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Numerical analysis of dams

PREDICTION OF PIEZOMETRIC LEVELS AT THE ROCK CONCRETE INTERFACE CONSIDERING THE NON LINEARITY OF PERMEABILITY IN THE FOUNDATIONS

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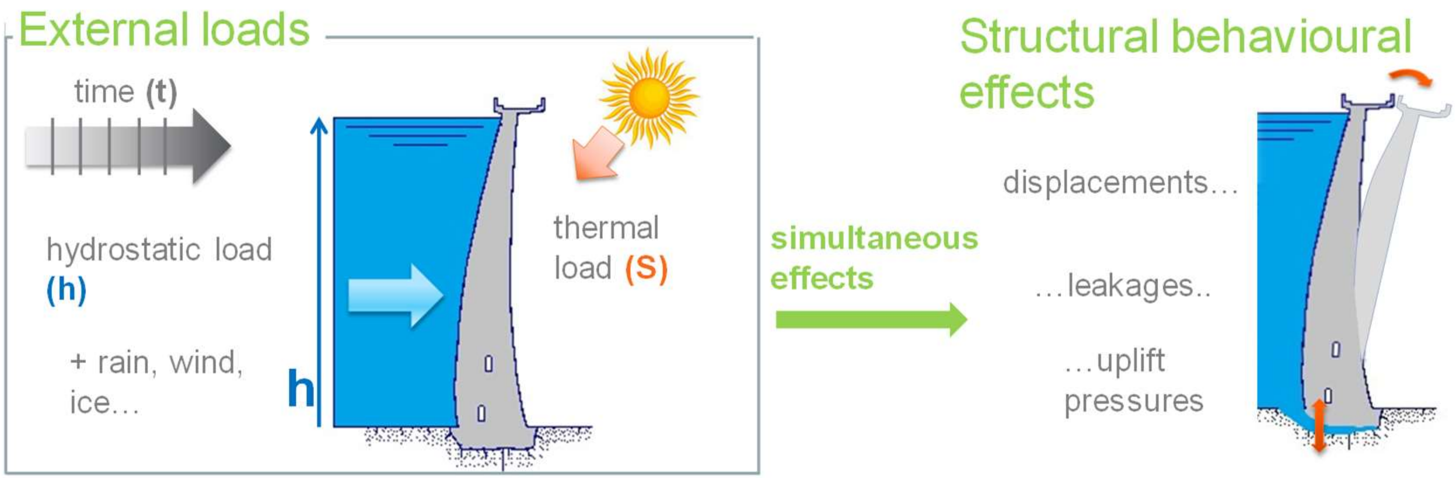
Context: dam surveillance



- Loads and effects are monitored and processed. **Raw times series are not easy to interpret.**
- Physico-statistical models to analyse time series of measurements:
  - Interpret the behaviour of the dam and assess its safety in real time
  - Understand the contribution of each external load
  - Follow the irreversible evolution of monitored phenomena, such as the aperture of the rock-concrete interface
  - …

In this study: a **non linear formulation** is proposed to describe monitored time series of **piezometric levels (PL)** at the rock-concrete interface of a French arch dam. Results are compared to the classical **linear model** (HST).

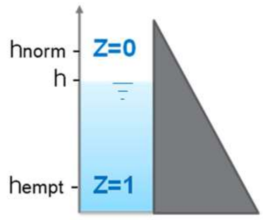
Hydrostatic Season Time model (HST)

- **A multi-linear regression model:**

PL: time series of monitored piezometric levels

$$\mathbf{PL_i = b_0 + f_1(t_i) + f_2(Z_i) + f_3(S_i) + \varepsilon_i}$$

	effect	Corresponding law	
Irreversible part	Time effect	$f_1(\mathbf{t}) = b_1\mathbf{t}$	(1)
Reversible part	Hydrostatic effect	$f_2(\mathbf{Z}) = b_2\mathbf{Z} + b_3\mathbf{Z}^2 + b_4\mathbf{Z}^3 + b_5\mathbf{Z}^4$	(2)
	Thermal (or seasonal) effect	$f_3(\mathbf{S}) = b_6\mathbf{cosS} + b_7\mathbf{sinS} + b_8\mathbf{cos2S} + b_9\mathbf{sin2S}$	(3)



- t: the day of the measurement
- $Z = \frac{h_{norm} - h}{h_{norm} - h_{empty}}$ the relative trough
- $S = 2\pi.\left(\frac{t}{365.25} - \text{floor}\left(\frac{t}{365.25}\right)\right)$ the season, angle equal to 0 on the 1st of January and 2π on the 31st of December

- **Correcting measurements by removing the reversible effects:** $\mathbf{CM_i = PL_i - f_2(Z_i) - f_3(S_i) = f_1(t_i) + \varepsilon}$

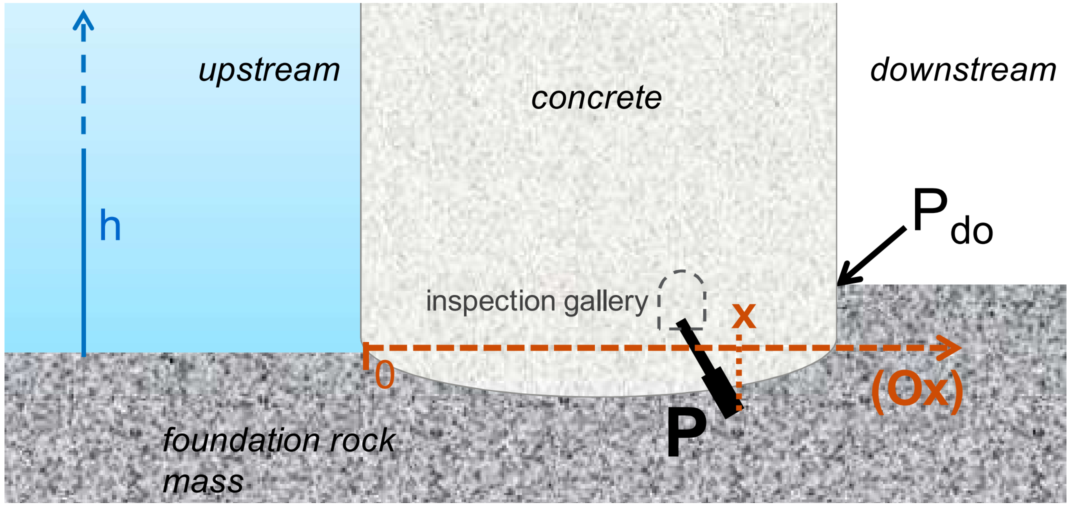
Identification of temporal effects, eventually abnormal evolutions ➔ **key diagnostic tool**

Assumption 1: reversible laws = time-independent

Assumption 2: Z, S have purely independent (additive) effects

Introducing non-linearity: NL HST

Aim: describe the piezometry (P) at the rock concrete interface by integrating the **non additive effects** of the loads, keeping **a high interpretability**



Representation of the rock-concrete interface

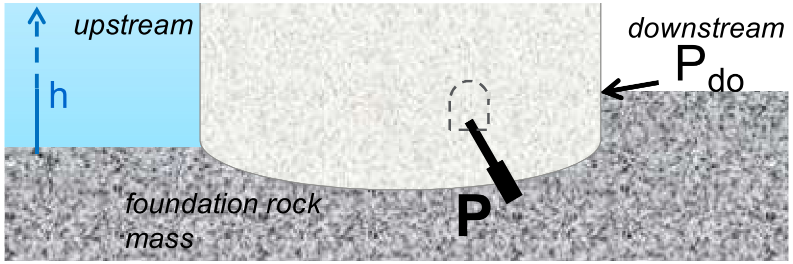
- **P** the piezometry measured at the contact
- $\mathbf{P_{do}}$ the piezometry at the downstream end
- $\mathbf{H_{load}} = h - P_{do}$ the hydrostatic load
- k(x) a dimensionless factor, written **k**

Principle:

P at the interface = a fraction of the total upstream load	$P = P_{do} + k \cdot H_{load}$

Introducing non-linearity

Expression of k



$$P = P_{do} + k \cdot H_{load}$$

The permeability of the medium is not homogeneous nor isotropic ➔ k varies with external loads

- **Variation of the rock-mass permeability**

External loads ➔ induce mechanical stresses on the structure ➔ mechanical strains in the foundation ➔ makes the permeability of the foundation vary

$$k = g(meca)$$

- **Effect of the mechanical stresses on the structure: additivity hypotheses**

$$meca = f_1(S) + f_2(Z) + f_3(t) + \varepsilon_i$$

- **Influence on the permeability:**

$$k = g_{non\ linear}\ (meca) \Longrightarrow \boxed{k = tanh(meca)}$$

Validation: *vertical displacements recorded at the rock-concrete interface*

Introducing non-linearity

- **Final expression:**

$$P_i = P_{do} + \left[b_1 + b_2 \cdot tanh\left(a_0 + a_1 \cdot cosS_i + a_2 \cdot sinS_i + a_3 \cdot cos2S_i + a_4 \cdot sin2S_i + a_5 \cdot Z_i + a_6 \cdot Z_i^2 + a_7 \cdot Z_i^3 + a_8 \cdot Z_i^4 + a_9 \cdot t_i\right)\right] \cdot \left[h_{norm} - Z \cdot \left(h_{norm} - h_{emp}\right) - P_{do}\right] + \varepsilon_i \; ; \qquad i \in \{1;N\}$$

➢ P_{do} is not precisely known ➔ optimize it as a regression parameter ➔ $P_{do} = b_0$

$$\boxed{P_i = b_0 + \left[b_1 + b_2 \cdot tanh\left(a_0 + a_1 \cdot cosS_i + a_2 \cdot sinS_i + a_3 \cdot cos2S_i + a_4 \cdot sin2S_i + a_5 \cdot Z_i + a_6 \cdot Z_i^2 + a_7 \cdot Z_i^3 + a_8 \cdot Z_i^4 + a_9 \cdot t_i\right)\right] \cdot \left[h_{norm} - Z_i \cdot \left(h_{norm} - h_{emp}\right) - b_0\right] + \varepsilon_i \; ; \qquad i \in \{1;N\}}$$

$b_1, b_2, a_0, \ldots, a_9$ 13 regression coefficients ➢ nonlinear least squares fitting, using the Levenberg Marquardt algorithm

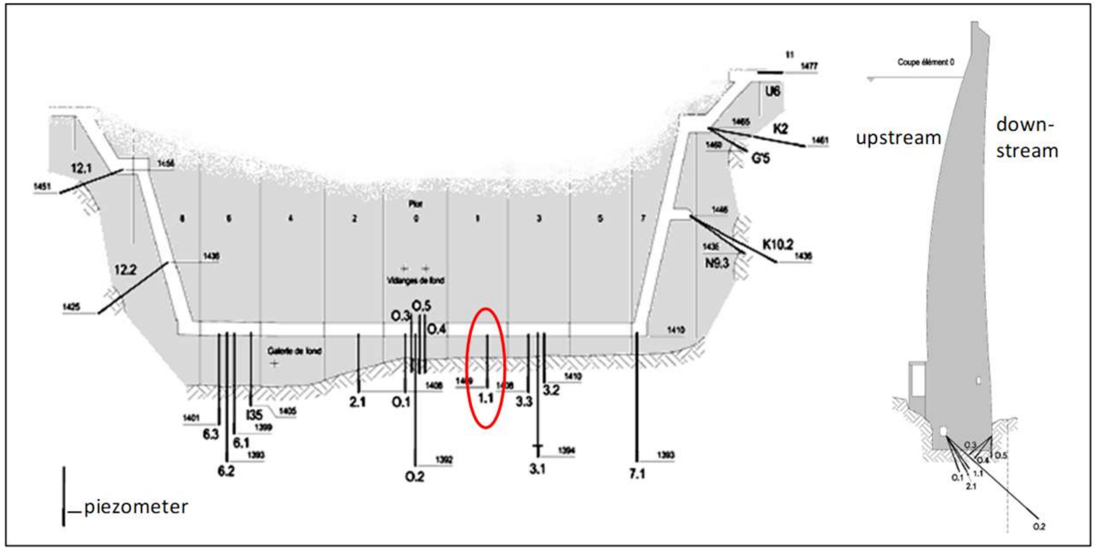
ε_i residuals

$$P = b_0 + \boxed{\left(b_1 + b_2 \cdot tanh(a_0 + f_1(S) + f_2(Z) + f_3(t)\right)} \cdot \boxed{H_{load}(Z)} + \varepsilon$$

k **x** H_{load}

Case study: studied dam

- composite structure comprising a gravity buttress which leans on a central **double curvature arch**
- maximal height: 150m
- total crest length: 804m
- **rock-concrete interface of the arch dam is open**



Studied sensor:

- Piezometer 1.1→ directly **influenced by the aperture** of the interface.

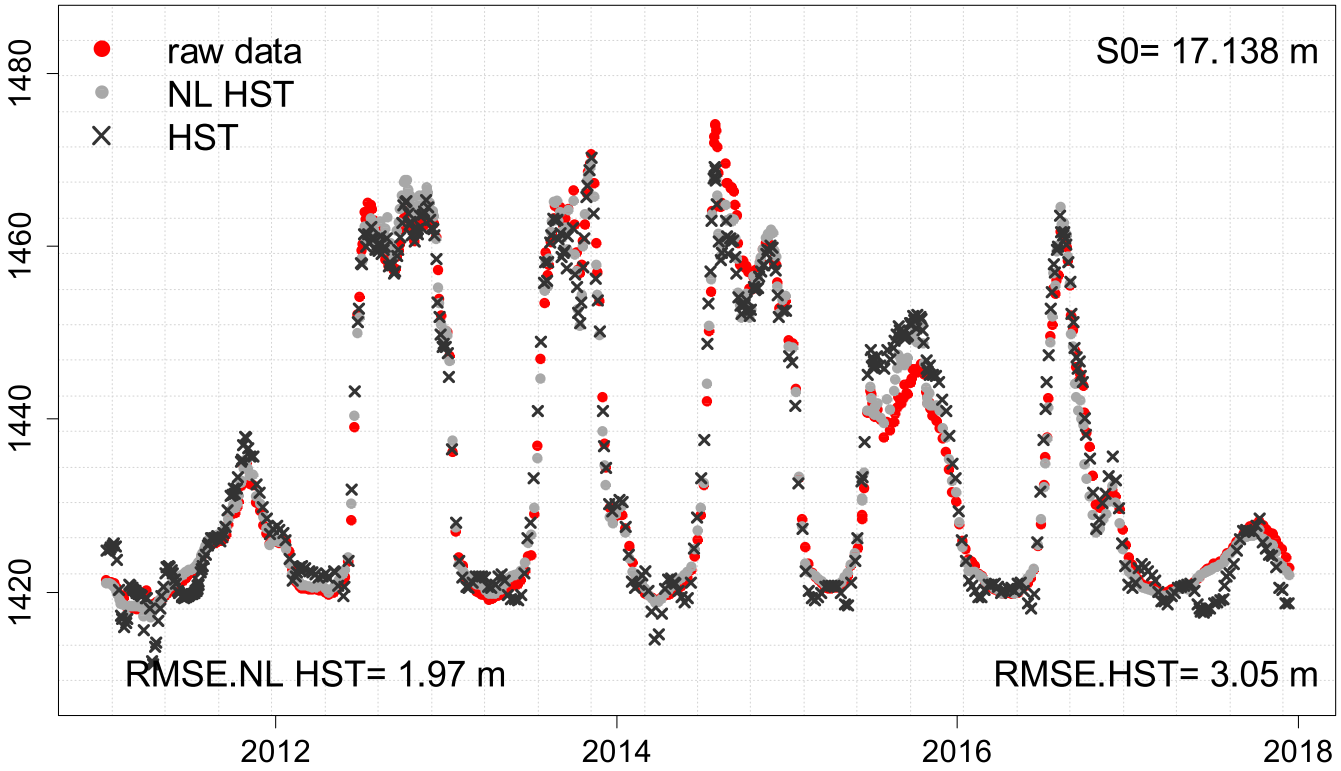
Results

- **Prediction performances**

	HST	NL HST
Initial standard deviation (m)	17.14	
Root Mean Square Error (m)	3.05	1.97

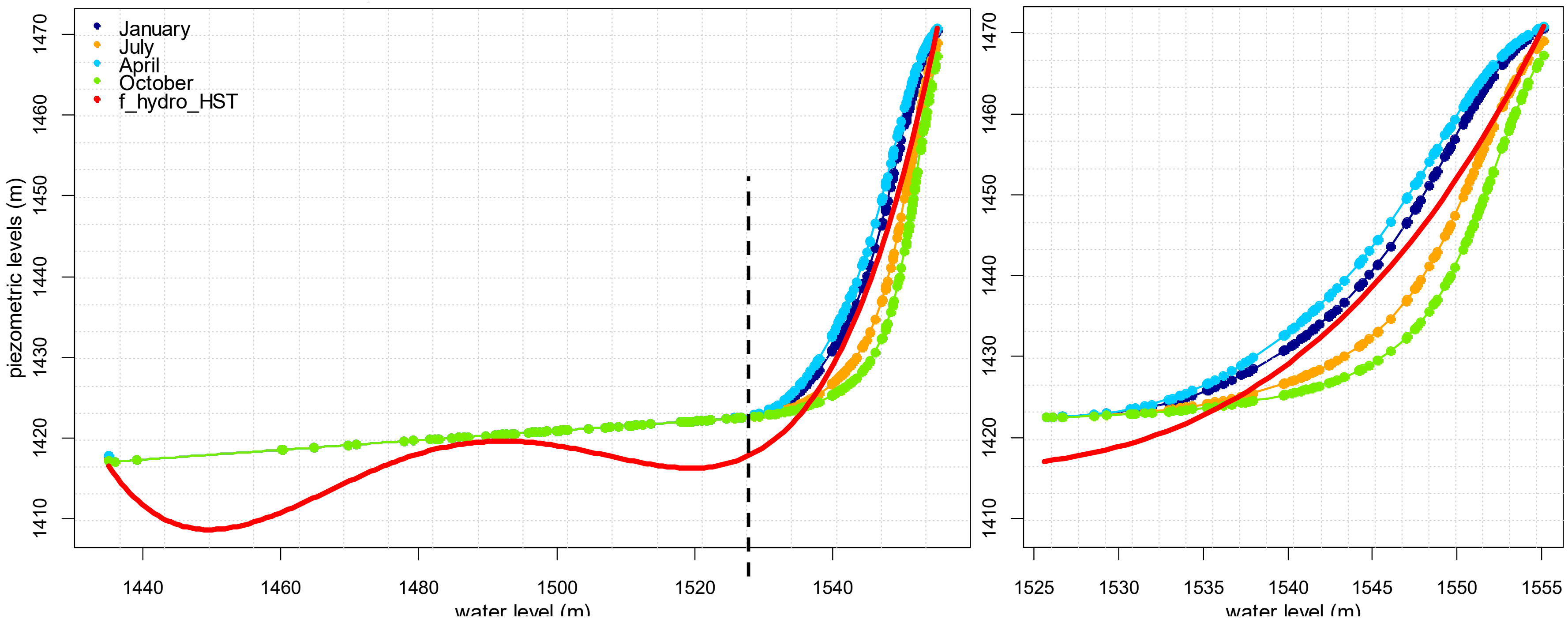
improves HST by 35.4%

Raw data and predicted piezometric levels (NL HST and HST) PZ1.1



Results

- **Reversible effects: hydrostatic effect**



NL HST:

1435m to 1528m: hardly any PL variation

Threshold: 1528m ➔ increase of the PL ➔ opening of the aperture, uplift pressures develop

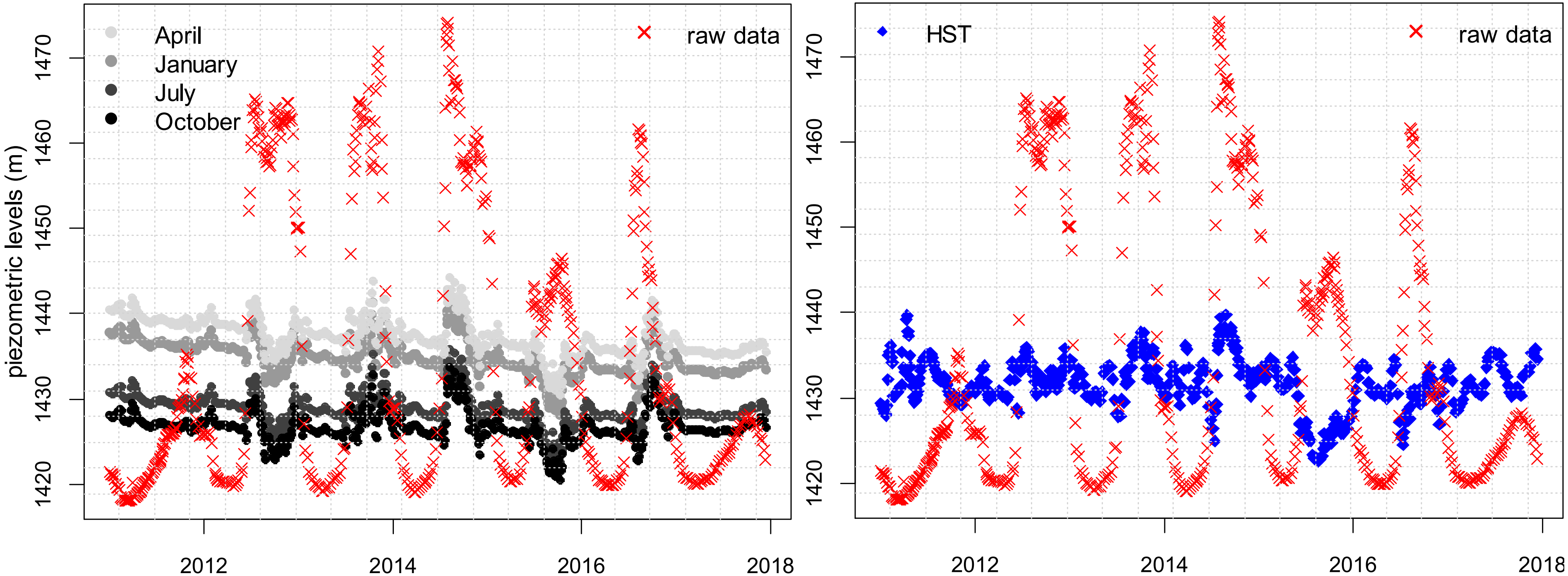
Above 1528m: **the thermal state controls the size of the aperture**

HST:

oscillations (polynomial VS tanh), average effect (no coupling with S)

Results

- **Irreversible effect: corrected measurements**



The corrected measurements provided by NL HST (left) and by HST (right), for a median water level

NL HST:

low remaining scattering, precise irreversible trend ➔ **improvement for monitoring purposes, diagnostic tool**

Temporal evolution: decrease ➔ **gradual closing of the R-C aperture**

HST:

No distinction between the thermal state ➔ average response, seasonal aspect is conserved ➔ no clear trend

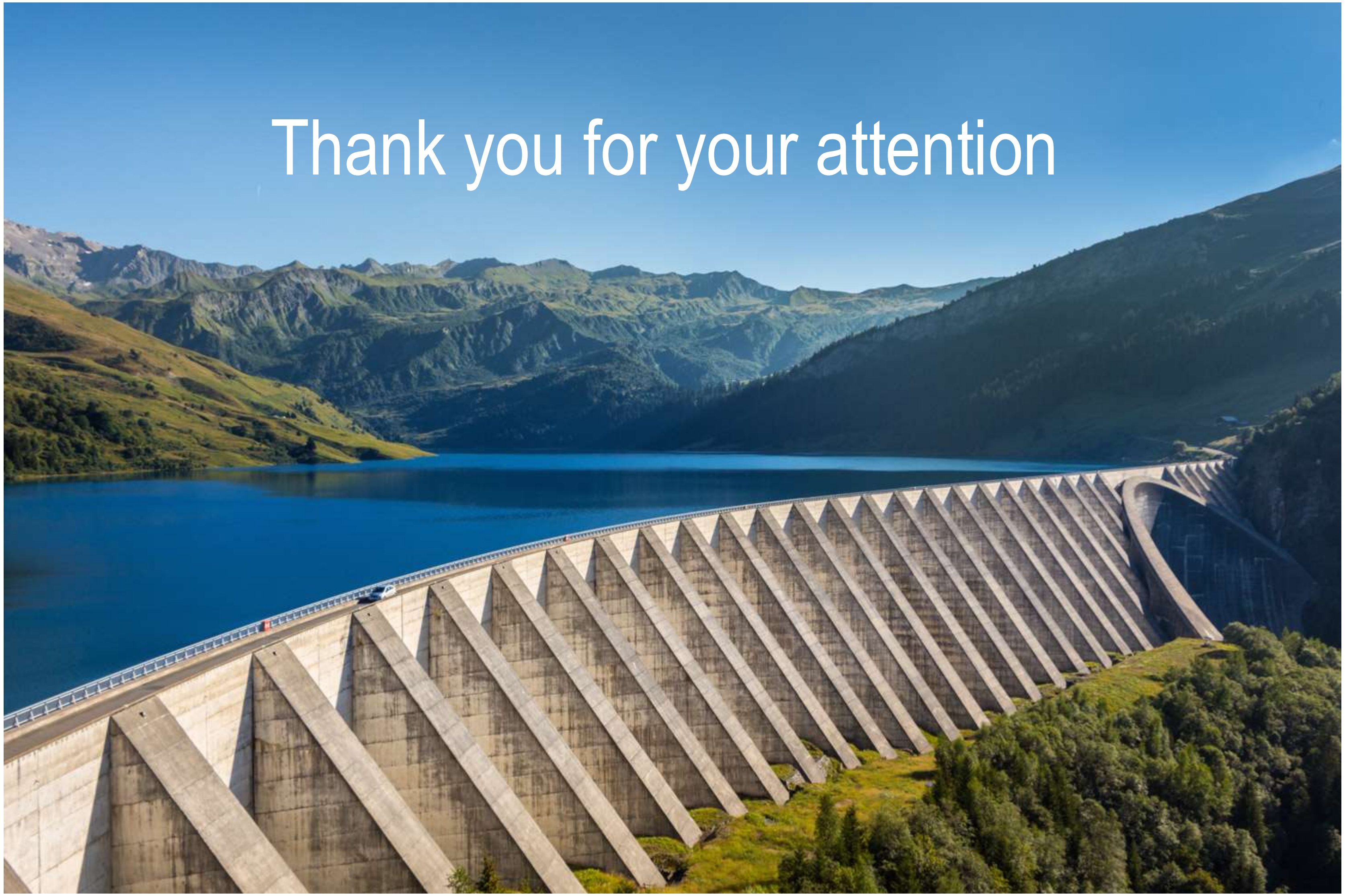
Conclusion

- Well adapted to monitoring purposes
  - ✓ Better accuracy than HST
  - ✓ Easy to implement
  - ✓ precise visualisation of the temporal evolution

- It permits to overcome the non additivity issue
  - ✓ Gives an account of the coupled effects of the loads
  - ✓ rich physical interpretation of the phenomenon (closing of the aperture, role of the thermal state)

Possible improvement

- ➢ Could be adapted to leakage
- ➢ Could take into account real temperatures


Thank you for your attention

Appendix: corrected measurements

- **aim:** reveal the temporal evolution of the phenomena.

- Linear model: $\mathbf{CM_i = PL_i - f_2(Z_i) - f_3(S_i)}$
  - Make very measurements comparable: observe measurements under « **identical conditions** »

    $$\mathbf{CM_i = f_1(t_i) + \varepsilon}$$

  it corresponds to calculating the PL that would have been observed had $f_1(Z) = 0$ and $f_2(S)=0$

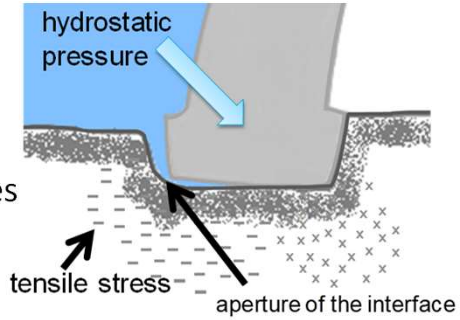
  $\{f_1(Z) = 0$ and $f_2(S)=0\}$ ⇔ $\{Z=0; S=S_{average}\}$ ⇔ $\{Z=Z_{ref}; S=S_{ref}\}$ ➔ $\mathbf{CM_i = f_1(t_i) + f_2(Z_{ref}) + f_3(S_{ref}) + \varepsilon_i}$

- Non linear model: $PL = f(Z, S, t)$
  - the effects are no longer additive ➔ impossible to remove the effect of Z and S as simply as with HST
  - set Z and S to reference values to observe the measurements under **identical conditions**

$$CM = f\left(Z_{ref}, S_{ref}, \boldsymbol{t}\right) + \boldsymbol{\varepsilon}$$

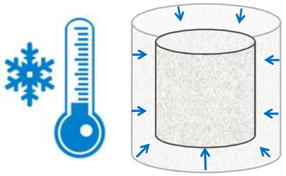
Context: aperture of the rock/concrete interface

- Thin arch dams, large valleys
- state of compression, hydraulic conductivity of the foundations vary from upst. to downst.
- heel: hydrostatic load transmitted to the foundations, propagation of uplift pressures
- mechanical stresses ↔ state of aperture
- Characterization of the aperture: monitoring the **piezometric levels**

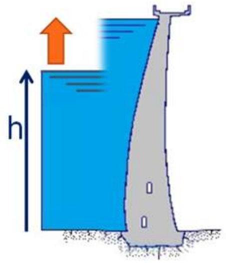


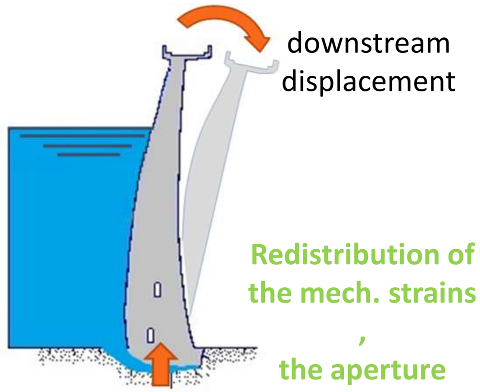
Non-linear features:

- Effect of S Season: thermal sensitivity of concrete



- Effect of h (water level):



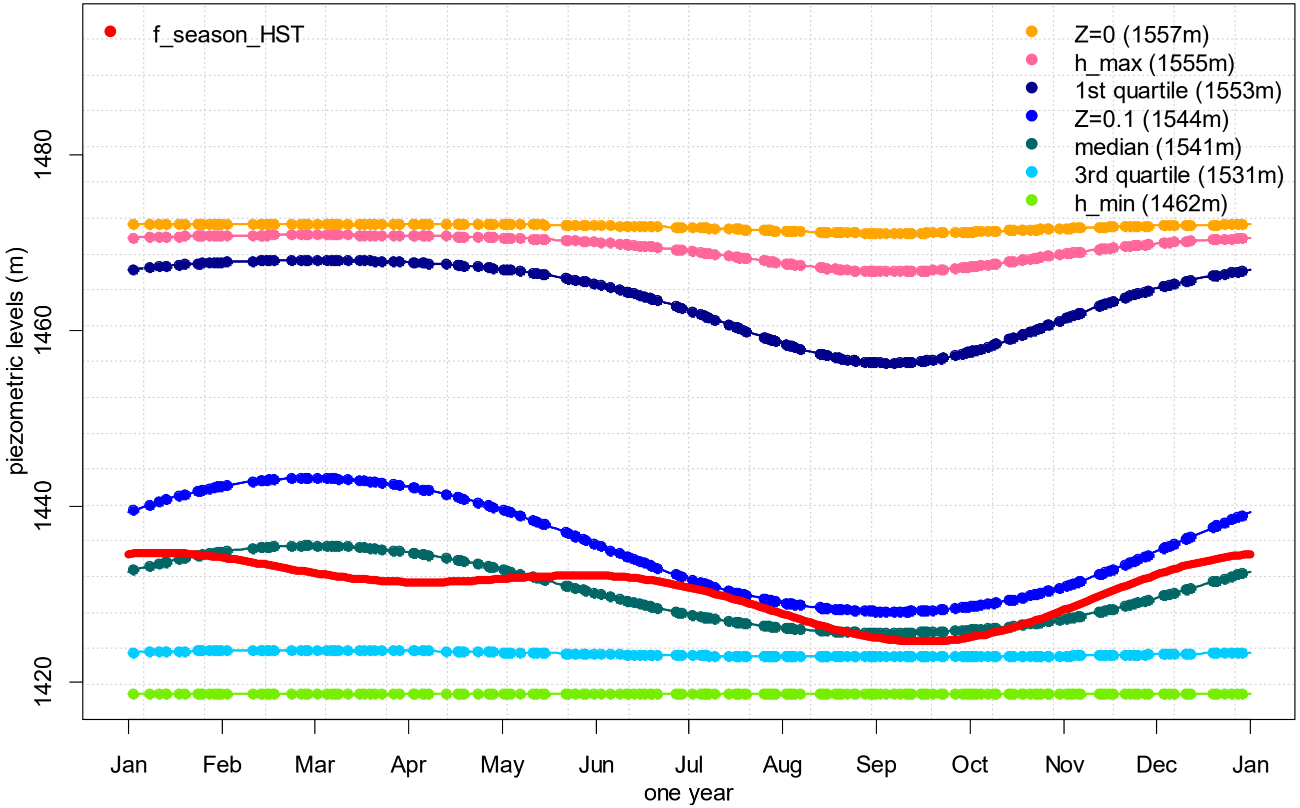


➔ not independent ➔ **need to include non-additive relationships between effects**

In this study: a **non linear formulation** is proposed to describe monitored **piezometric levels (PL)** at the rock-concrete interface of a French arch dam. Results are compared to the classical **linear model** (HST).

Results

- **Reversible effects: seasonal effect**



NL HST:

Min (resp. max) in October (resp. April) ➔ thermal sensitivity of concrete

Threshold between 1462m and 1531m

HST:

Two minima (April and Oct) ➔ limit of the additivity hypothesis. HST artificially separates the effects of S and Z

Interpretability: method

- **Reversible and irreversible effects:**

Analogy with HST

Identification of the contribution of each load ⇨ **simulation of the PL, one input vary at a time**

Variables are no longer independent ➔ **parameter**

$$P = b_0 + (b_1 + b_2 \cdot tanh(a_0 + f_1(S) + f_2(Z) + f_3(t)) \cdot H_{load}(Z) + \varepsilon \Longrightarrow P = f(Z, S, t)$$

➢ Reversible effects:

- **hydrostatic effect:** $P_{hyd} = f(\boldsymbol{Z}, S_{ref}, t_{ref})$
  parameter S=(S_1, S_2, S_3, S_4) (Jan, Apr, Jul, Oct)

- **seasonal effect:** $P_{seas} = f(Z_{ref}, \boldsymbol{S}, t_{ref})$
  parameter Z=(Z_1, ..., Z_7) (quartile values and extrema)

➢ Irreversible effects :

- **corrected measurements:** $CM = f(Z_{ref}, S_{ref}, \boldsymbol{t}) + \boldsymbol{\varepsilon}$