# The Perfect Section – (or) what did the geotechnics say?

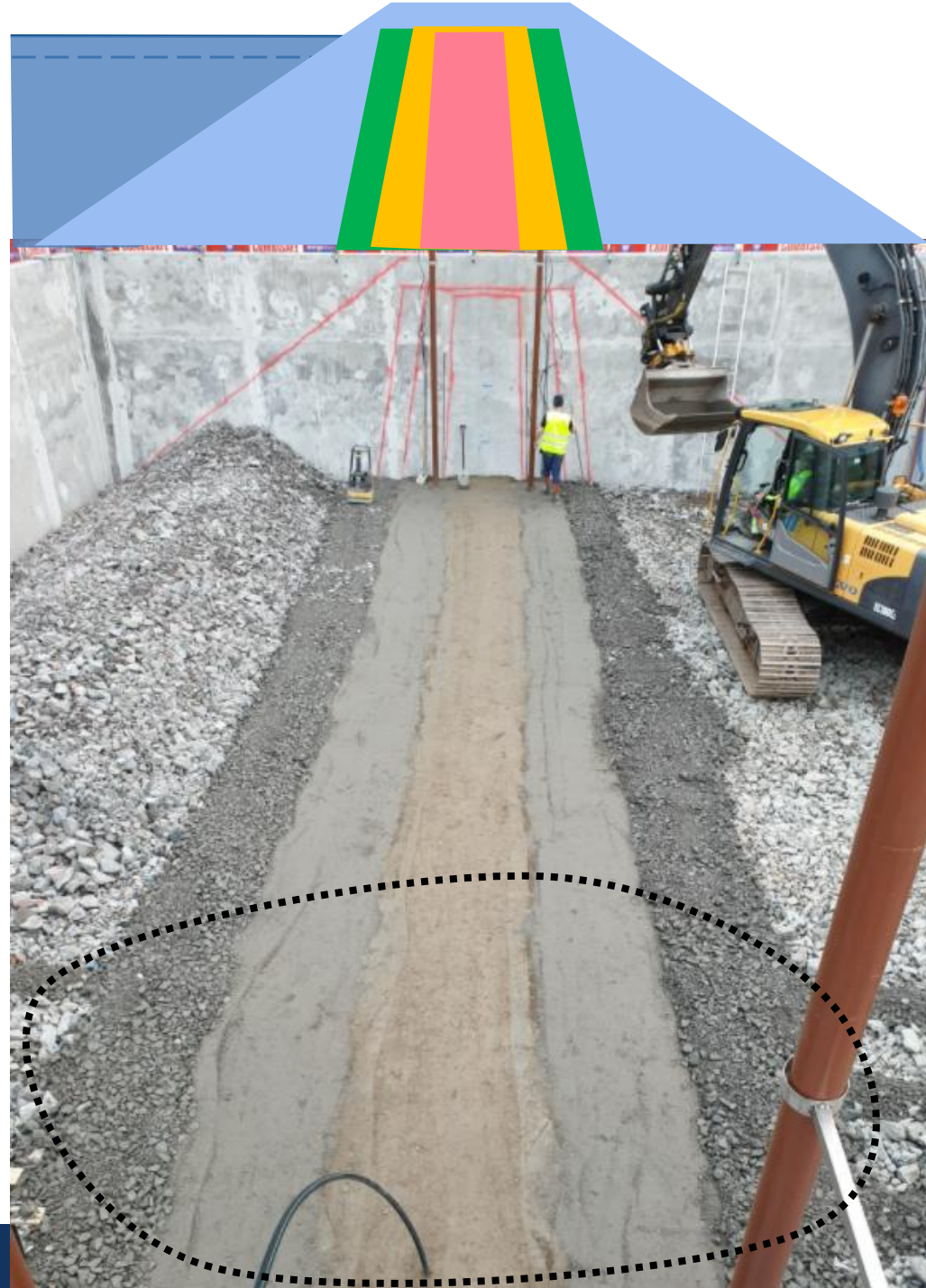
Jasmina Toromanovic

# What did the geotechnics say?

- Not a homogeneous dam
- Changes over time – focus on pore pressure
- How did we reach this?

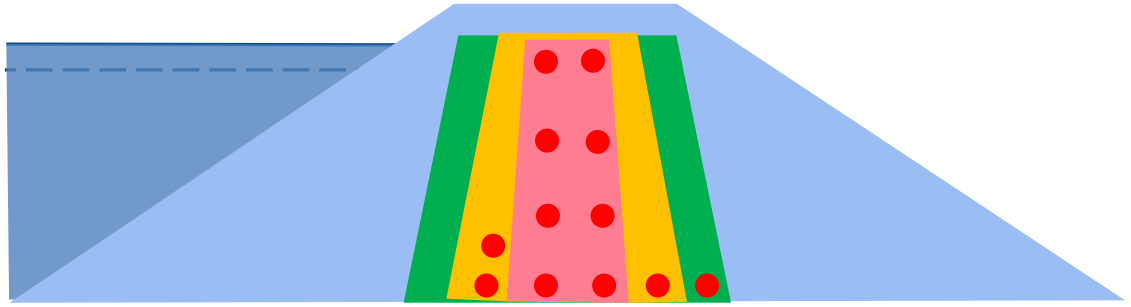
# Instrumentation

- Built in during construction
- One section
  - All geotechnical instrumentation gathered
  - Monitoring of
    - Pore pressure
    - Strain
    - Deformations



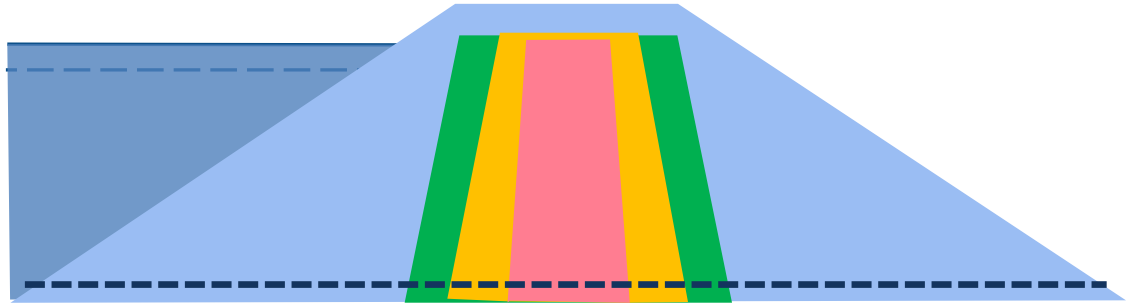
# Instrumentation

- Pore pressure
  - Vibrating wire piezometer
  - 12 transducers
    - Core and filter zones
    - Placed directly on a compacted layer



# Instrumentation

- Strain
  - Fibre optics
  - Strain and temperature
  - Four sections
    - Crossing all material zones
    - 20 cm above the bottom
  - One loop

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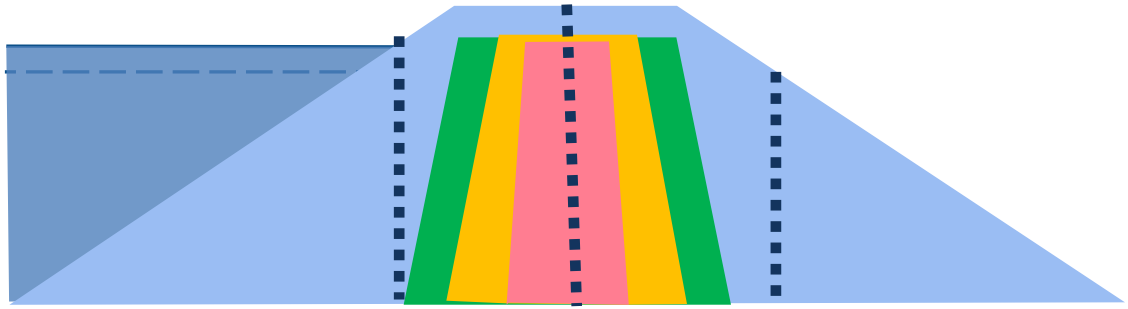
PROTECTION OF THE CABLES IN THE SHOULDER AND COARSE FILTER

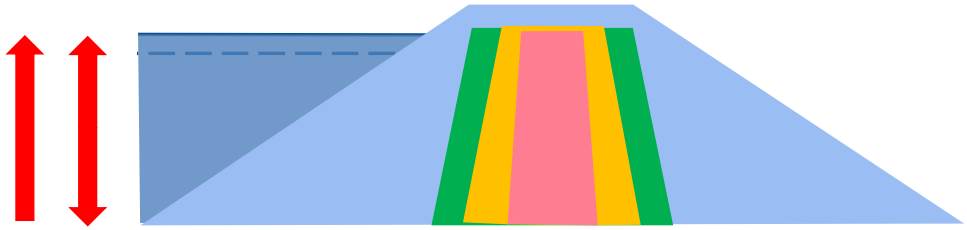
SEALING IN THE CORE BY BENTONITE TO MINIMISE SEEPAGE PATHS

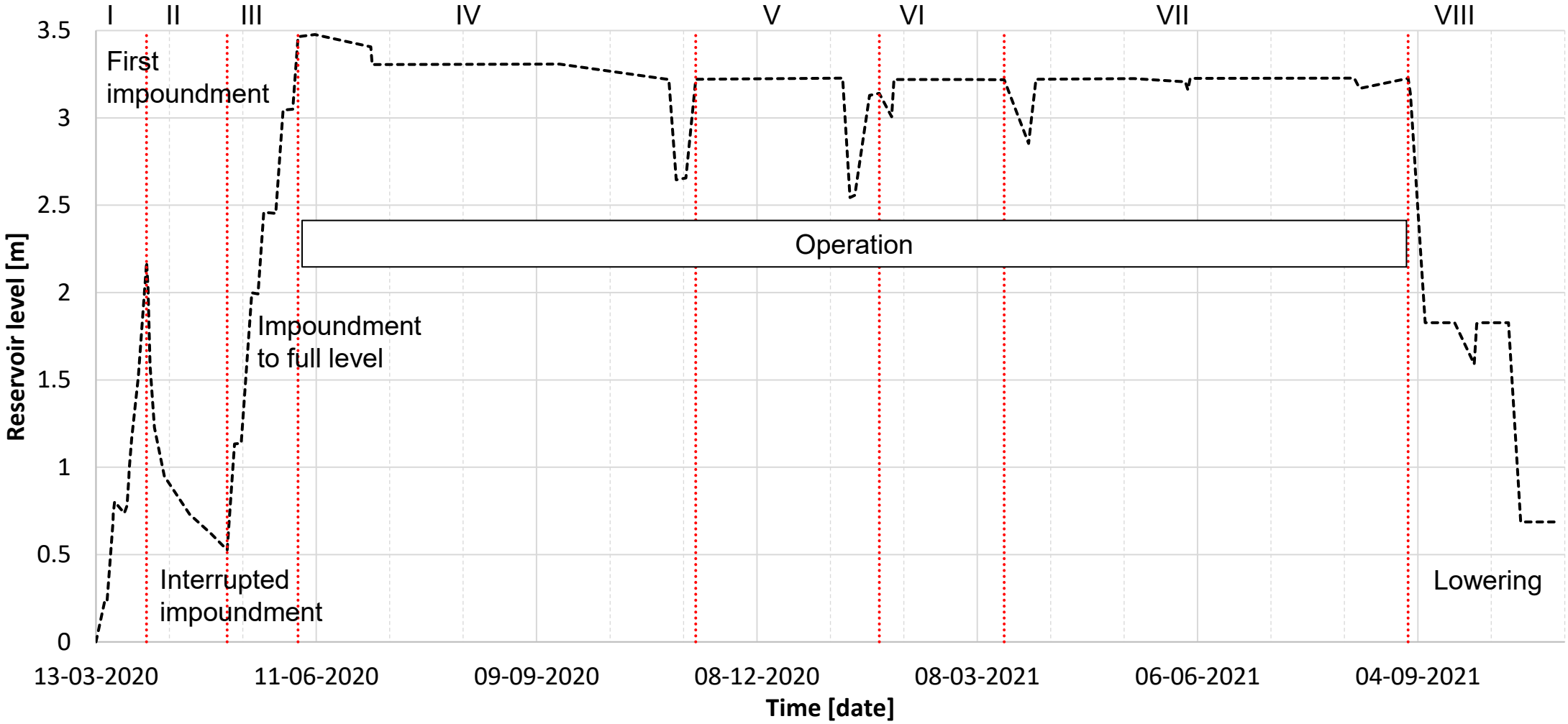
# Instrumentation

- Deformations
  - Shape Accelerometer Array
  - Three inclinometers
    - Upstream: 3.5 m
    - Middle: 4.0 m
    - Downstream: 3.0 m
  - Tubes built in during construction



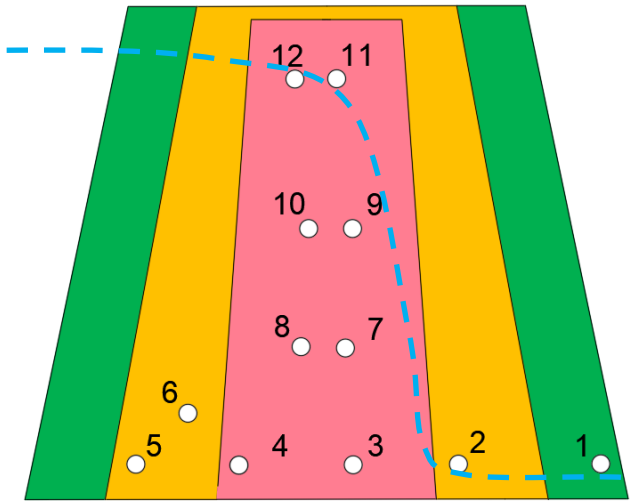
# Impoundment and operation

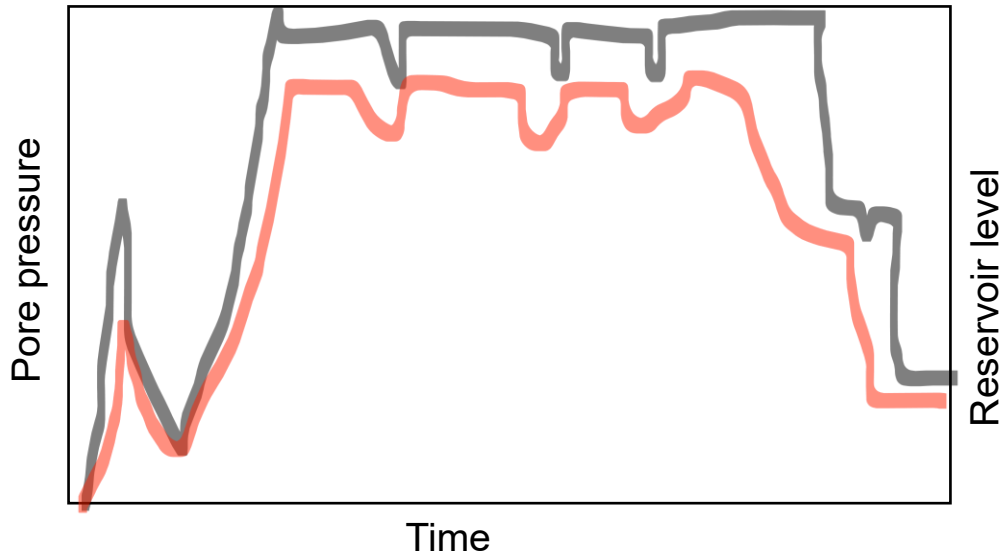




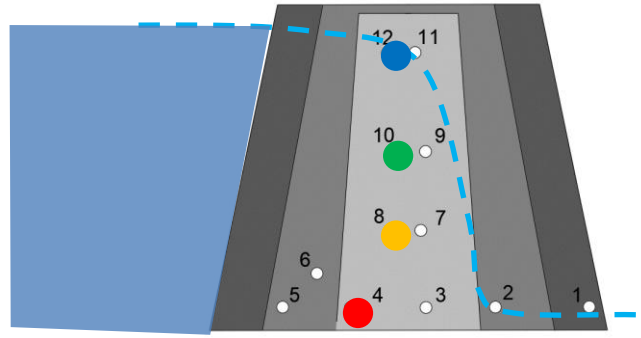
# Pore pressure

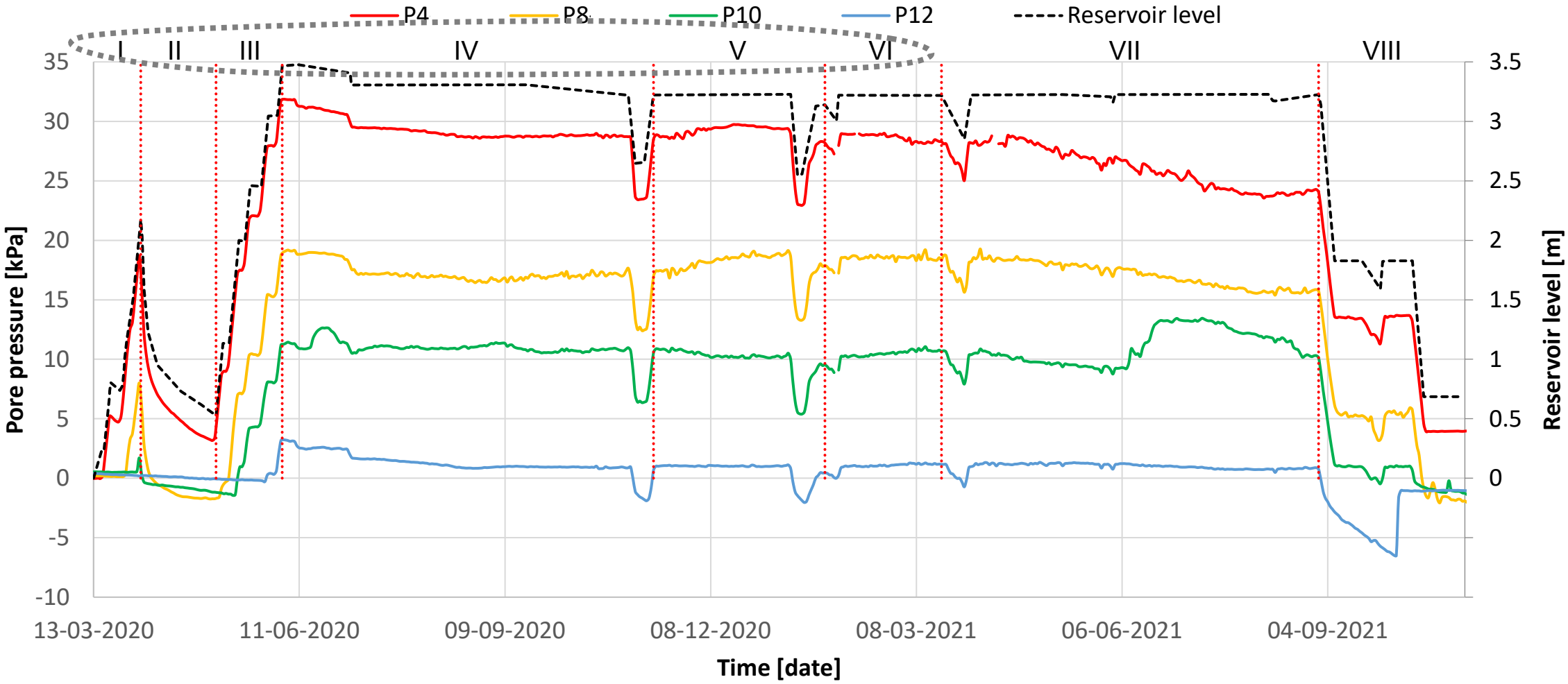
- Phases I-VIII
  - Changes in the pore pressure
  - Gathered interpretations of the whole core
- Measurements (left vertical axis)
  - Filters
  - Core focused on
    - Upstream
    - Downstream
- Reservoir level (right vertical axis)



# Pore pressure – upstream side of the core



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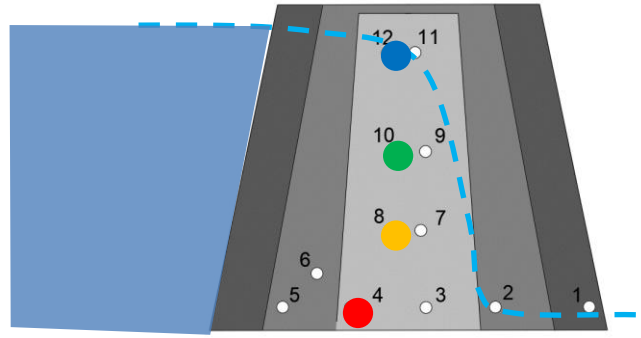
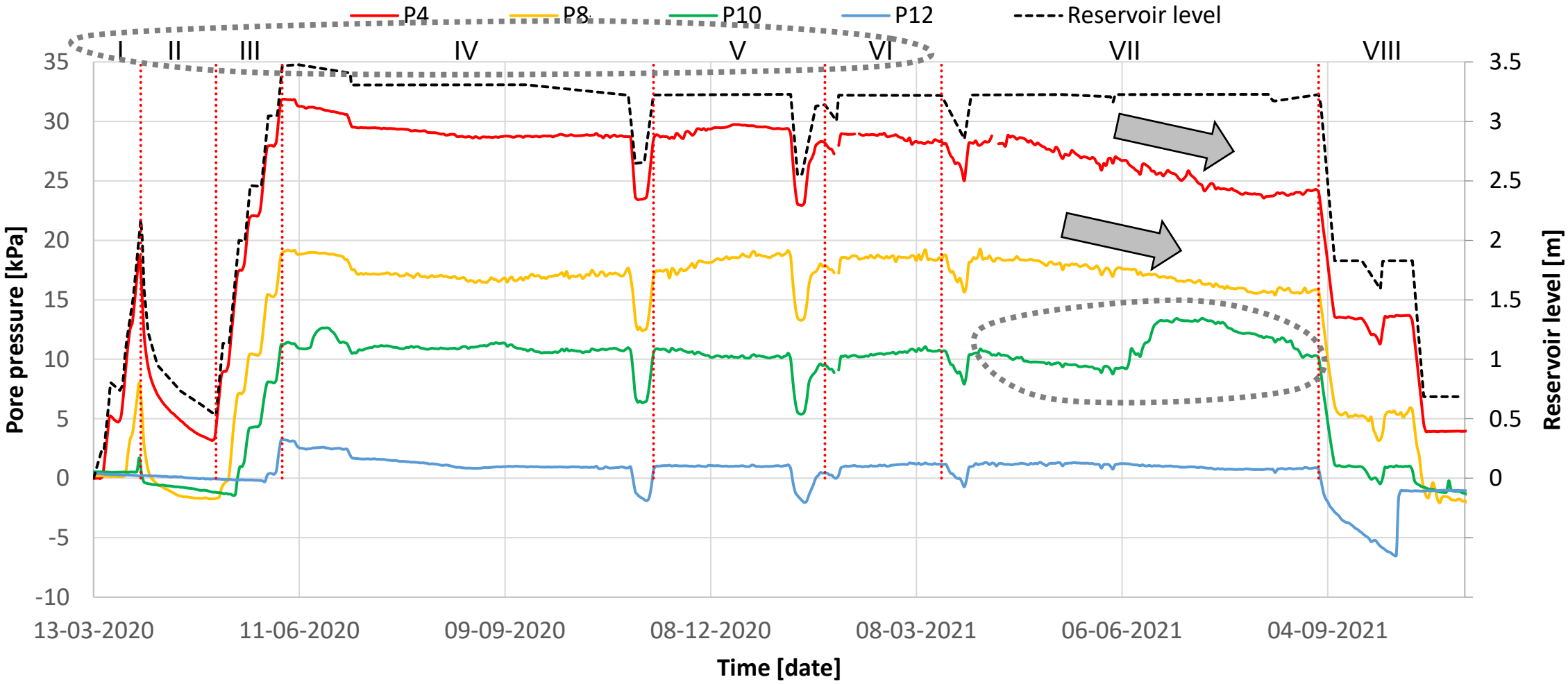
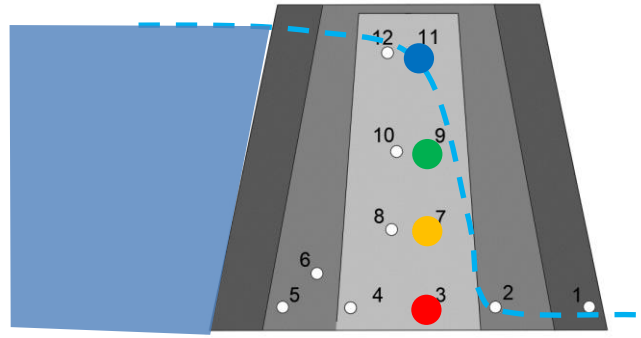
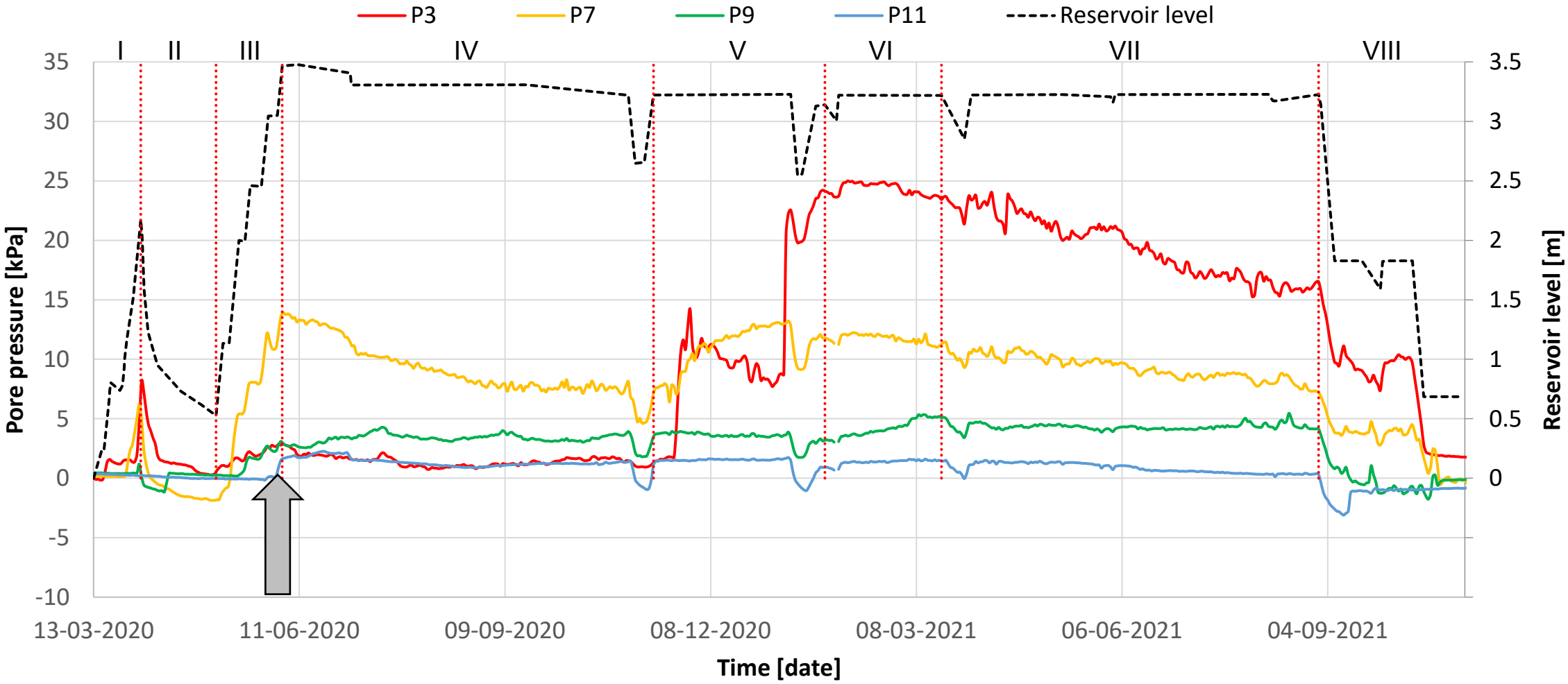


# Pore pressures – downstream side of the core



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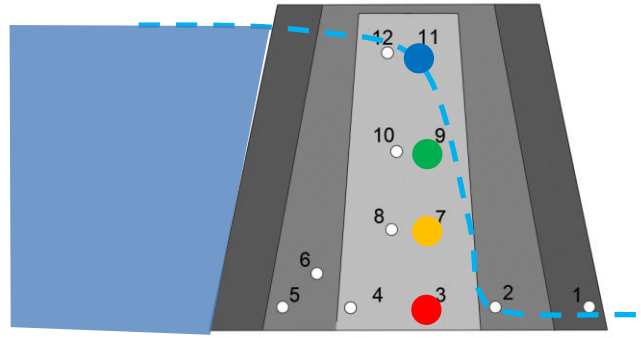


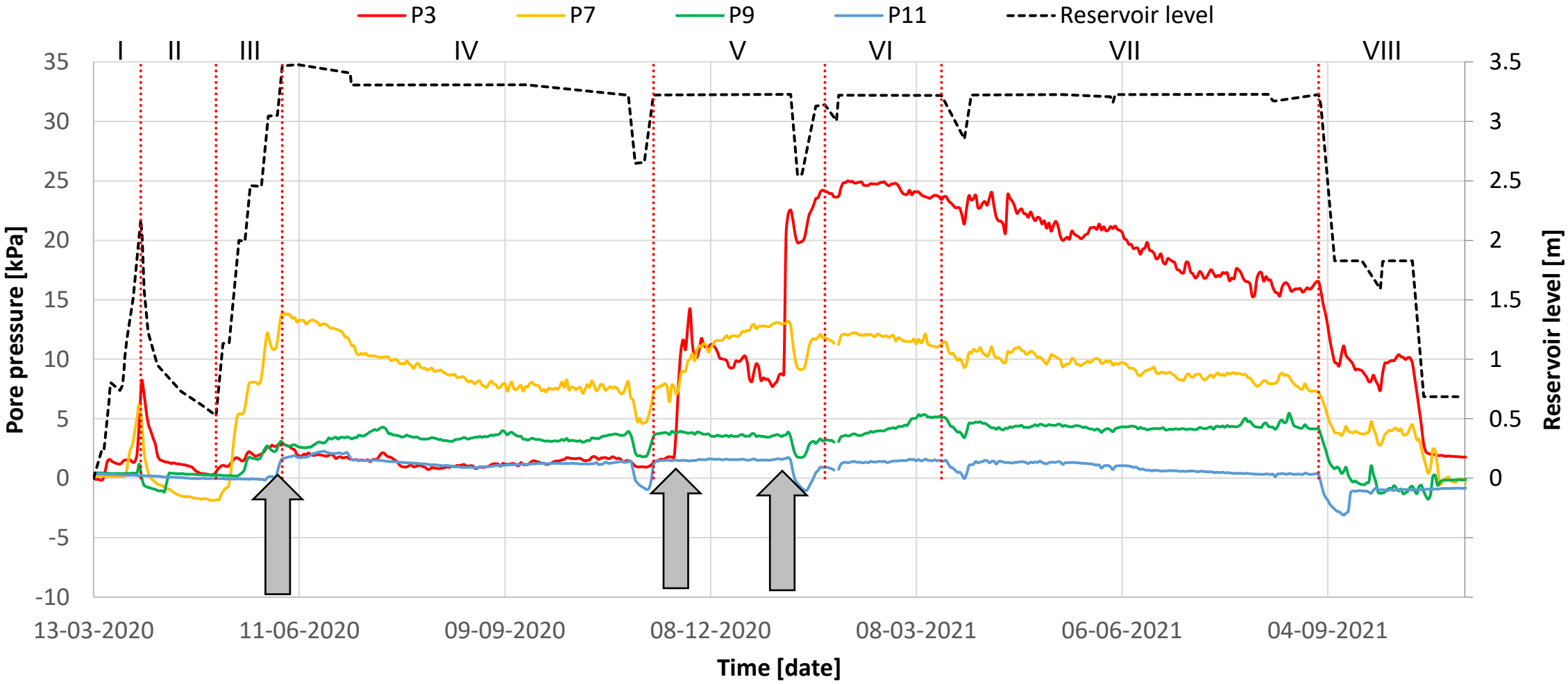

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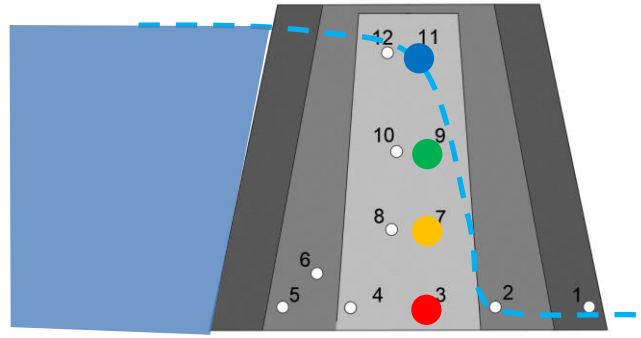


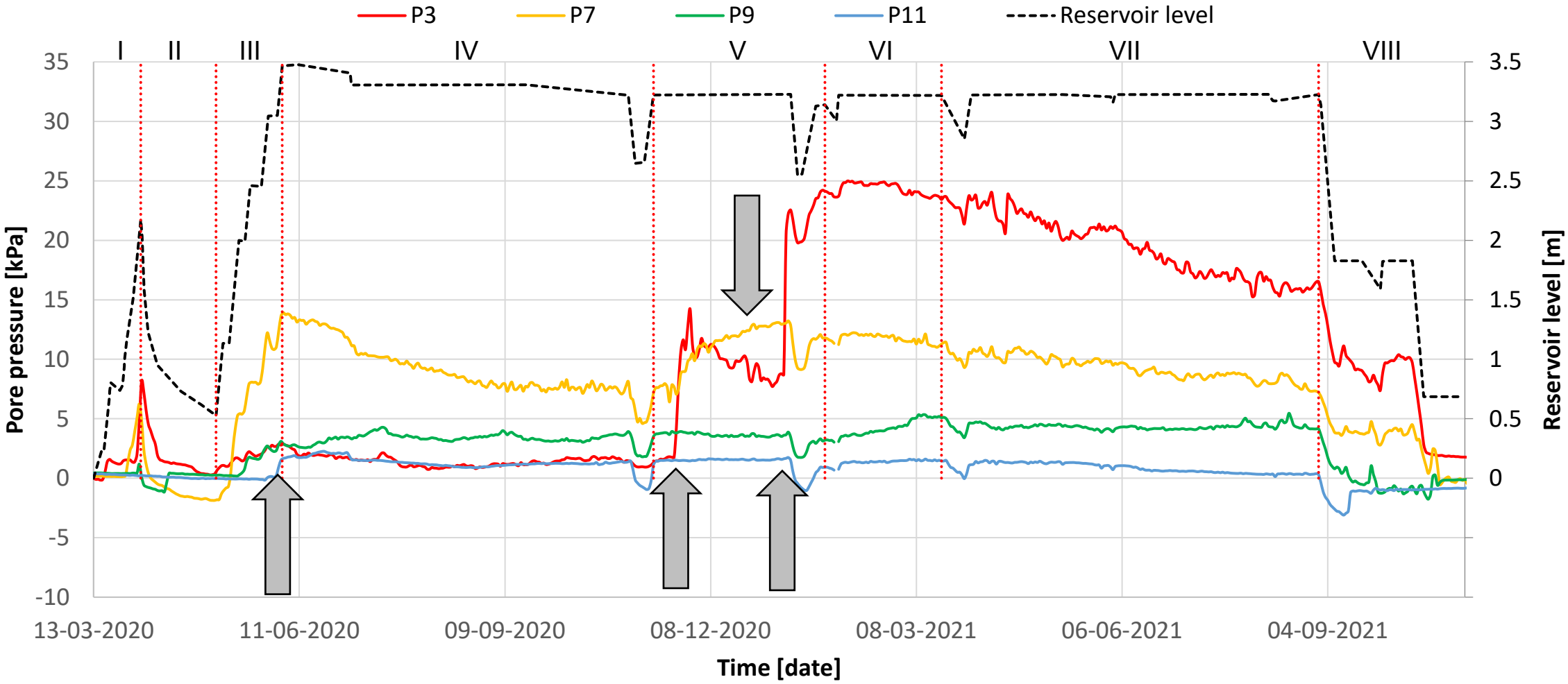

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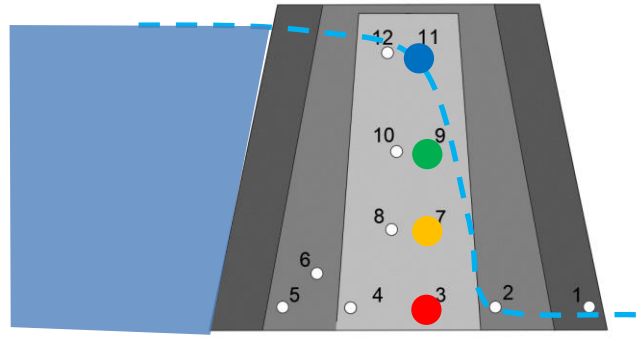


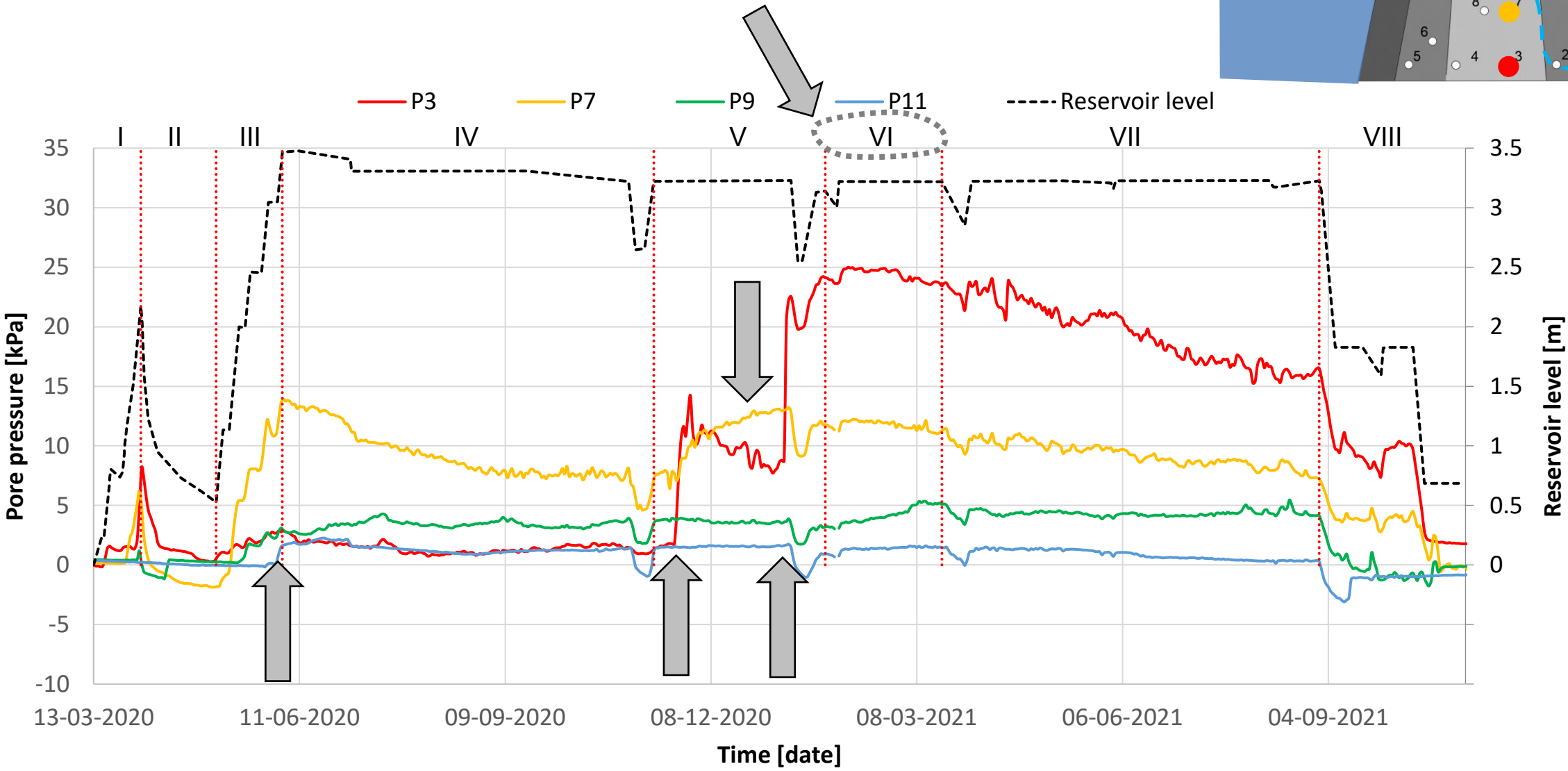

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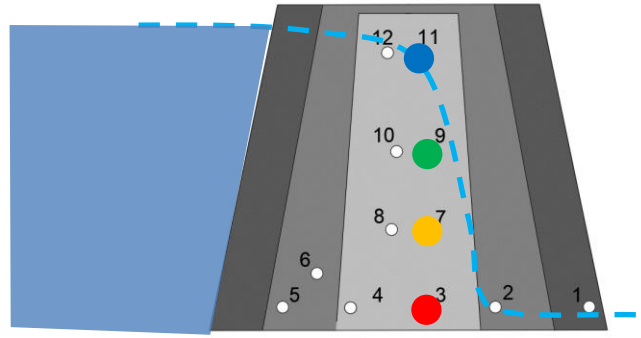
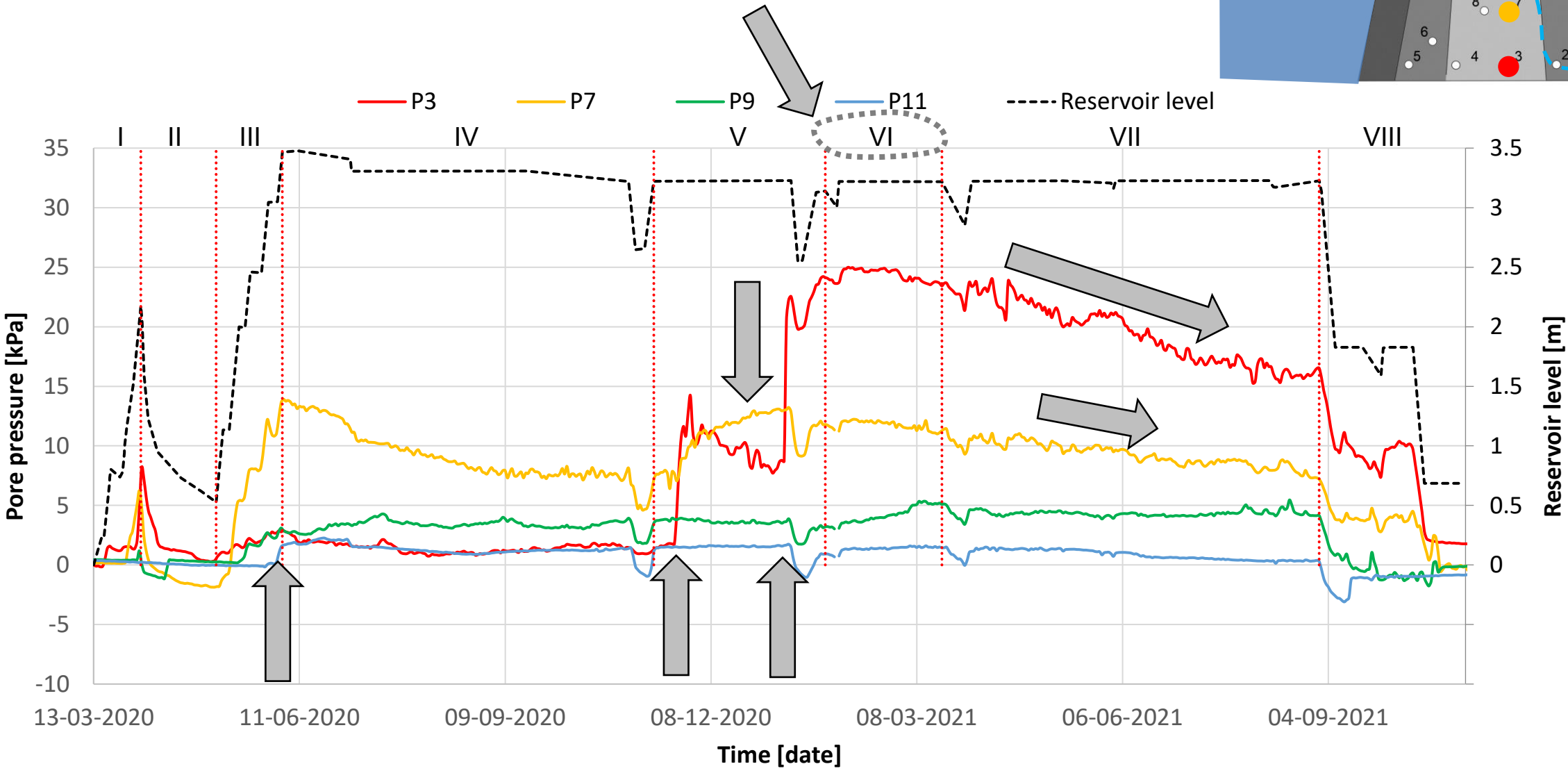
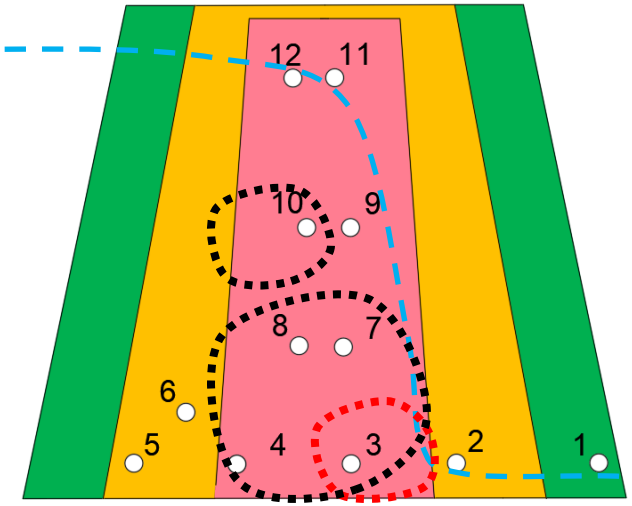
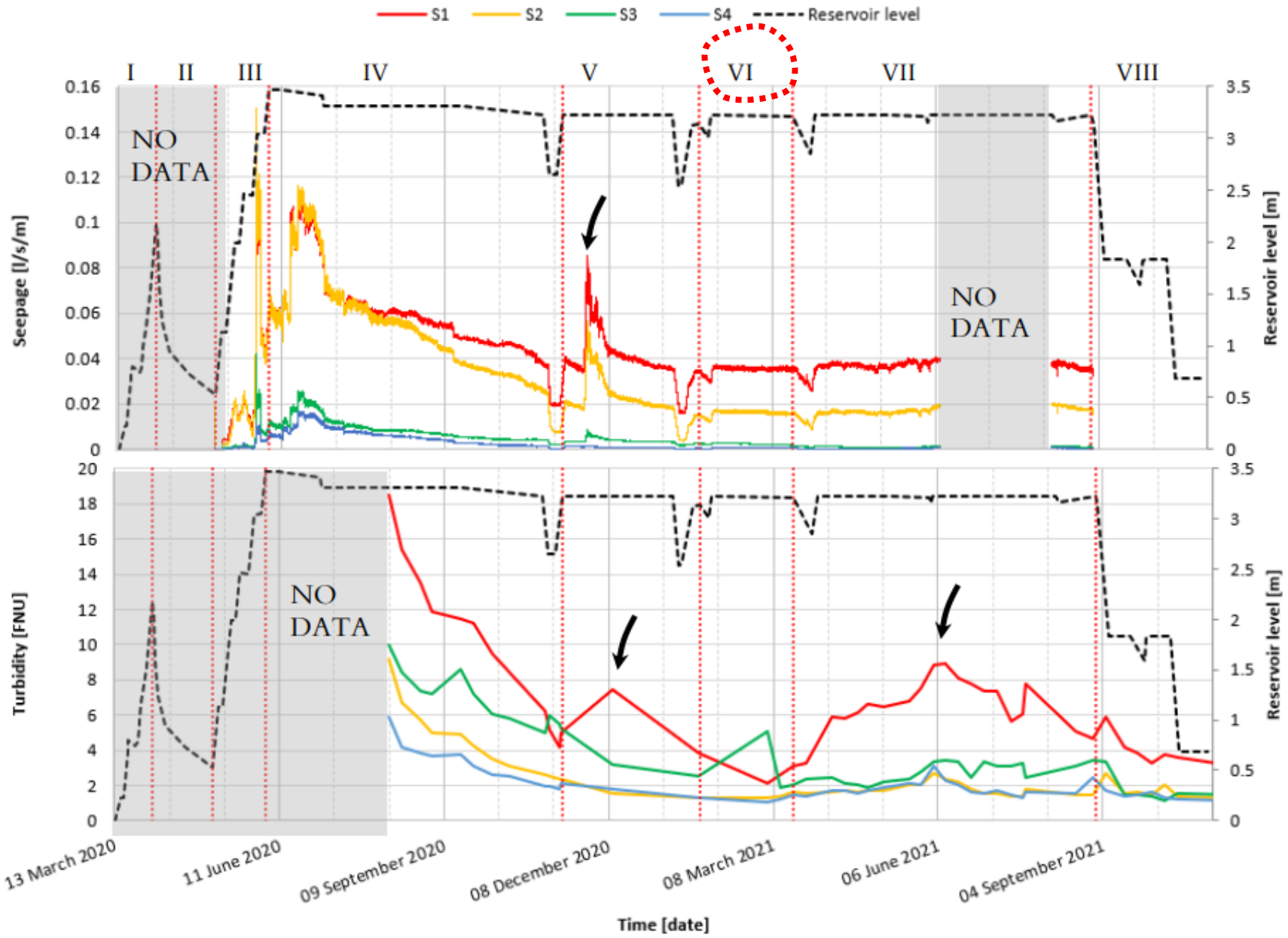


# Summary of observations

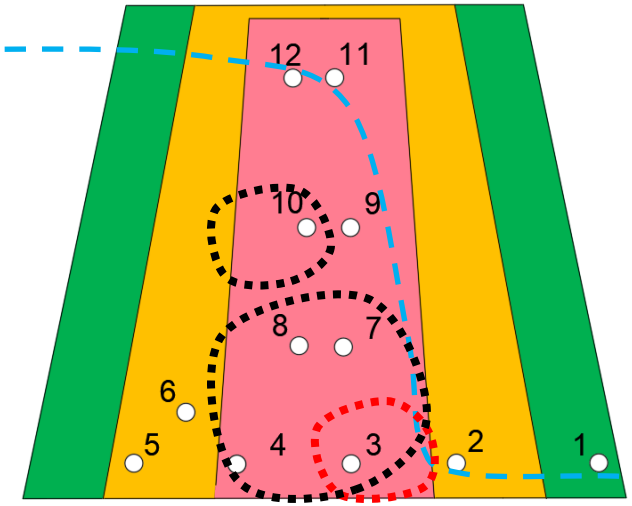
- Delay at downstream side of the core
  - Combined interpretations of pore pressure, seepage and turbidity
  - Patterns are visible across several types of measurements




S1
S2
S3
S4
Reservoir level
I
II
III
IV
V
VI
VII
VIII
NO DATA
NO DATA
NO DATA
Seepage [l/s/m]
Turbidity [FNU]
Reservoir level [m]
Time [date]
13 March 2020
11 June 2020
09 September 2020
08 December 2020
08 March 2021
06 June 2021
04 September 2021

# Summary of observations

- Delay at downstream side of the core
  - Combined interpretations of pore pressure, seepage and turbidity
  - Patterns are visible across several types of measurements
- Interpreted steady state in Phase VI
  - Pressures in the bottom catch up
  - Most stable pore pressure and seepage
  - Takes long time to develop (one year of operation)
  - Short time of stable pressures in the whole core
- Re-distribution of pressure in Phase VII



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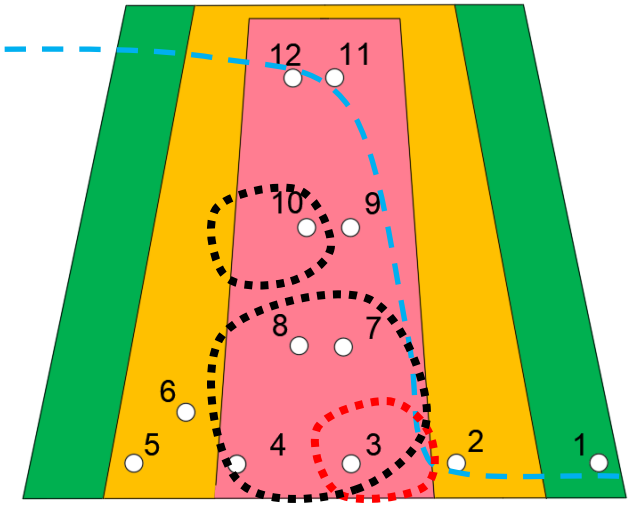


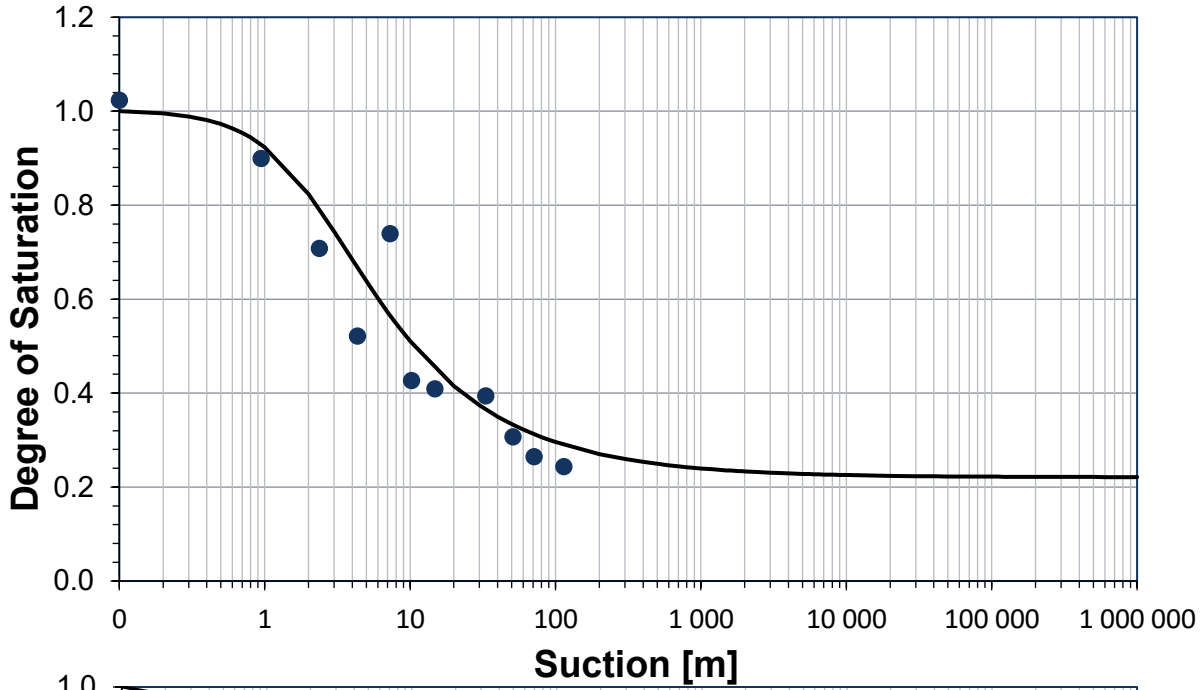

**AND NOW?**

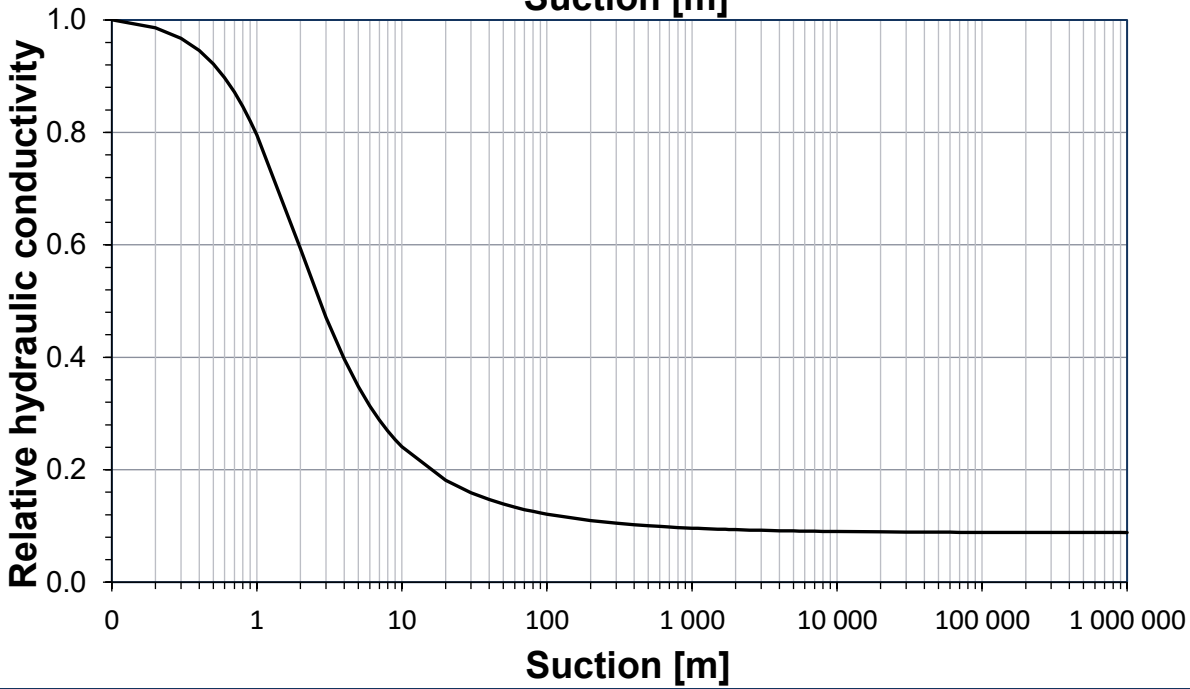
# Modelling of pore pressure

- Can modelling help to understand?
- How does reality vary from the idealised case?
  - Predictions by modelling
- Learned quickly that
  - Very bad agreement for homogeneous conditions.
- At that stage, the dam was not demolished yet

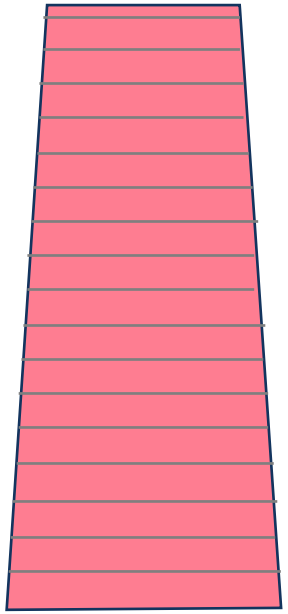
# Modelling of pore pressure

- Fully-coupled analyses
  - PLAXIS 2D
  - Gradual saturation
    - Unsaturated conditions
    - Water retention curves
    - The hydraulic conductivity is fully developed at full saturation
- Homogeneous conditions
  - Not suitable for the core
  - The laboratory results do not reflect the as-built conditions
  - Varying densities
  - The fines content is increasing with depth
- Modelling as support
  - Different scenarios assessed

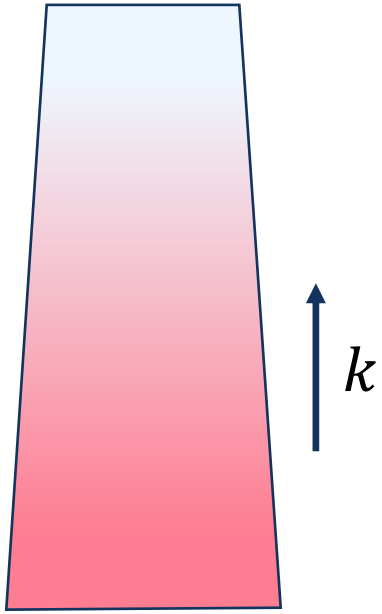


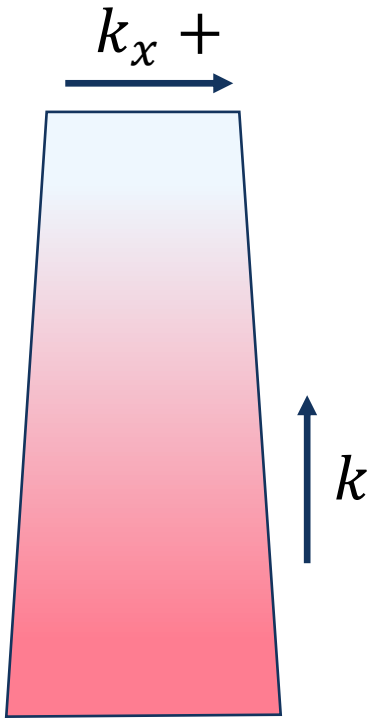
# Modelling cases - core



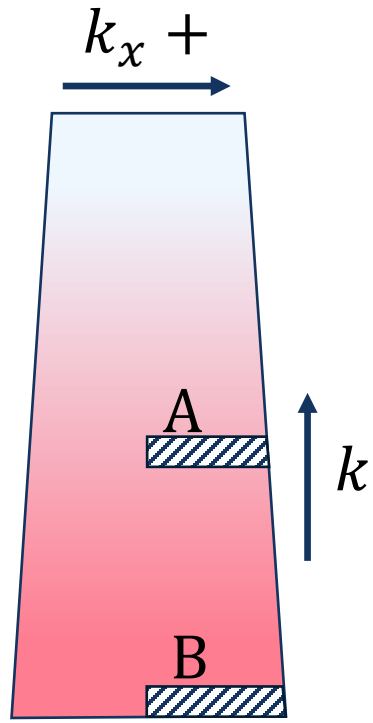
- **Homogeneous**




- **Increasing hydraulic conductivity with height**



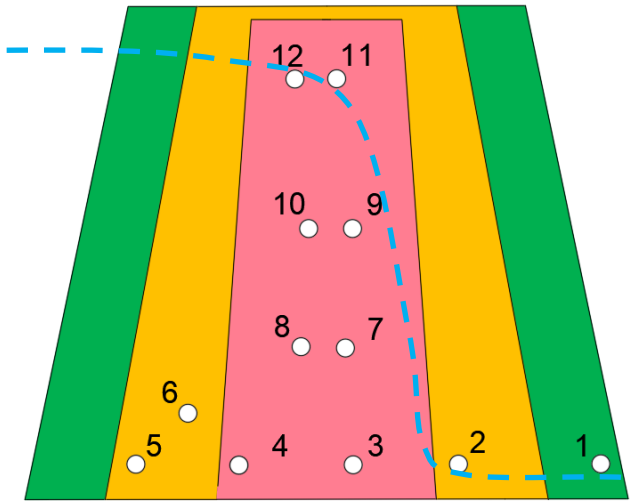

- Increasing hydraulic conductivity with height
- **Higher hydraulic conductivity in the horizontal direction**

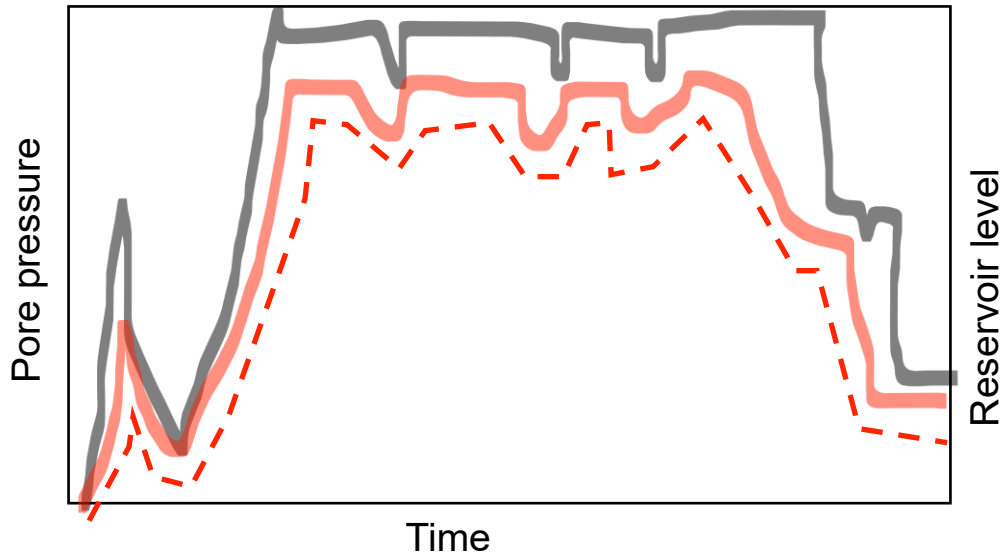



- Increasing hydraulic conductivity with height
- Higher hydraulic conductivity in the horizontal direction
- **Very low hydraulic conductivity in areas A and B → Delay**

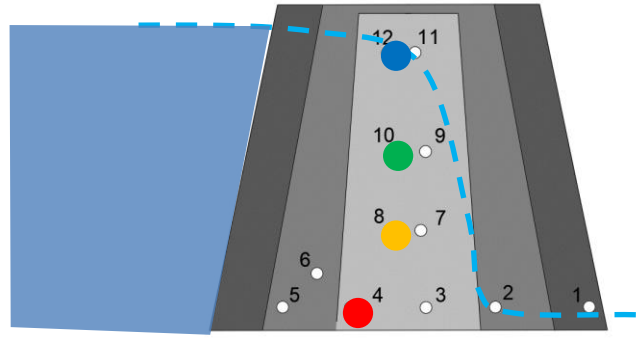
# Modelling of pore pressure

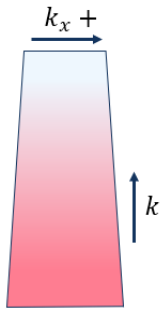
- Phases
  - I-IV shown (impoundment and first part of operation)
- Measurements
  - Left vertical axis (solid)
- Modelling
  - Left vertical axis (dashed)
- Reservoir level
  - Right vertical axis



# Upstream side of the core




I II III IV

Pore pressure [kPa]

35 30 25 20 15 10 5 0 -5 -10

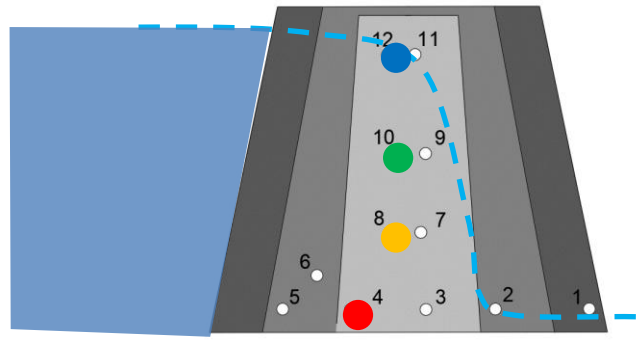
Reservoir level [m]

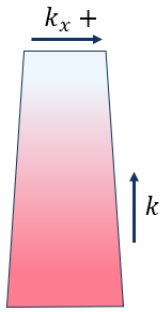
3.5 3 2.5 2 1.5 1 0.5 0

13 March 2020 12 April 2020 12 May 2020 11 June 2020 11 July 2020

Time [date]

# Upstream side of the core

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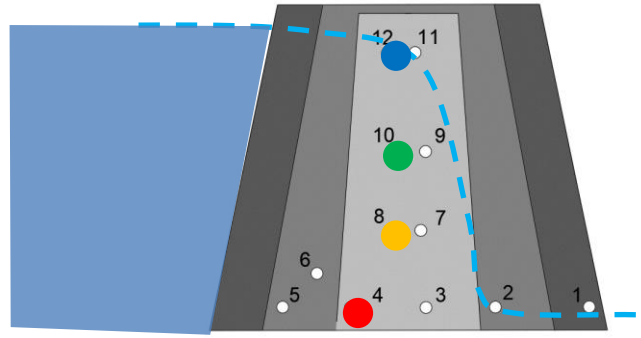


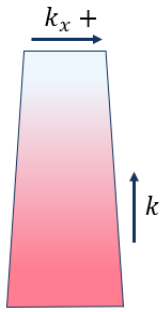


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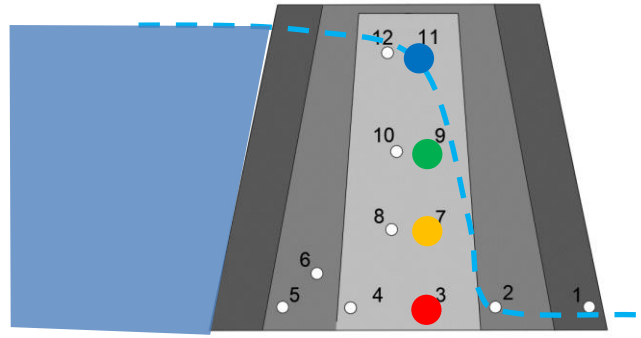
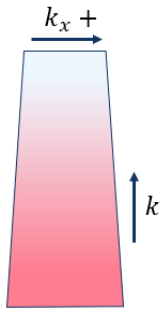
Time [date]

# Downstream side of the core




I II III IV

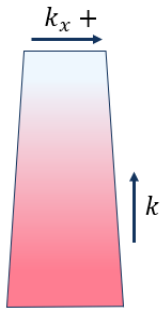
Pore pressure [kPa]

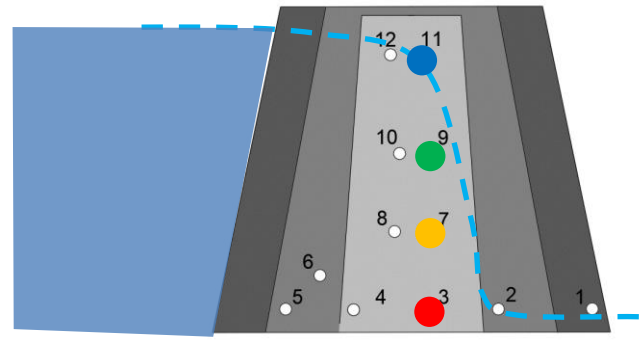
Reservoir level [m]

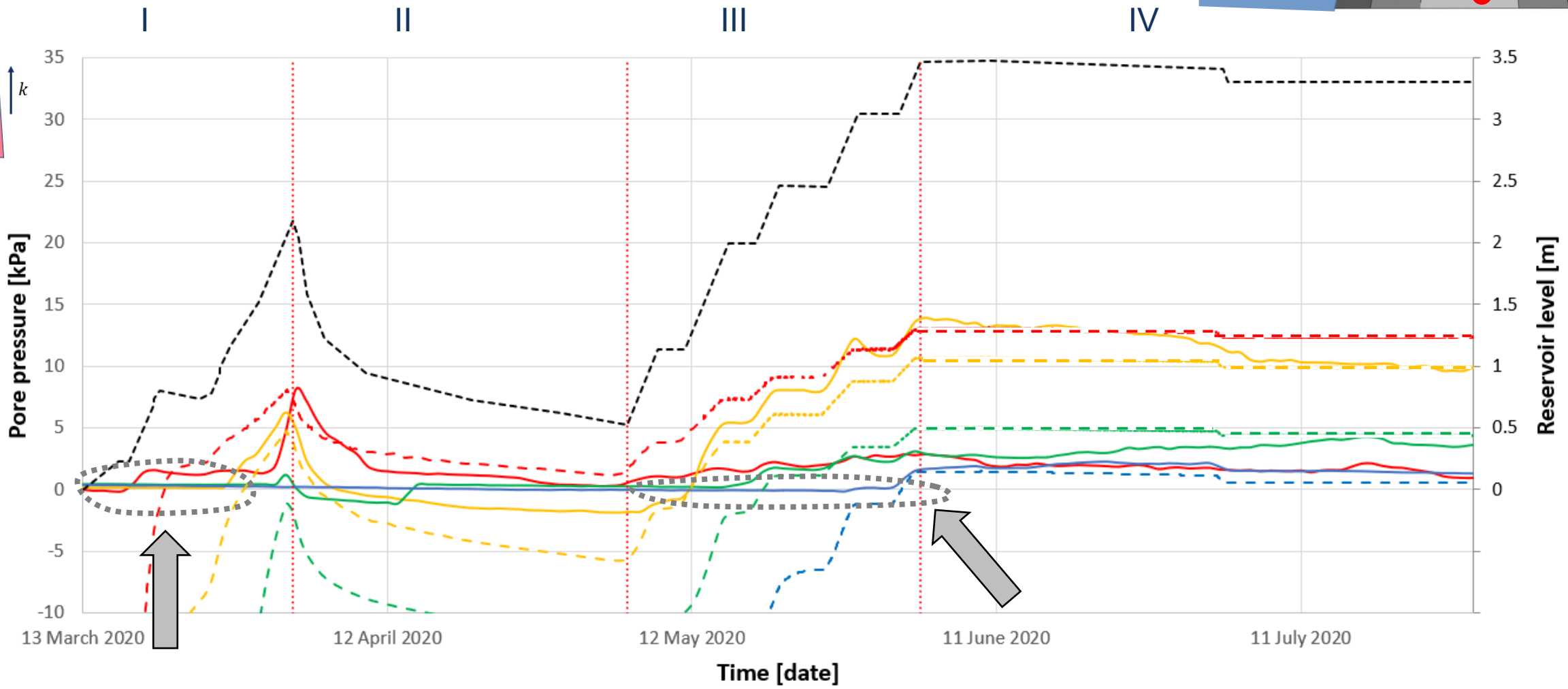
Time [date]

13 March 2020 | 12 April 2020 | 12 May 2020 | 11 June 2020 | 11 July 2020

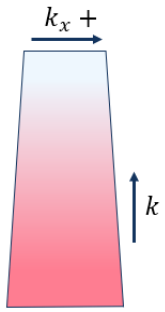
# Downstream side of the core

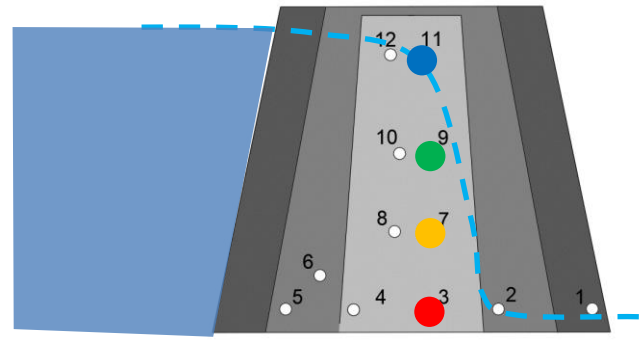


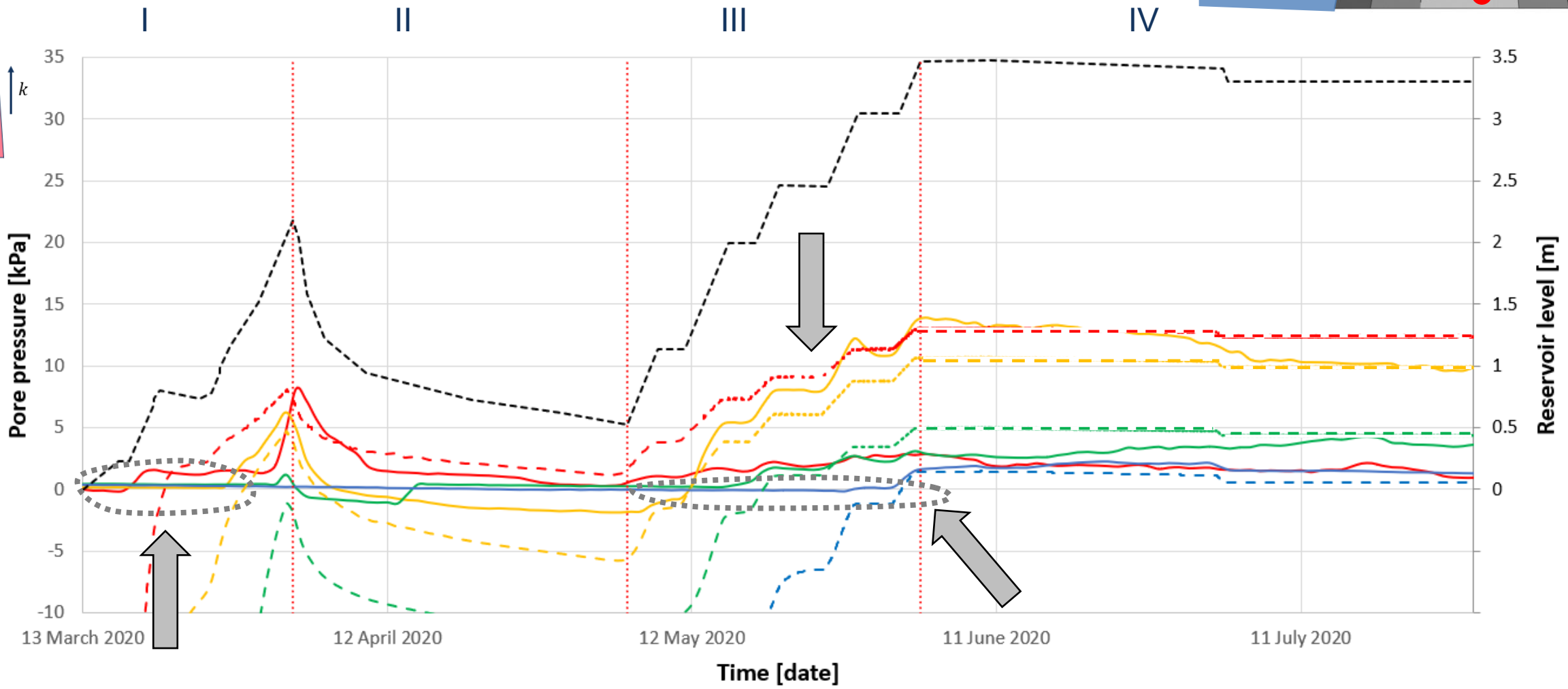



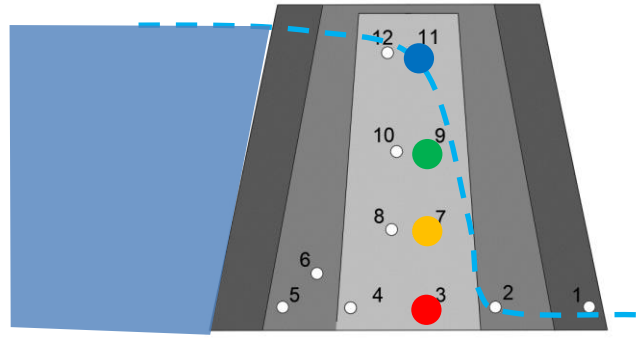
# Downstream side of the core

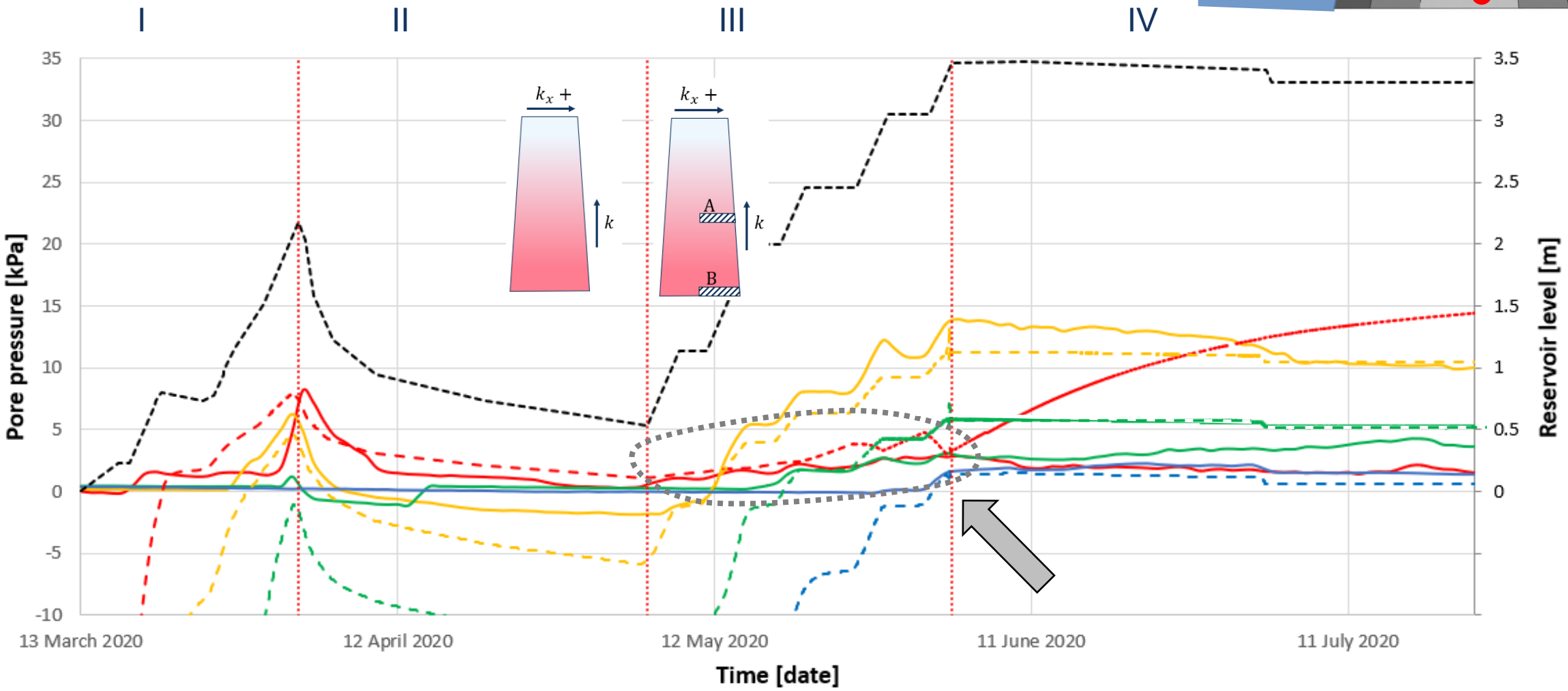


# Downstream side of the core



# Summary of modelling of pore pressure

- The modelling suggests that the core is not homogeneous
  - Homogeneous conditions give poor agreement
  - Models with modifications of hydraulic conductivity give better agreement
    - Increasing with height
    - Larger in the horizontal direction
    - Areas with lower hydraulic conductivity
- Good agreement for impoundment and operation
  - Phases I-IV (positive pressure)
- Further modifications needed
  - Only hydraulic conductivity so far

# What did the geotechnics say?

- Not a homogeneous dam
- Changes over time – focus on pore pressure
- How did we reach this?

# What did the geotechnics say?

- Not a homogeneous dam
- Changes over time – focus on pore pressure
- How did we reach this?
- Further modelling of pore pressure
  - Update of material characteristics. Internal erosion scenarios → Better agreement!
- How non-homogeneous is the dam? Why?
  - Filter criteria and comparison to the demolition results
  - Many findings ☺


# On-going

- **Combine measurements → Start in an SVC senior project**
  - “Samtolkning” of results so far
  - Ideas for future research

# Thank you!



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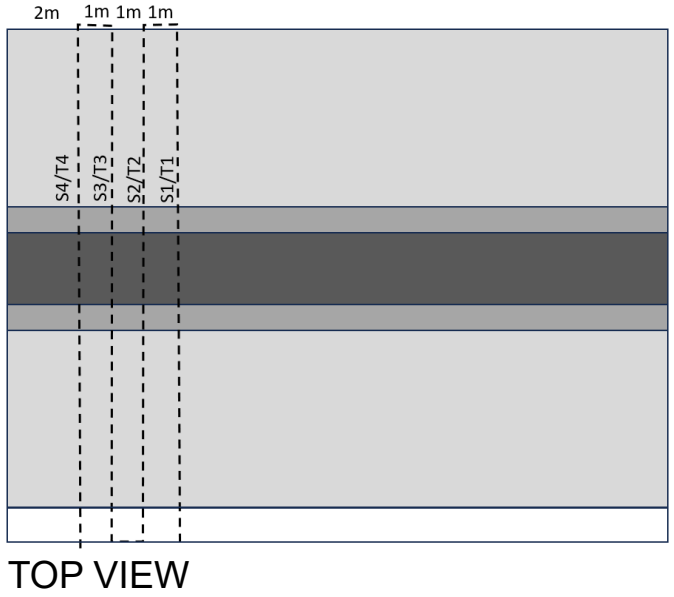
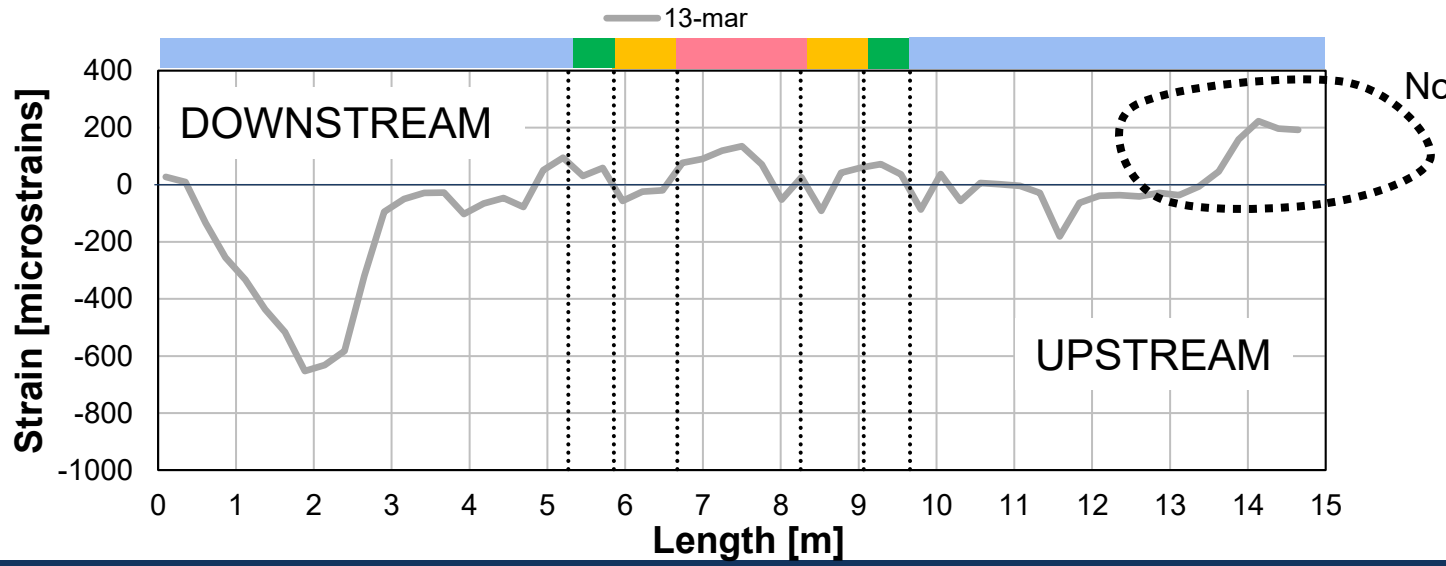
# Strain

- Behaviour at the base of the dam
  - Empiric relationships are available
  - Not measurements
- Unusual installation
  - Different materials and different shielding
  - How will it work? What can be observed?
- Measurements
  - Microstrains (μm/m)
  - Tension (+) and compression (-)

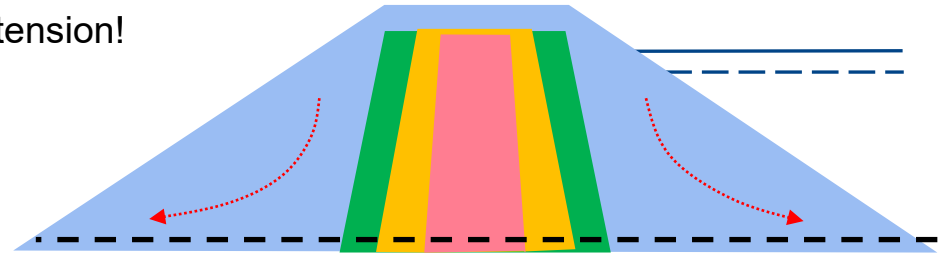
# Strain

- ”Rest phase”
  - November 2019 – March 2020
  - Empty reservoir
  - Deformations in the dam post construction
    - Compression in different directions



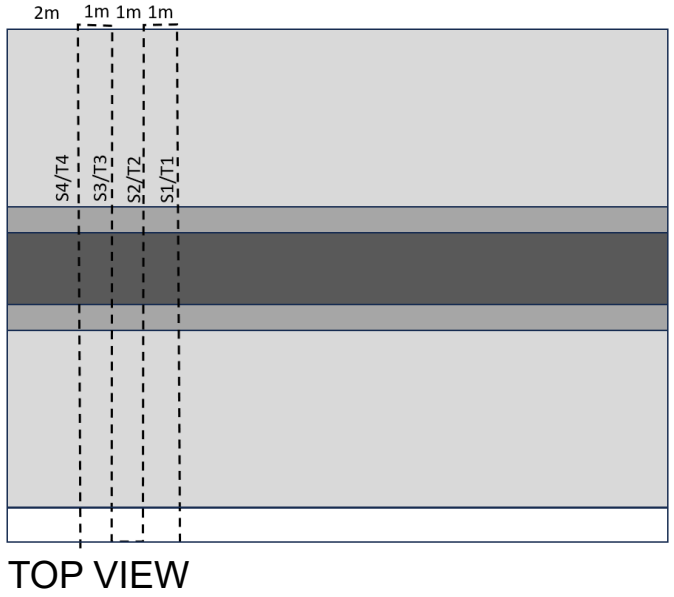



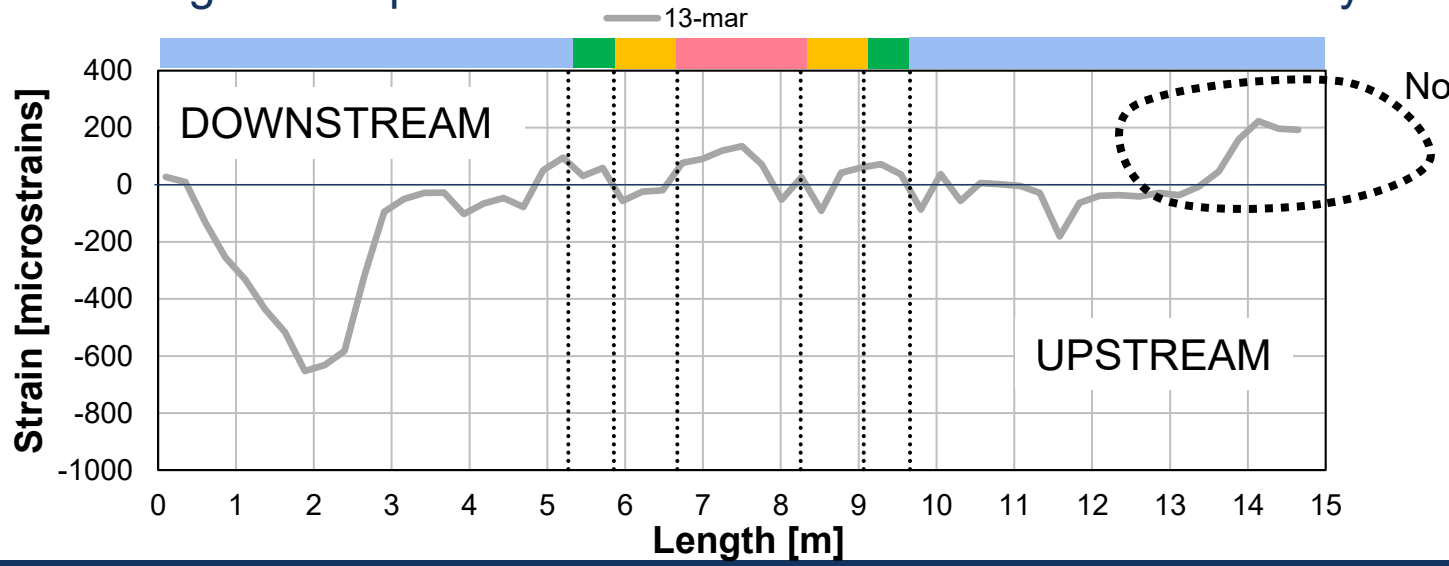

Not tension!

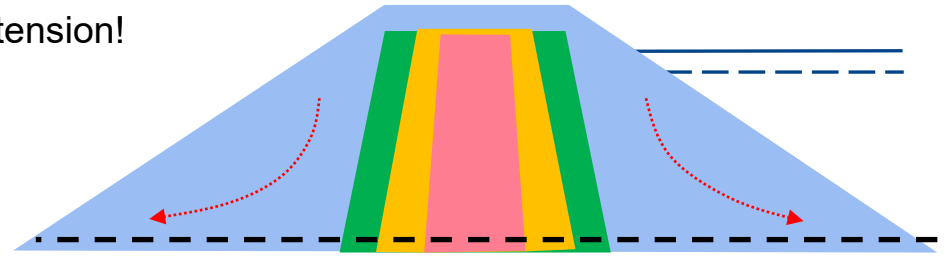


# Strain

- ”Rest phase”
  - November 2019 – March 2020
  - Empty reservoir
  - Deformations in the dam post construction
    - Compression in different directions
  - Why not symmetric strain behaviour?
    - Higher compression downstream – inclined foundation by 1%

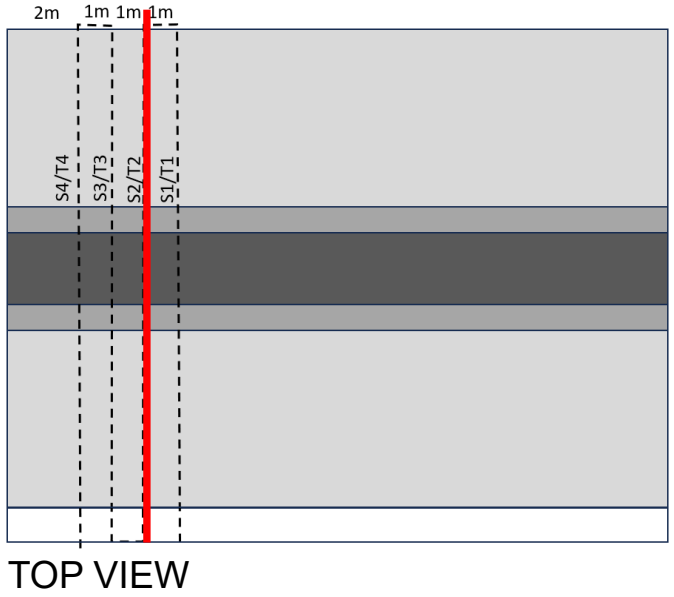


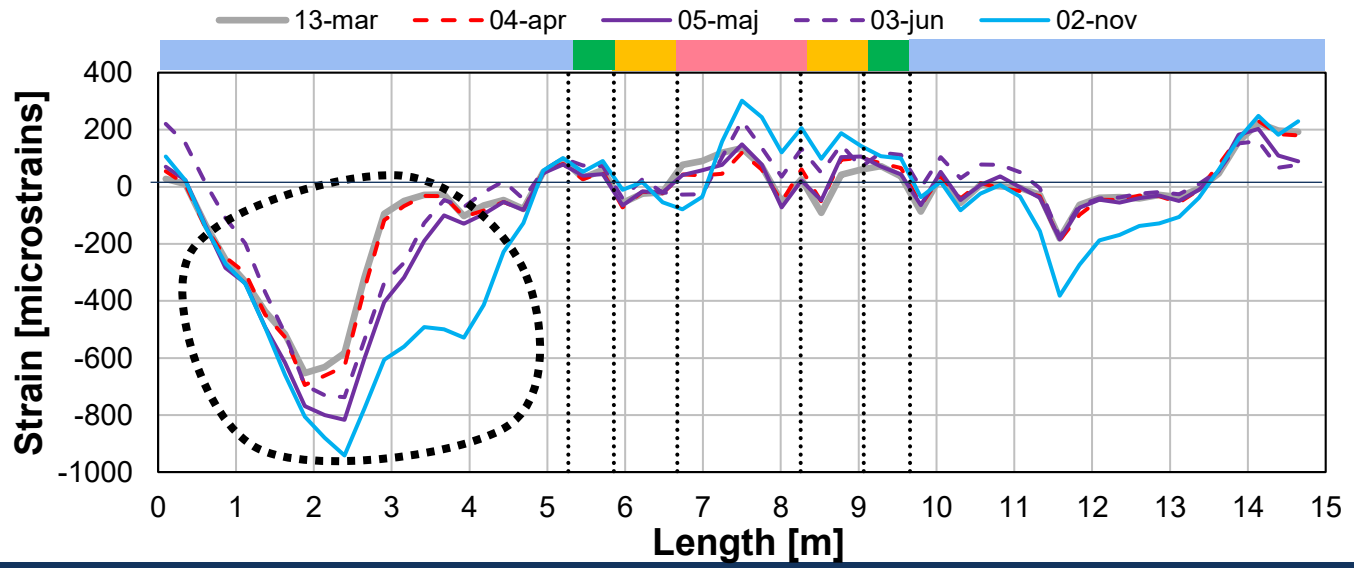



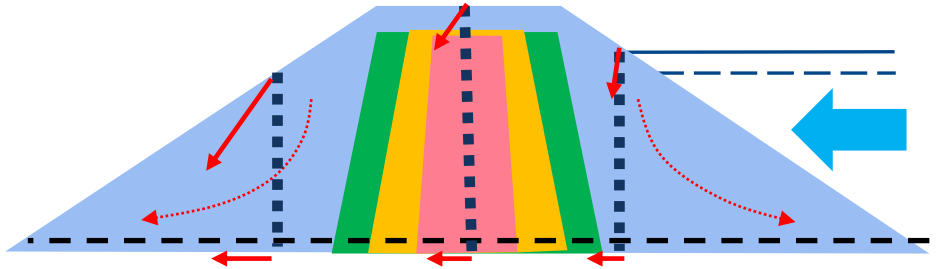



# Strain

- Impoundment and operation (S3)
  - Increased compression downstream
    - Supported by the deformations

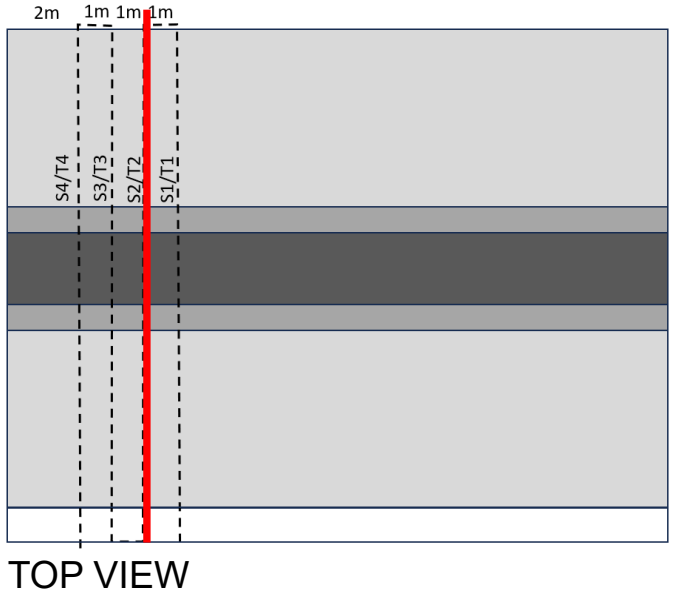


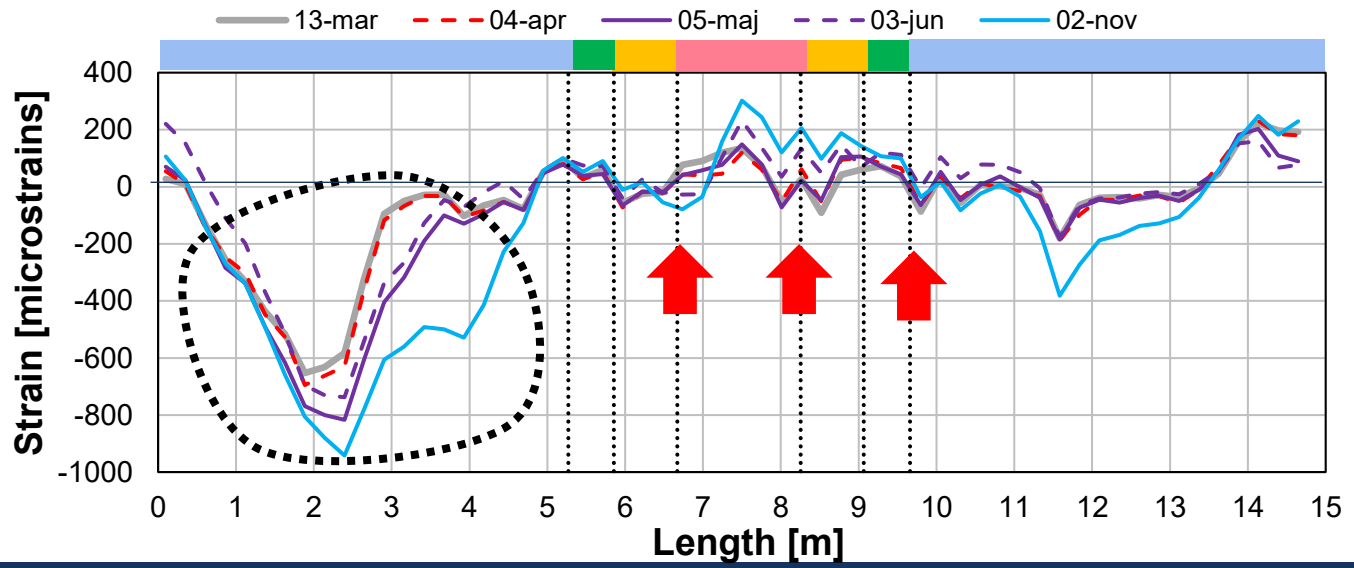



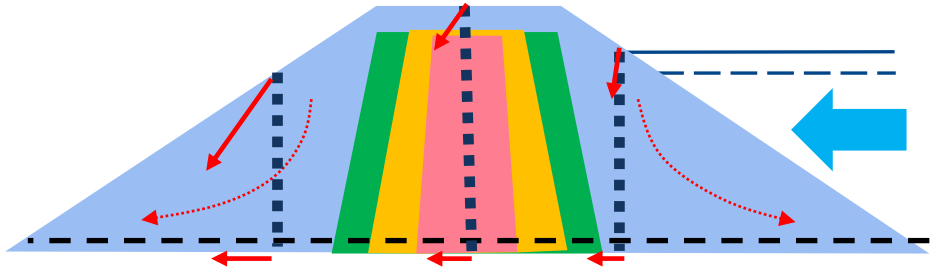



# Strain

- Impoundment and operation (S3)
  - Increased compression downstream
    - Supported by the deformations
  - Behaviour close to zone borders



# Strain

- Impoundment and operation (S3)
  - Increased compression downstream
    - Supported by the deformations
  - Behaviour close to zone borders
  - Tension in the core