

Surveillance and monitoring



Laurent Mouvet
Civil engineer EPFL-SIA, INSEAD-IEP

Vice-President ICOLD
Laurent.mouvet@hydropartners.ch

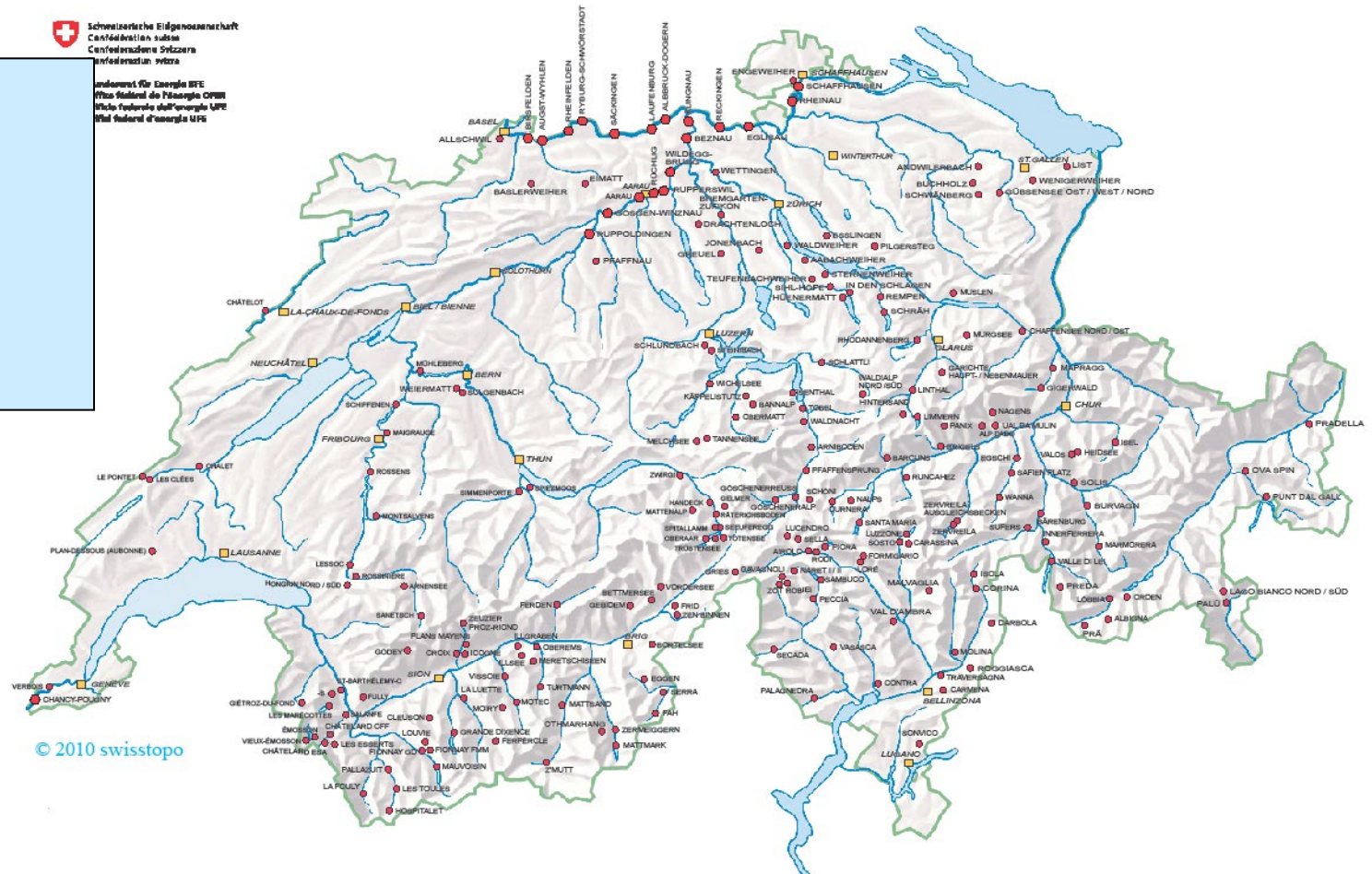
Infrastructure safety - common points



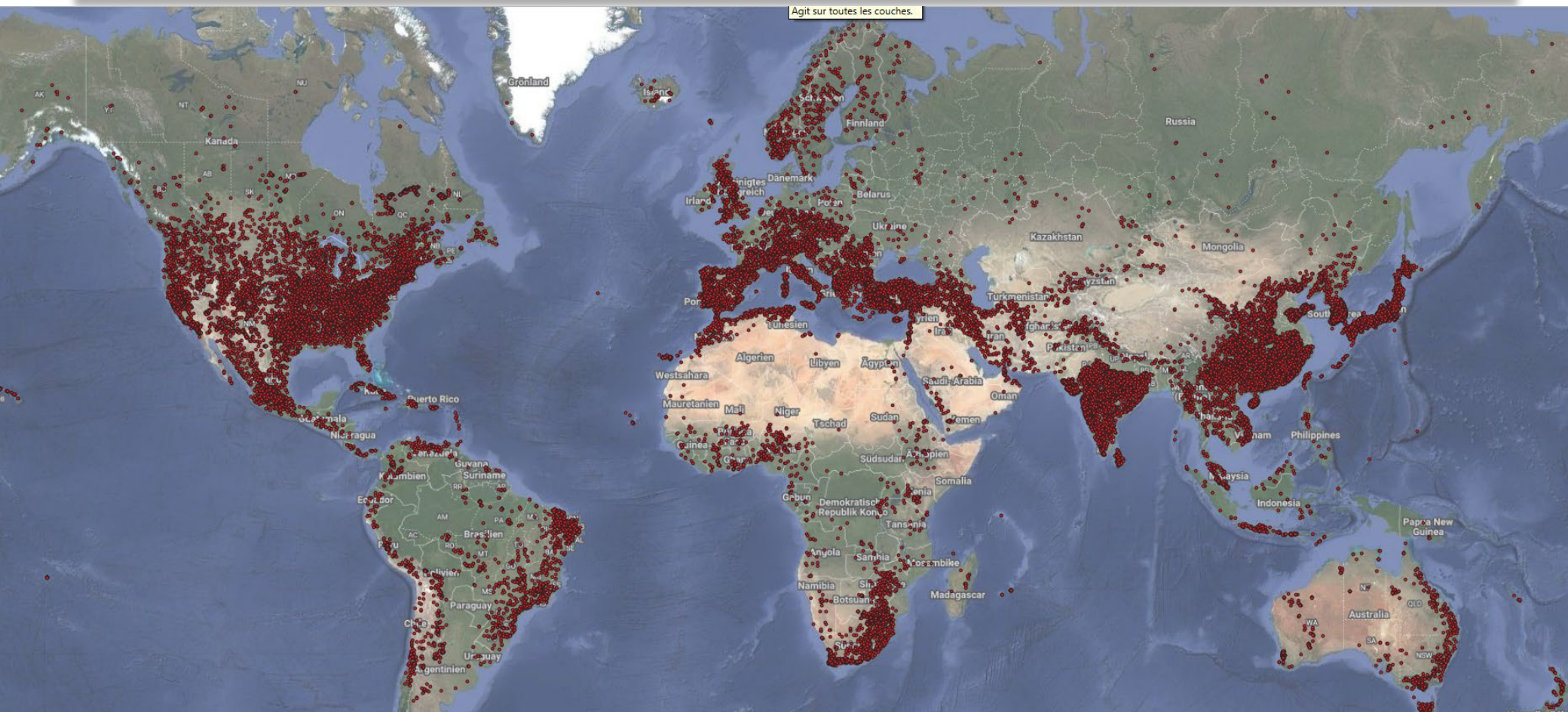
- Human design
- Stored potential energy
- Potential damage

Large dams in Switzerland

- 227 large dams
4 over 200 m,
25 over 100 m
- 20 river dams
- 955 small dams



Large dams around the world



Dam Engineering

Dam Safety and Surveillance

Grande Dixence (285 m)



Luzzone (225 m)



Mattmark (117 m)



Contra (220 m)



Mauvoisin (250 m)



We learn from accidents and incidents

Exploratory gallery
Rawyl tunnel
1978



Dam Engineering

Dam Safety and Surveillance

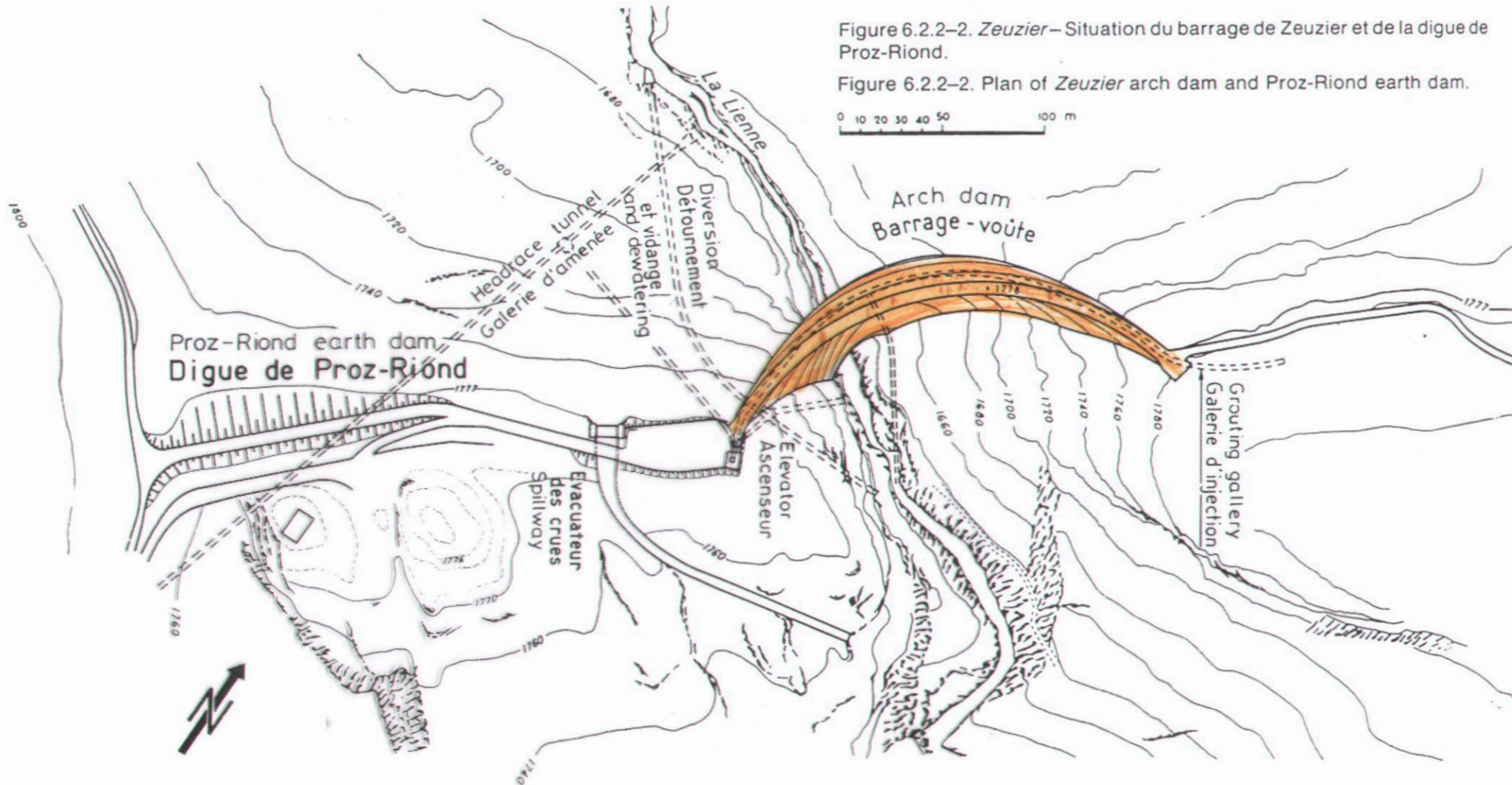
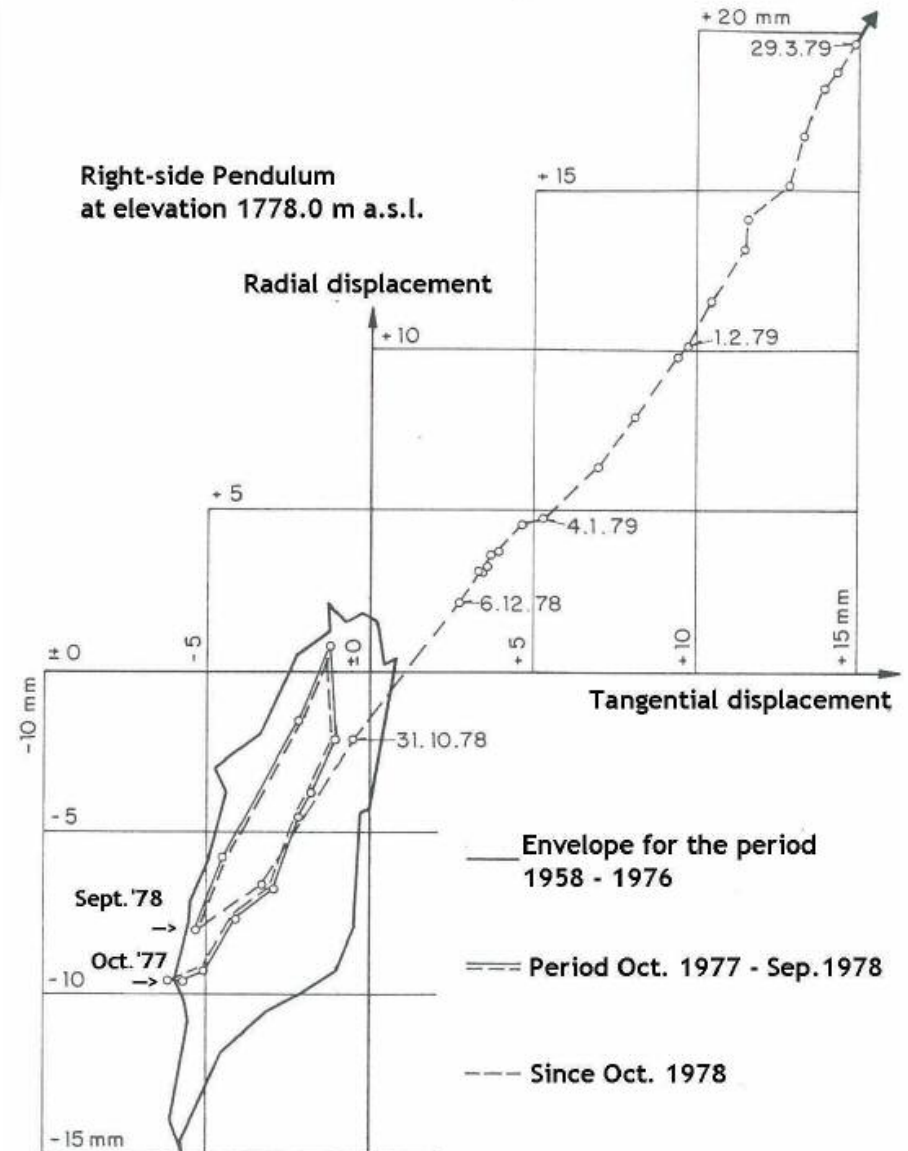
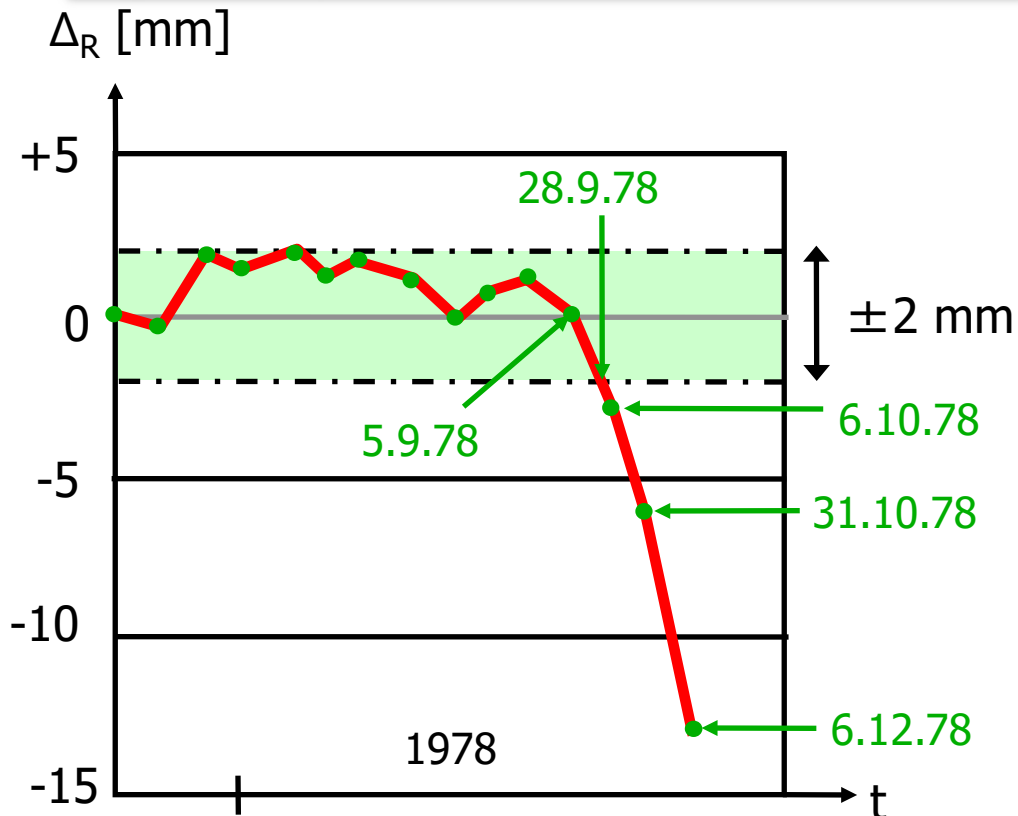


Figure 6.2.2-2. Zeuzier— Situation du barrage de Zeuzier et de la digue de Proz-Riond.

Figure 6.2.2-2. Plan of Zeuzier arch dam and Proz-Riond earth dam.

1978: movement measured by the pendulum



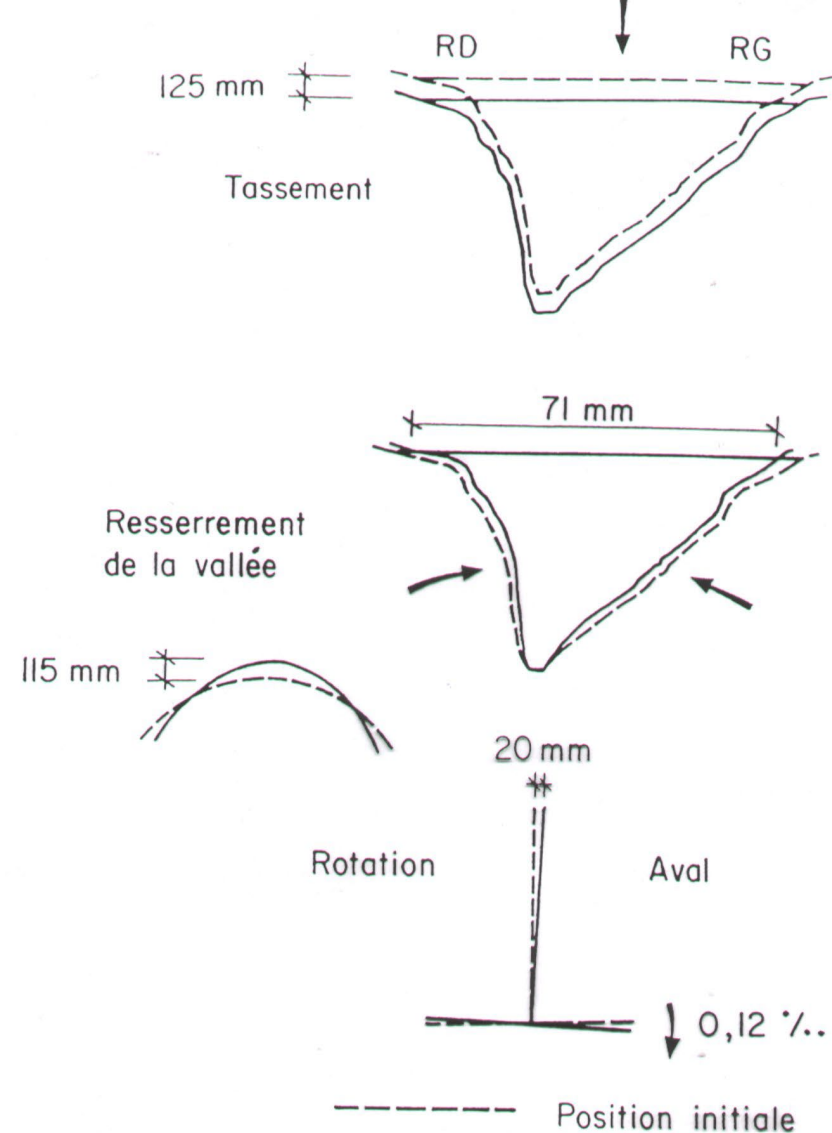
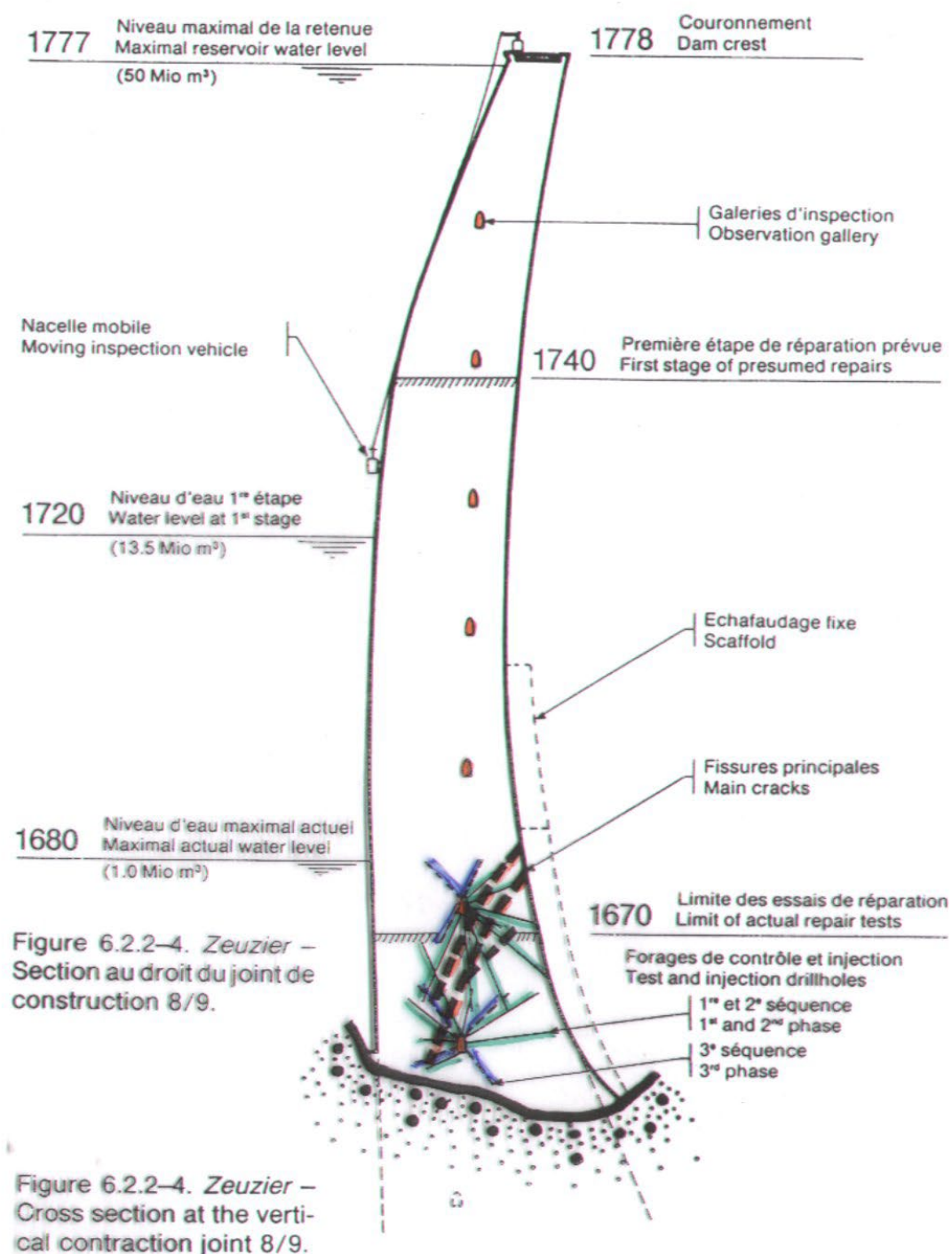


Figure 8, à gauche. Déformations totales observées sur le barrage entre 1978 et 1989.



Dam Engineering

Dam Safety and Surveillance

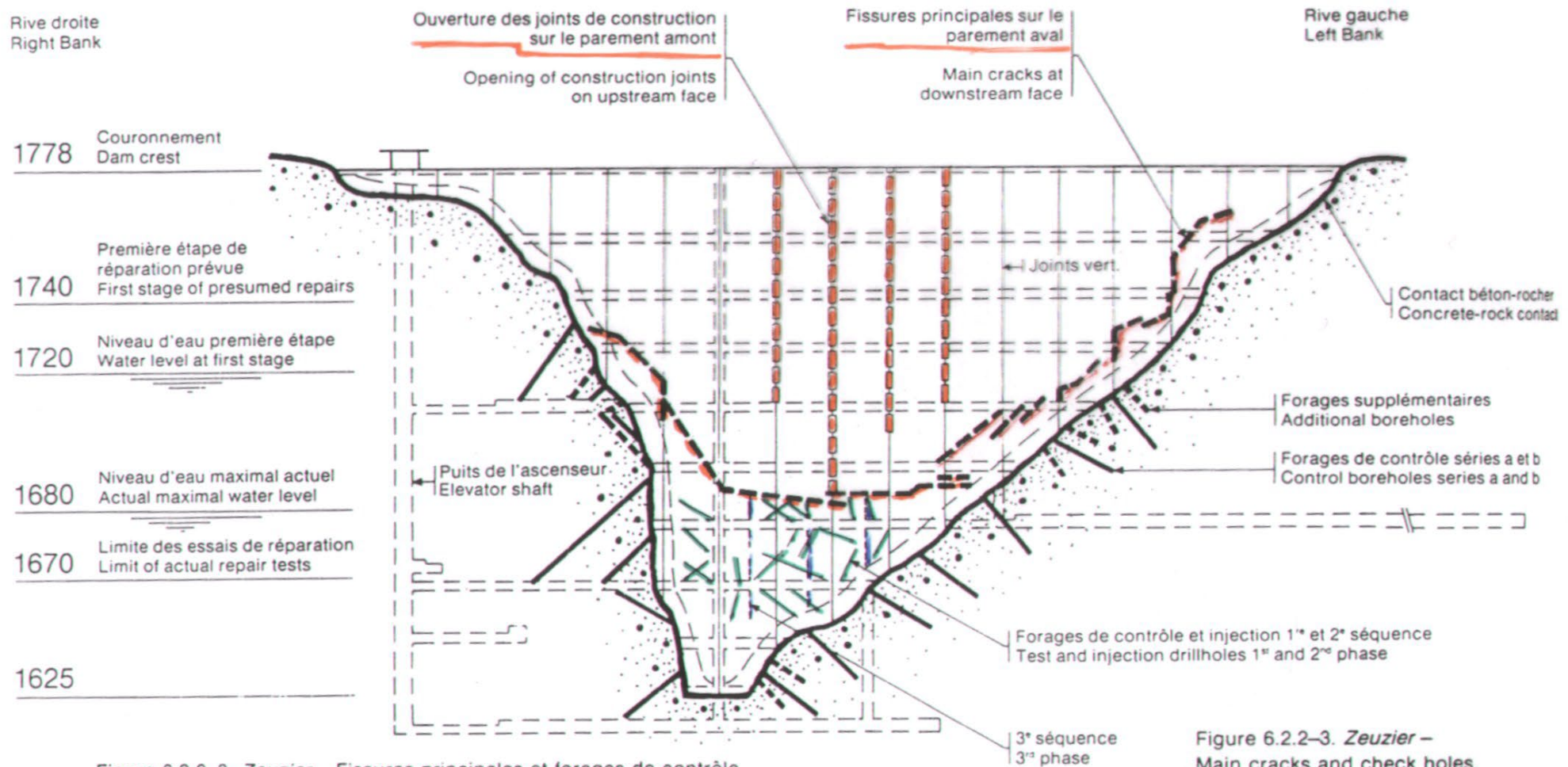


Figure 6.2.2-3. Zeuzier – Fissures principales et forages de contrôle.

Figure 6.2.2-3. Zeuzier – Main cracks and check holes.

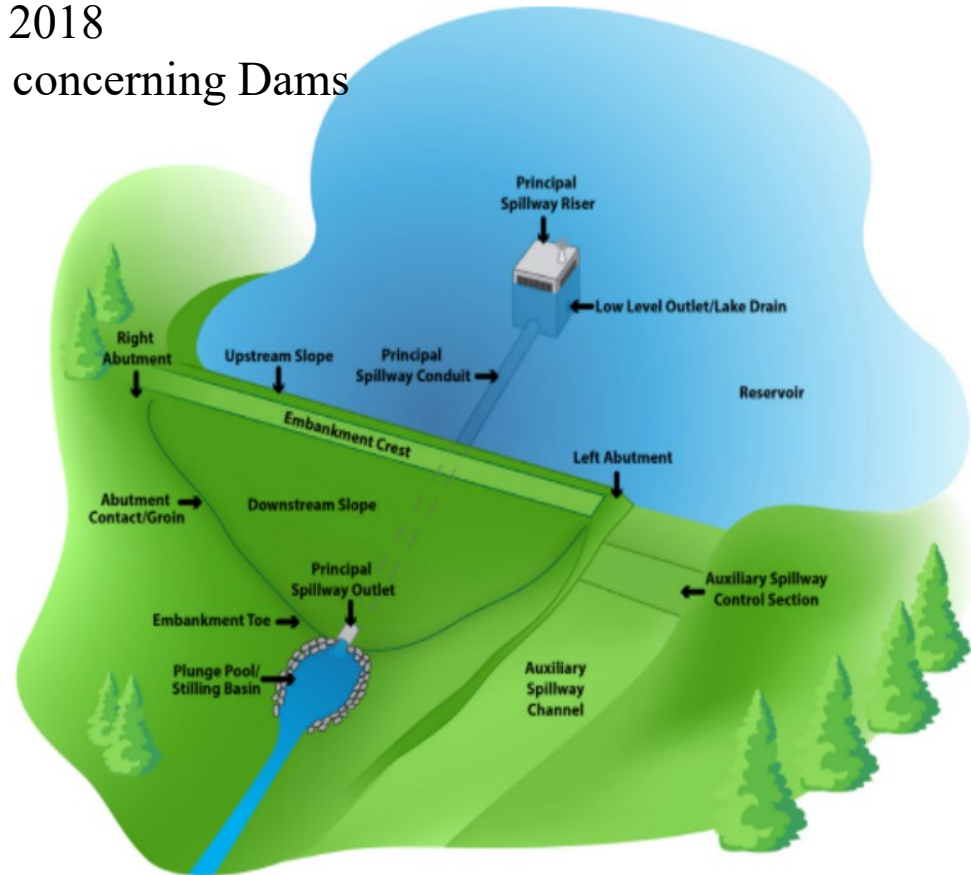
Causes of dam failures

Statistics issued from ICOLD Congress 2018
Question 105 – Incidents and Accidents concerning Dams

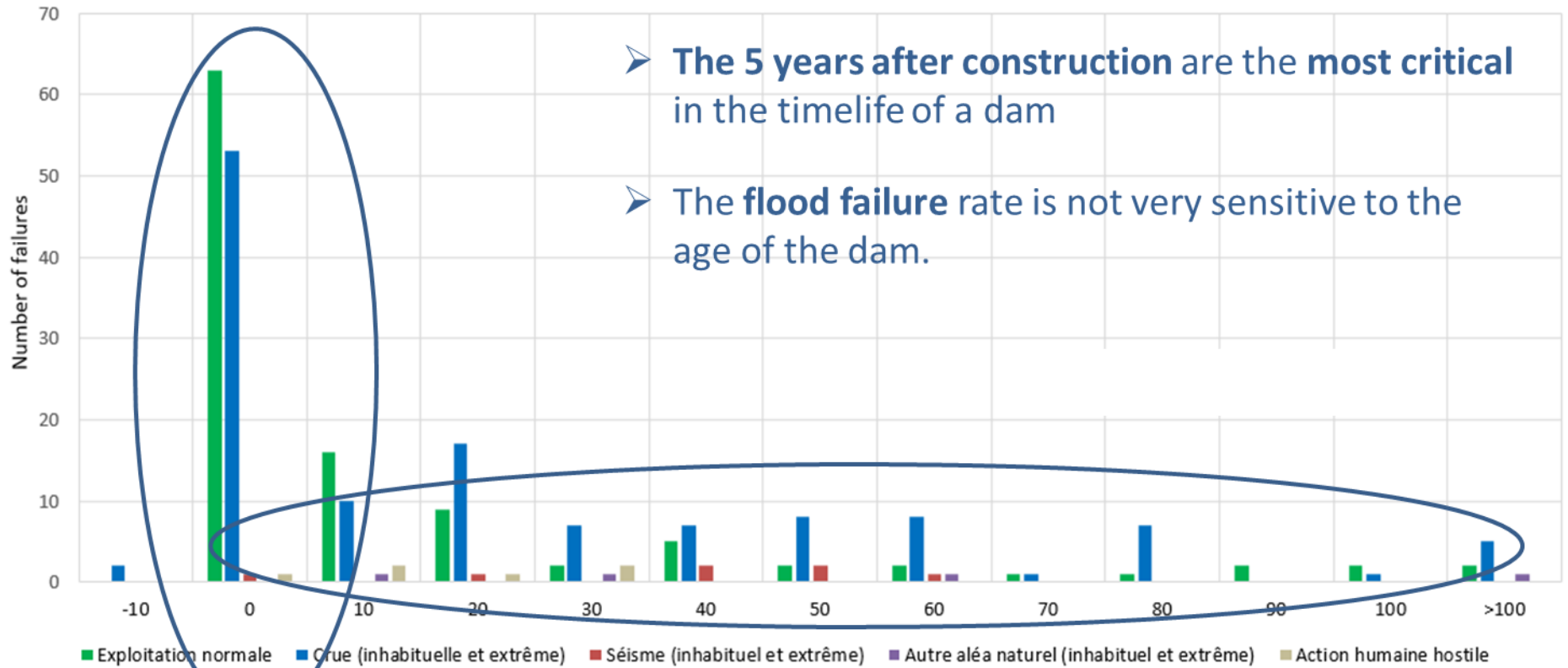
ICOLD Bulletin 99, updated 2021

Causes of dam failure:

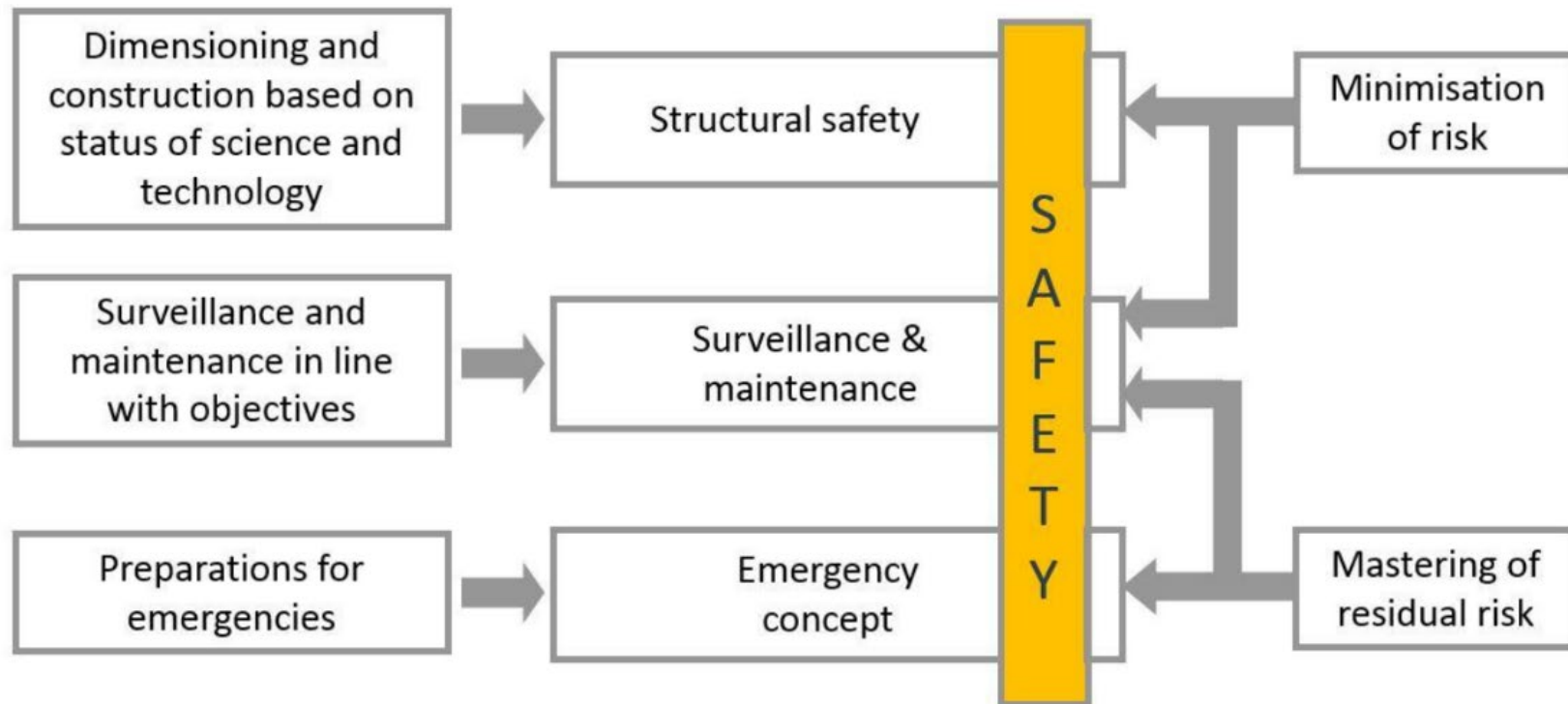
- ✓ Dam overtopping ~ 40 %
- ✓ Internal erosion ~ 40 %
- ✓ Other cause ~ 20 %
(structural, human factor, earthquake, etc)



Failure context versus age at failure

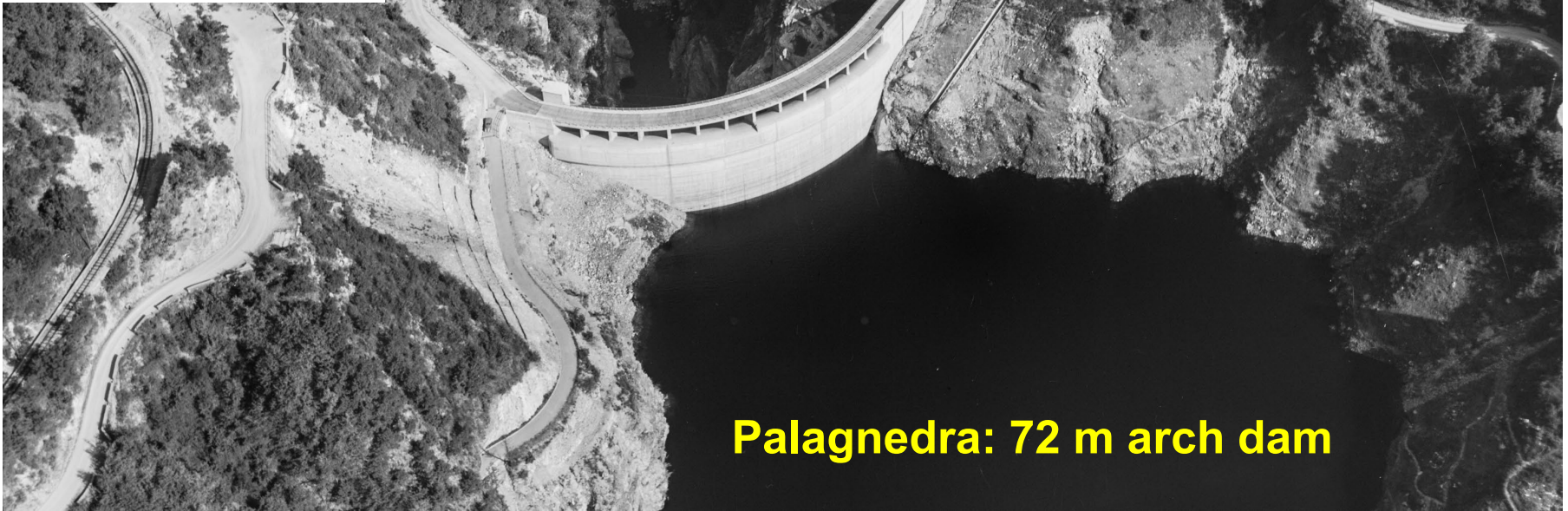


Swiss Dam Safety Concept



Dam Engineering

Dam Safety and Surveillance



Palagnedra: 72 m arch dam



Palagnedra: arch-weight dam $H=72$ m dam

7th August 1978:

- Heavy rain → flood
- 25,000 tree trunks swept away
- flood spillway blocked
- the bypass gallery remained closed
- spillage and shoreline erosion





Historical accidents



Vajont (Italy) 1963
Malpasset (France) 1959



World Declaration on Dam Safety

⇒ ICOLD Mission statement says

*“ICOLD leads the profession in setting standards and establishing guidelines to ensure that **dams are built and operated safely, efficiently, economically, and are environmentally sustainable and socially equitable.**”*

⇒ Core value of ICOLD since its foundation in 1928

⇒ ICOLD issued in 2019 a World Declaration on Dam Safety



World Declaration on Dam Safety

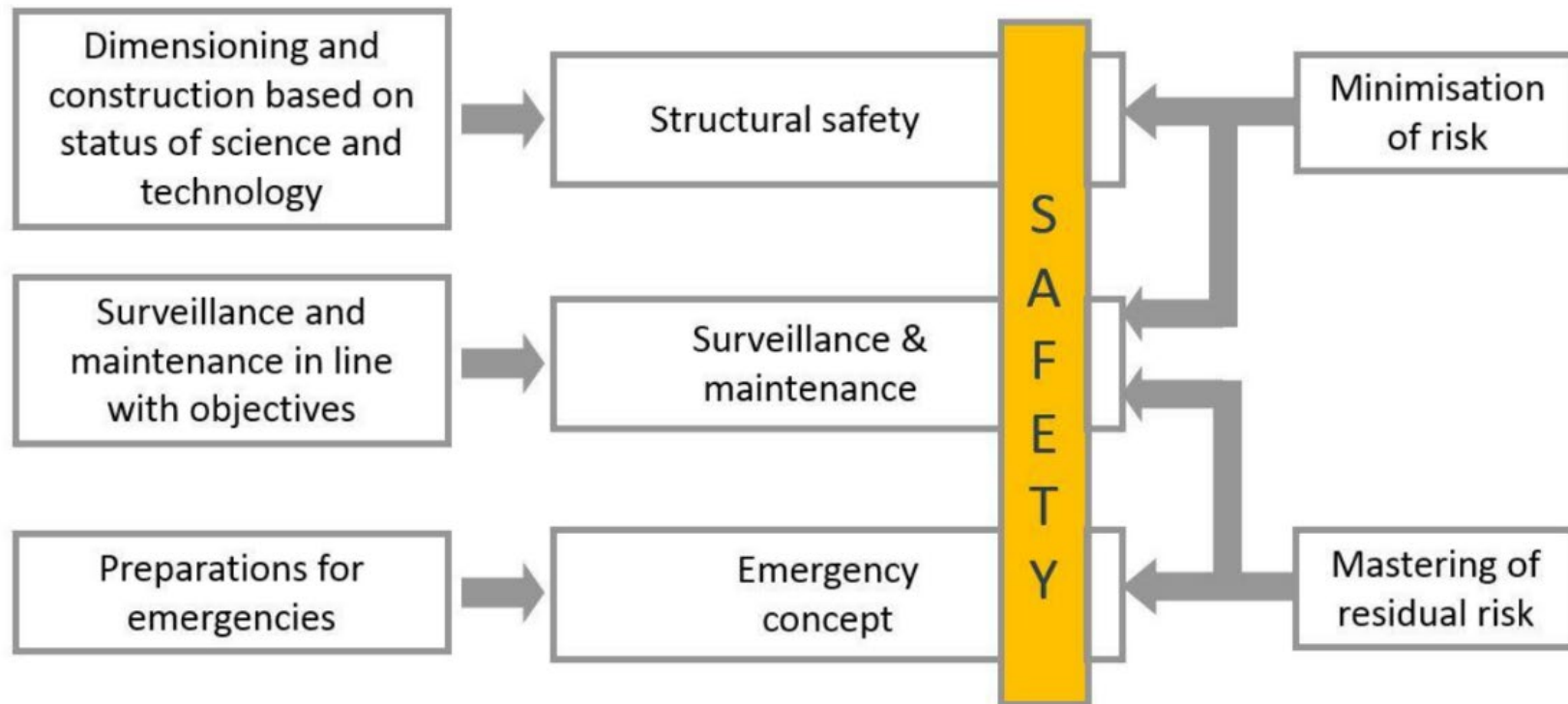
Pillars of Dam Safety

- Structural safety
 - Normal operation and extreme conditions
 - ICOLD bulletin
- Surveillance and monitoring
 - Understanding the performance of the dam
 - Check the design conditions still prevail
- Emergency planning
 - Minimize the residual risk



Nurek dam in Tadjikistan (h= 300m)

Swiss Dam Safety Concept

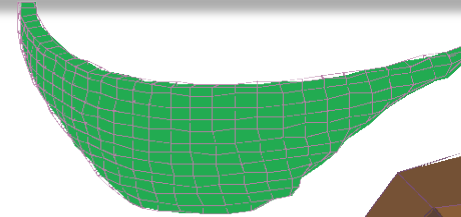
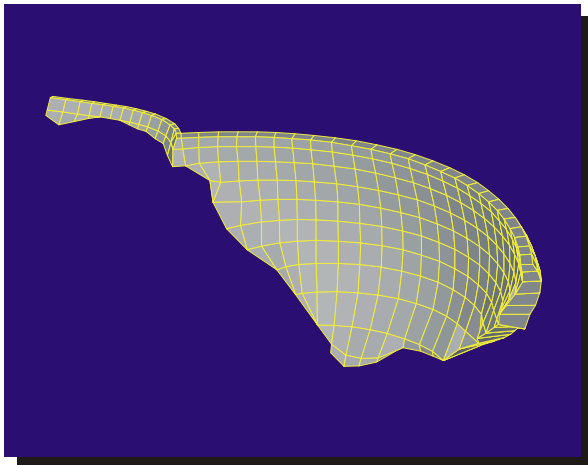


World Declaration on Dam Safety

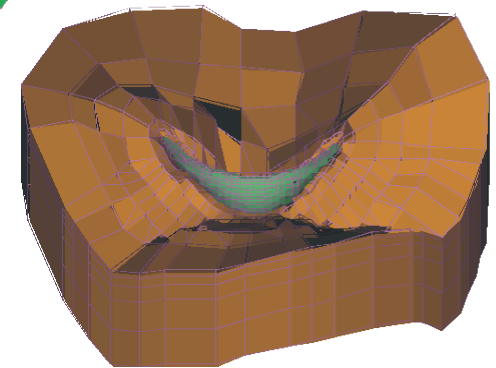
Main principles and issues

- Safety criteria of Existing Dams – Same as New Dams
- Safety of Systems – cascades, transboundary jurisdiction's, etc.
- Reservoir Sedimentation Impact
- Climate Change Impact
- Performant Operation and Maintenance

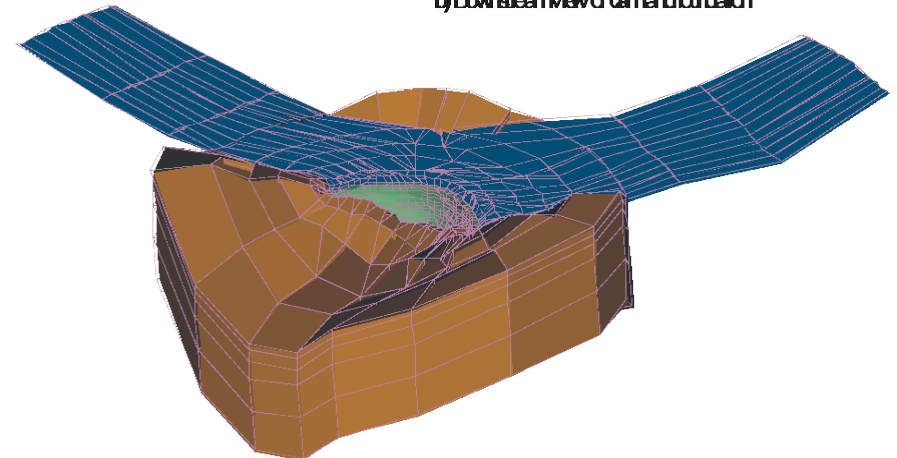
Correct design of the dam



a) Upstream view of dam



b) Downstream view of dam and foundation



c) Downstream view of dam and foundation reservoir system

Correct design of the dam

- A. At initial design
- B. Periodic verification of safety conditions

Must be considered :

- ☐ Alteration of material properties
- ☐ Alteration of foundation conditions
- ☐ Changes in design loads
- ☐ Evolution of standards and norms
- ☐ Changes in the acceptability of societal risk
- ☐ Changes in the assessment of environmental impact
- ☐ Adapting to changing business needs

Reassessment of flood conditions

Montsalvens dam
Arch dam. 52 m, 1920, raised in 1926
New spillway in 1999



Chemical alteration

AAR - Alkali-
aggregate
reaction

Lago Bianco dam

Waterproofing
measures using a
synthetic
membrane to
prevent water
penetrating the
concrete



TOKWE MUKOSI – Zimbabwe, 2014

90 m high CFRD
C = 1.75 billion m³

Reservoir filled up
without upstream
facing

Cause:
Diversion tunnel
undersized

No failure...

**Failure/incident at a
young age**



ITUANGO dam - Colombia, May 2018

Central Clay Core
Rockfill Dam
227 m high
 $C = 2,7 \text{ billions m}^3$

- The diversion tunnel was blocked by a landslide and fontis **near the end of construction.**
- Uncontrolled raising of the reservoir level.

**Discharge by the power plant cavern
 $\approx 1000 \text{ m}^3/\text{s}$ under 200 m head!!!**



**Failure/incident at a
young age**



ITUANGO dam - Colombia, May 2018

Failure/incident at a young age



Speed race
between the rise of
reservoir (100 m in
a few days) and
the rise of an
emergency
upstream
emergency
cofferdam
**Finally, the dam
was saved**

Xe Pian - Xe Namnoy – Laos, July 2018

Failure of saddle dam
of a large
hydroelectric scheme
during first filling

- Homogeneous dike - $H = 16$ m
- On 16 m deep lateritic foundation
- no foundation treatment

Failure/incident at a young age



- ✓ Abnormal settlements recorded before failure
- ✓ No overtopping
- **Cause of failure : regressive erosion in the pervious and erodible lateritic foundation**

Xe Pian - Xe Namnoy – Laos, July 2018



Failure/incident at a
young age

- ✓ Total volume of the Xe Namnoy reservoir : 1 billion m³
- ✓ Volume released : 0,5 billion m³
- ✓ 140 casualties
- ✓ More than 12 000 affected people

SARDOBA dam – Ouzbekistan, May 2020

Dam

Embankment dam

Commissioning : 2017

Height : 29 m

Volume reservoir : $\approx 922 \text{ Mm}^3$

Failure during flood

Consequences :

Transboundary issues

Few casualties

Inundation and damages

Emergency plan

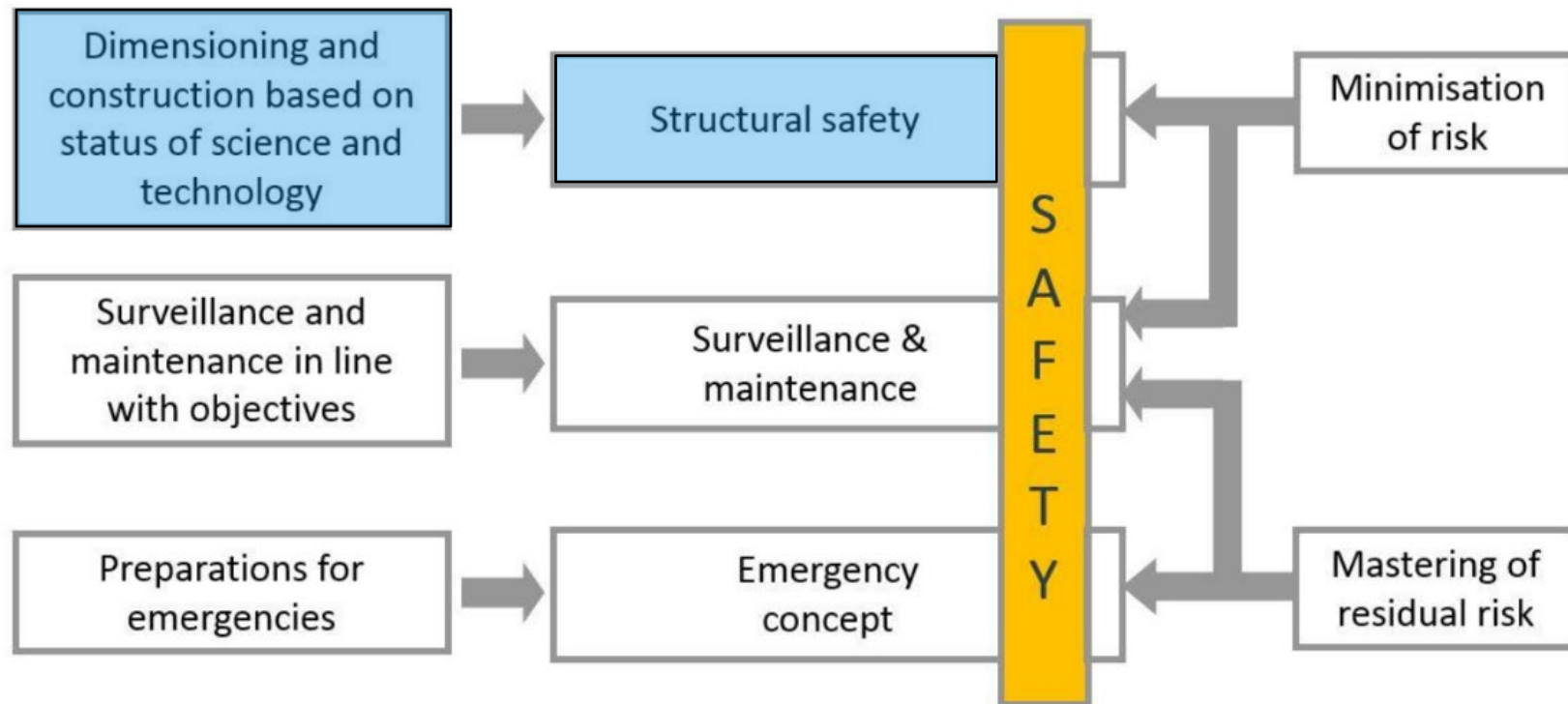
70 000 p evacuated in Ouzbekistan

20 000 p evacuated in Kazakhstan

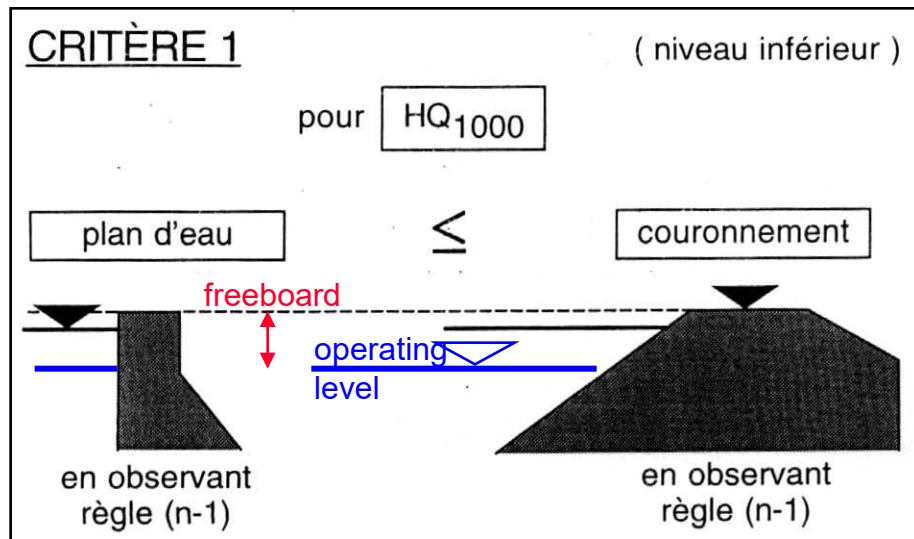
**Failure/incident at a
young age**



Swiss Dam Safety Concept



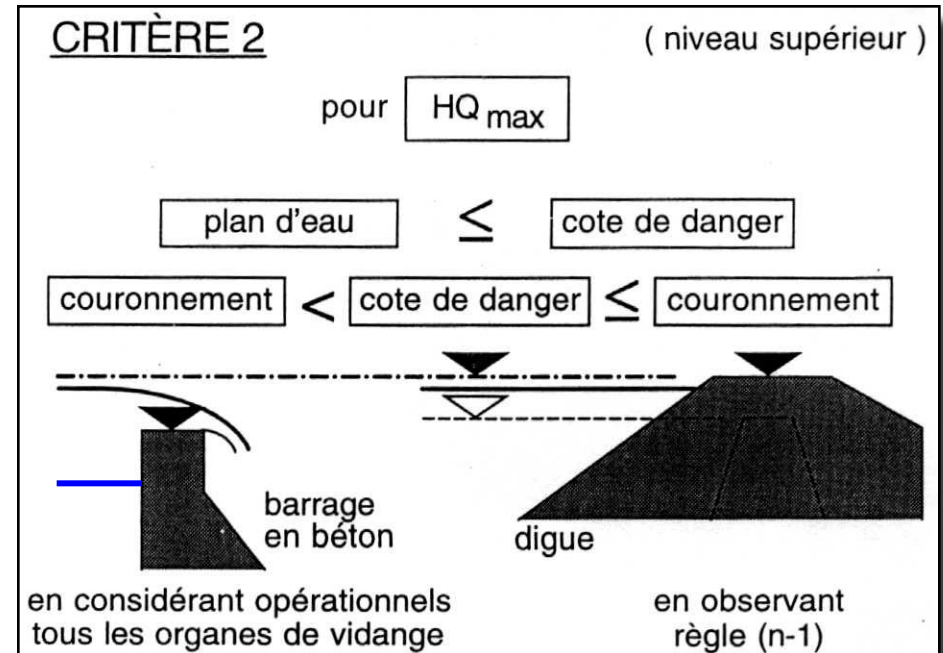
Design criteria for the "flood" case



Minimum Freeboard

Concrete dams: 1 to 2 m

Embankment dams: 2 to 4 m



Design criteria for the "flood" case

→ Avoid uncontrolled water release and overtopping	Concrete dams		Embankment Dams	
	Design flood Q_{1000}	Safety flood	Design flood Q_{1000}	Safety flood PMF
Gates / Valves	1 blocked	all operational	1 blocked	1 blocked
Turbine flow	none	(yes)	none	none



Derna & Mansur dams – Libya, September 2023

Mansur Dam

Embankment dam with clay core

Commissioning : 1977

Height : 75 m

Volume reservoir : $\approx 25 \text{ Mm}^3$

Failure during flood

Consequences :

Failure of Derna dam downstream

4,500 casualties

8,500 missing

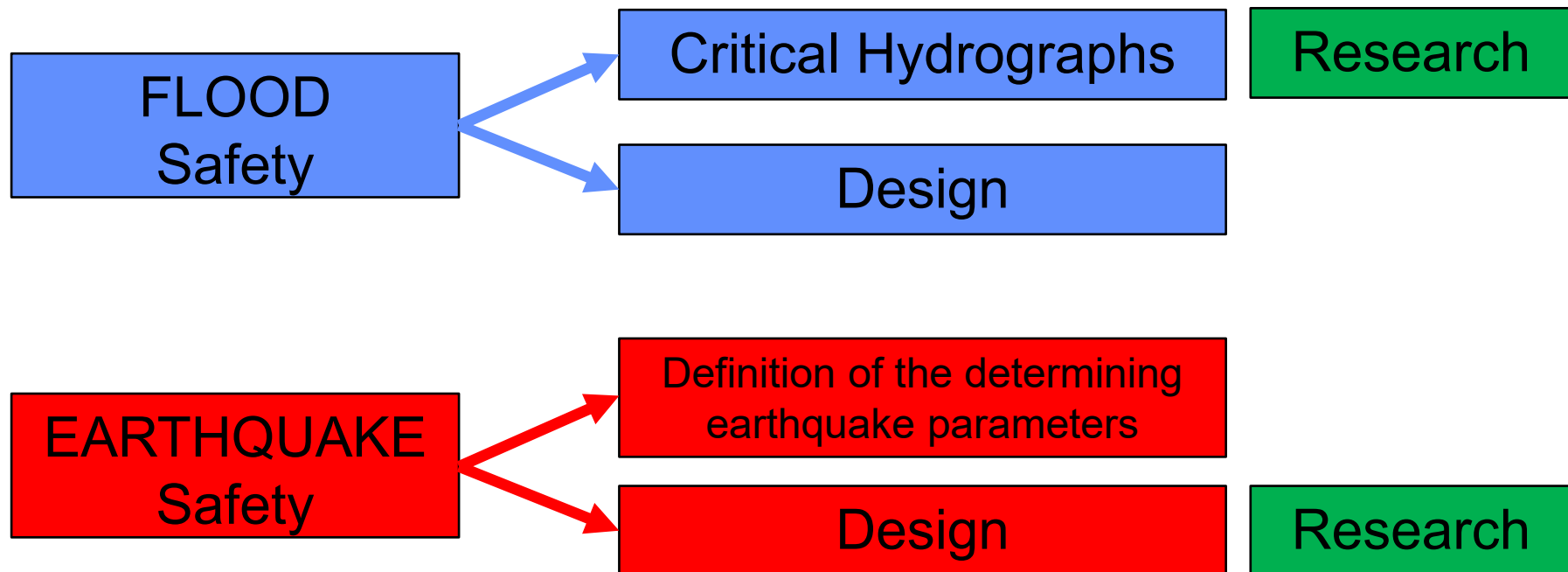
Emergency plan

42'000 p evacuated





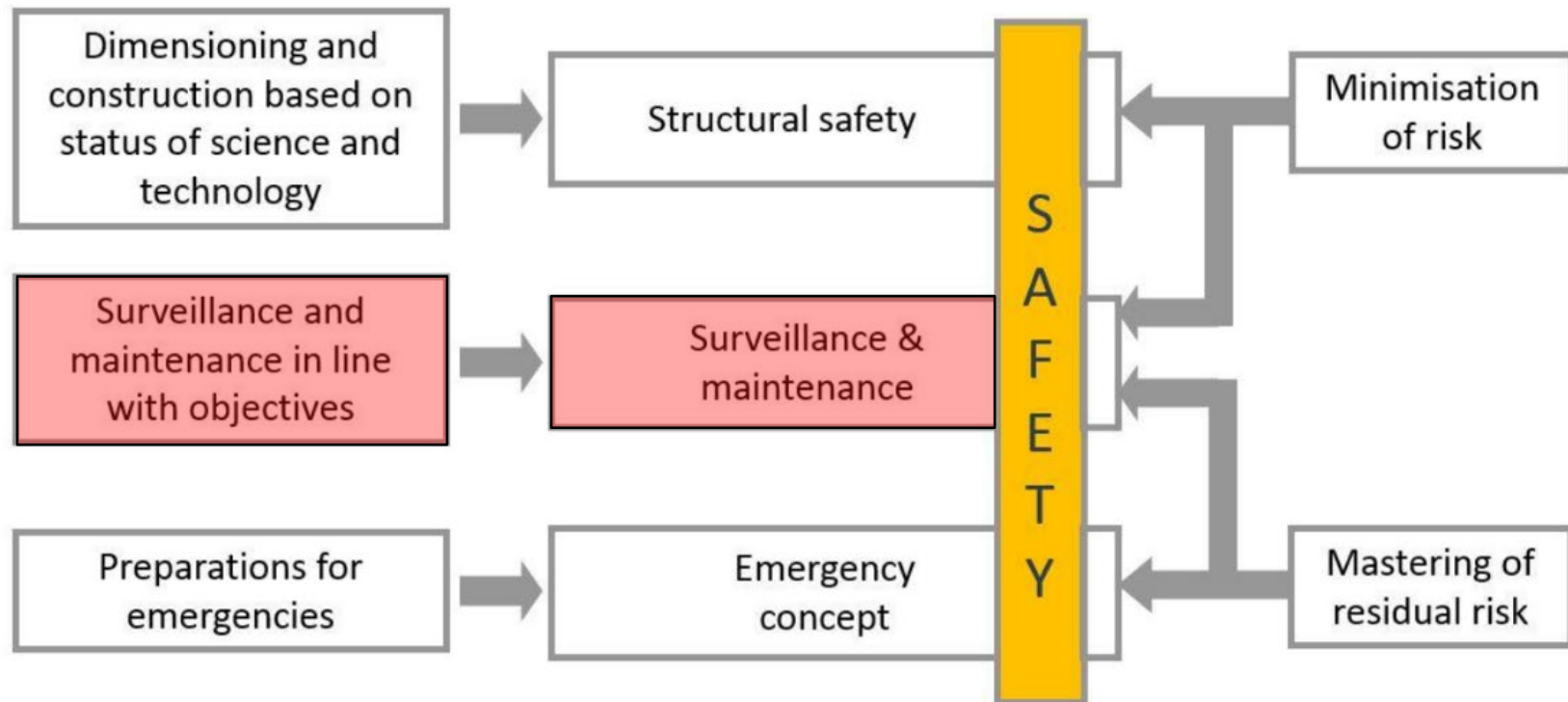
Difficulties in formulating design criteria for *natural hazard* load cases

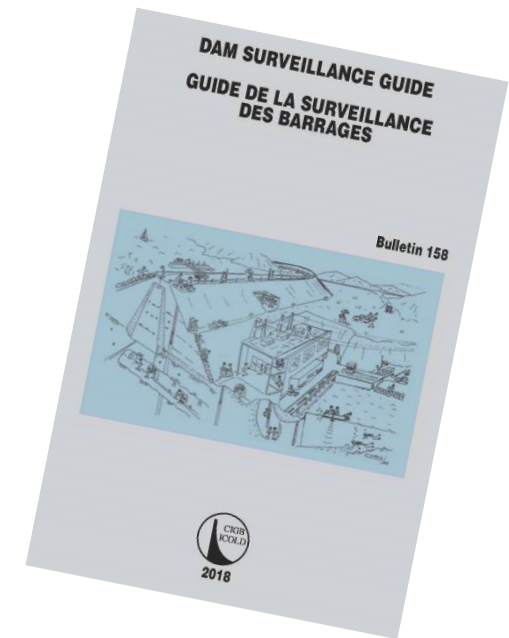
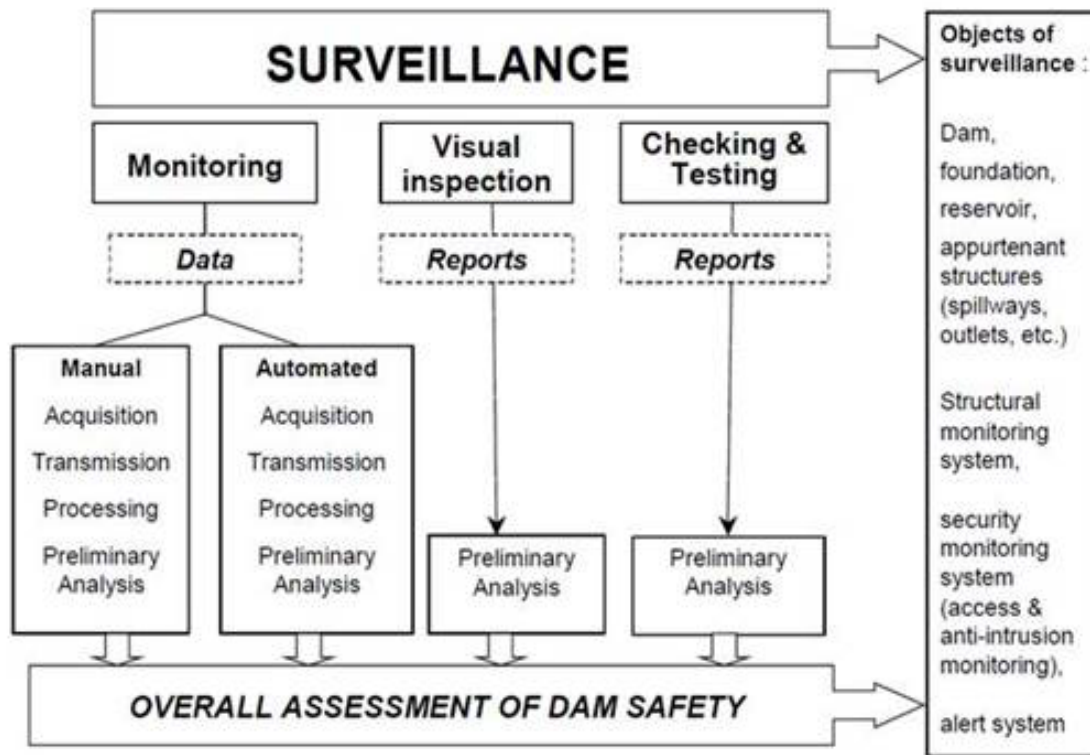


Research areas for dams in Switzerland

- ☐ Safety of concrete dams in case of earthquake
- ☐ Safety of embankment dams in case of earthquake
- ☐ Evaluation of the PMF and the design flood
- ☐ Long-term behaviour and mechanical properties of dam concrete
- ☐ Static and dynamic behaviour of rock foundation

Swiss Dam Safety Concept





The purpose of dam surveillance is to detect as quickly as possible

- any damage
- any structural safety deficiency

According to the safety concept, **surveillance** is based on 3 components:

1. **Visual inspection** of all parts of the dam, according to a pre-established programme;
2. **Monitoring** the dam to check its behaviour;
3. **Checking and testing** valves and other hydraulic safety devices (with full-open test if possible).

Operational levels of surveillance

I	Dam Warden (operating staff)	Visual inspections Measurements and surveys Testing (valves)
II	Qualified Engineer (civil engineer)	Ongoing assessment of inspection results. Detailed annual inspection Analysis of behaviour Annual report
Only for large dams III	Experts (civil engineer and geologist)	Five-year safety assessment report
IV	Supervisory Authority	Verification of compliance Validation of reports Inspections Technical and operational measures

Level 1: The Dam Warden

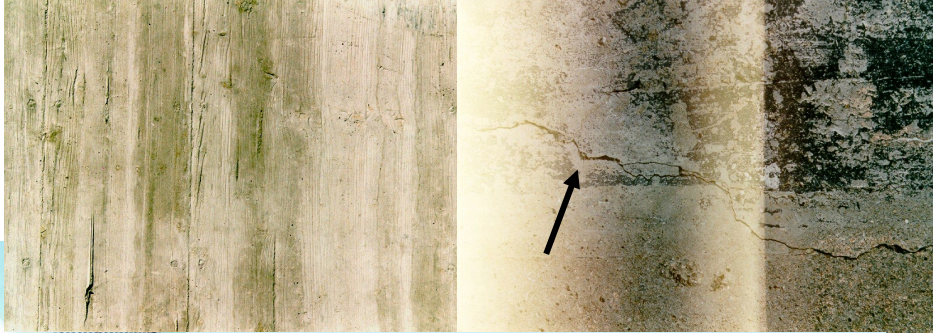
Visits and inspections

- ⇒ Measurements and visual inspections following the surveillance plan;
- ⇒ Validation of electronically transmitted measurement data by carrying out manual measurements on-site.

Checking and testing gates and valves

- ⇒ Annual inspection;
- ⇒ Each inspection must be carried out with a high water level in the reservoir and must include a discharge test (wet function test) if technically feasible;
- ⇒ The way the inspection is performed and the findings must be recorded in a report.

Dam Surveillance - Visual Inspection



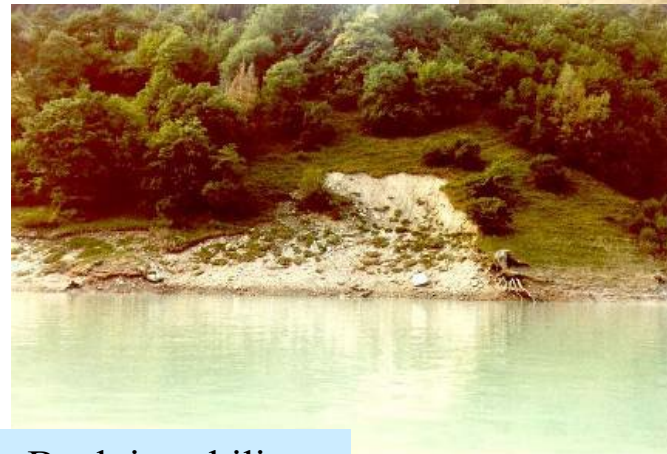
General condition, cracks



State of embankments,
settlements, landslides,
wetlands



Leakage



Bank instability

Condition of hydromechanical
equipment



Monitoring: Instrumentation



Mikrometer
zum Messen der
Breite von Fugen und
Rissen (es gibt keine
Staumauer ohne Risse)



**Theodolit
(Winkelmesser)**
zum geodätischen
Vermessen der
Verformung der
Staumauer



Thermometer
zur Messung der
Wasser- und der
Betontemperatur



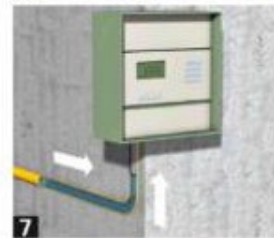
**Stoppuhr und
Massbecher**
zum Messen der
Sickerwassermenge



Nivelliergerät
zum geodätischen
Vermessen von Höhen-
unterschieden und
damit der Verformung
der Staumauer



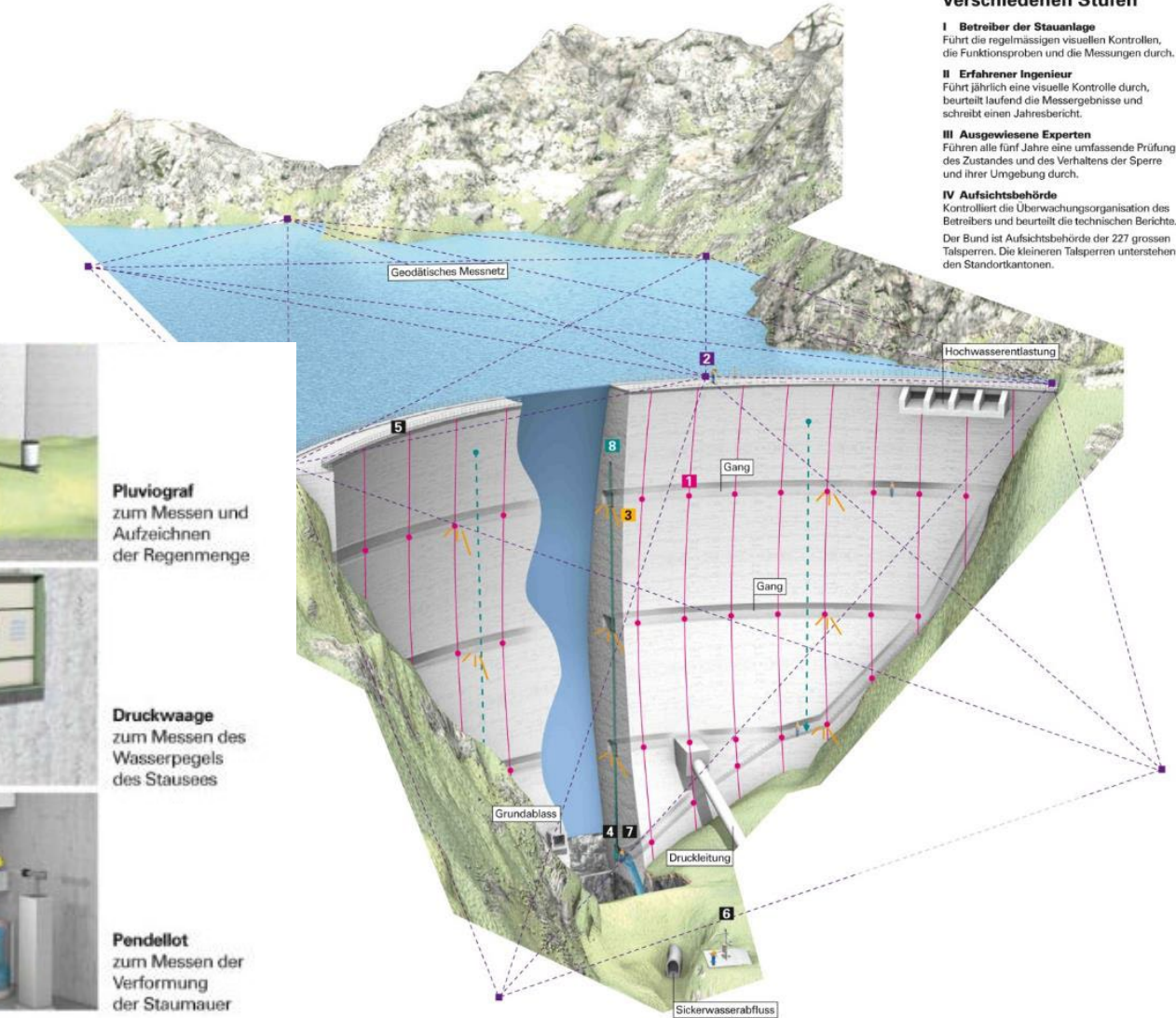
Pluviograf
zum Messen und
Aufzeichnen
der Regenmenge



Druckwaage
zum Messen des
Wasserpegels
des Stausees



Pendellot
zum Messen der
Verformung
der Staumauer



Überwachung auf vier verschiedenen Stufen

I Betreiber der Stauanlage

Führt die regelmässigen visuellen Kontrollen, die Funktionsproben und die Messungen durch.

II Erfahrener Ingenieur

Führt jährlich eine visuelle Kontrolle durch, beurteilt laufend die Messergebnisse und schreibt einen Jahresbericht.

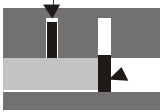
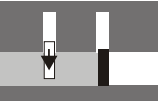
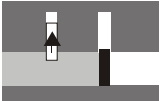
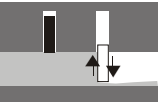
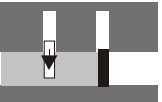
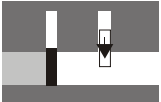
III Ausgewiesene Experten

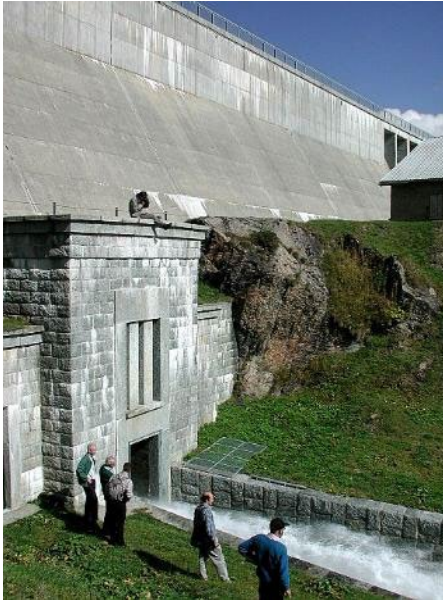
Führen alle fünf Jahre eine umfassende Prüfung des Zustandes und des Verhaltens der Sperre und ihrer Umgebung durch.

IV Aufsichtsbehörde

Kontrolliert die Überwachungsorganisation des Betreibers und beurteilt die technischen Berichte. Der Bund ist Aufsichtsbehörde der 227 grossen Talsperren. Die kleineren Talsperren unterstehen den Standortkantonen.

Valve operation tests

- ① initial 
- ②  
- ③  $\downarrow \uparrow$ 10 - 20 cm
- ④  
- ⑤ 



Level 2: The Qualified Engineer

Annual inspection

⇒ Visual inspection once a year;

⇒ Preparation of annual report, which includes

1. Report on operation tests of the gates;
2. Monitoring reports;
3. Visual inspection report;

with, in particular

- Representation and synthetic explanation of the tests, measurements and inspections performed;
- Analysis of the results and findings concerning the condition and behavior of the dam (including auxiliary safety-relevant structures and slopes around the reservoir);
- Assessment if operation is still safe;
- Recommendations about necessary maintenance, construction measures, monitoring.

Level 3: the Experts

Five-yearly inspections

- ⇒ Comprehensive safety review;
- ⇒ Conducted by experienced experts in the fields of civil engineering and geology;
- ⇒ Main tasks:
 - Comprehensive analysis of condition and behaviour of all components of the facility, including possible links between condition and behaviour as well as possible occurrence of long-term trends;
 - Assessment about the state of the art in science and technology;
 - Assessment if operation is still safe;
 - Recommendations in particular about necessary maintenance, construction measures, monitoring or further studies.

Level 4: The Supervisory Authority

Elaborates guidelines

Approves projects (new projects and rehabilitation)

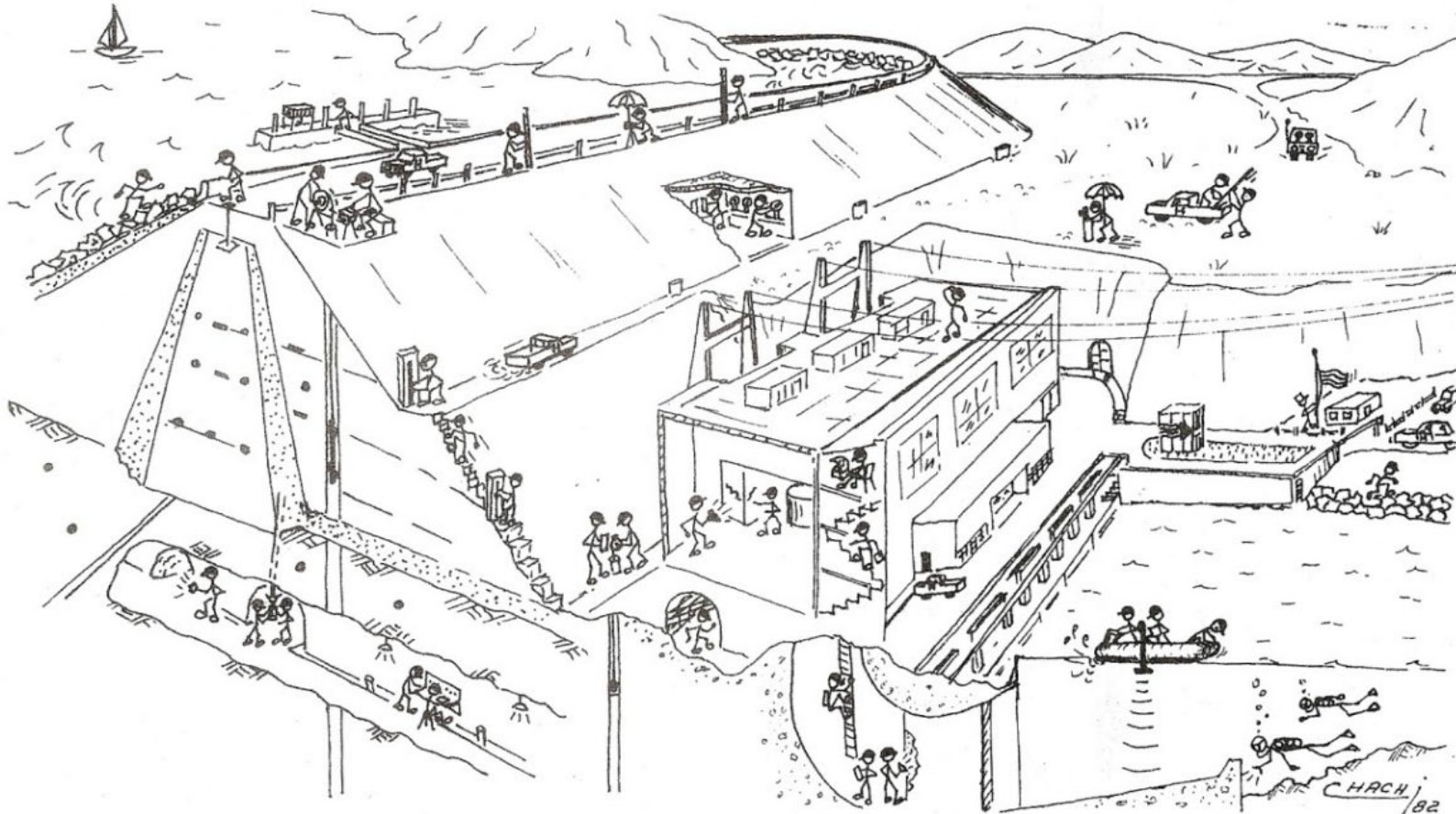
Inspections by the supervisory authority

- ⇒ Supervisory authority participates in five-yearly inspections and additionally inspects the facilities concerned once every 5 years;

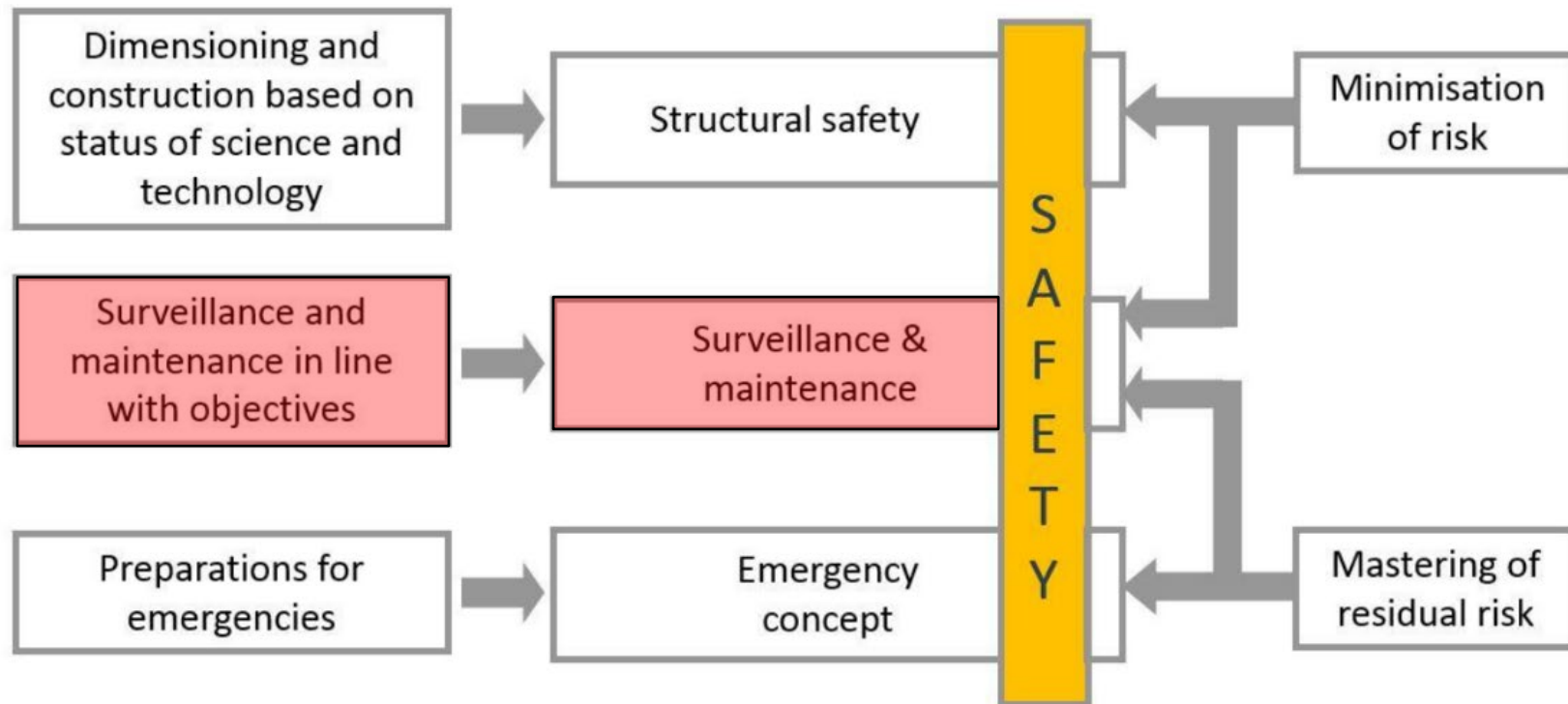
Also:

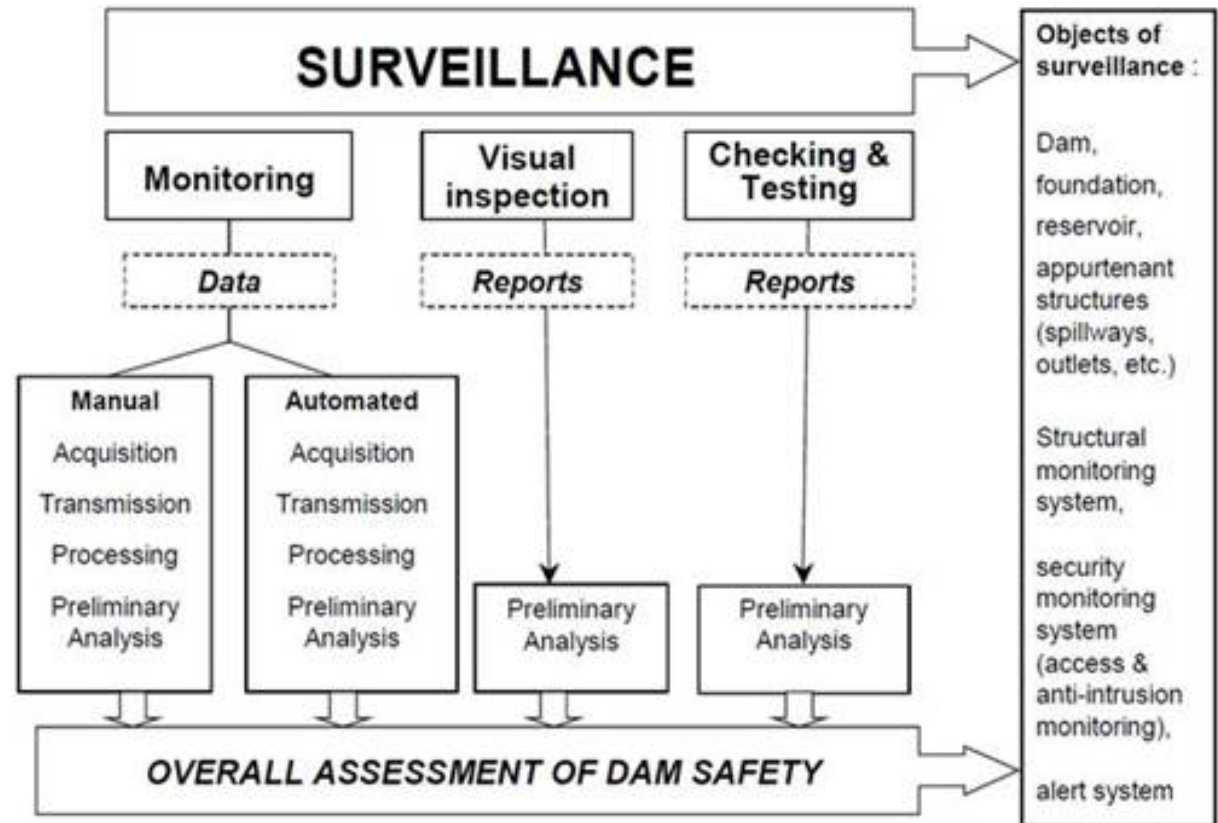
- ⇒ Formal review and validation of safety reports;
- ⇒ Order technical or operational measures for dam safety;
- ⇒ Order draw-down of the reservoir or other precautionary measures if necessary.

Surveillance and monitoring



Swiss Dam Safety Concept

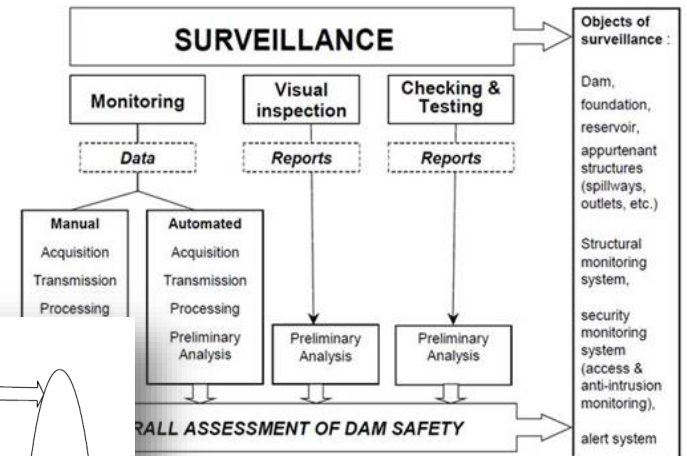
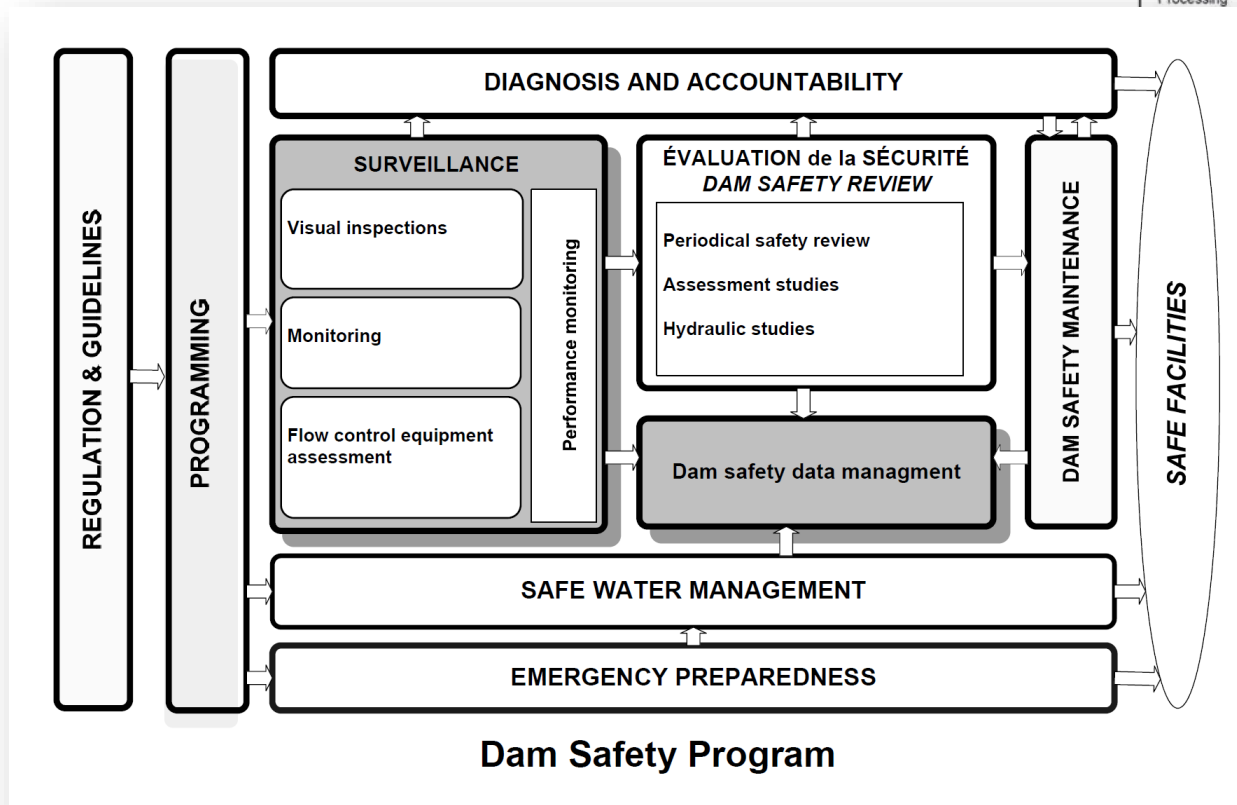




In case of abnormal behaviour :

- Enhanced surveillance
- Investigations
- Precautionary measures

ICOLD concept



Concept of monitoring

Failure mode

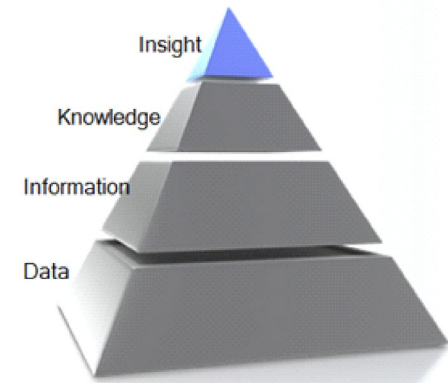
Behaviour indicators

Parameter to be measured

Sollicitations, loads
Response

Instrumentation

Accuracy
Redundancy



Concept of monitoring

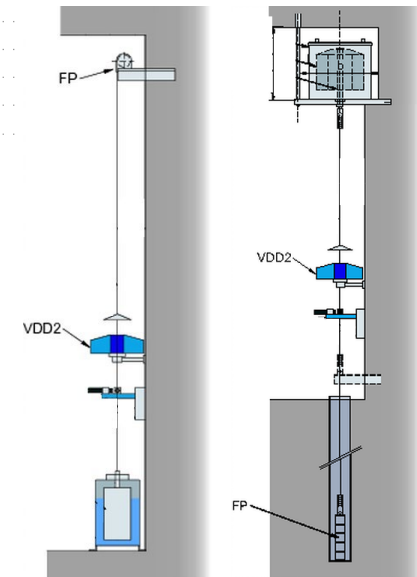
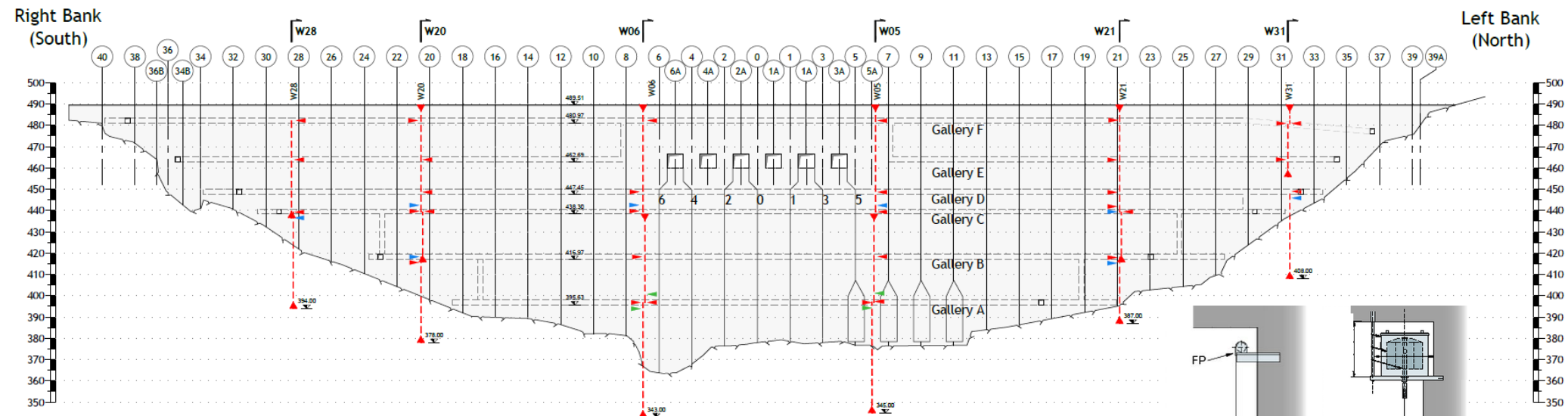
Deformations

- ⇒ along vertical lines
(extension underground)
Plumblines and inverted plumblines
geodetic survey (angle and distance measurements)
- ⇒ along horizontal lines
(extension in abutments)
wire alignment, levelling, optical alignment, angle and distance measurements, polygons
- ⇒ Rock deformation
variation in length and deformation along lines in boreholes (extensometer, sliding micrometer, sliding clinometer)
- ⇒ in cracks and joints
accessible reference points (micrometer, dilatometer, clinometer),
stress gauges

Seepage and pore pressures

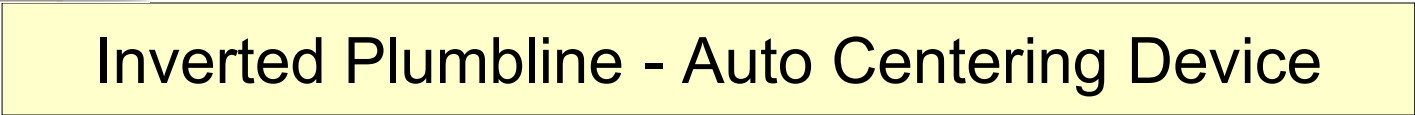
- ⇒ Seepage flow in galleries
 - ◆ volumetric measurement with container and chronometer
 - ◆ calibrated weir, measuring channel
- ⇒ Pore pressure
 - ◆ open boreholes / wells (piezometer)
 - ◆ closed boreholes (manometers)
 - ◆ pressure cells
 - ✓ pneumatic,
 - ✓ hydraulic or
 - ✓ Vibrating wire cells VW

Monitoring system – Plumblines / inverted plumblines

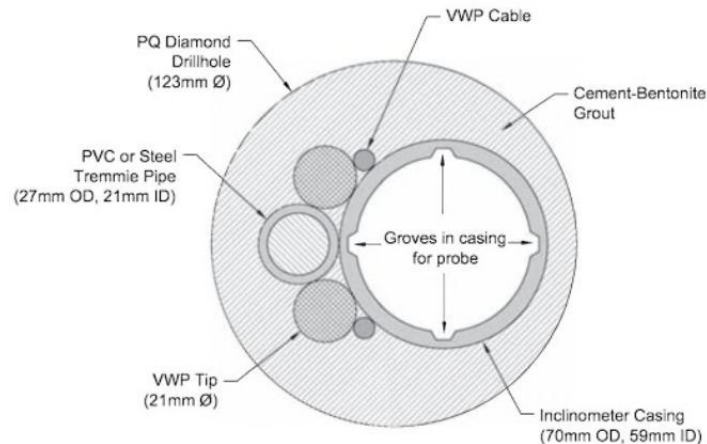
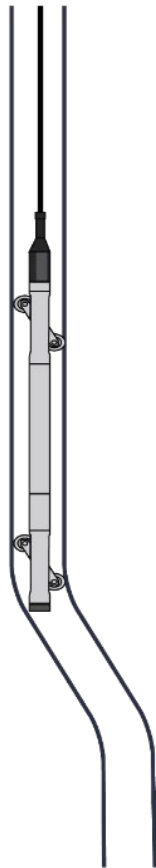




Monitoring system – Plumblines
Optical measurement

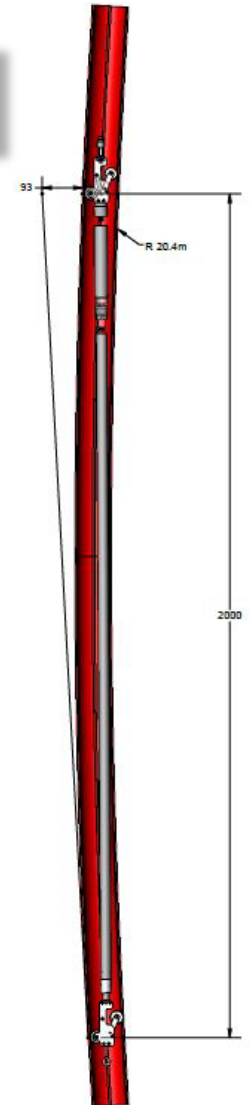


Deep inclinometers

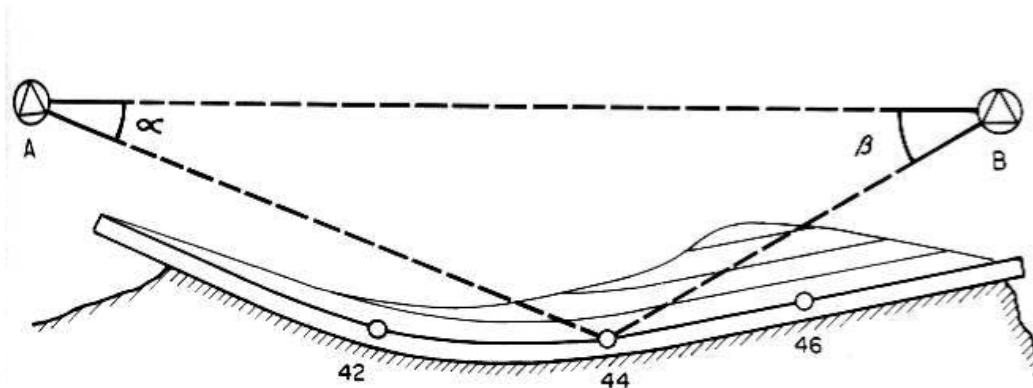


Conditions

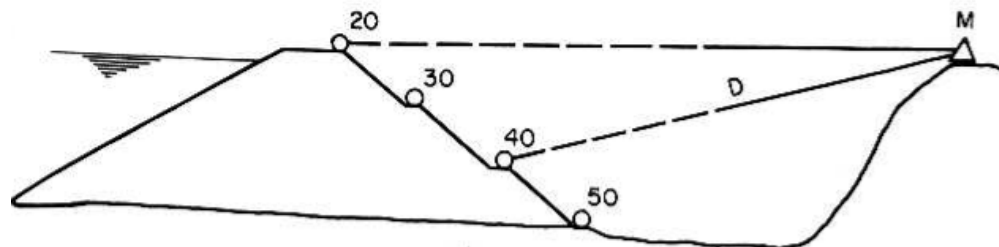
- The measurement and math of inclinometers works much better when plumb. Need vertical casing!
- Borehole should be straight and vertical ± 1 degree
- Casing straight (no vertical buckling; duct tape on couplings)
- No helix (avoid turning drill casing)
- Groove pair aligned in the direction of expected movement from top to bottom
- Clean water inside (no sand, grout, dirt, ...)
- Good lateral connection to the ground outside (e.g. proper grouting)



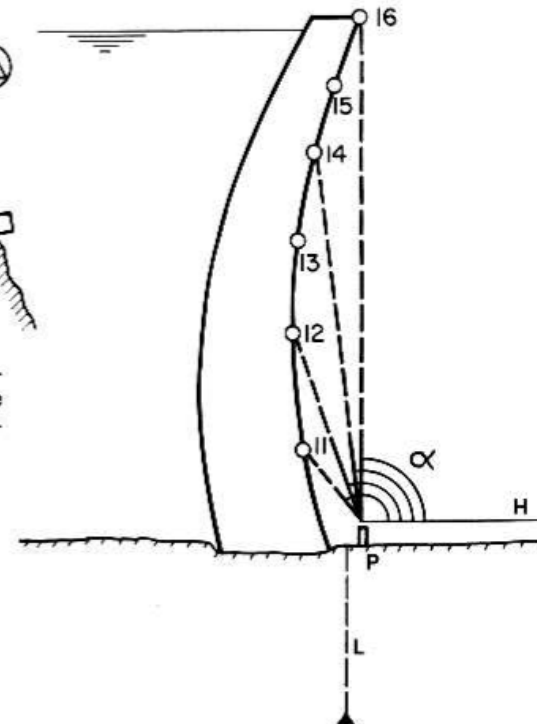
Monitoring system - Measuring angles and distances



Reference number 2.101(1). Simple measurement of angles used for determining horizontal displacements. The measurement system uses observations with a theodolite from a pillar (reference point A) to the control points on the dam (targets 42, 44, and 46) using reference point (B) as orientation. As a check analogical measurements can be made from the opposite reference point (B).



Reference number 2.101(3). Simple measurement of distances between control targets on the dam and fixed reference points downstream displacements of the dam using an electro-optical distance meter. (M) Reference point, (D) Measured distance, 20 to 50 Control targets.



Reference number 2.101(2). Simple measurement of vertical angles used for determining the upstream/downstream displacements of targets located on the downstream face of the dam. (P) Reference point, usually an observation pillar, (H) Horizon, (L) Inverted plumb line, 11 to 16 Control targets.

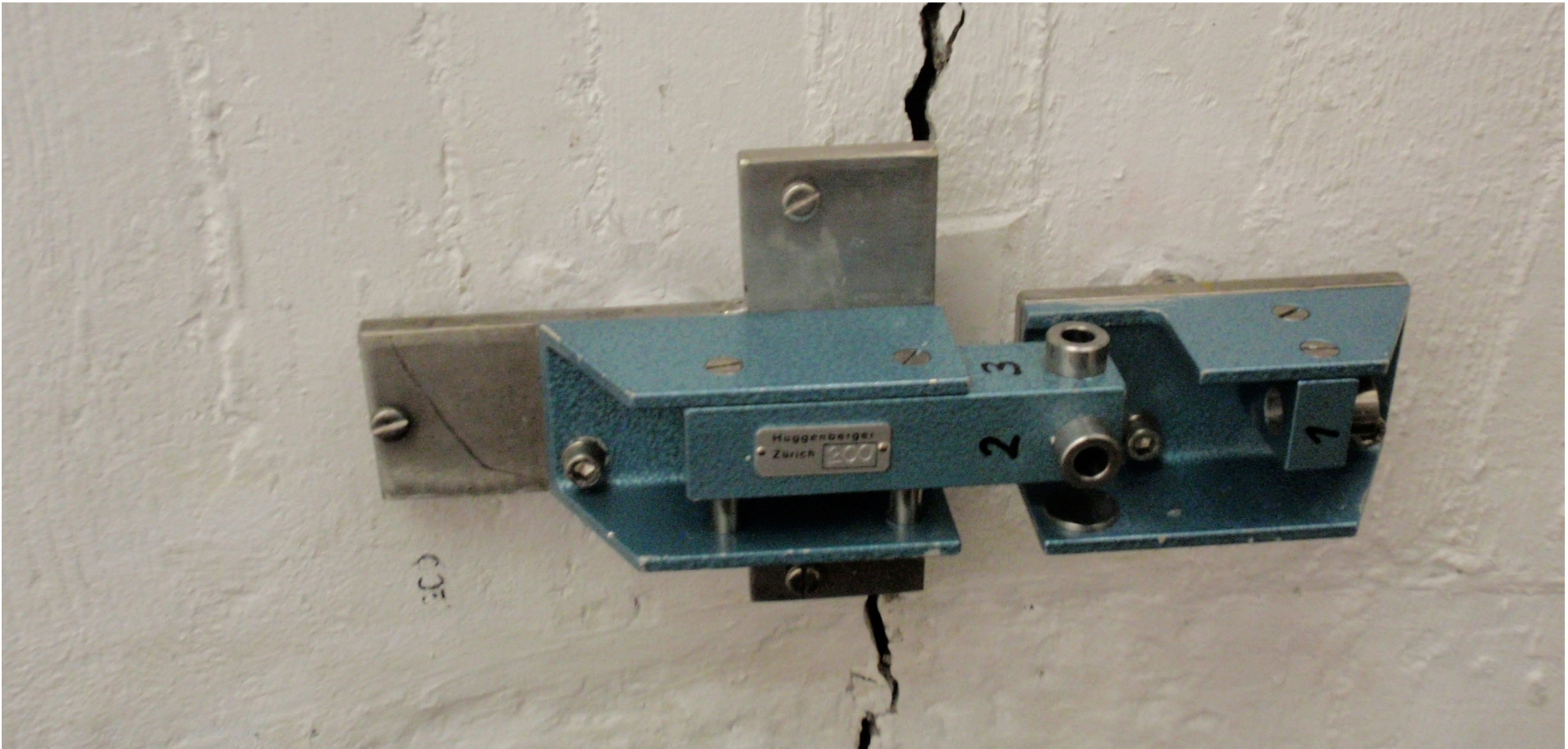
Monitoring system – Geodetic survey



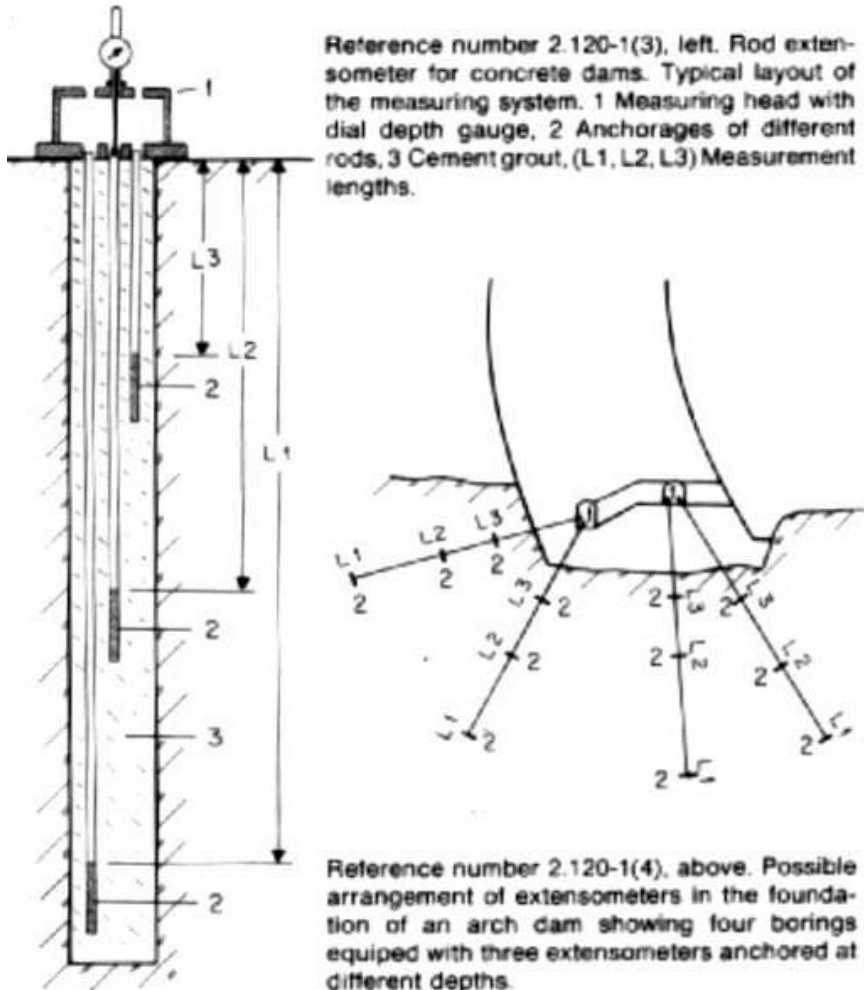
Dam Engineering Dam Safety and Surveillance



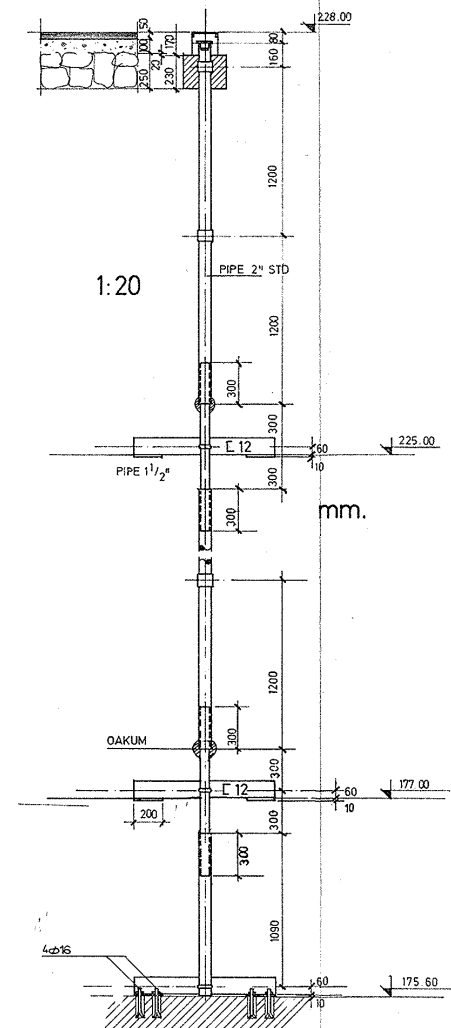
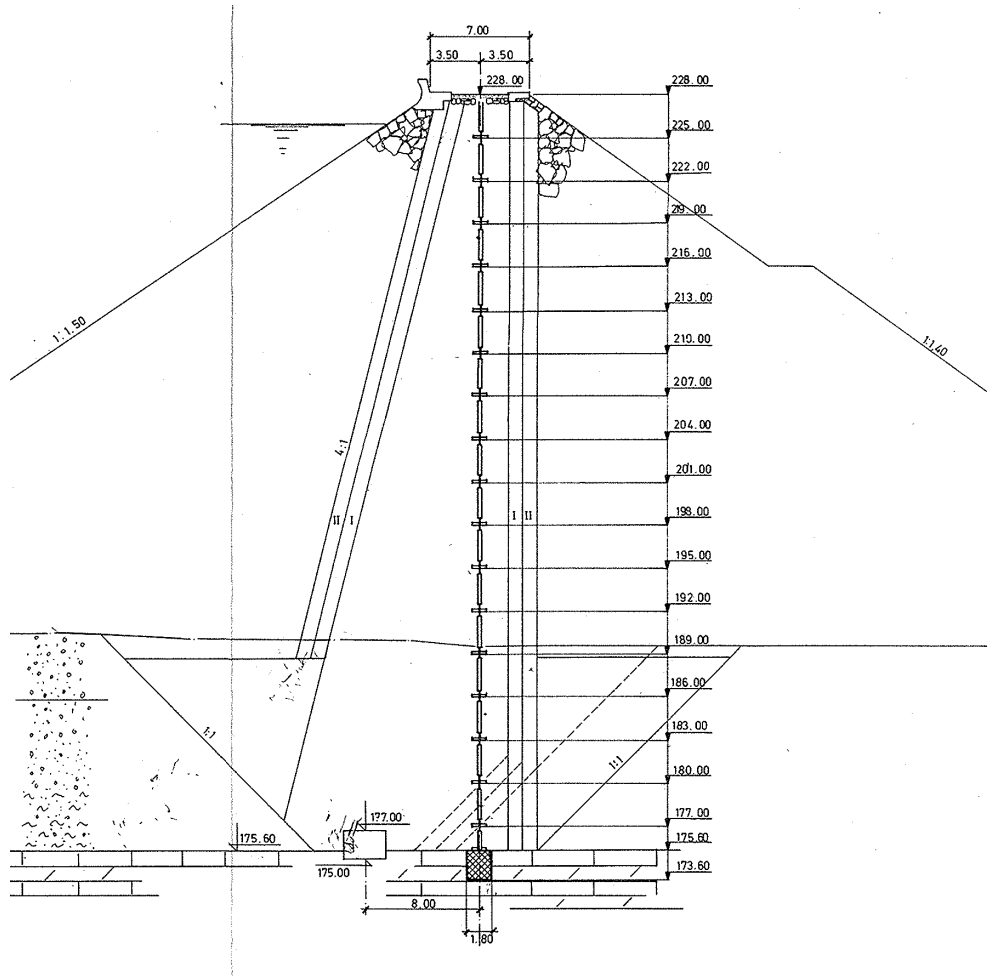
Crack opening measurement: Micrometer



Auscultation system - Rod extensometer (rockmeter)



Monitoring system - Vertical settlement marker



Example: Châtelot dam

SOCIÉTÉ DES FORCES MOTRICES DU CHÂTELOT

Barrage du Châtelot

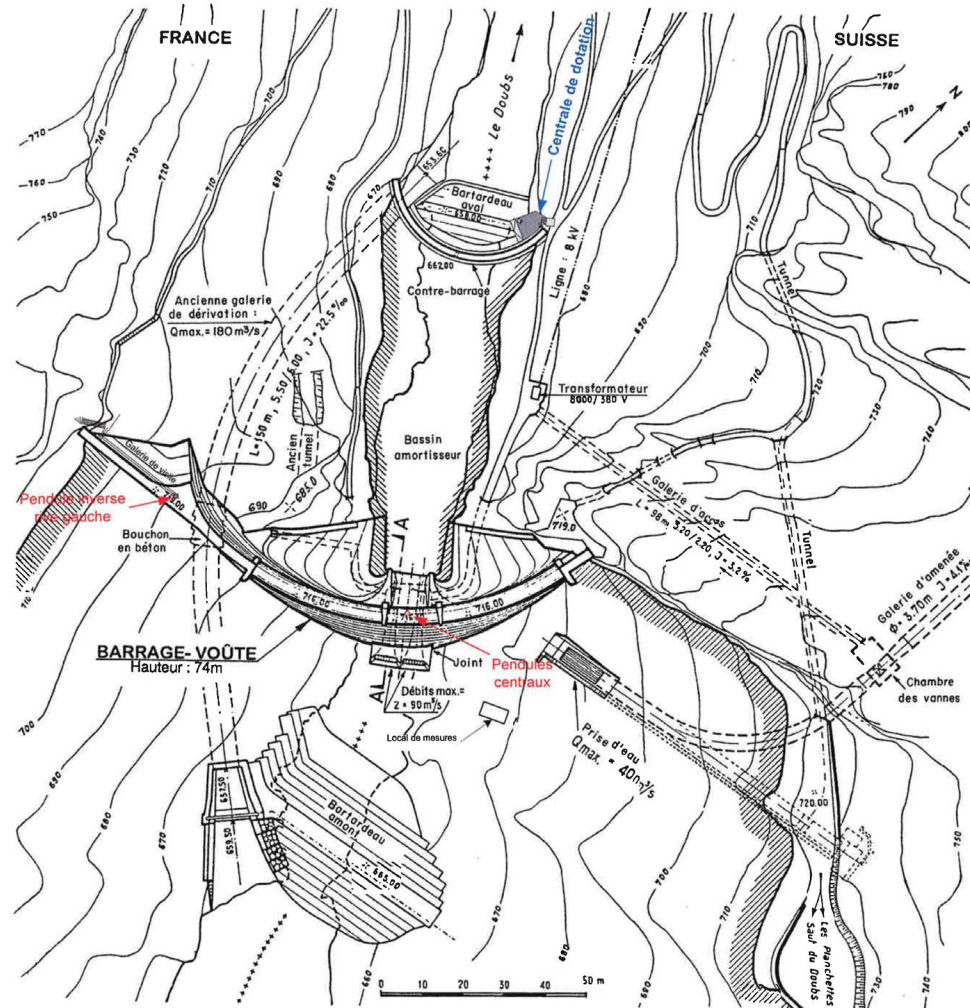
Expertise quinquennale 2018

Mémoire et annexes



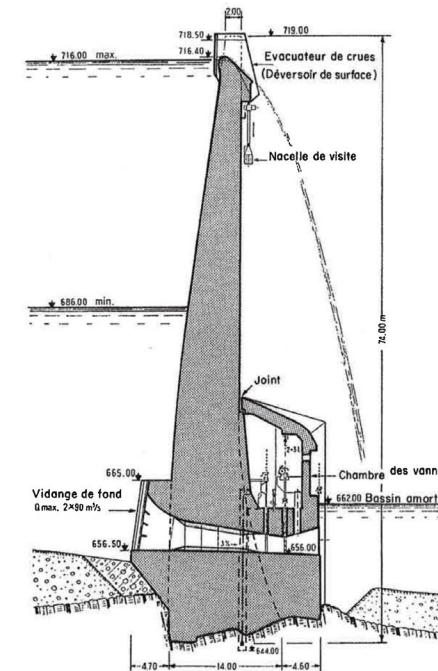
PLAN DE SITUATION

1 : 1000



COUPE TRANSVERSALE A-A

1 : 500

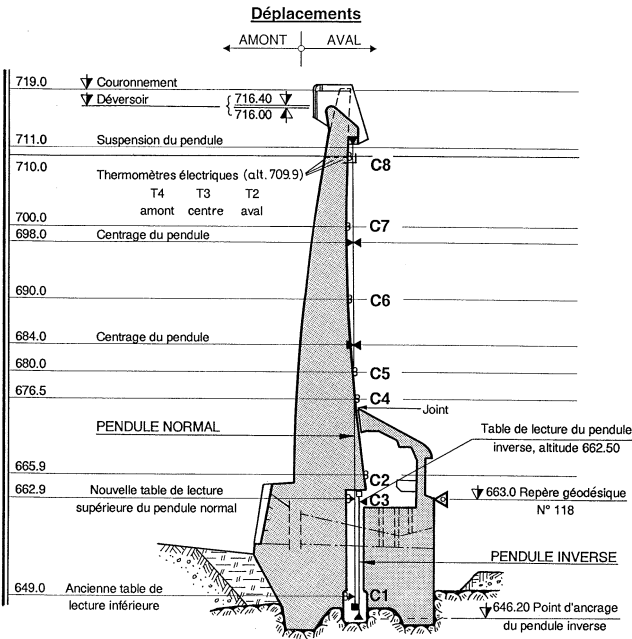




Barrage du Châtelot
Expertise quinquennale 2018

DISPOSITIFS DE MESURES (Section centrale du barrage)

- Modernisation et installation de nouveaux appareils de mesure : mai 1987
- Installation de 12 nouveaux capteurs de pression : automne 1995



LEGENDE

- ▼ Point de suspension
- Centrage du pendule
- ◄ Poste de lecture
- ▽ Cuve du flotteur
- ⬇ Poids tendeur
- ▲ Ancrage du pendule inverse
- Ci Clinomètre - poste de lecture

Voir Annexe 19

Anciennes prises installées lors de la construction :
- 9 prises de pression entre le béton et le rocher, réparties de part et d'autre de la section centrale.

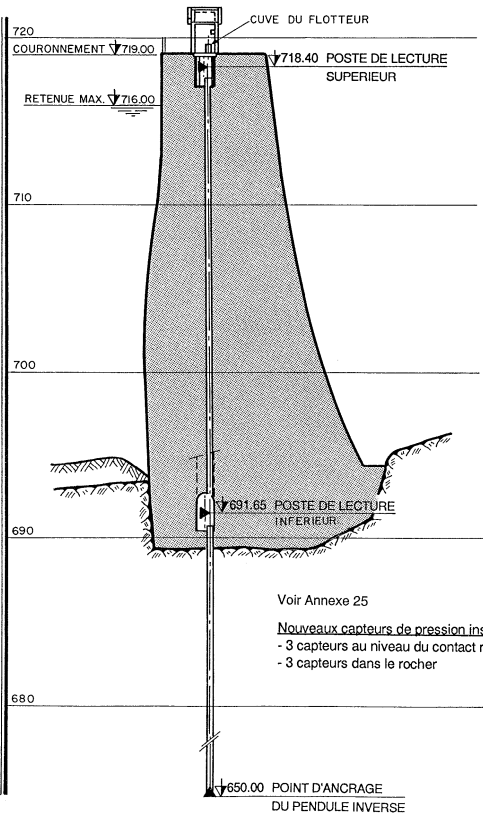
Nouveaux capteurs de pression installés en 1995 :
- 6 capteurs au niveau du contact rocher - béton
- 6 capteurs dans le rocher

Remarque : Mesure des débits d'infiltration : Vidange périodique du puits, mesure par compteur.

INSTALLATION D'UN PENDULE INVERSE (Culée Rive Gauche / Bloc22)

Mesure origine : 22.03.1996 / Niveau du lac 708.39

Coupe Transversale



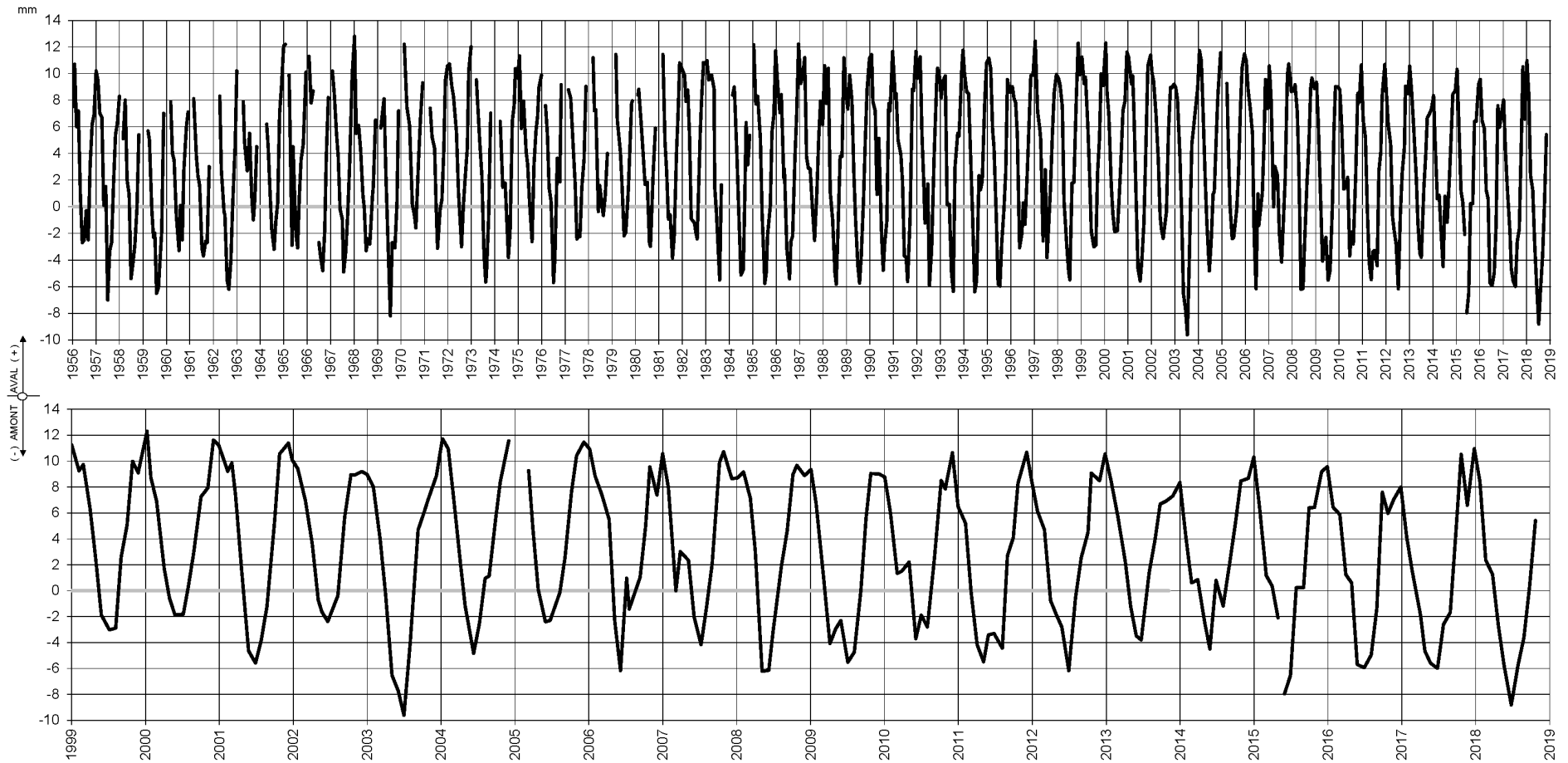
CH09/R01
Annexe 2

DEPLACEMENTS MESURES AMONT - AVAL DU POINT ALTITUDE 711.00 M.S.M.

(Pendule normal de la section centrale du barrage)

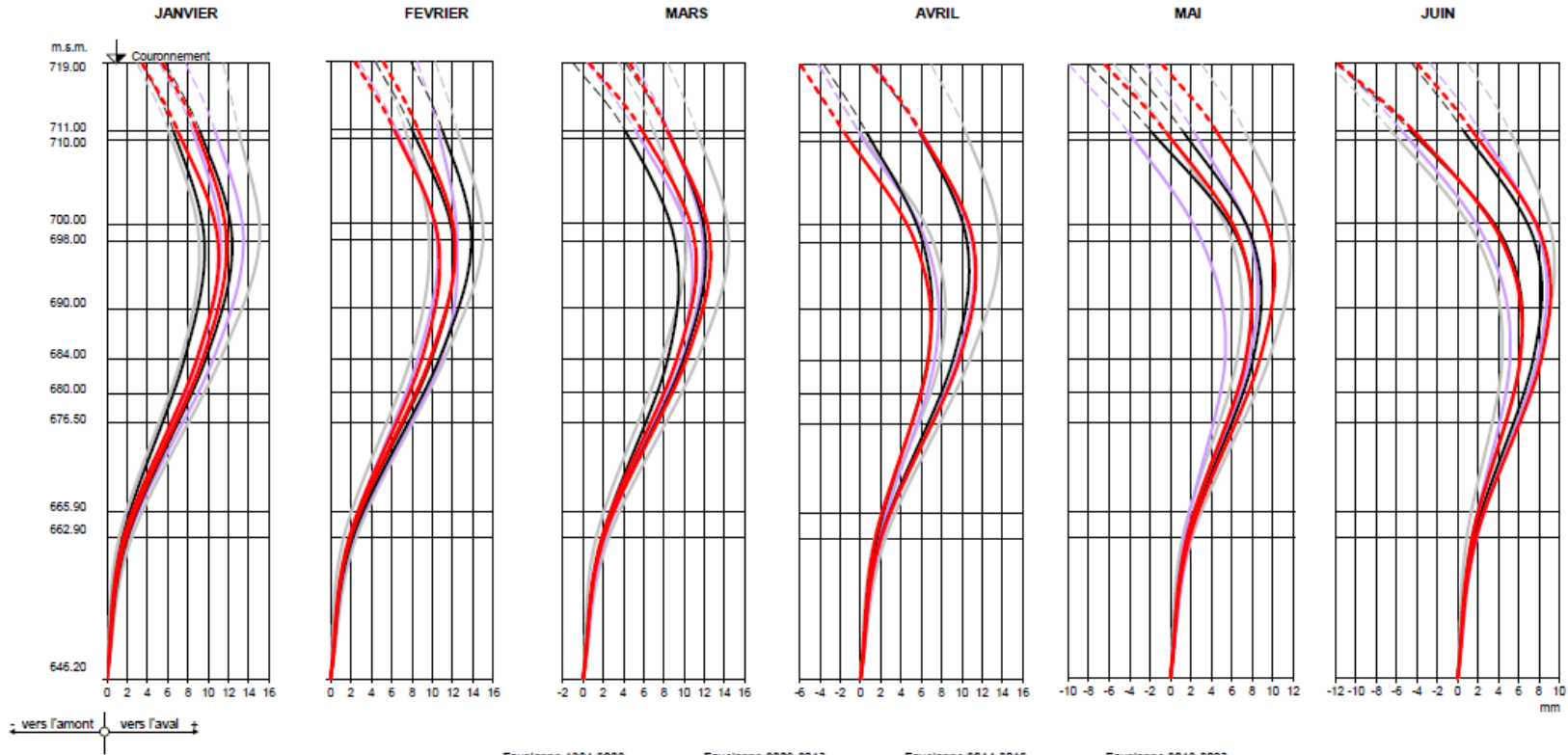
Mesure d'origine : 15.01.1953 / Niveau du lac : 657.00 m.s.m.

Poste de lecture 711



DEFORMATIONS AMONT - AVAL MESUREES AU MOYEN DES PENDULES
(Section centrale du barrage)

Mesure d'origine : 15.01.1953 / Niveau du lac : 657.00 m.s.m.



		TEMP. °C		
		NIV. LAC	AIR	EAU
PERIODE 1984-2008	MAX.	716.02	+4.50	+9.00
	MIN.	705.50	-5.00	gelée
PERIODE 2009-2013	MAX.	715.42	+3.50	+5.00
	MIN.	701.13	-4.50	+1.00
PERIODE 2014-2018	MAX.	712.77	+3.50	+8.00
	MIN.	705.50	-9.50	+4.00
PERIODE 2019-2023	MAX.	715.42	+7.50	+6.20
	MIN.	701.13	+0.00	+4.00

		TEMP. °C		
		NIV. LAC	AIR	EAU
MAX.	715.75	+4.50	+6.00	
MIN.	700.88	-8.00	gelée	
MAX.	710.44	+5.00	+5.00	
MIN.	699.04	-1.95	+1.00	
MAX.	714.08	+6.50	+5.30	
MIN.	708.65	-2.00	+3.70	
MAX.	710.44	+4.50	+5.00	
MIN.	699.04	+3.50	+3.00	

		TEMP. °C		
		NIV. LAC	AIR	EAU
MAX.	716.29	+7.00	+8.00	
MIN.	707.20	+0.50	gelée	
MAX.	707.82	+9.00	+8.00	
MIN.	704.47	+1.00	+5.00	
MAX.	716.29	+5.00	+7.00	
MIN.	708.12	-2.00	+5.00	
MAX.	707.82	+9.00	+7.00	
MIN.	704.47	+3.15	+3.70	

		TEMP. °C		
		NIV. LAC	AIR	EAU
MAX.	716.40	+12.50	+14.00	
MIN.	705.39	+2.00	+2.00	
MAX.	709.32	+11.50	+12.00	
MIN.	700.49	+6.00	+6.00	
MAX.	716.40	+10.00	+13.10	
MIN.	705.39	+2.00	+8.50	
MAX.	709.32	+13.50	+8.00	
MIN.	700.49	+8.50	+6.00	

		TEMP. °C		
		NIV. LAC	AIR	EAU
MAX.	715.93	+13.00	+18.00	
MIN.	702.74	+4.50	+9.00	
MAX.	706.48	+13.50	+17.00	
MIN.	696.39	+7.00	+9.00	
MAX.	714.14	+18.00	+16.00	
MIN.	705.55	+9.00	+12.00	
MAX.	706.48	+14.00	+11.00	
MIN.	696.39	+8.00	+8.00	

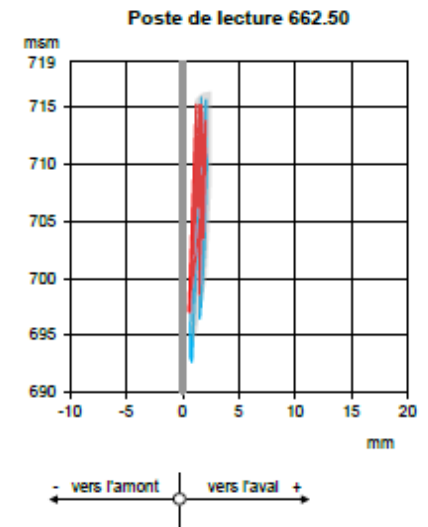
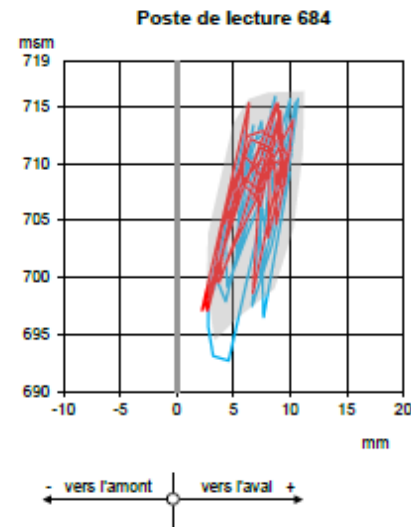
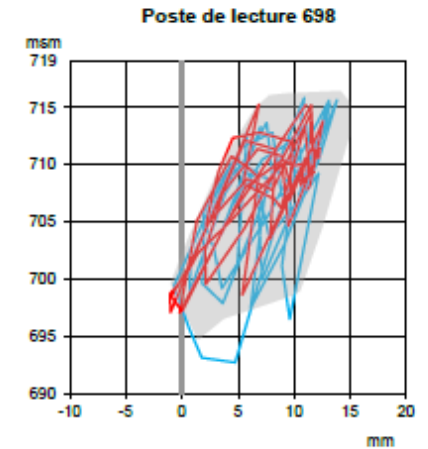
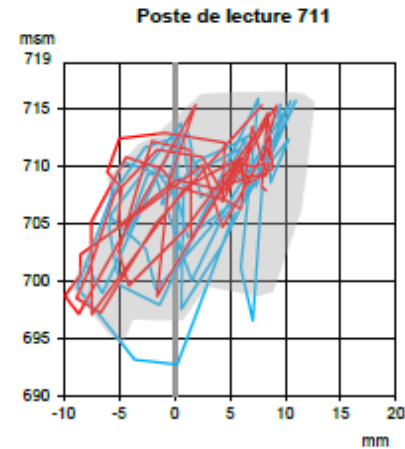
		TEMP. °C		
		NIV. LAC	AIR	EAU
MAX.	715.96	+18.00	+21.00	
MIN.	696.33	+8.25	+13.00	
MAX.	714.33	+22.50	+24.00	
MIN.	703.25	+9.50	+12.00	
MAX.	715.96	+21.50	+19.40	
MIN.	696.33	+12.00	+14.00	
MAX.	714.33	+18.00	+14.00	
MIN.	703.25	+13.90	+10.30	

Dam Engineering

Dam Safety and Surveillance

DEPLACEMENTS AMONT - AVAL MESURES AUX POSTES DE LECTURE DES PENDULES EN FONCTION DU NIVEAU DU LAC (Section centrale du barrage)

Mesure d'origine : 15.01.1953 / Niveau du lac : 657.00 m.s.m.



Enveloppe 1989 - 2013

— 2014 - 2018

— 2019-2023

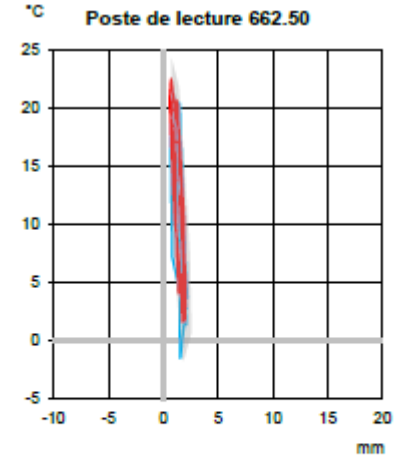
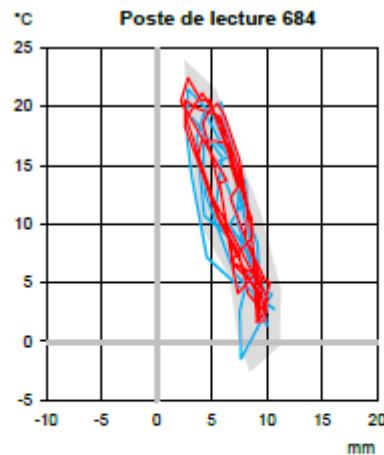
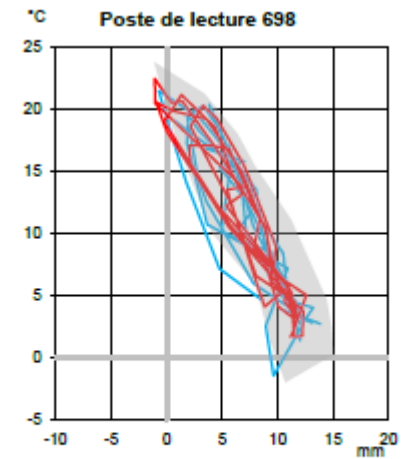
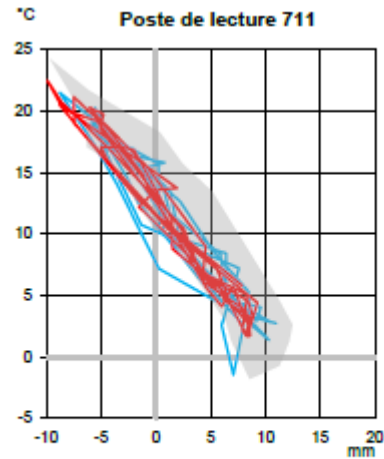
Dam Engineering

Dam Safety and Surveillance

DEPLACEMENTS AMONT - AVAL MESURES AUX POSTES DE LECTURE DES PENDULES EN FONCTION DE LA TEMPERATURE DU BETON AU NIVEAU 711.00 M.S.M.

(Section centrale du barrage)

Mesure d'origine : 15.01.1953 / Niveau du lac : 657.00 m.s.m.



- vers l'amont vers l'aval +

- vers l'amont vers l'aval +

Enveloppe 1989 - 2013

2014 - 2018

2019-2023

Stochastic predictive approach to determine behaviour patterns

Process

- Establishment of a database
- Selection of a structural dam behavior model
- Estimates of predictor coefficient values
- Validation of the model
- Calculation of the prediction
- Allowable deviations and presentation of the results
- Engineer's analysis
- Reassessment of the model

Stochastic predictive approach to determine behaviour patterns

A time series of measurement M is the **sum** of 3 factors:

- an irreversible factor :
 - ✓ Evolution over **time** t = function $f_1(t)$
- Reversible factors
 - ✓ hydrostatics due to **reservoir level** h = function $f_2(h)$
 - ✓ **Temperature** $Temp$ into the dam = function $f_3(Temp)$

$$M(t,h,Temp) = f_1(t) + f_2(h) + f_3(Temp) + \text{residual}(t,h,Temp)$$

$$\text{Measurement}(t,l) = \text{Predictions}(t,l) + \text{Deviation}(t,l)$$

The model is not perfect, it means that the residuals (also called deviations) are not zero.

- Important assumption: effects are **independent** and **additive**

Examples of common influence functions

Algebraic expression of irreversible factor:

$$f_1(t) = a_1 * \exp(-t/t_0) \text{ (or } a_1 * \exp(+t/t_0) \text{) } + a_2 * t$$

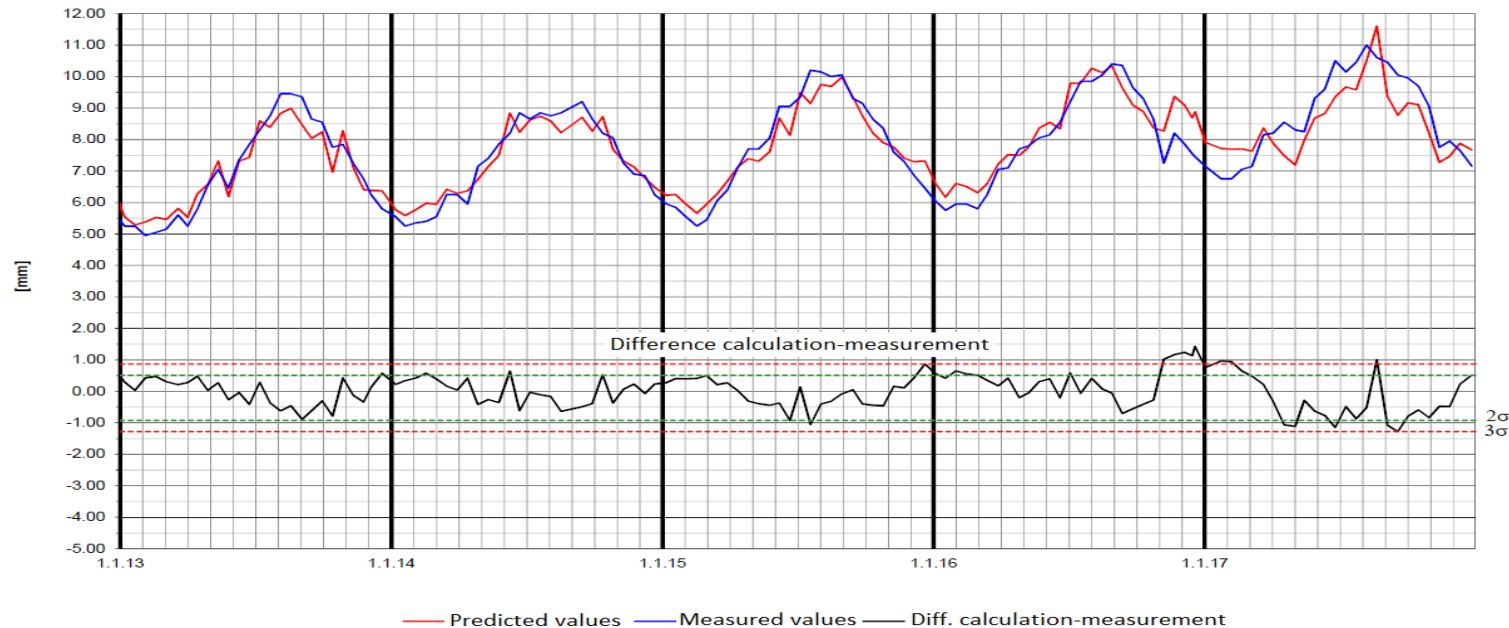
Algebraic expression of the effect of water level:

$$f_2(h) = a_3 * h + a_4 * h^2 + a_5 * h^3 + a_6 * h^4$$

Approximation: the thermal effects only depends on the season ($=S$), which is represented by a one-year periodic function

- Approx. $f_3(Temp) = f_3(S)$
- $f_3(S) = a_7 \cos(S) + a_8 \sin(S) + a_9 \sin(2S) + a_{10} \cos(2S)$
- $S = 0^\circ$ angle is the 1st January and 360° is the 31st december

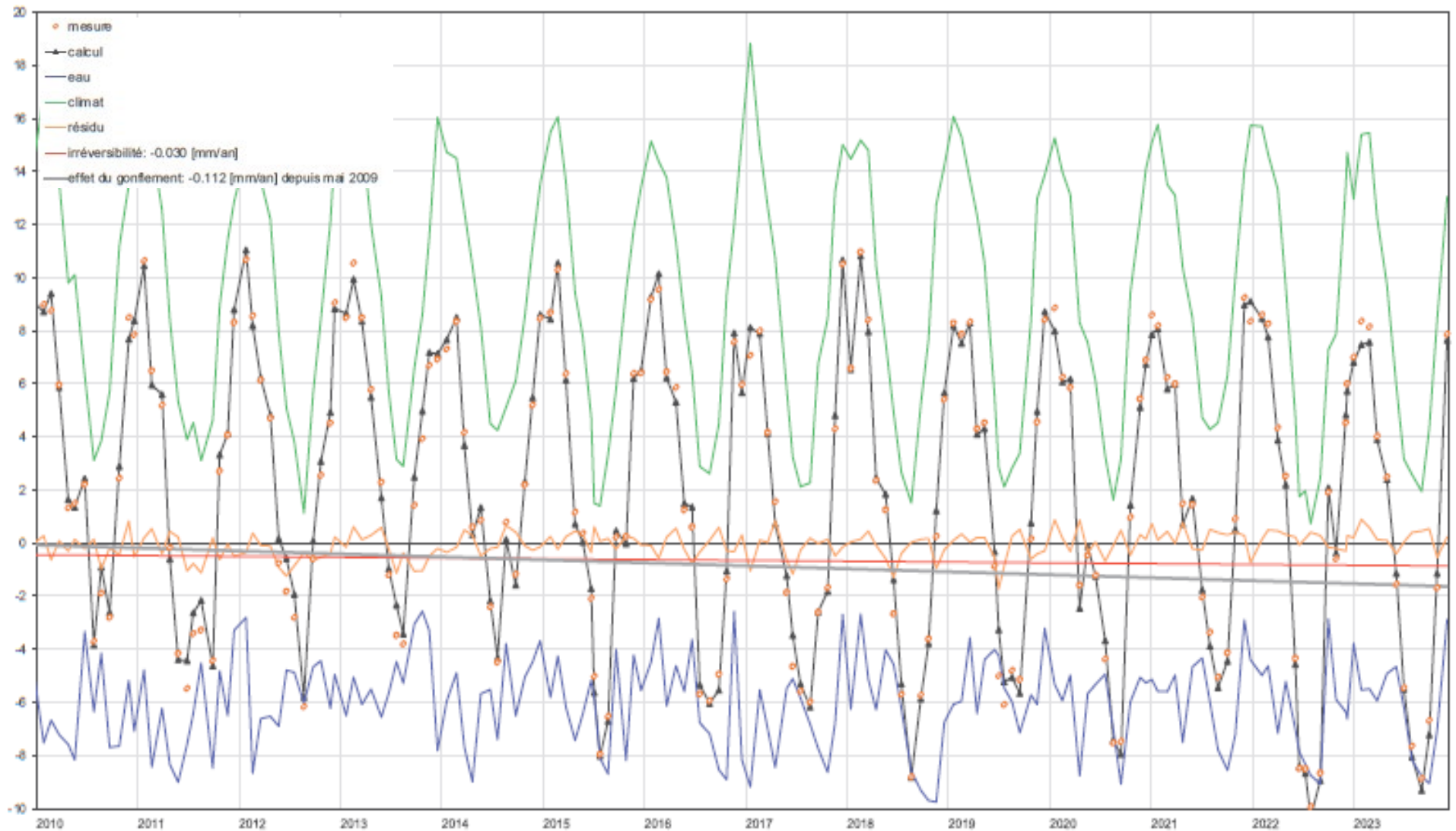
Allowable deviations and presentation of results



- ⇒ Gaps between predicted and measured values
- ⇒ Gap is allowable? Allowable deviation is the responsibility of engineer.
- ⇒ Usually permissible deviation range: multiple of standard deviation, typically between 2 or 3
- ⇒ Limits can also be fixed according to safety or operational constraints or if the owner does not want to exceed historical values

Dam Engineering

Dam Safety and Surveillance



Deterministic, stochastic, hybrid models?

Deterministic model

- ⇒ Cause effect based on physical laws
- ⇒ Mainly used for the prediction of displacement of dams
- ⇒ Purely deterministic models rarely present: use of fitted deterministic models.
- ⇒ Needs a good knowledge of the dam parameters (modulus of elasticity of the dam and its foundation)
- ⇒ Only model when there is little data or during 1st filling

Hybrid model

- ⇒ Combination of an analytical model and a statistical model.
- ⇒ deterministic part: calculated with a simplified analytical model.
- ⇒ statistical part: helps the model fit measurements.

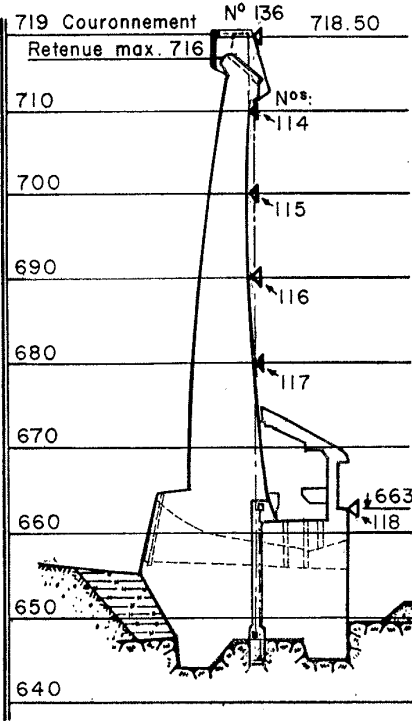
Benefits of hybrid models

- ⇒ directly interpretable. thermal diffusivity, hydraulic conductivity, or modulus of elasticity are often adjusted on measurements. By tracking the evolution over time of those parameters, the dam engineer is able to determine the effects of ageing.
- ⇒ appropriate to adjust to measurements: This advantage is a decisive argument when it comes to analyzing day-to-day measurements.

MESURES GEODESIQUES

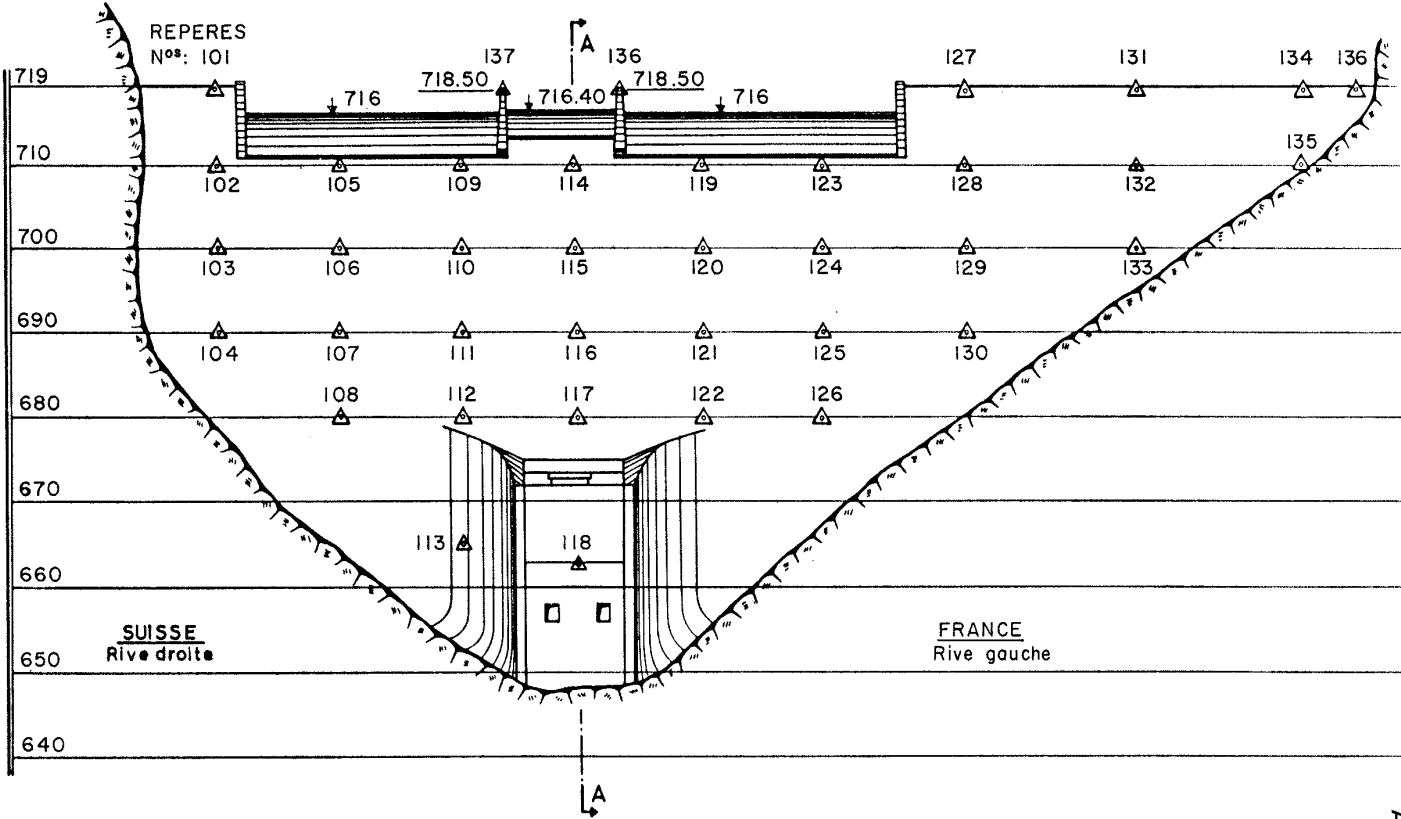
Coupe transversale A-A

1 : 500



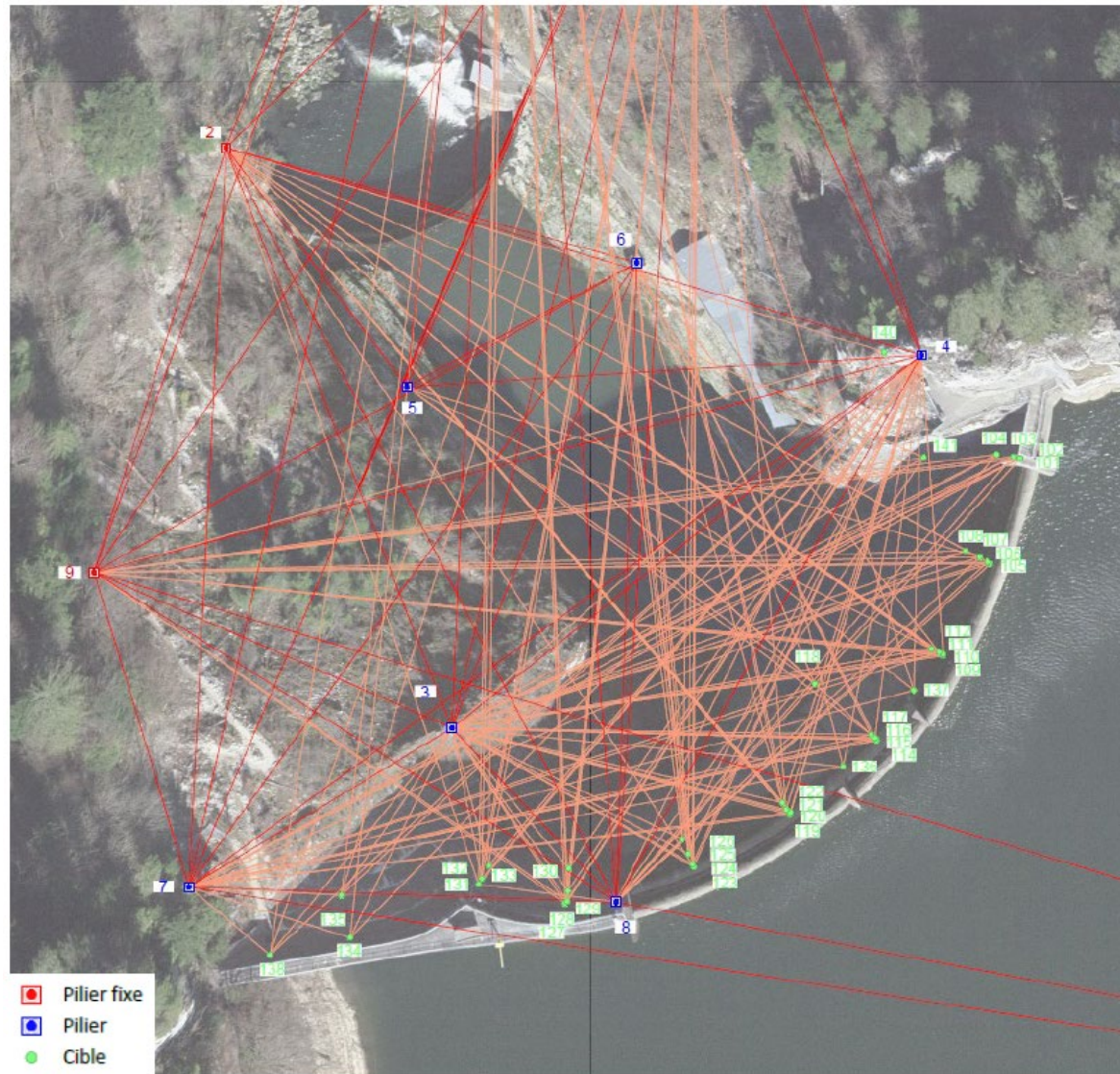
Disposition des repères scellés sur le parement aval

1 : 500



du 1^{er} janvier
au 31 décembre 2018

Ann

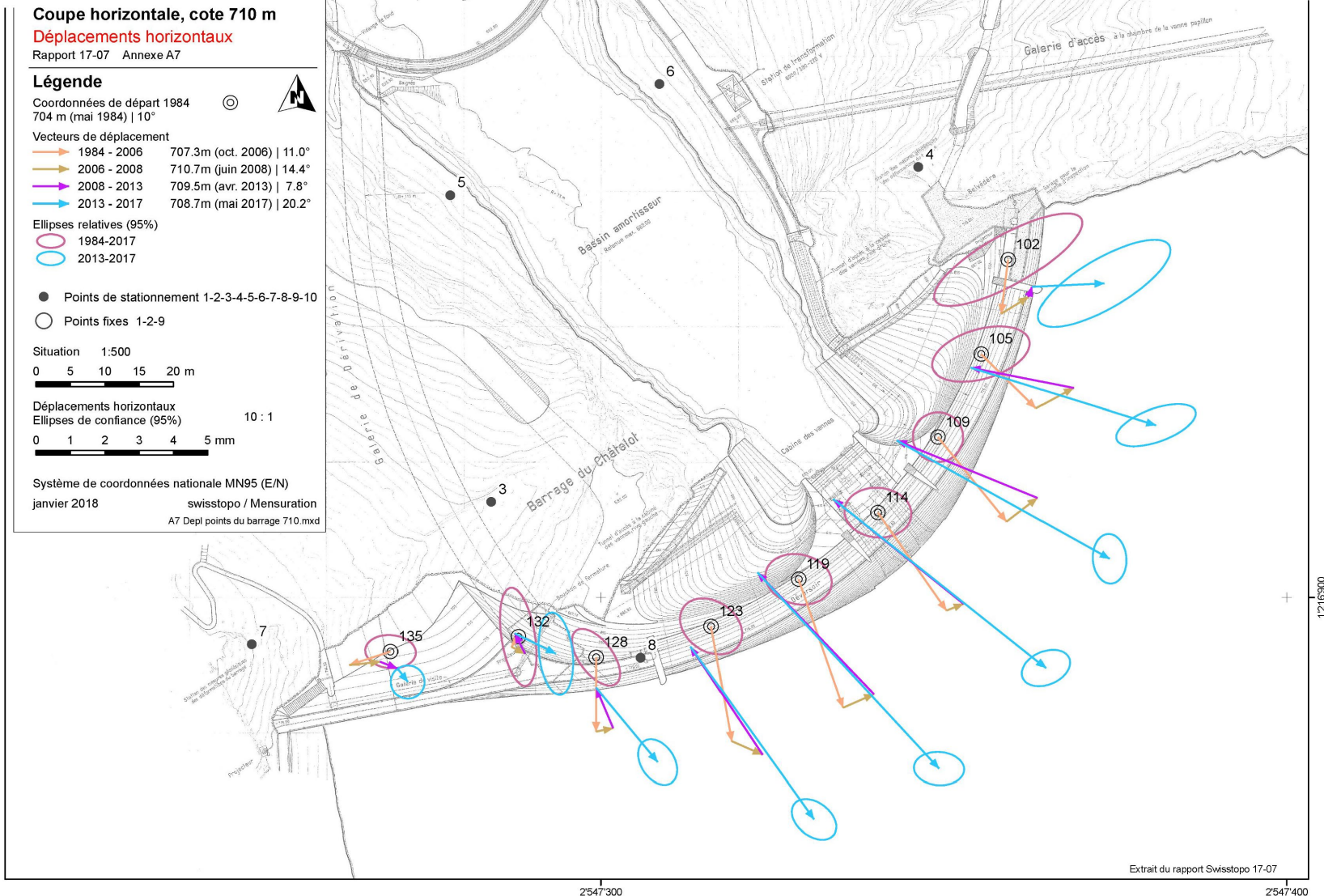


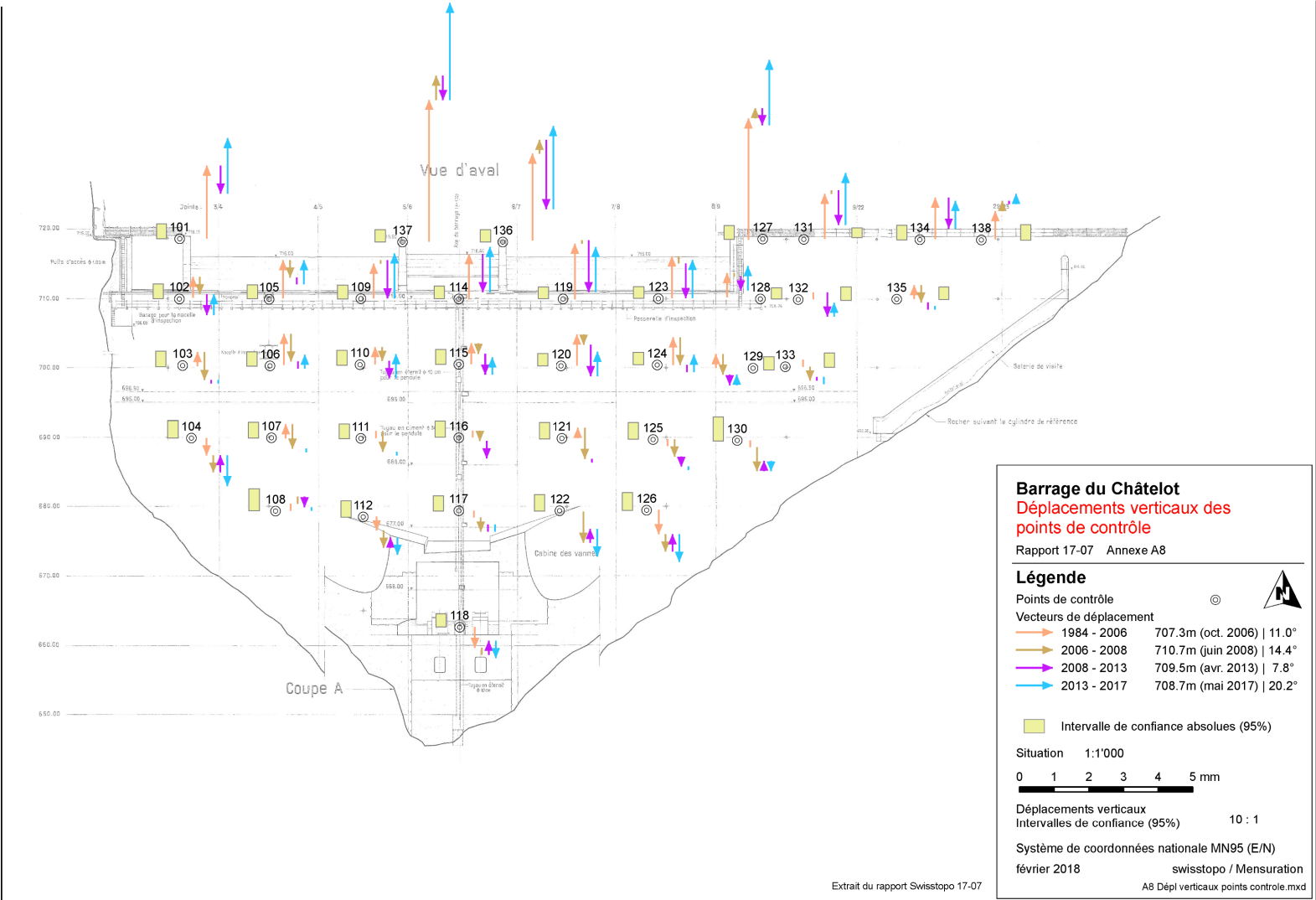
Dam Engineering

Dam Safety and Surveillance

Barrage du Châtelot
Expertise quinquennale 2018

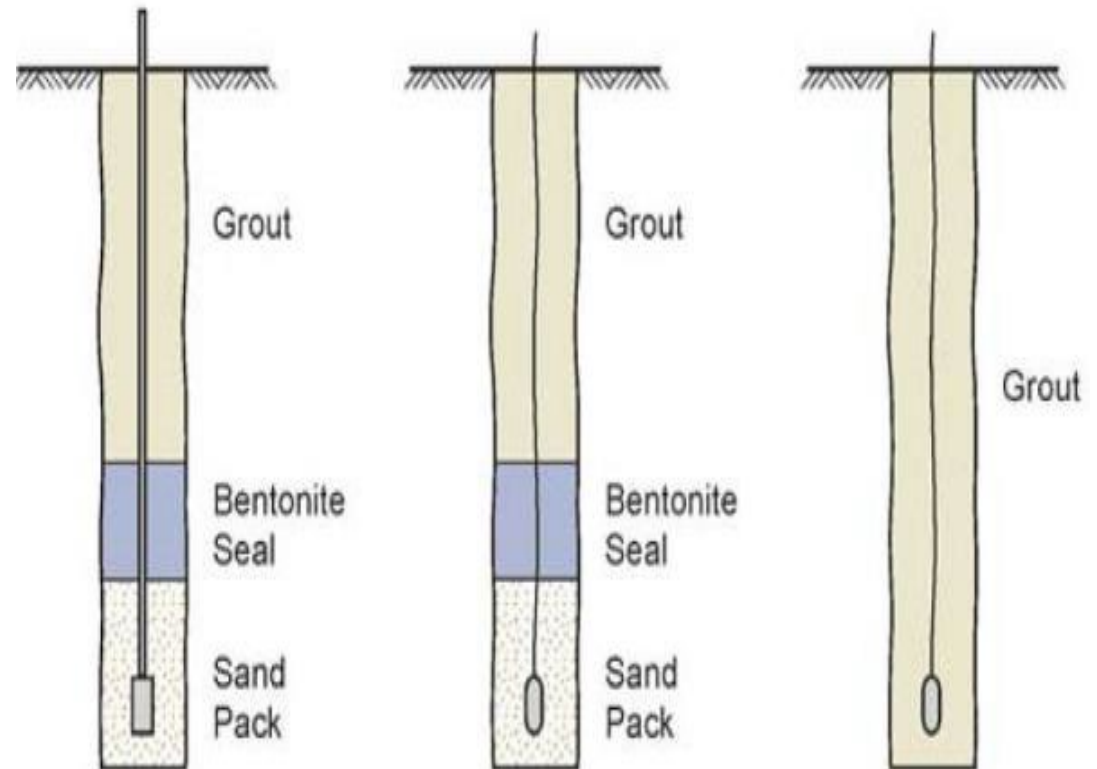
CH09/R01
Annexe 14.2





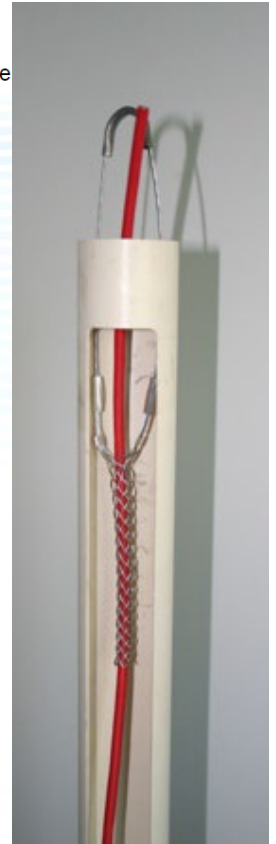
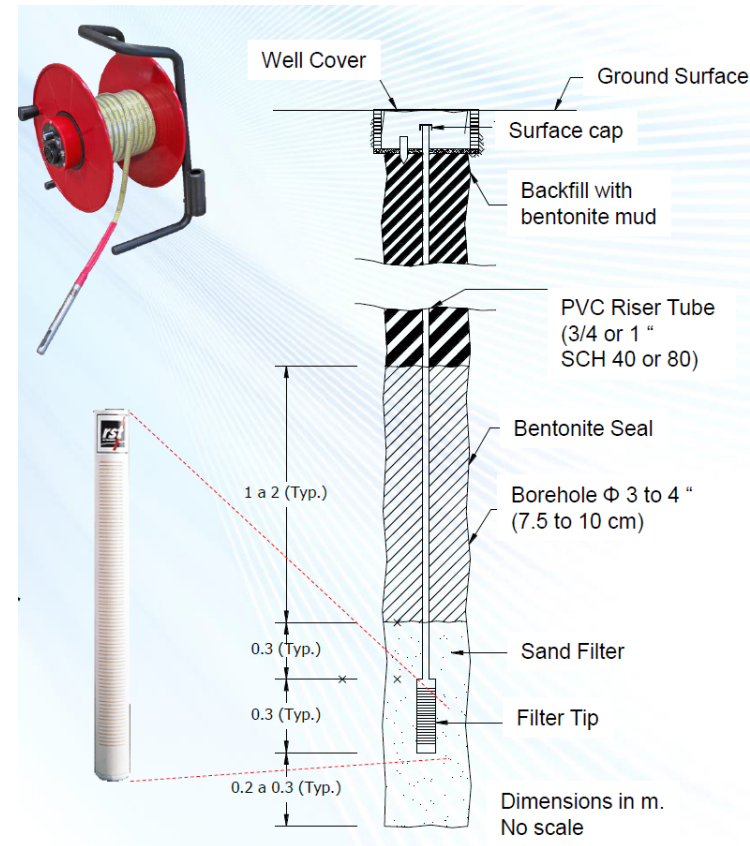
Monitoring system – Uplift pressure

- Open Well/Standpipe (with or without vibrating wire – VW piezometer)
- VW piezometer with Sand Pack and bentonite seal
- Fully Grouted VW piezometer



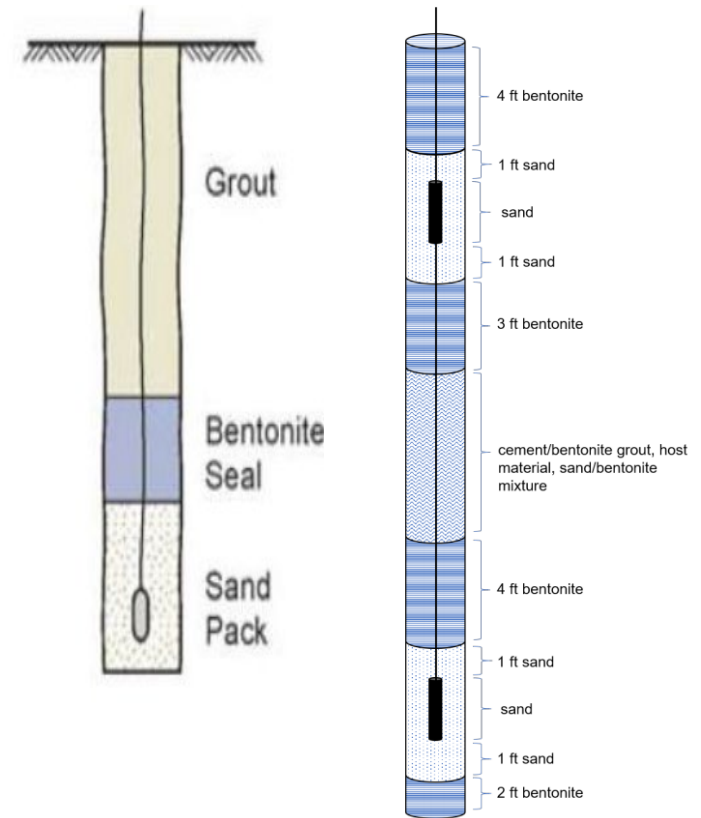
Standpipe Casagrande Piezometers

- Often preferred because electric sensor can be removed, water sampling, redundancy check
- Can be retrofit with VW piezometers to provide continuous readings
- Typically requires periodic cleaning and flushing (time lag test*)
- Two standpipes per borehole is possible. Three is difficult (not recommended)

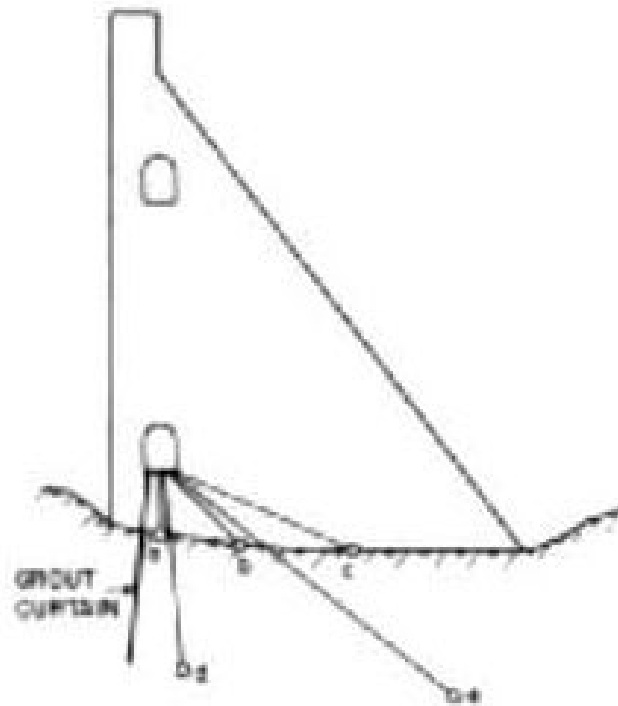


Standpipe Casagrande Piezometers

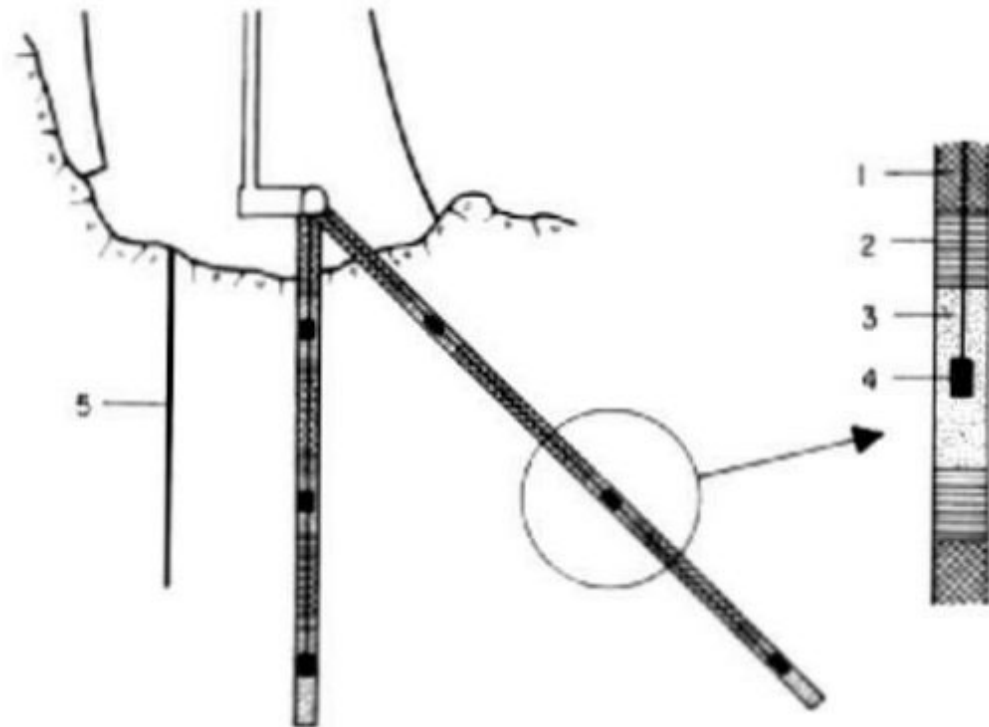
- Provides faster response time than standpipe piezometer in low permeability materials
- Alternating sand at piezometer zones, sealed by bentonite above and below.
- Preferred method as compared to the fully-grouted method for some users (more confident to target specific formation).
- Can be more difficult for boreholes deeper than ~30-50m due to risk of bridging of bentonite (use coarse bentonite chips or coarse coated bentonite pellets. Don't use bentonite powder).
- Maximum 2 or 3 per borehole



Monitoring system – Uplift pressures

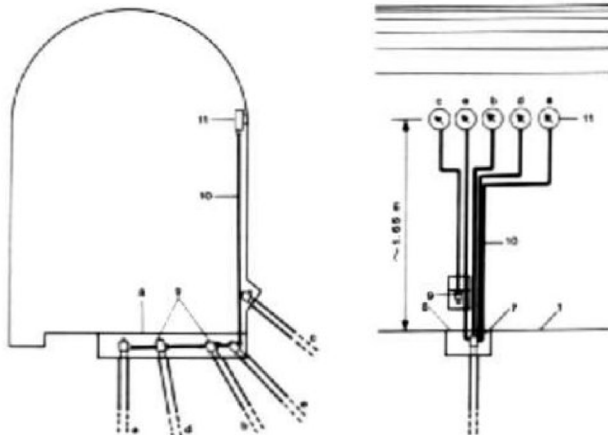


Reference number 2.301-1(2). Typical layout of uplift measurements of type (a).

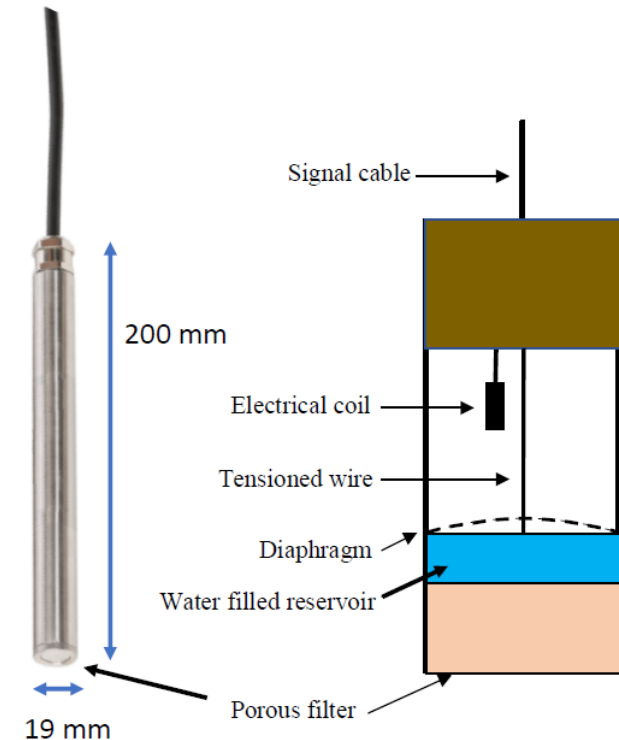
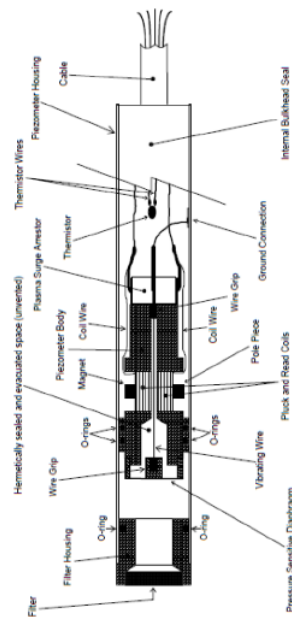


Reference number 2.301-1(6). Possible layout of uplift measurements of types (c) and (d) in the foundation of a dam. 1 Grout, 2 Clay pellets, 3 Quartz sand (grain size 1,5 to 2 mm), 4 Piezometer, 5 Grout curtain.

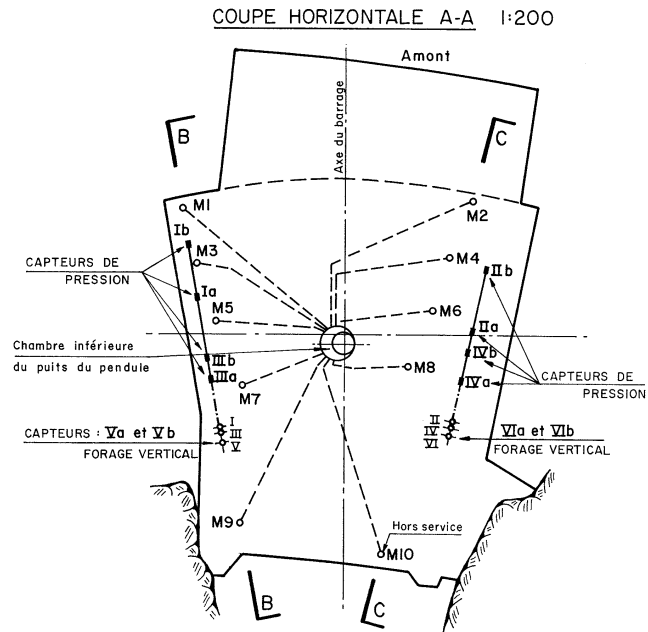
Monitoring system – Uplift pressures



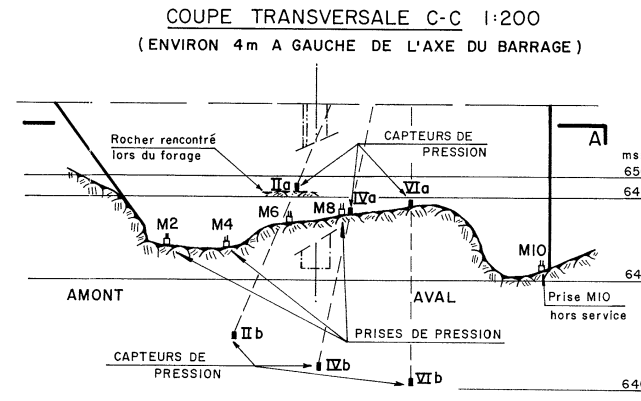
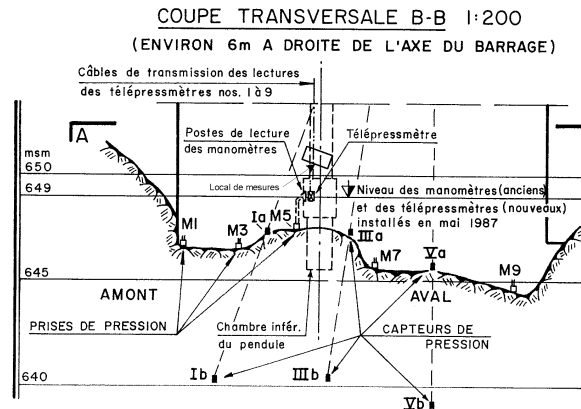
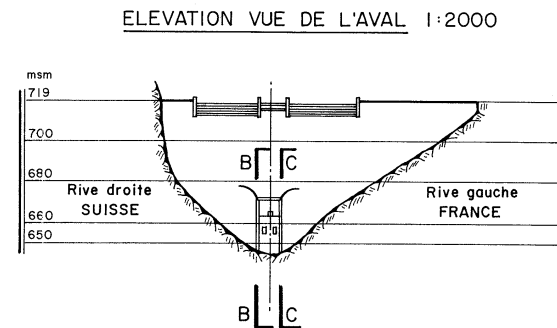
Reference number 2.301-1(3). Connections of pipes to manometers. Floor wall, 2 Grout, 3 Concrete, 4 Rock-concrete interface, 5 T-bud length of borehole, 6 Non-tubed borehole, 7 Ditch, 8 Metal cover, 9 T-piece (e.g. 2" to 2.5") acting as pipe closure and connection to pressure tube, 10 Flexible pressure tube, 11 Manometer.



Vibrating wire piezometer principle

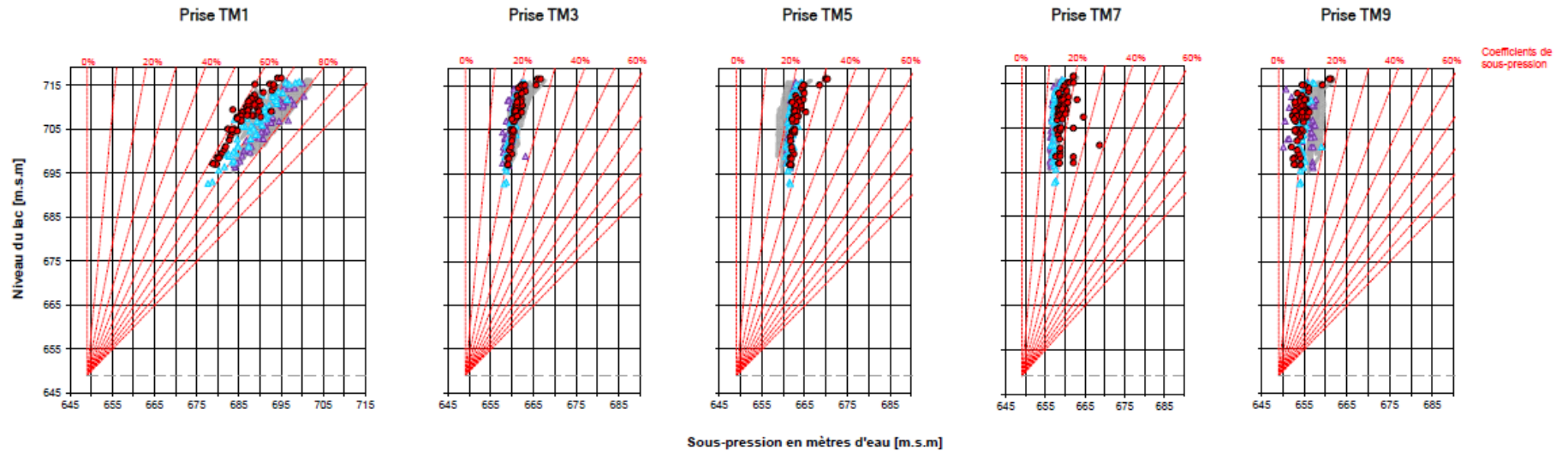


DISPOSITION DES PRISES M1 à M9
ET DES CAPTEURS DE PRESSION 1a à VIb

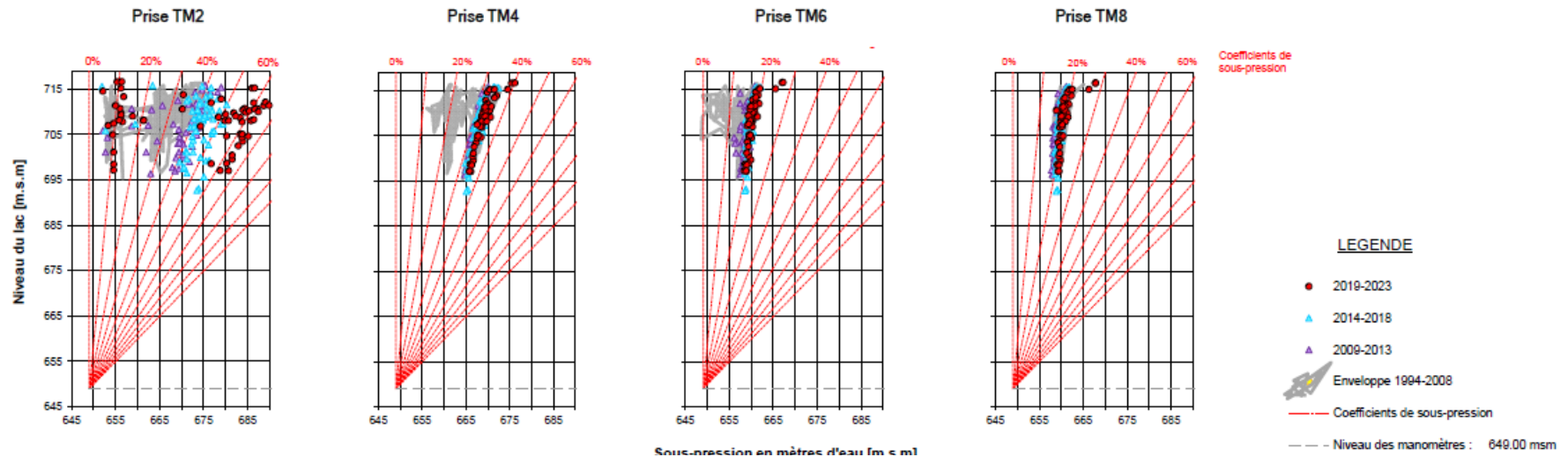


Dam Engineering

Dam Safety and Surveillance



RIVE GAUCHE : PRISES TM2, TM4, TM6 et TM8

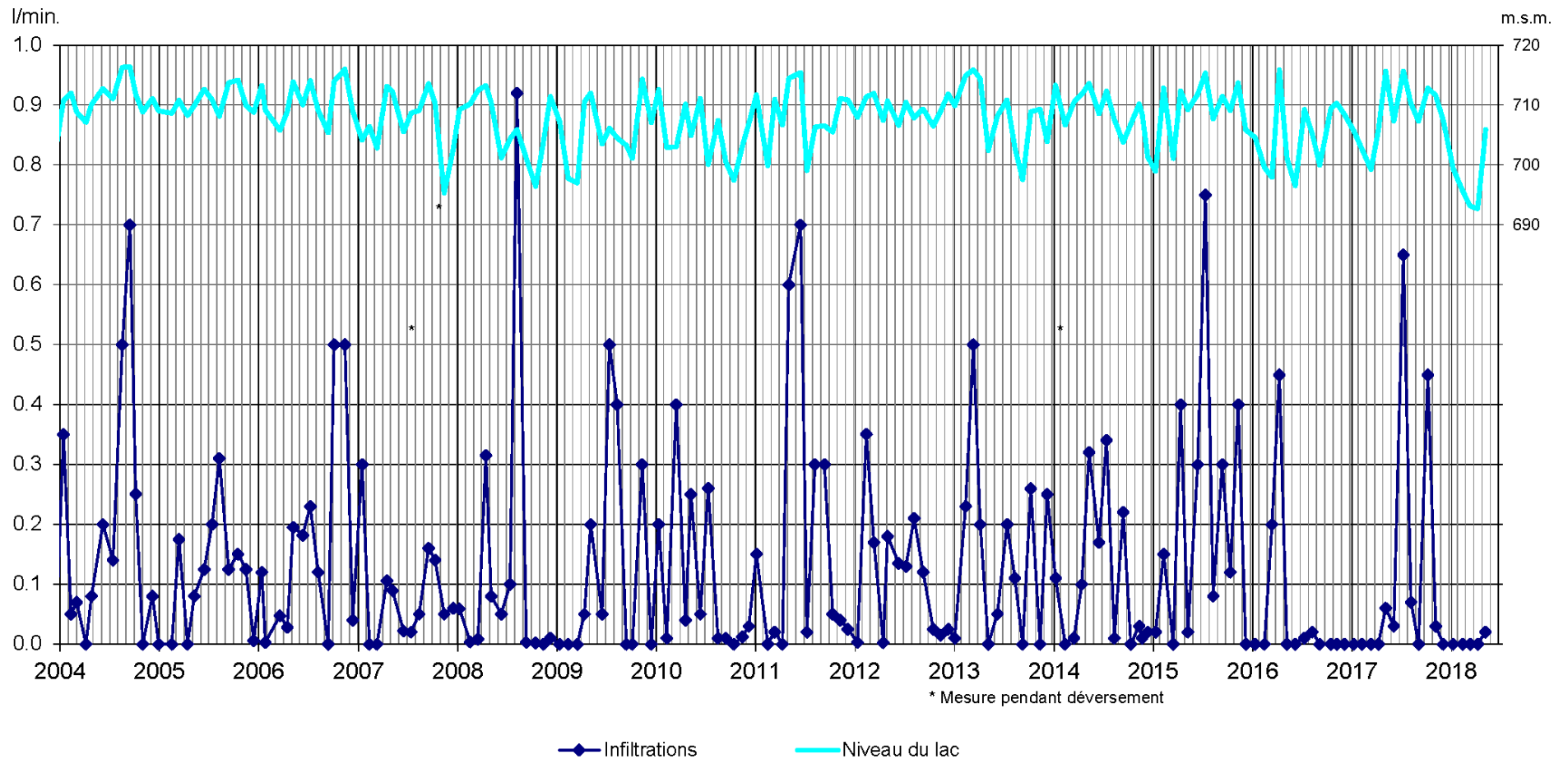


Monitoring system - Leakage

- Volumetric measurements
- Calibrated weir
- Turbidity measurement



Débits maximaux d'infiltrations dans la culée, rive gauche

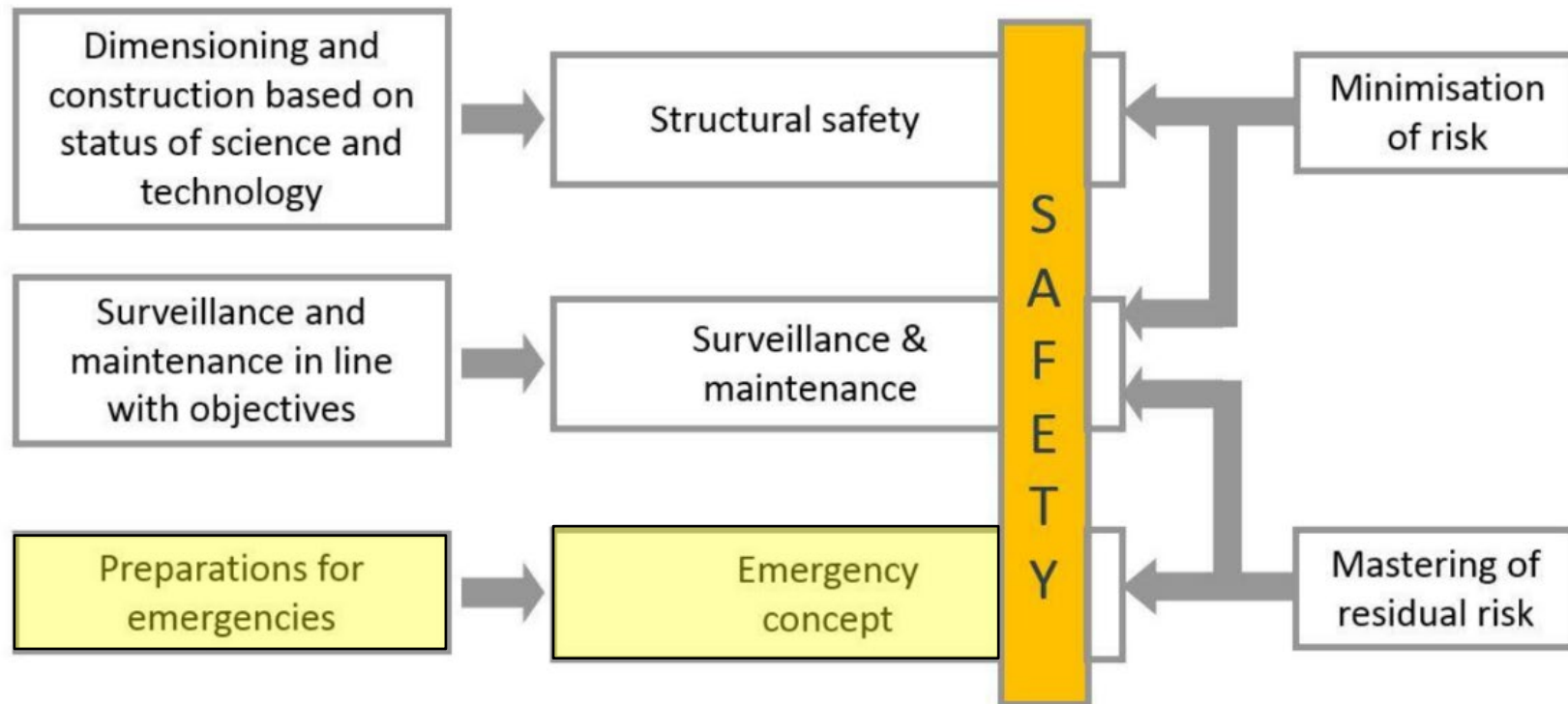


Frequency of measurements

Large <u>dams</u> facilities				
		Concrete dam	Embankment dam	Comments
Continual visual inspections		1 or 2 times a month	1 or 2 times a month	When the reservoir is been filled ²
Measurements to monitor the behavior of the facility	Deformations (with plumb lines or geodetic measurements)	1 or 2 times a month	1 or 2 times a month	When the reservoir is filled
	Seepage and drainage water (turbidity)	1 or 2 times a month	1 or 2 times a month	When the reservoir is filled
	Uplift and pore water pressure	1 or 2 times a month (interface between concrete-rock and foundations)	1 or 2 times a month (pore water pressure)	When the reservoir is filled
Other measurements		Once a month to once every two months	Once a month to once every two months	For measurements that ensure redundancy

Example.
Frequency is to be determined case by case

Swiss Dam Safety Concept

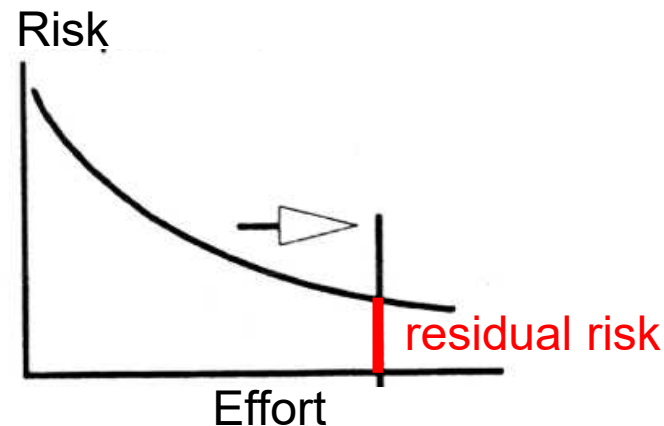


Emergency concept

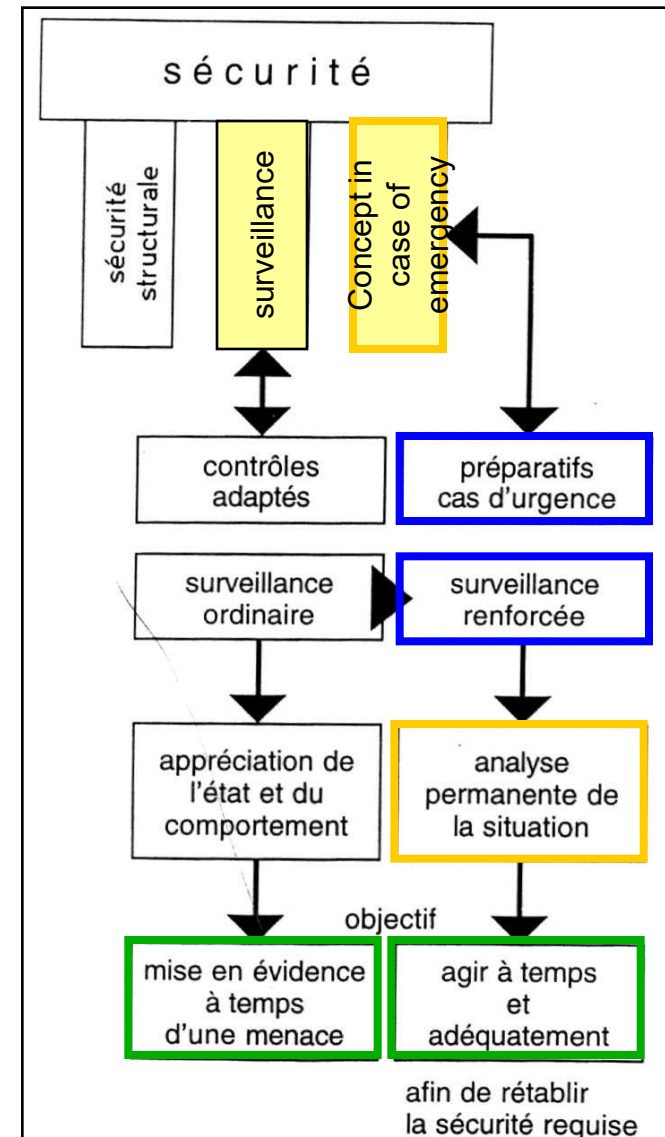
- a) Structural safety is verified
Periodic review
- b) Surveillance is performant
Monitoring
Inspections
Test of HM equipment
- c) Periodic safety assessment



Minimisation of risk

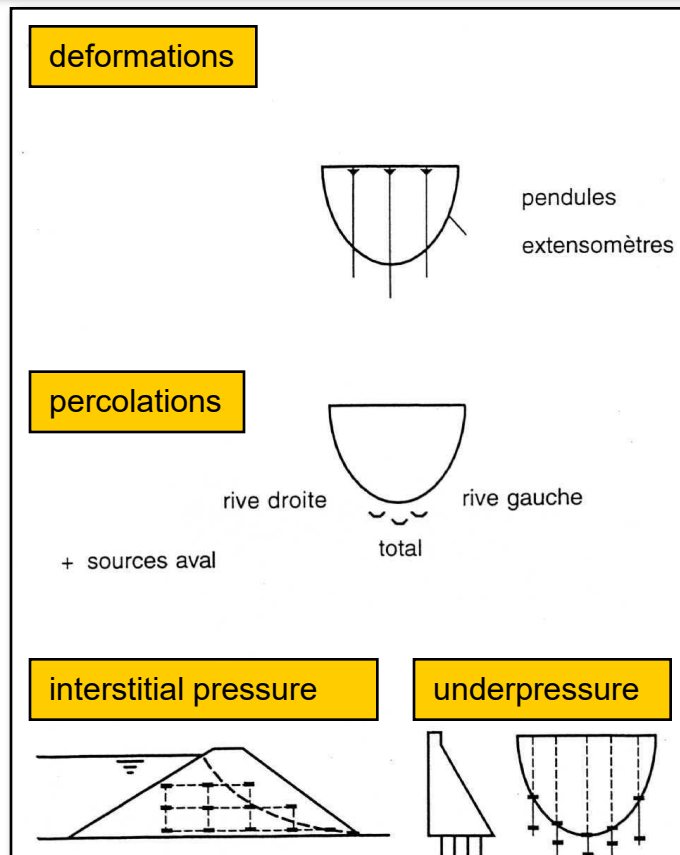


Correspondence between
ordinary surveillance and
enhanced surveillance

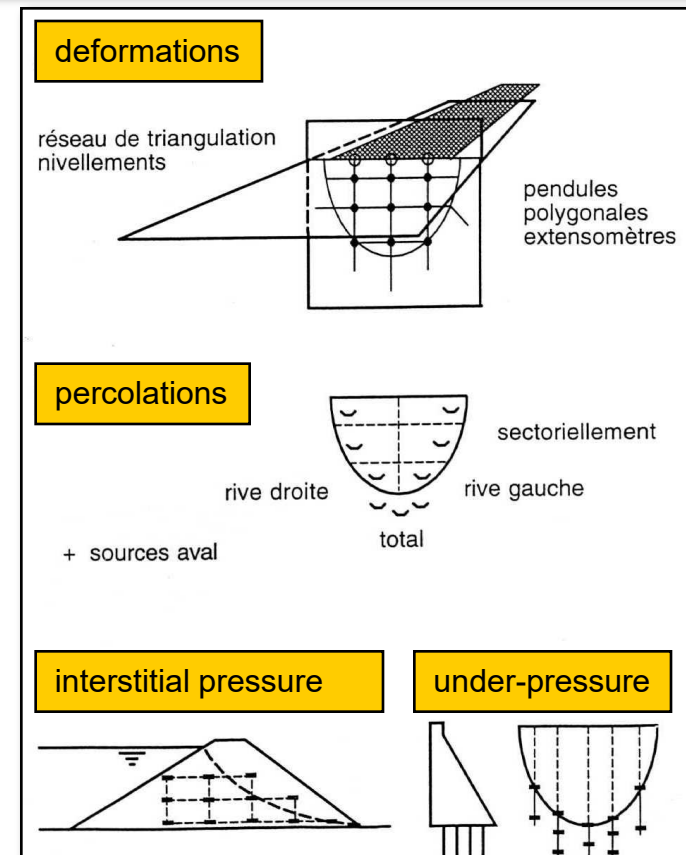


Concept of auscultation

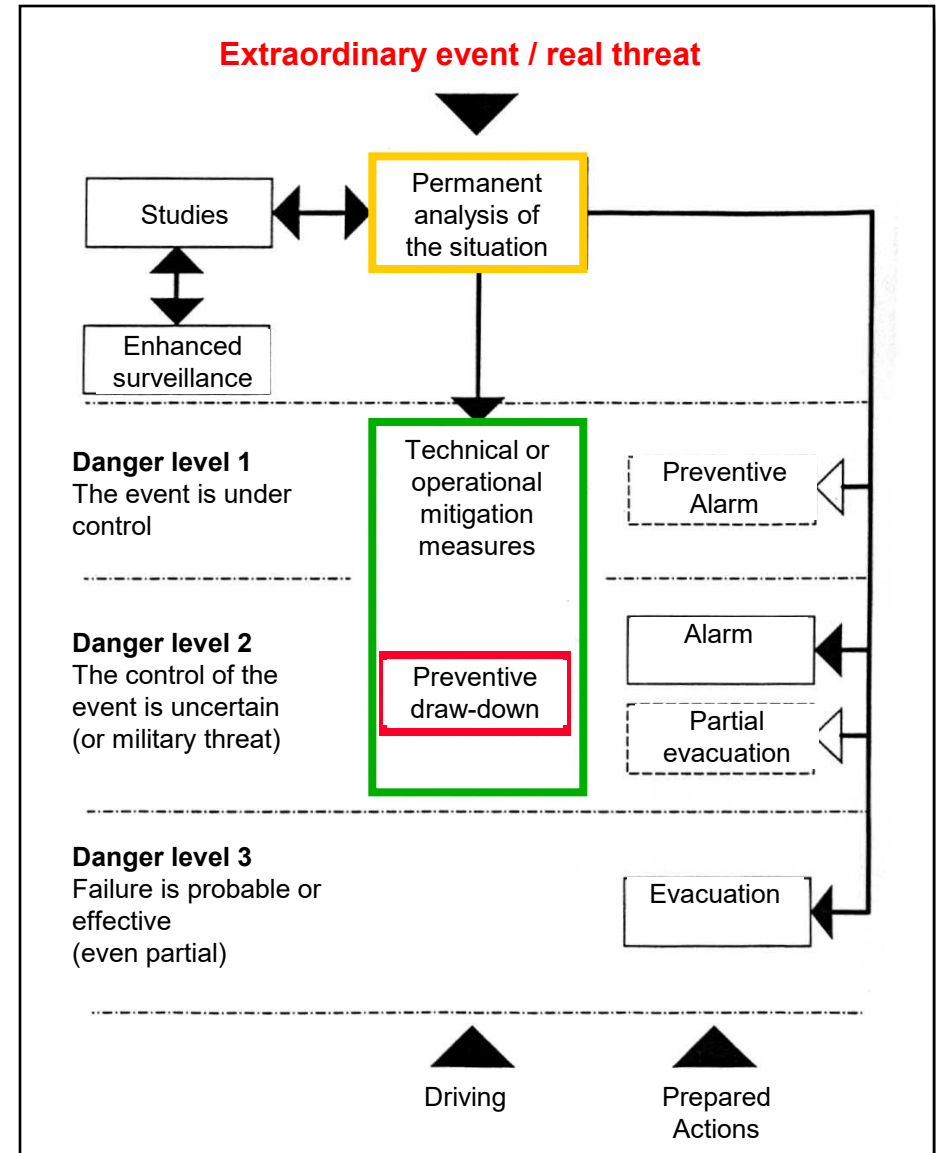
Ordinary surveillance



Enhanced surveillance



Emergency strategy

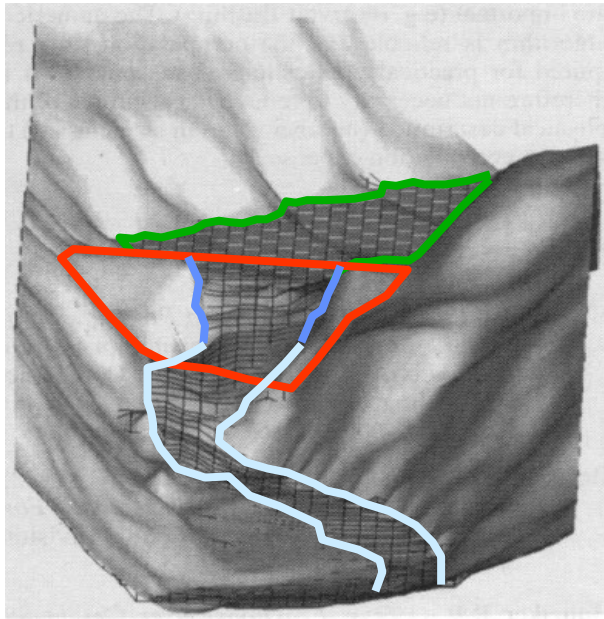


Flood maps – Failure mode

- Instantaneous failure
- Breach development

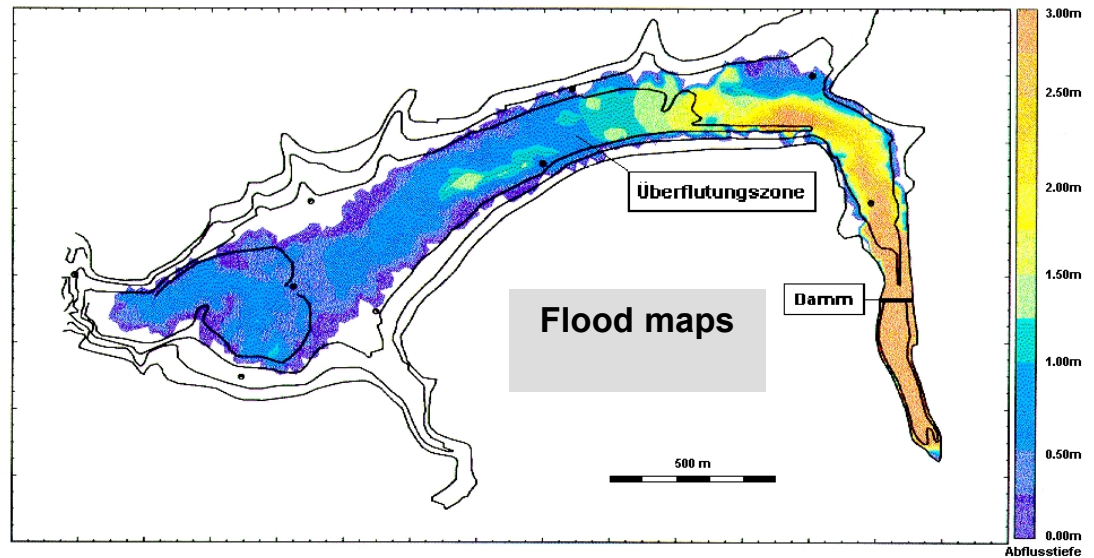


Flood maps - analysis of the rupture wave

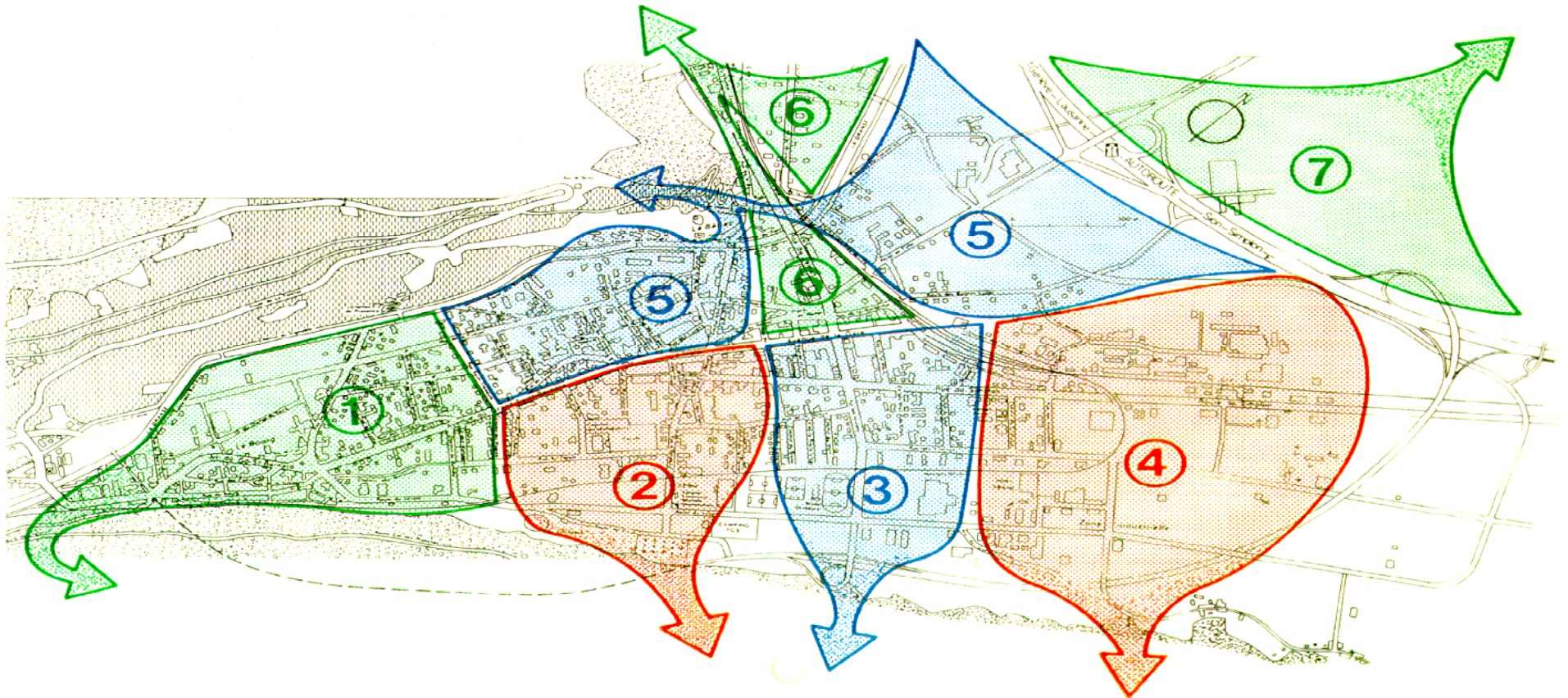


For further information:

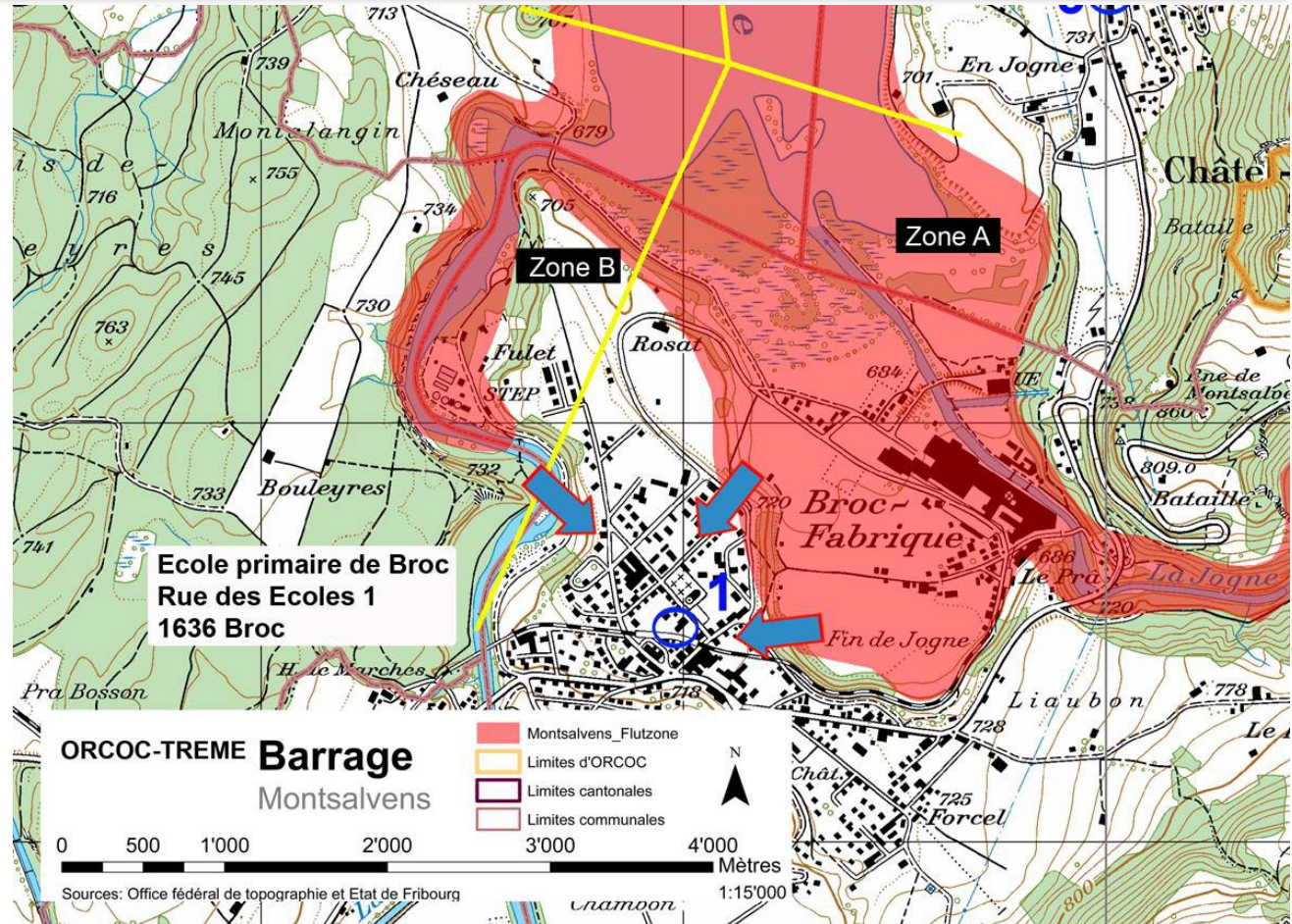
- Water depth and velocity
- Arrival time



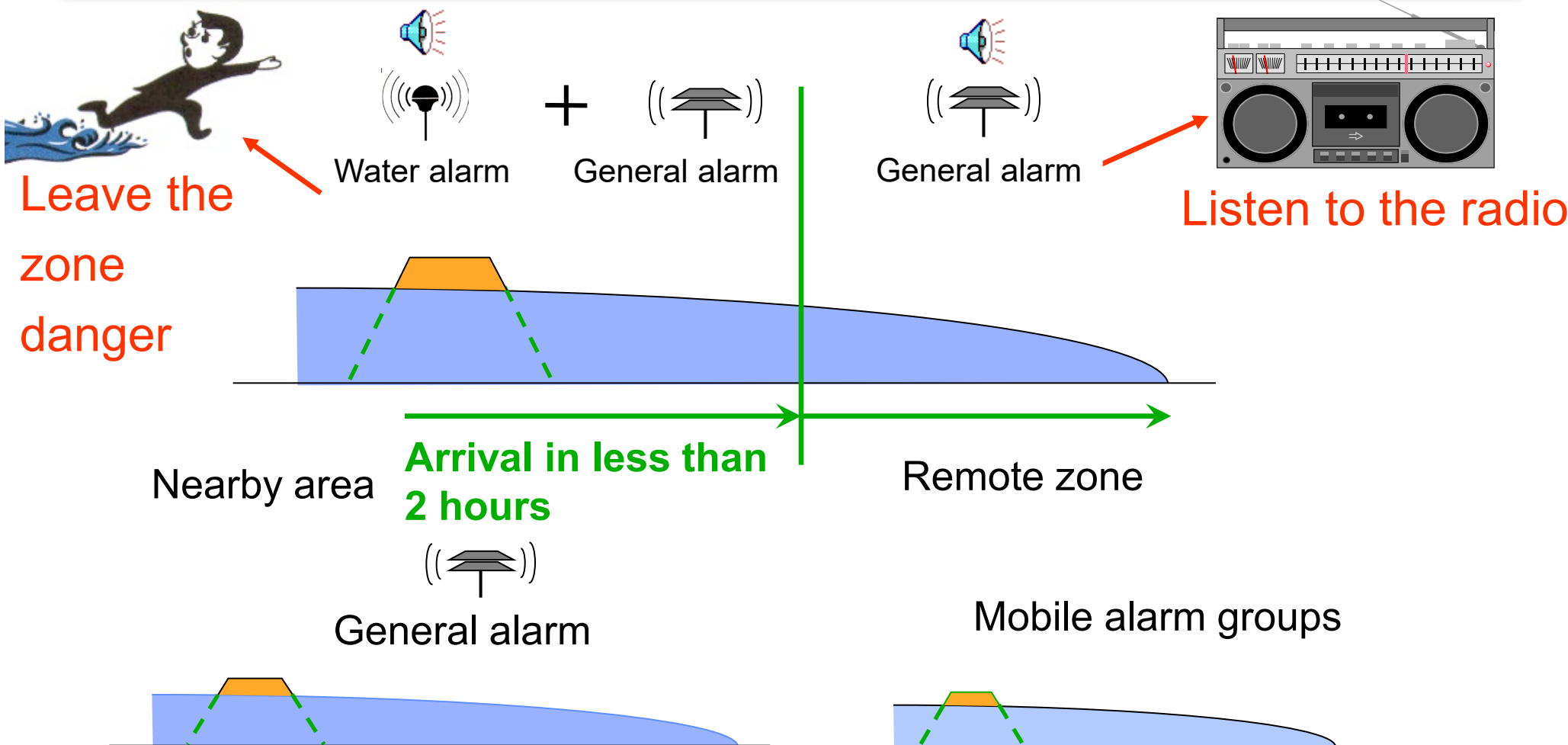
Evacuation plans



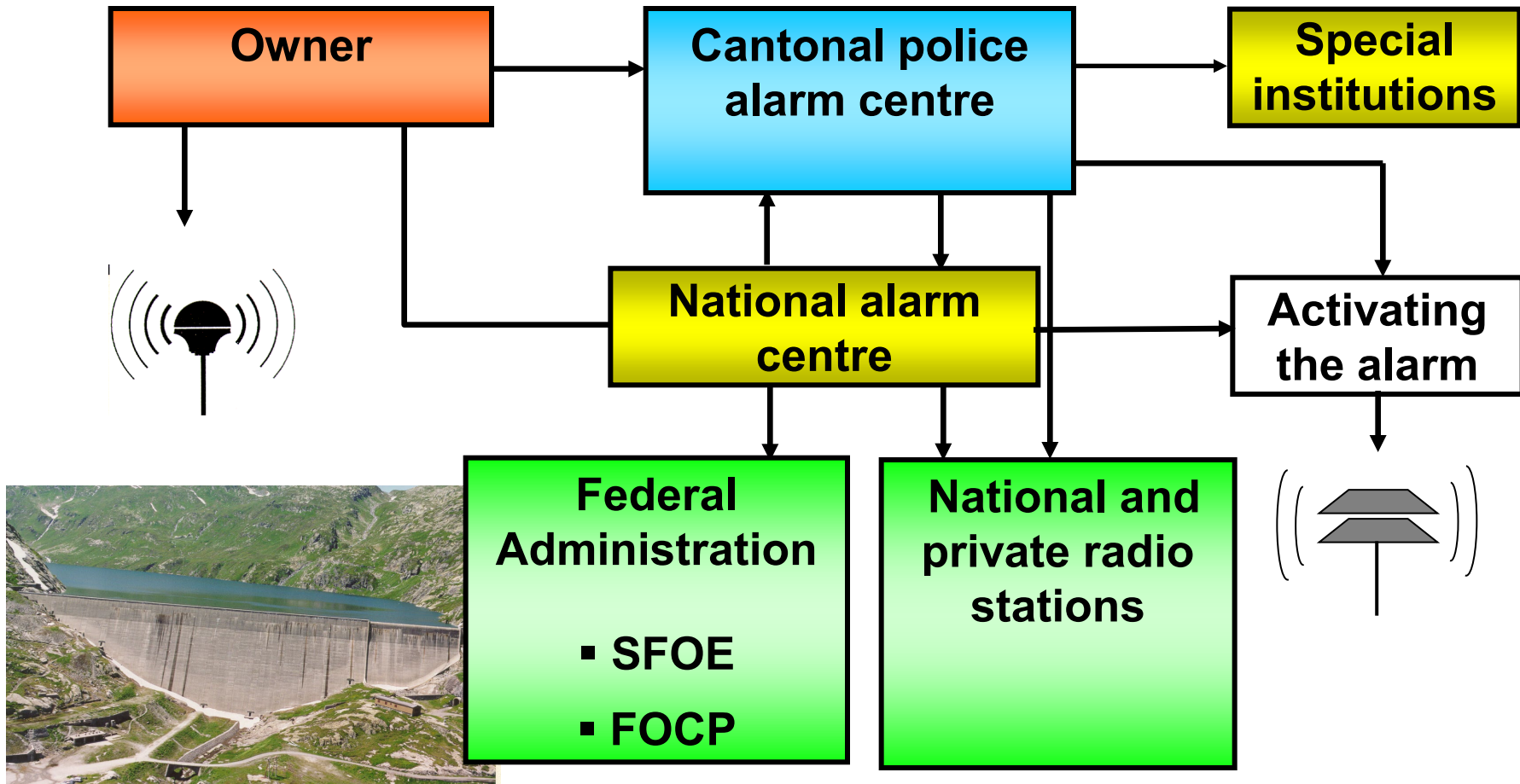
Evacuation plans



Alarm system



Alarm organisation



New trends and new developments

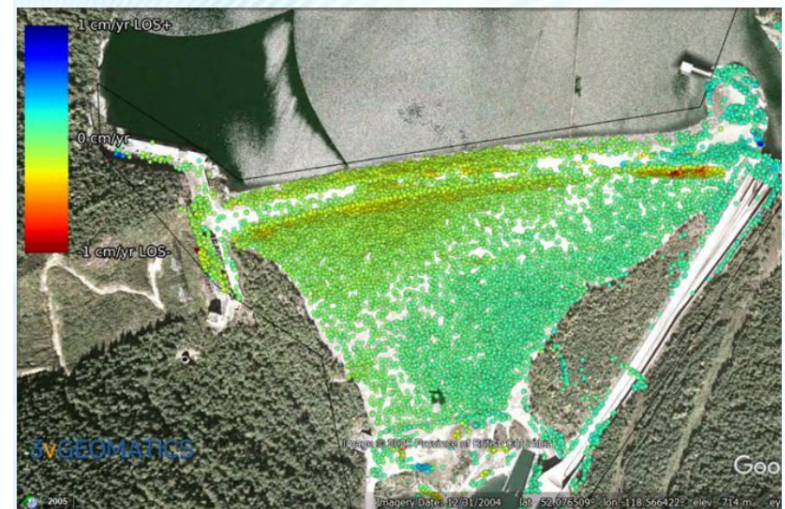
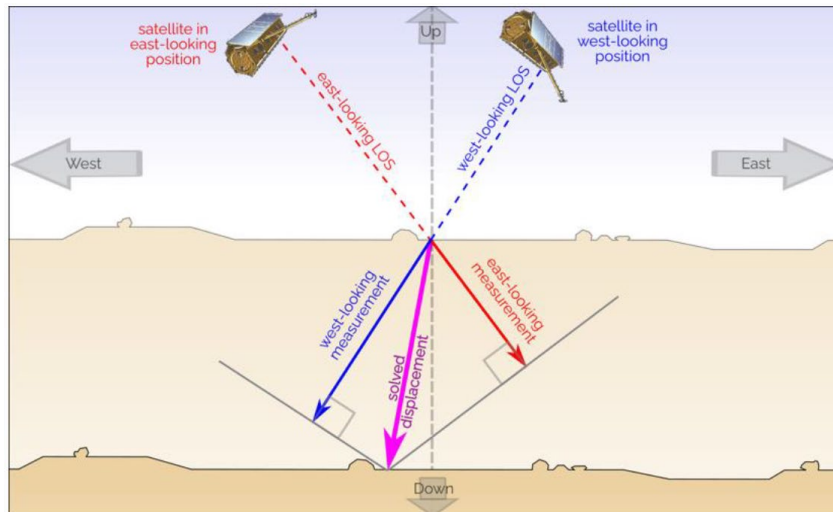
⇒ New technologies in instrumentation and monitoring

- ◆ Satellite InSAR(Interferometric Synthetic Aperture Radar)
- ◆ Terrestrial SAR
- ◆ Strong (and Weak) Motion Accelerograph (SMA)
- ◆ Distributed Fiber Optic Sensing Technology
- ◆ GNSS
- ◆ Robotized Total Stations
- ◆ Lidar, UAV Lidar
- ◆ UAV Photogrammetry
- ◆ Geophysics - Electric Resistivity Tomography
- ◆ Geophysics – Seismic – Acoustic Resonance
- ◆ Underwater Survey – ROV
- ◆ Multibeam sonar, side scan sonar

New trends and new developments

⇒ New technologies in instrumentation and monitoring

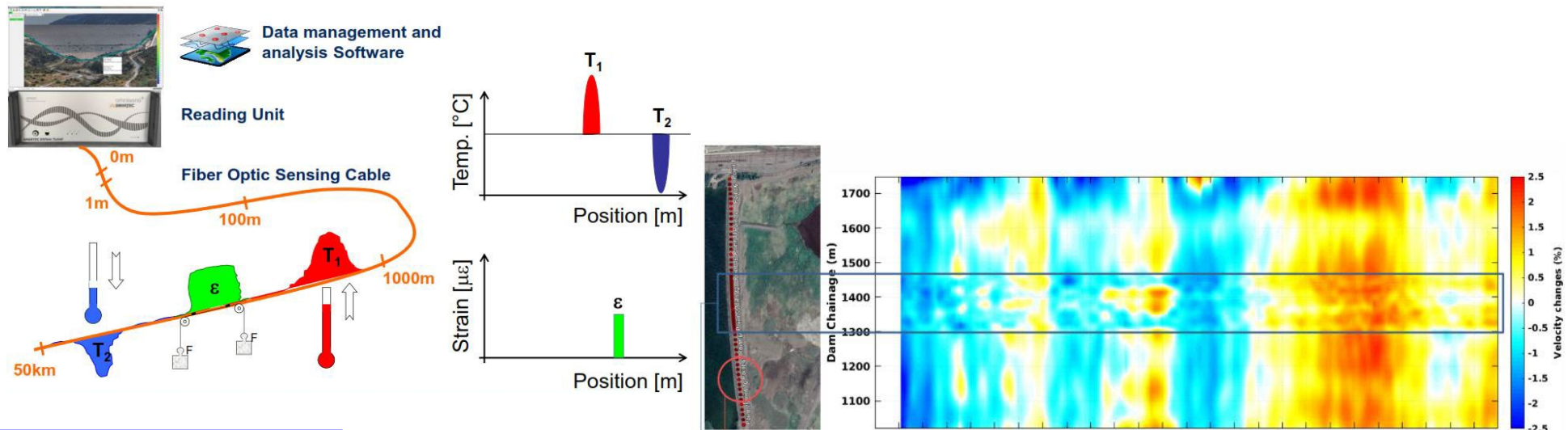
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New trends and new developments

⇒ New technologies in instrumentation and monitoring

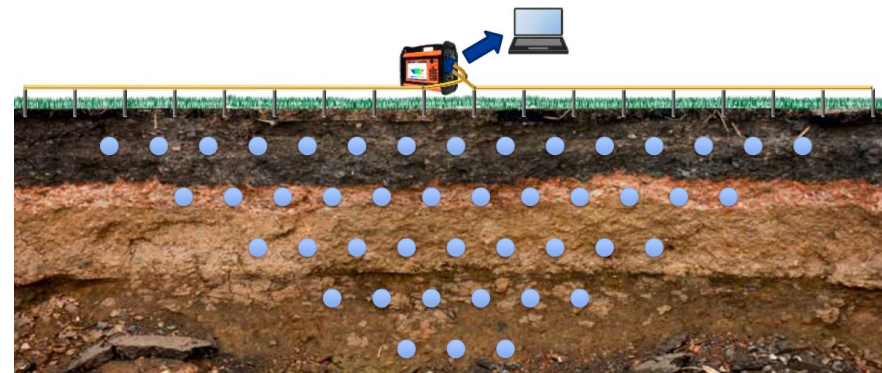
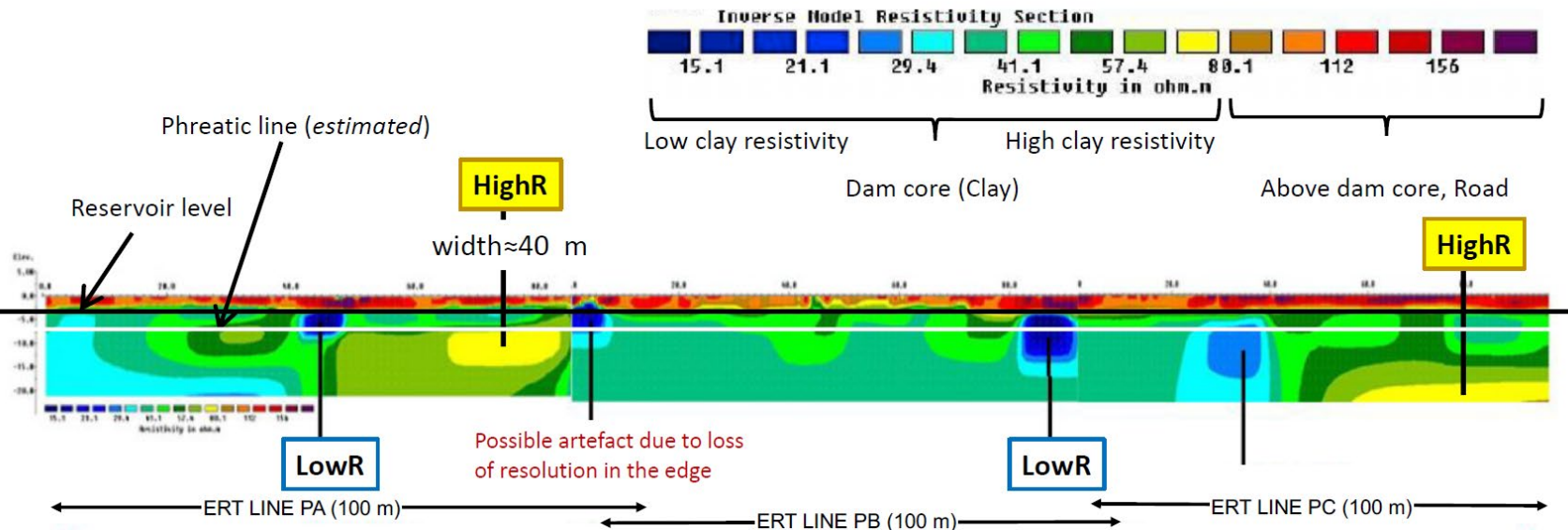
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- ◆ GNSS



New trends and new developments

⇒ New trends

- ◆ Satellite
- ◆ Terrestrial
- ◆ Strain
- ◆ Disturbance
- ◆ GNSS
- ◆ Robotics
- ◆ Lidar
- ◆ UAV Photogrammetry
- ◆ **Geophysics - Electric Resistivity Tomography**
- ◆ Geophysics – Seismic – Acoustic Resonance
- ◆ Underwater Survey – ROV
- ◆ Multibeam sonar, side scan sonar

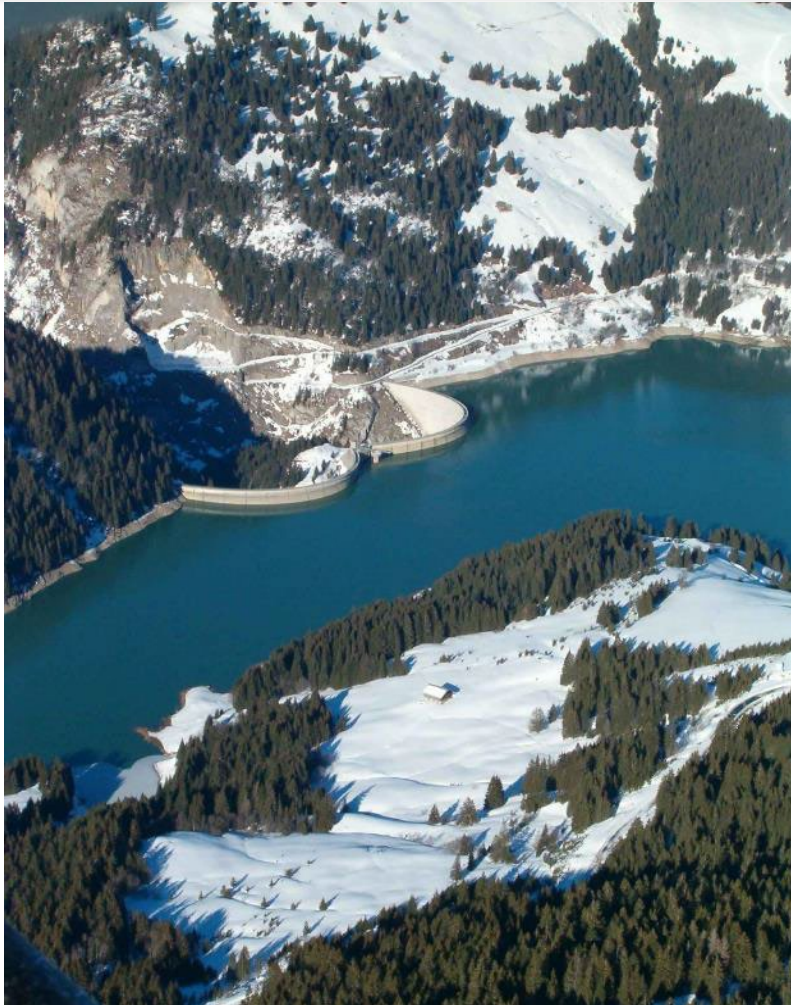


New trends and new developments

⇒ New technologies in instrumentation and monitoring

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Conclusions



- The Swiss dam safety concept developed in Switzerland is a success:
 - To date, there have been no major accidents;
 - No significant and lasting interruption to hydroelectric operations.
- The Swiss concept serves as a reference and working basis for several of ICOLD's international technical committees.
- It sets an example in many countries for the development of dam safety regulations.

Further information



www.swissdams.ch
www.icold-cigb.org

Laurent Mouvet
Civil engineer EPFL-SIA, INSEAD-IEP

Vice-President ICOLD
Laurent.mouvet@hydropartners.ch