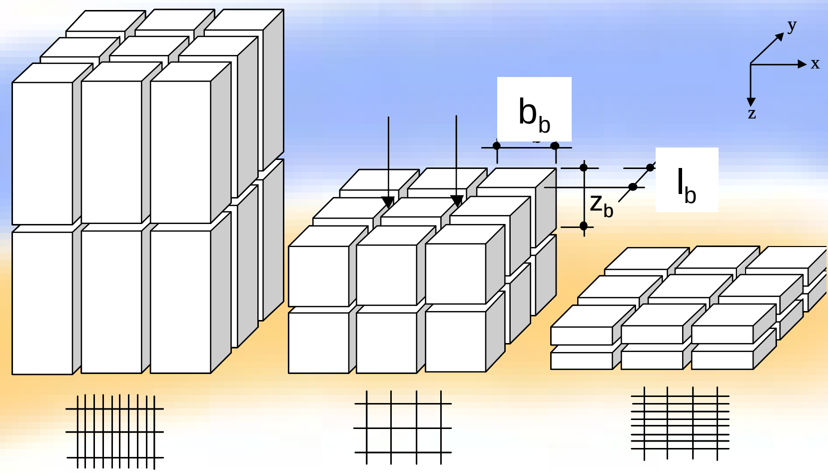
Rock mass properties (CSM model)

	Parameter	Symbol	Unit	VALUE
Fracture Mechanics	Type of rock	-	-	granite
	Unconfined Compressive Strength	UCS	MPa	131
	In-situ stress ratio	K_0	-	0
	Joint wave celerity for break-up	c	m/s	150
	Amplification factor Γ	-	-	2
	Number of joint sets	N_j	-	3
	Typical maximum joint length	L	m	1
	Initial break-up of joint	P	-	varies
	Form of joints	-	-	varies
	Fatigue sensibility	m_f	-	10
	Fatigue coefficient	C_f	-	1.00E-07
Dynamic Impulsion	Ratio height/side length of block	h_b/l_b	-	0.25
	Density rock	γ_r	kg/m^3	2650
	Joint wave celerity for uplift	c	m/s	100

Semi-elliptical (EL)
Circular (C)

Single-edge (SE)





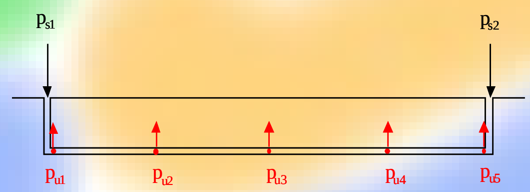
Laboratory model tests (USBR, Denver)

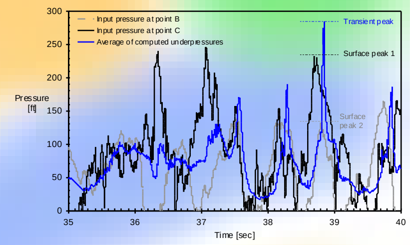
1/36 model

- main functioning of jet flows and hydraulic jump in stilling basin
- pressure fluctuations on slabs and sidewalls
- 2D hydrodynamic pressure field on a slab
- flow turbulence and erosion potential in stilling basin and in downstream rock bed channel

1/17 model

- detailed functioning of jet flows
- detailed 2D hydrodynamic pressure field on slab
- input to transient numerical modelling of concrete slab uplift and design of anchors



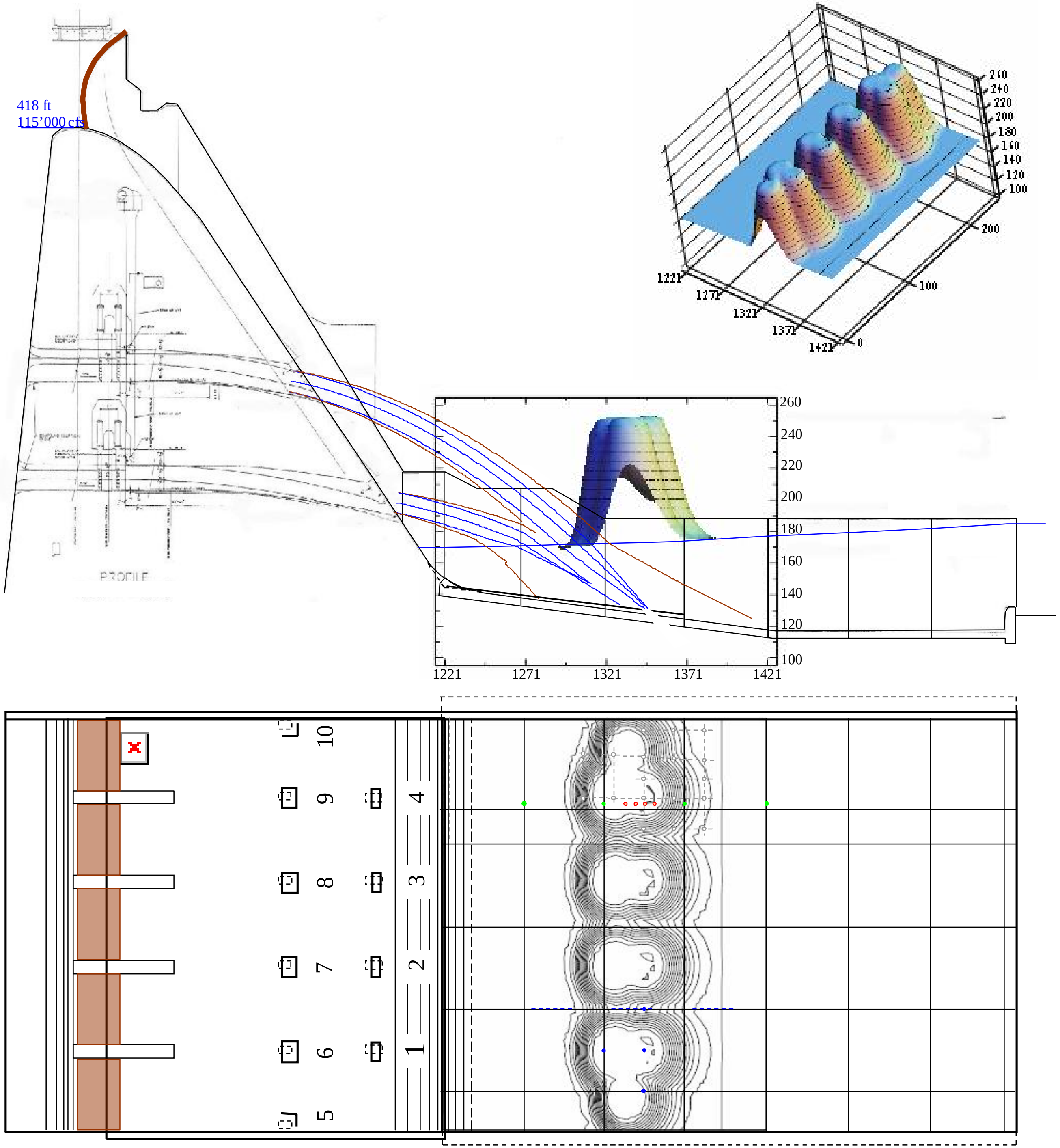


(Bollaert et al. 2007, paper submitted to the Journal of Hydraulic Engineering, ASCE)

Application of Scour Model (service gates)

Determination of 2D dynamic surface pressure field

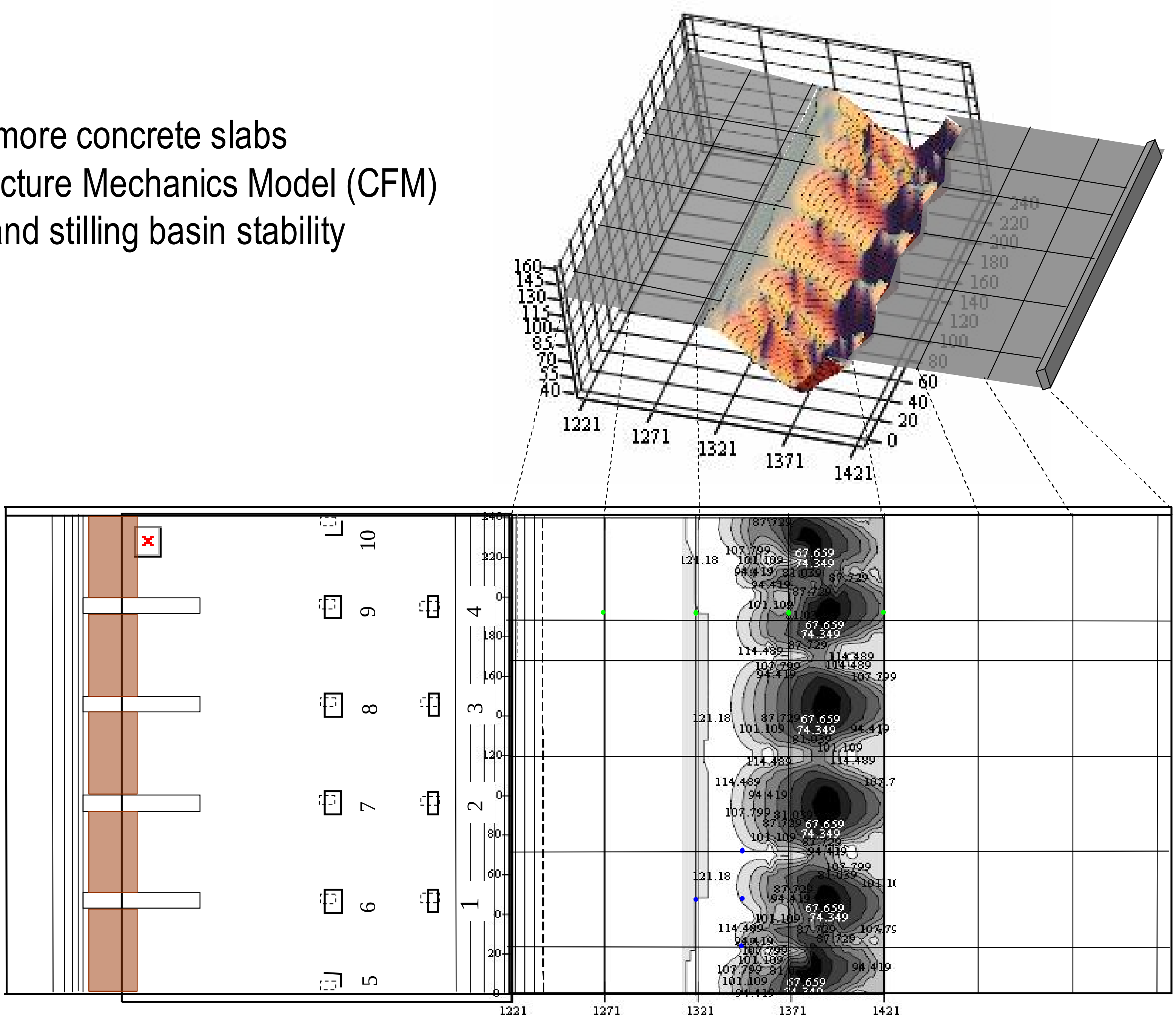
- mean values
- RMS values
- extreme values



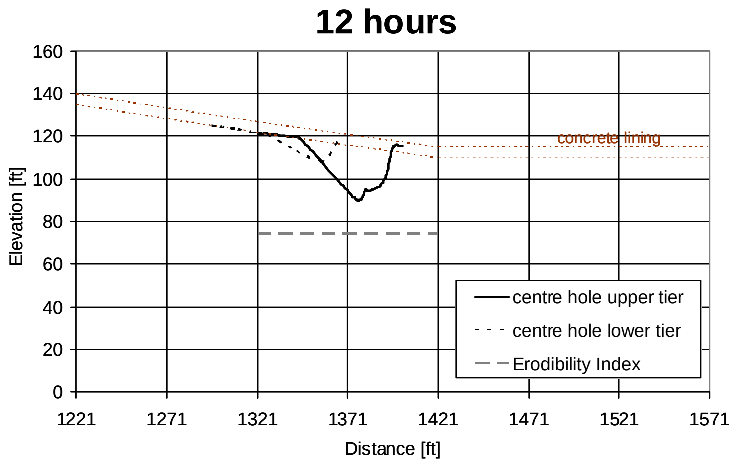
Application of Scour Model (service gates)

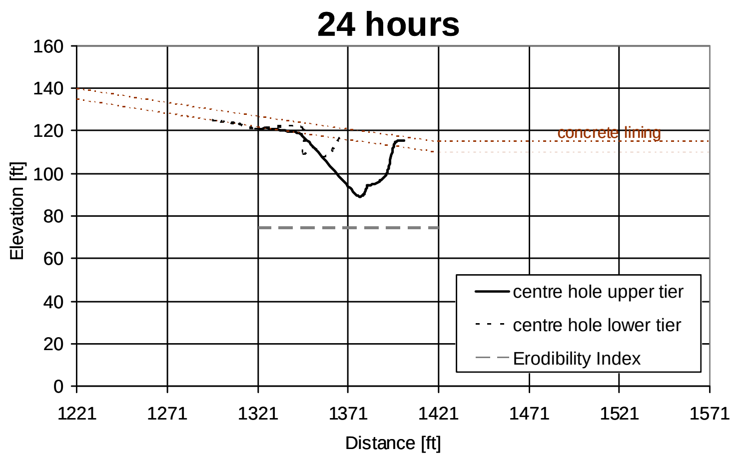
Steps:

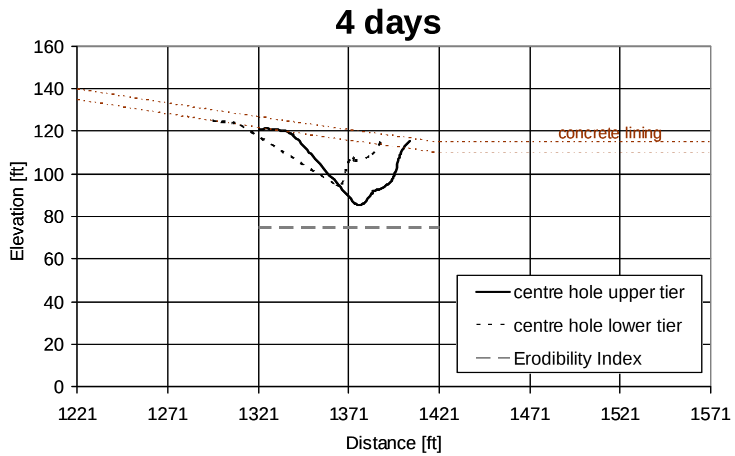
1. Failure of one or more concrete slabs
2. Application of Fracture Mechanics Model (CFM)
3. Analysis of dam and stilling basin stability

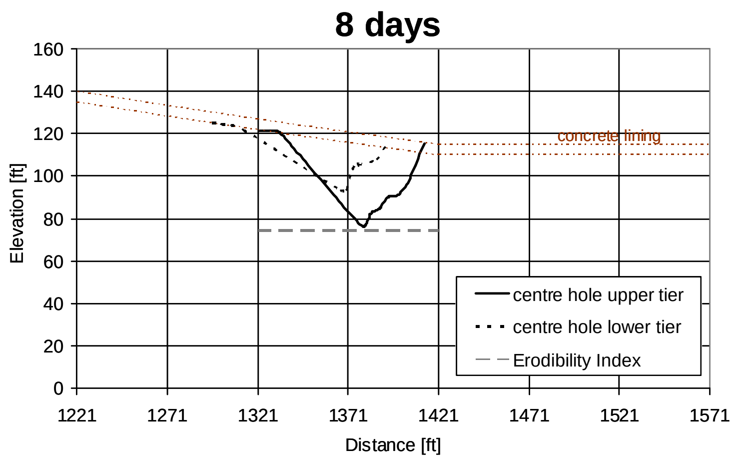


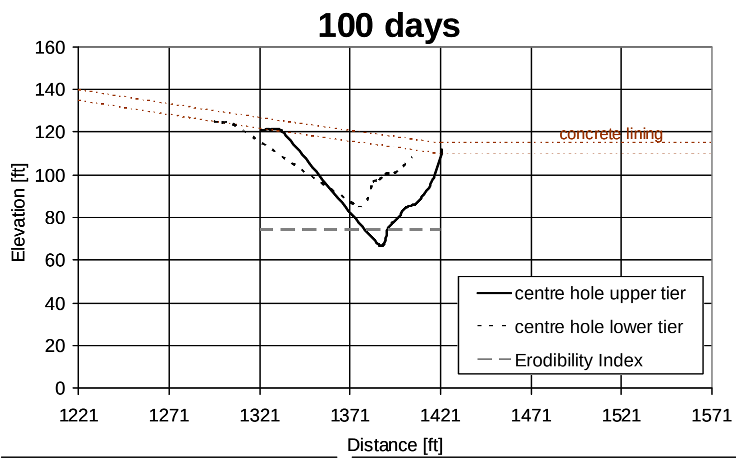
Application of Scour Model (service gates)

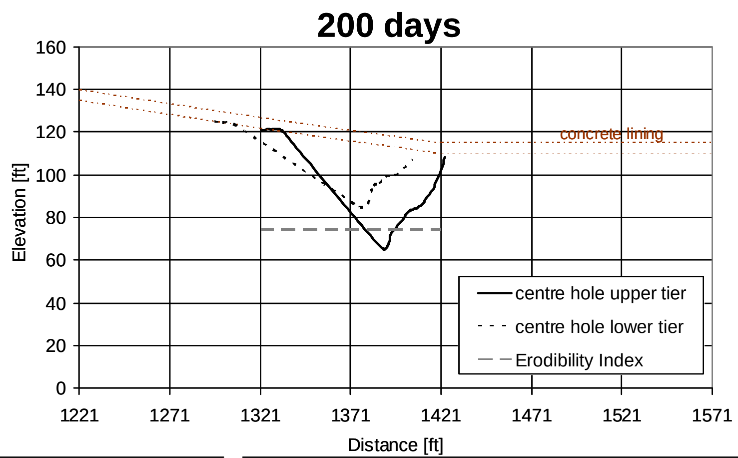












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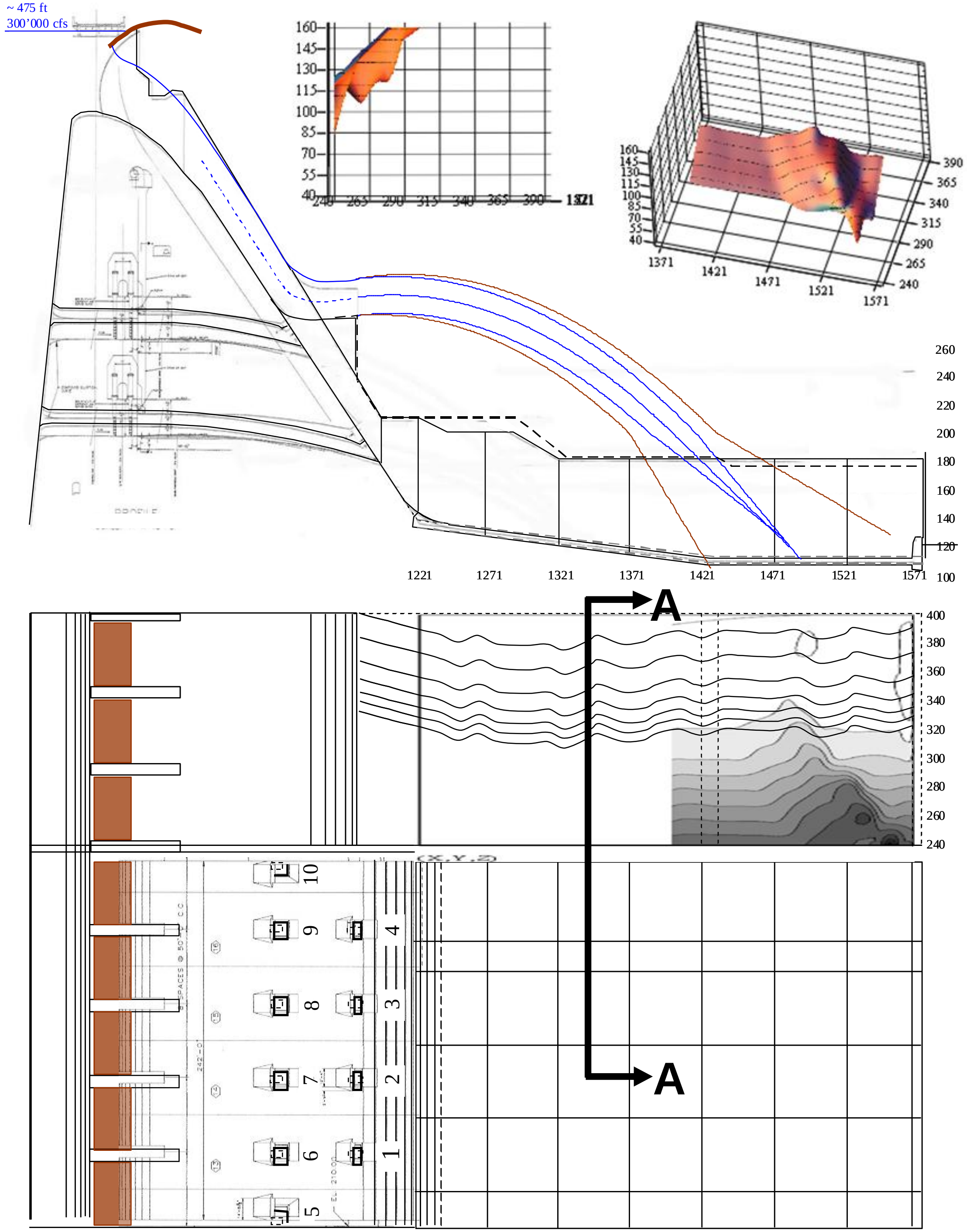
Application of Scour Model (emergency gates)

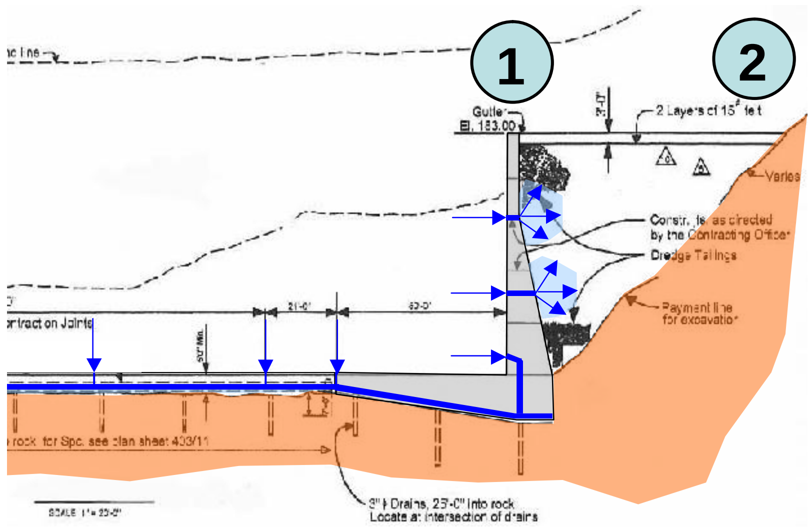


1

	Flood duration	Ultimate Scour Elevation	Depth of Scour
	h	m a.s.l.	m
Fracture Mechanics Model	24 192 4800	no scour (50-55) 46 24.5	0 4-9 26-31
Dynamic Impulsion Model	infinity	17	33-38

2

	Flood duration	Ultimate Scour Elevation	Depth of Scour
	h	m a.s.l.	m
Fracture Mechanics Model	24 192 4800	no scour (64) 64 61.5	0 0 2.5
Dynamic Impulsion Model	infinity	22.5	41.5



Section A-A

Conclusions

1. For a flood discharge of 3,300 cms, passing through the upper and lower tiers of the outlet works, *only minor scour forms* along the sloped (upstream) part of the stilling basin bottom.

2. This scour forms almost completely *within the first few days of the event*.

3. Subsequent scour formation takes much more time to happen. No danger for dam stability is apparent.

4. Scour formation following 8,500 cms through the emergency spillway gates result in scour depths of about 26-31 m after very long times of discharge (hundreds of days) (Fracture Mechanics Model). This scour only forms locally, directly next to the left sidewall of the stilling basin, but may extend deeper than the concrete slabs of the stilling basin.

5. Application of the Dynamic Impulsion Model indicates a scour hole of about 40 m deep. This model, however, assumes fully broken up rock at all depths and is far too conservative.

6. Hence, it may be stated that, for an emergency flood through the emergency spillway gates, no significant scour will form into the downstream concrete plateau during the lifetime of the dam. Nevertheless, local minor scour may form and generate damage to the plateau.

7. Design of concrete slabs of stilling basin can be found in:

Bollaert (2004). *"A new procedure to evaluate dynamic uplift of concrete linings or rock blocks in plunge pools", Symposium* Hydraulics of Dams and River Structures, Teheran, Iran, pp. 125-132.