Trondheim, 30.01.2024

NORWEGIAN TUNNELLING SOCIETY

# 275 m high Yusufeli arch dam

## Digital ground model - data handling and applications


Photos by Limak

Jonas Weil, Johannes Kleberger, Irmina Pöschl, www.ic-group.org

# Yusufeli arch dam - digital ground model

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2013: DSI awarded design & built contract to a Turkish consortium, lead by LIMAK, with iC consulenten acting as geotechnical consultant.

July 2018: completion of dam foundation excavation.

February 2022: completion of dam concreting & grouting.

November 2022: start of impounding.

End 2023: completion of impounding.

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# Yusufeli arch dam - digital ground model

Up to 480 m high cut slopes, stabilized by ~ 6 500 prestressed anchors, top-down excavation accessed via network of tunnels including spiral galleries.

2.2 billion m³ reservoir volume.

**Rough terrain with very steep and high valley flanks**

558 MW underground powerhouse.

275 m high double curved concrete dam.

**Deformation properties at some areas of the foundation less favorable than expected**

> 4 million m³ concrete in dam body.

Extensive consolidation grouting required:

> 8 500 m³ cement grout in approximately

12 000 grout holes with an accumulated length of

216 000 m.

# Yusufeli arch dam - digital ground model

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| Year | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Site activities** | | | | | | | | | | |
| diversion tunnel | started 2012 | | | | | | | | | |
| access roads and tunnels | including drainage and grouting alleries | | | | including spillway tunnels | | | | | |
| caverns and shafts | | | | | | | | | | |
| cut slope excavation | access roads | above crest | | | | | | | | |
| dam foundation excavation | | | | | | | | | | |
| dam + abutment concrete | | | | | | | | | | |
| grouting | | | grouting test panels | | | curtain, consolidation and "relaxed-rock mass-grouting" | | | | |
| **Year** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** |
| **Geological input data** | | | | | | | | | | |
| field mapping | especially left valley flank | | | | | | | | | |
| boreholes and in situ testing | including pre-tender data | | | | | | verification survey | | | |
| tunnel documentation | | | | | | | | | | |
| slope documentation | | | above crest | dam footprint | | | | | | |
| refraction seismic | | | from surface and galleries | | | | | | | |
| displacement monitoring | | | natural- and cut slopes, including InSAR | | | | | | | |
| grouting records | | | | | | | | | | |
| **Model applications** | | | | | | | | | | |
| geological + geotechnical understanding and concept | | | | | | | | | | |
| dam foundation model | | | | | | | post grout model | | | |
| grouting concept | | | | | | | optimisation | | | |
| slope design (iC) | | | | | | | spillway | | | |
| tunnel and cavern design | | | | | | | spillway | | | |
| verification and optimisation | | | | | | | | | | |
| Project coordination | **guiding and coordinating the design and construction processes** | | | | | | | | | |

Johannes Kleberger, Irmina Pöschl, Jonas Weil

# Yusufeli arch dam - digital ground model

## Data handling

No mature digital work space at project start (2013)

- Existing information in PDF formats, simple terrain models, 2D CAD drawings
- Site investigation data received in paper, PDF and contractor's native excel formats
- Classical field mapping and tunnel documentation etc. with pencil and paper
- Project-specific classification systems developed during construction
- No database solutions and specifications

→ Successive development of custom system for data handling and storage, using:

- Excel templates suitable for interpretation and analysis
- Custom scripts (e.g. software R) for extraction from native formats, processing and analysis
- Export and storage of complex csv files corresponding to Leapfrog's internal database
- Complex model hosted on Seequent's Central platform

# Yusufeli arch dam - digital ground model

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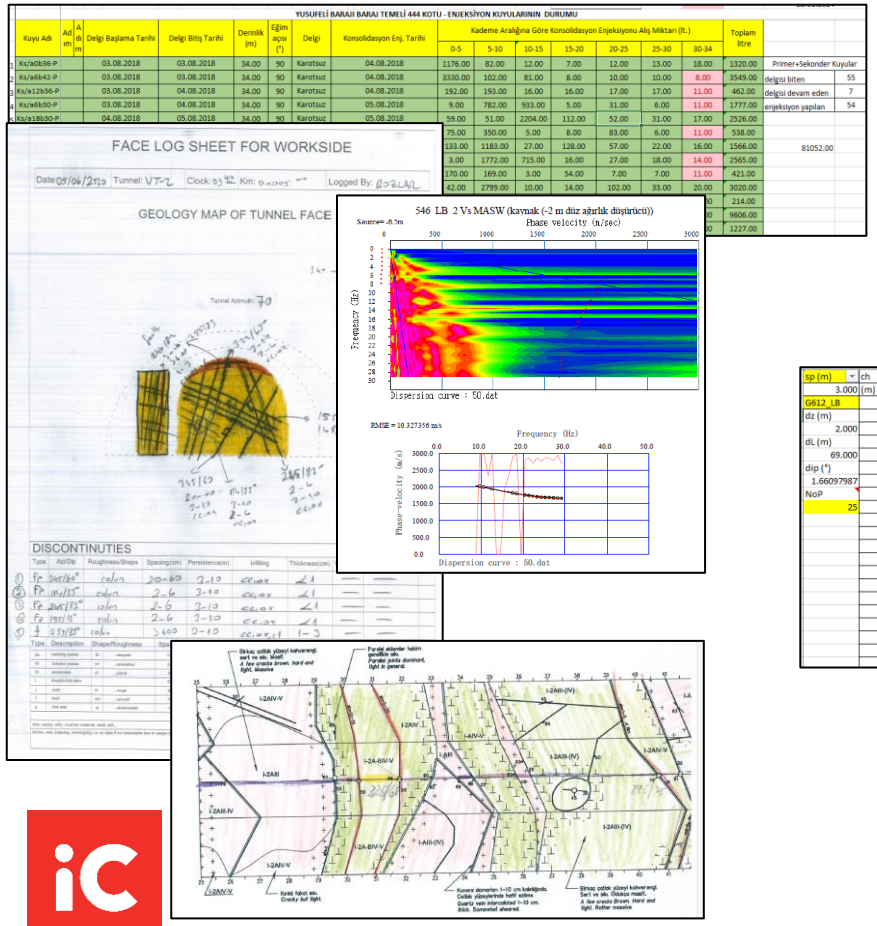
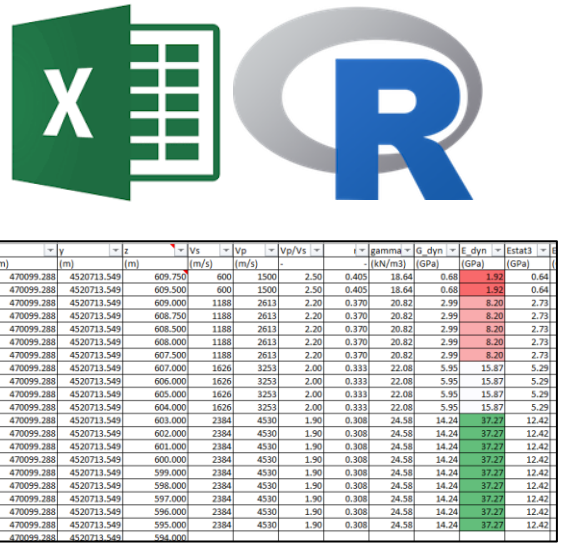
## **Data handling**: Digitalization and model import

### Original records from SI contractor




### Interpretation and processing

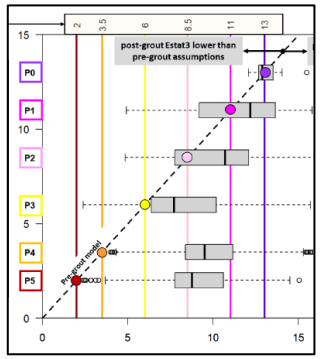


| sp (m) | ch | depth | Vp | Vs | x | y | z | Vs | Vp | Vp/Vs | | gamma | G_dyn | E_dyn | Estat3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.000 | (m) | (m) | (m/s) | (m/s) | (m) | (m) | (m) | (m/s) | (m/s) | - | - | (kN/m3) | (GPa) | (GPa) | (GPa) |
| G612_LB | 3.00 | 0.25 | 1500 | 600 | 470099.288 | 4520713.549 | 609.750 | 600 | 1500 | 2.50 | 0.405 | 18.64 | 0.68 | 1.92 | 0.64 |
| dz (m) | 3.00 | 0.50 | 1500 | 600 | 470099.288 | 4520713.549 | 609.500 | 600 | 1500 | 2.50 | 0.405 | 18.64 | 0.68 | 1.92 | 0.64 |
| 2.000 | 3.00 | 1.00 | 2613 | 1188 | 470099.288 | 4520713.549 | 609.000 | 1188 | 2613 | 2.20 | 0.370 | 20.82 | 2.99 | 8.20 | 2.73 |
| dL (m) | 3.00 | 1.25 | 2613 | 1188 | 470099.288 | 4520713.549 | 608.750 | 1188 | 2613 | 2.20 | 0.370 | 20.82 | 2.99 | 8.20 | 2.73 |
| 69.000 | 3.00 | 1.50 | 2613 | 1188 | 470099.288 | 4520713.549 | 608.500 | 1188 | 2613 | 2.20 | 0.370 | 20.82 | 2.99 | 8.20 | 2.73 |
| dip (°) | 3.00 | 2.00 | 2613 | 1188 | 470099.288 | 4520713.549 | 608.000 | 1188 | 2613 | 2.20 | 0.370 | 20.82 | 2.99 | 8.20 | 2.73 |
| 1.66097987 | 3.00 | 2.50 | 2613 | 1188 | 470099.288 | 4520713.549 | 607.500 | 1188 | 2613 | 2.20 | 0.370 | 20.82 | 2.99 | 8.20 | 2.73 |
| NoP | 3.00 | 3.00 | 3253 | 1626 | 470099.288 | 4520713.549 | 607.000 | 1626 | 3253 | 2.00 | 0.333 | 22.08 | 5.95 | 15.87 | 5.29 |
| 25 | 3.00 | 4.00 | 3253 | 1626 | 470099.288 | 4520713.549 | 606.000 | 1626 | 3253 | 2.00 | 0.333 | 22.08 | 5.95 | 15.87 | 5.29 |
| | 3.00 | 5.00 | 3253 | 1626 | 470099.288 | 4520713.549 | 605.000 | 1626 | 3253 | 2.00 | 0.333 | 22.08 | 5.95 | 15.87 | 5.29 |
| | 3.00 | 6.00 | 3253 | 1626 | 470099.288 | 4520713.549 | 604.000 | 1626 | 3253 | 2.00 | 0.333 | 22.08 | 5.95 | 15.87 | 5.29 |
| | 3.00 | 7.00 | 4530 | 2384 | 470099.288 | 4520713.549 | 603.000 | 2384 | 4530 | 1.90 | 0.308 | 24.58 | 14.24 | 37.27 | 12.42 |
| | 3.00 | 8.00 | 4530 | 2384 | 470099.288 | 4520713.549 | 602.000 | 2384 | 4530 | 1.90 | 0.308 | 24.58 | 14.24 | 37.27 | 12.42 |
| | 3.00 | 9.00 | 4530 | 2384 | 470099.288 | 4520713.549 | 601.000 | 2384 | 4530 | 1.90 | 0.308 | 24.58 | 14.24 | 37.27 | 12.42 |
| | 3.00 | 10.00 | 4530 | 2384 | 470099.288 | 4520713.549 | 600.000 | 2384 | 4530 | 1.90 | 0.308 | 24.58 | 14.24 | 37.27 | 12.42 |
| | 3.00 | 11.00 | 4530 | 2384 | 470099.288 | 4520713.549 | 599.000 | 2384 | 4530 | 1.90 | 0.308 | 24.58 | 14.24 | 37.27 | 12.42 |
| | 3.00 | 12.00 | 4530 | 2384 | 470099.288 | 4520713.549 | 598.000 | 2384 | 4530 | 1.90 | 0.308 | 24.58 | 14.24 | 37.27 | 12.42 |
| | 3.00 | 13.00 | 4530 | 2384 | 470099.288 | 4520713.549 | 597.000 | 2384 | 4530 | 1.90 | 0.308 | 24.58 | 14.24 | 37.27 | 12.42 |
| | 3.00 | 14.00 | 4530 | 2384 | 470099.288 | 4520713.549 | 596.000 | 2384 | 4530 | 1.90 | 0.308 | 24.58 | 14.24 | 37.27 | 12.42 |
| | 3.00 | 15.00 | 4530 | 2384 | 470099.288 | 4520713.549 | 595.000 | 2384 | 4530 | 1.90 | 0.308 | 24.58 | 14.24 | 37.27 | 12.42 |
| | 3.00 | 16.00 | 4530 | 2384 | 470099.288 | 4520713.549 | 594.000 | | | | | | | | |

### Preparation of key-content for model import, analysis and reporting

.csv

leapfrog

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## Factual data in Leapfrog model:

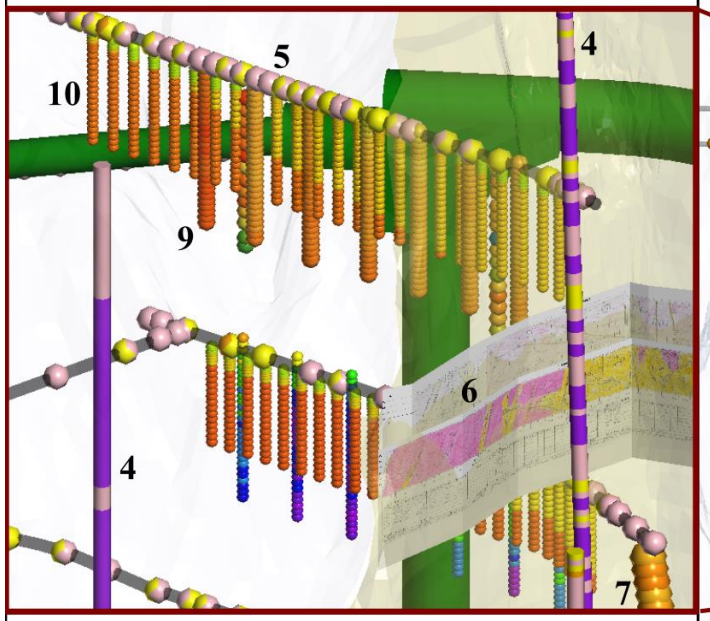
Data-driven:

- Borehole data
- Points
- Block models
- GIS data

Visual:

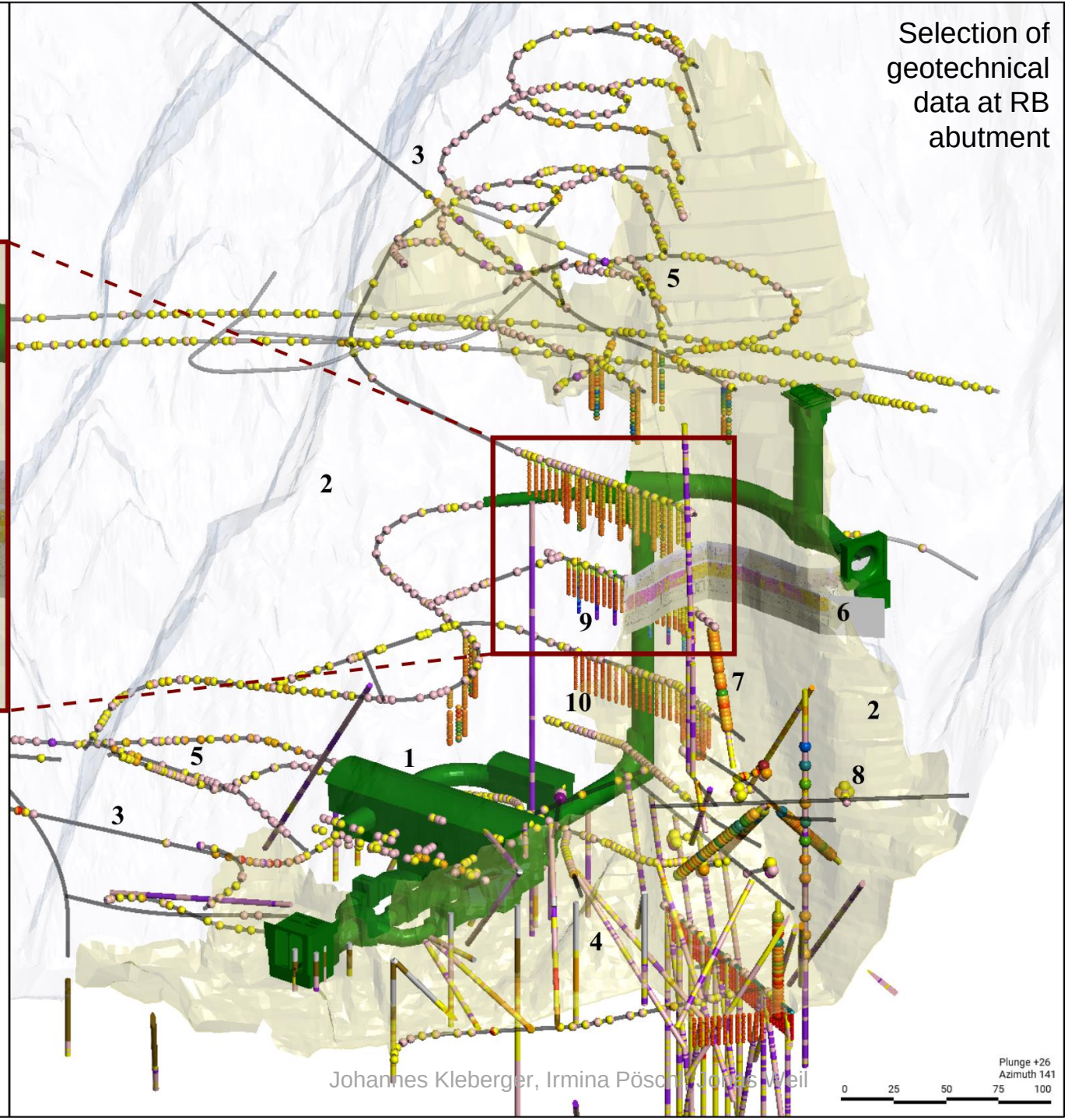
- Polylines
- References maps and sections

**Model content**
**1 underground facilities**
**2 terrain models and excavation (transparent)**
**3 tunnel axis (>20km / 130 adits, galleries and tunnels for construction and operation)**




**Factual data in digital model**
**(excluding grouting and verification survey)**
**4 borehole logs (ca. 16,300m / 280 holes)**
**5 geological tunnel and shaft documentation (>2250 face logs)**
**6 geological slope documentation (ca. 200,000m² / >1000 A4 logging sheets)**
**7 dilatometer tests (>500 tests)**
**8 plateload test (44 tests)**
**9 crosshole seismic survey (> 30 profiles)**
**10 refraction seismic profiles (>60 profiles)**

Selection of geotechnical data at RB abutment

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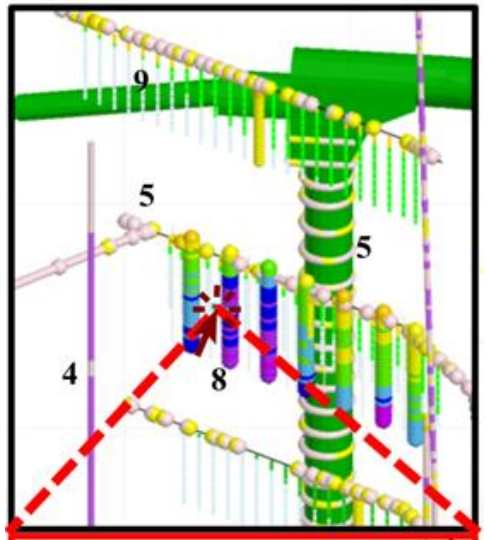
## Factual data in Leapfrog model - data-driven:

Leapfrog “Boreholes” were used for classical borehole information, but also for other data that could be displayed along “alignments”, such as

- Tunnel alignments:
  - Face logging data
  - Discontinuity data
  - Seismic velocities
  - In situ testing (e.g. plate-load tests in galleries)
  - Water inflow
- Seismic profiles
- Scan line mapping
- Monitoring devices
  - installed equipment (e.g. extensometers, inclinometers)
  - Measured deformation rates
- Displacement paths
  - Including time-dependent information




Estat3_SeisCrossHole_1810

| | |
|---|---|
| Location | 470332.849997, 4520319.5, 600.599999237 |
| id | 339 |
| column | S18_RGD-5_2-3 |
| Vs | 2277.00 |
| Vp | 5832.00 |
| Vp_Vs | 2.56 |
| poisson | 0.41 |
| gamma | 27.14 |
| G_dyn | 14.34 |
| E_dyn | 40.45 |
| Estat3 | 13.48 |

# Yusufeli arch dam - digital ground model

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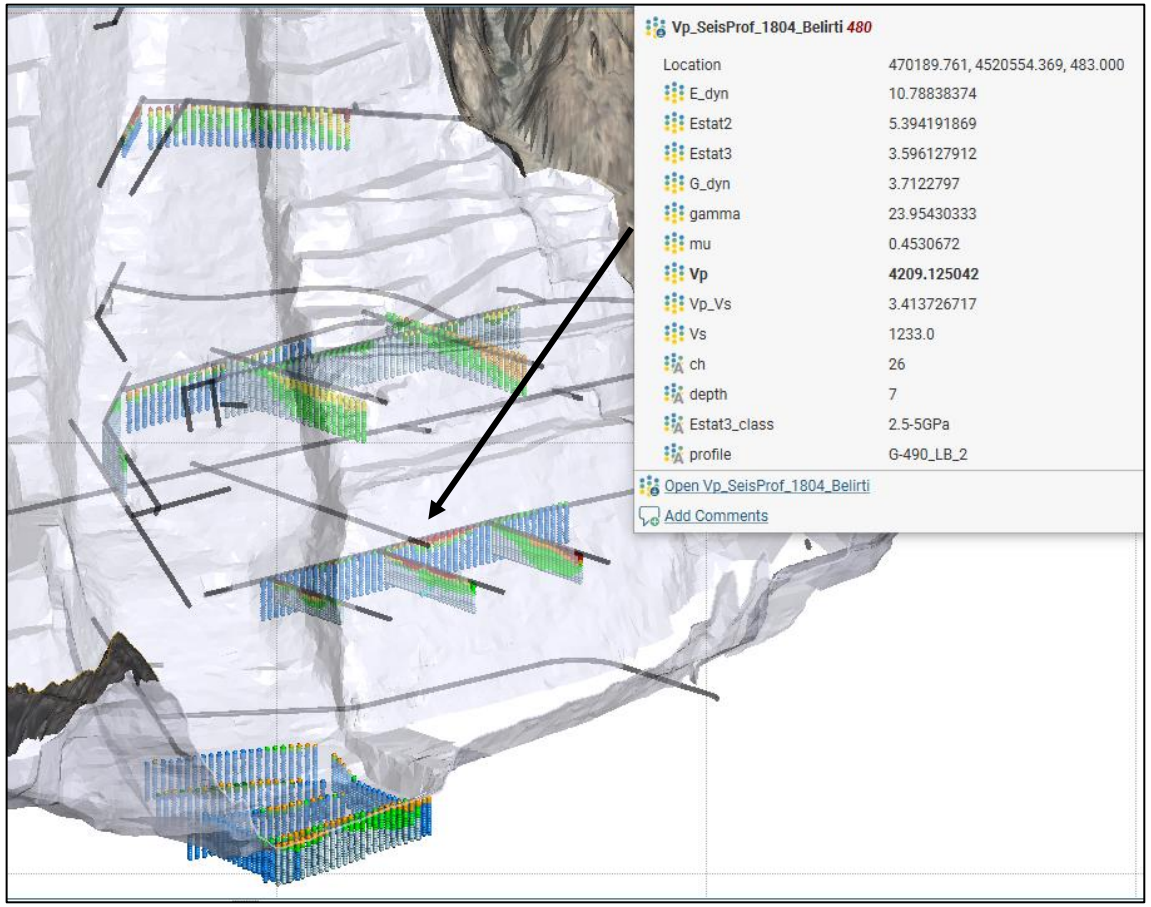
**Factual data in Leapfrog model - data-driven:**

Many other observations and measurements were imported as points with xyz-coordinates,

- Grids with results from seismic surveys
- Field observations
- Monitoring devises (e.g. load cells from pre-stressed anchors)
- Displacements measurements e.g. from InSAR
- Relevant design structures / information




Applications:

- Query information in model during “manual analysis”
- Interpretation and interpolation of numerical values

# Yusufeli arch dam - digital ground model

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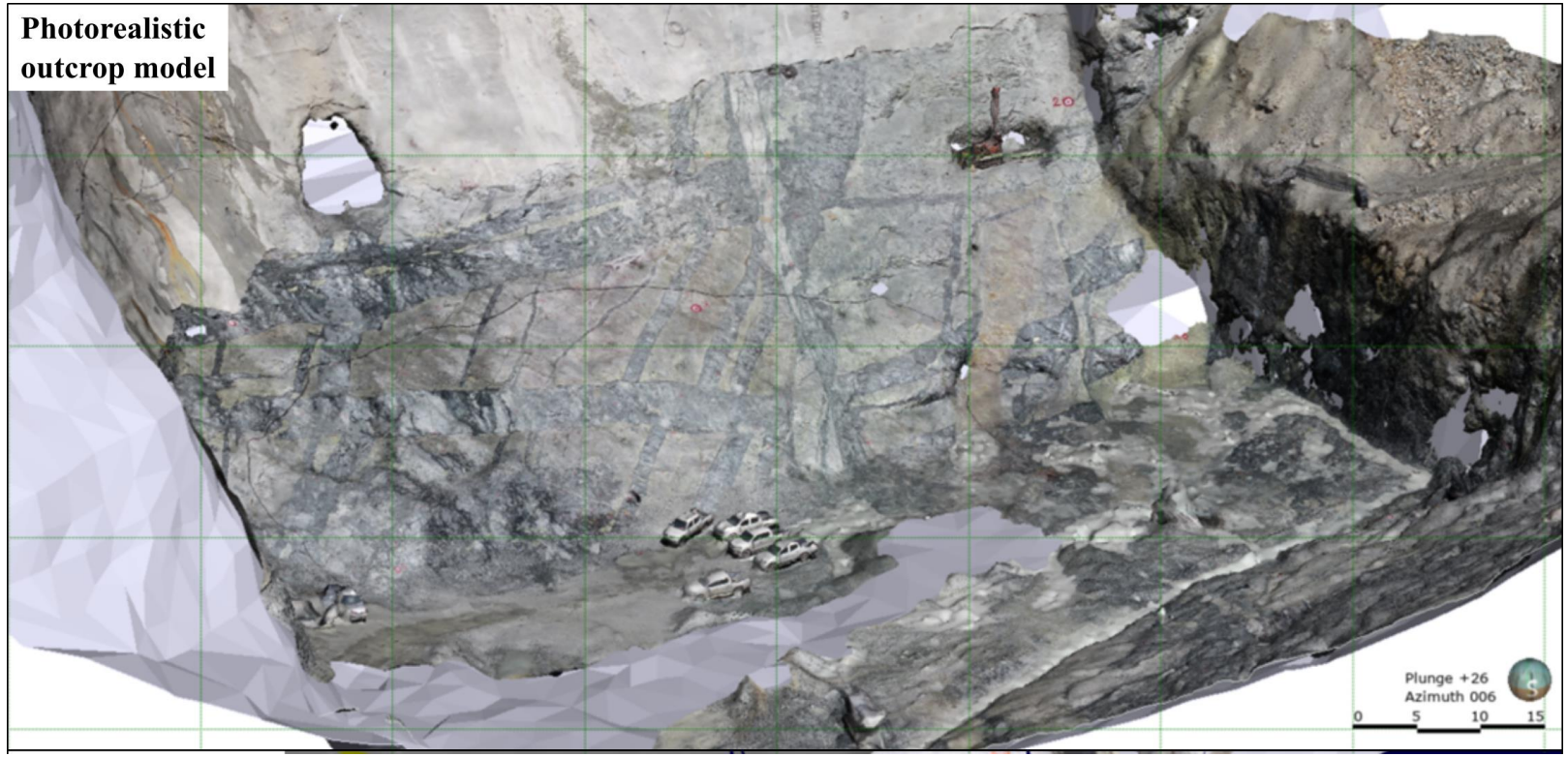
## Factual data in Leapfrog model – visual only

Information that was implemented in the form im images, maps and drawings:

- Classical orthophotos, maps and technical layouts
- Textured 3D meshes from e.g. photogrammetry
- Interpretation from geophysical surveys
- Geological documentation drawings
  - Tunnels
  - Cut slopes
- Interpreted sections for local geotechnical analysis




Photorealistic terrain model of excavation base at a dam site…

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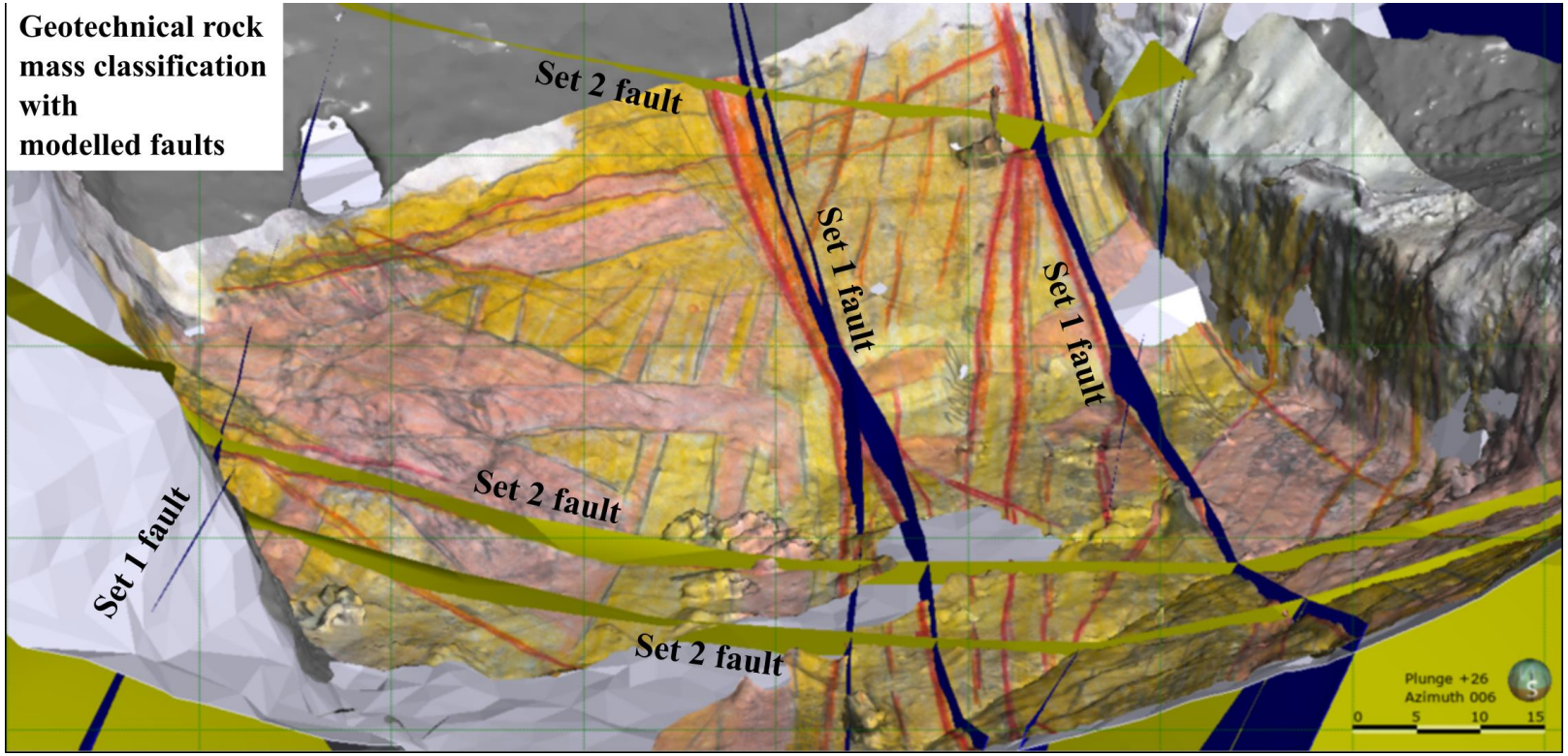


… used as the basis for geological documentation and 3D-modelling of faults and rock mass types


Yusufeli Dam, Turkey

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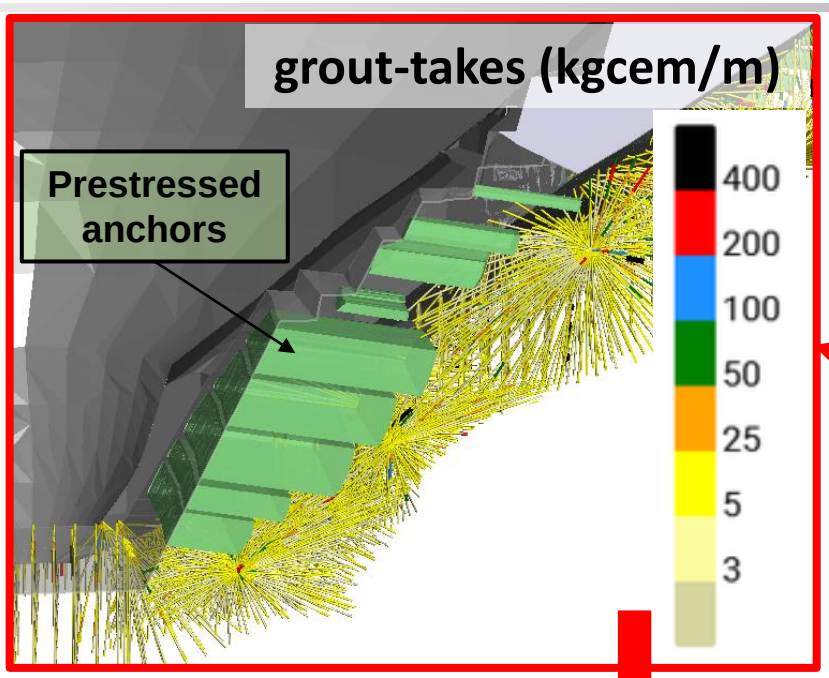
# Yusufeli arch dam - digital ground model

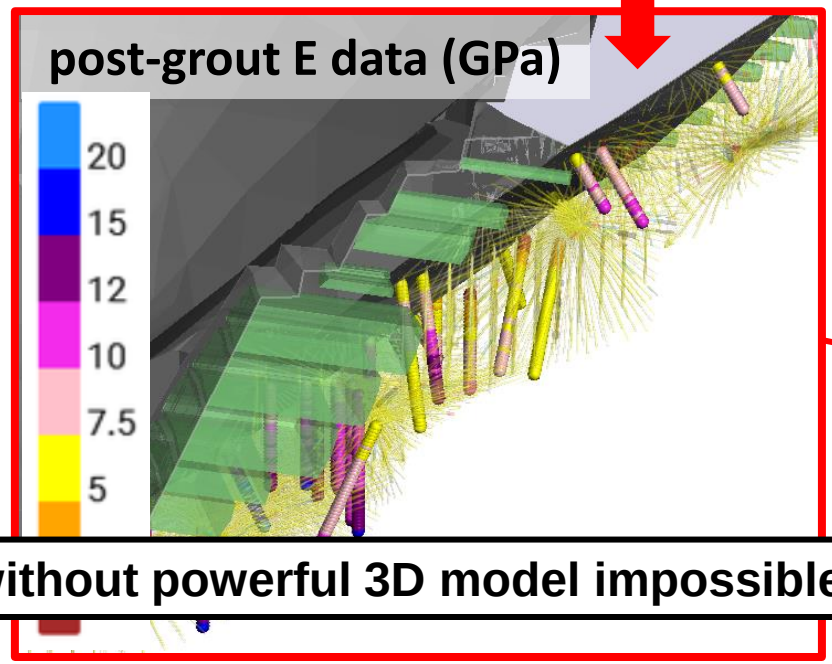
Unsuitable rock mass at dam foundation = complication of next project phase

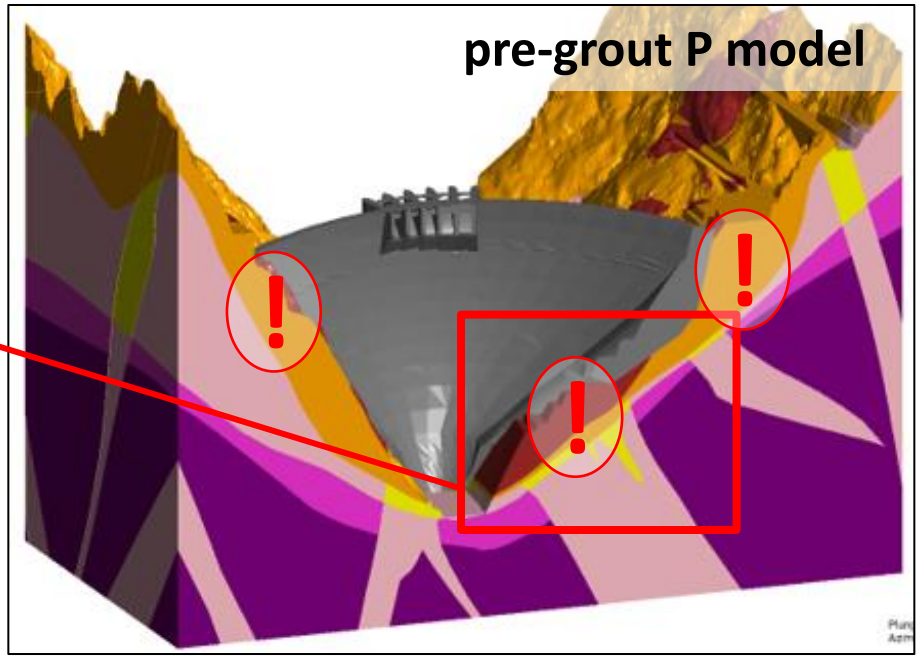
Significant improvement of foundation rock by grouting required

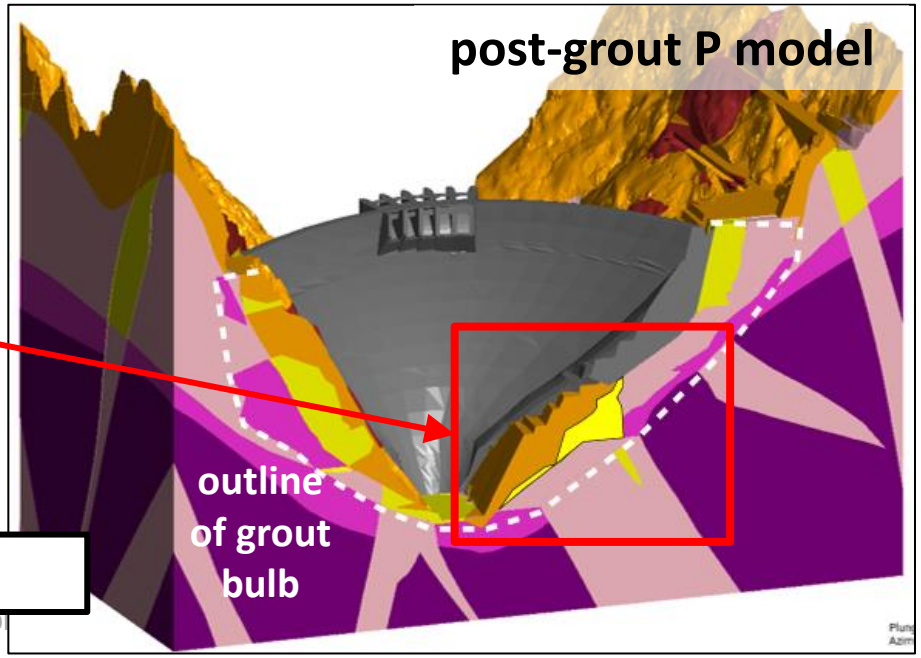
Improvement to be verified by large coverage pre- & post-grout testing

Before impounding: dam design to be verified by calculations based on post-grout model

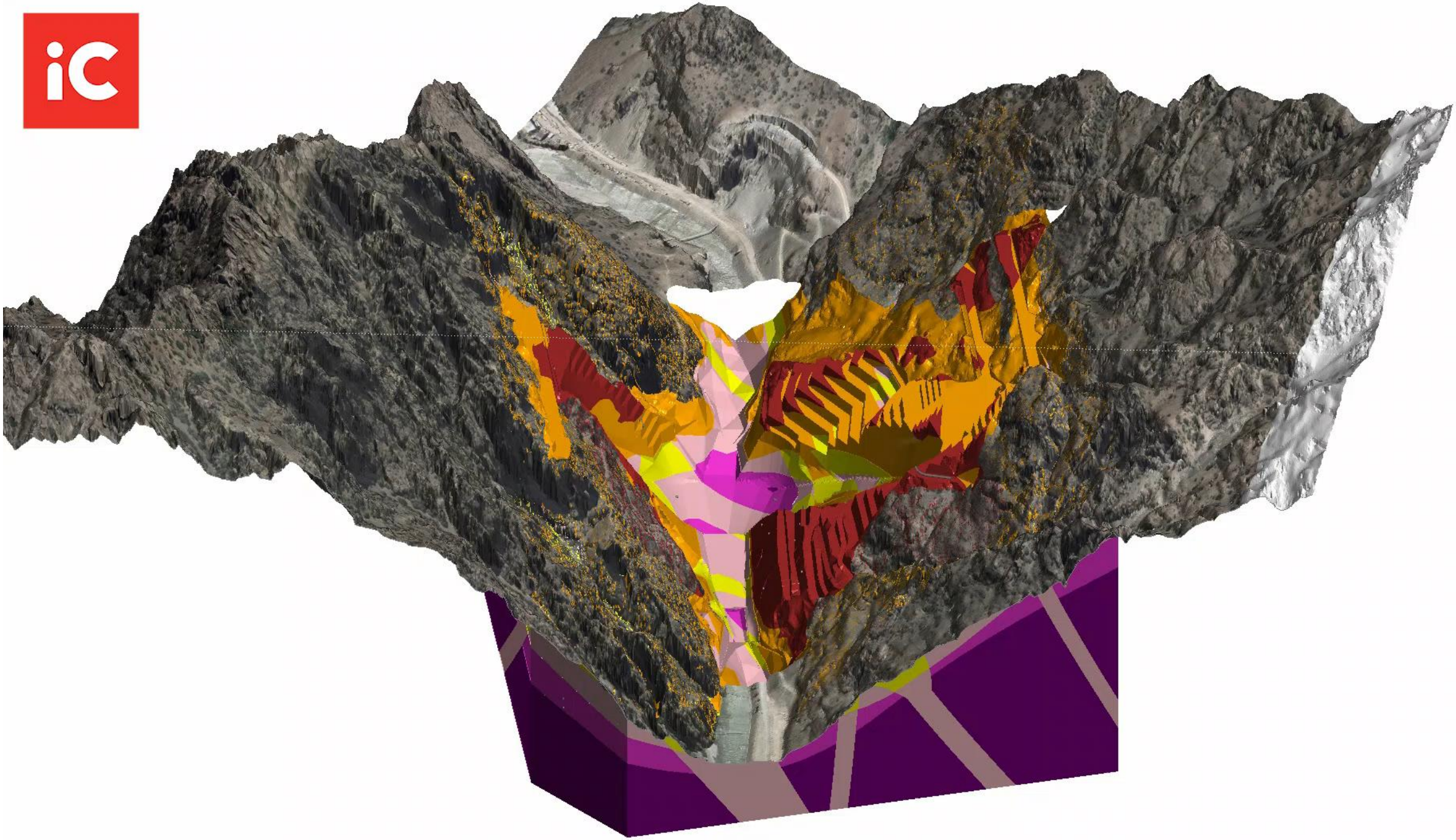



**Timely execution without powerful 3D model impossible**



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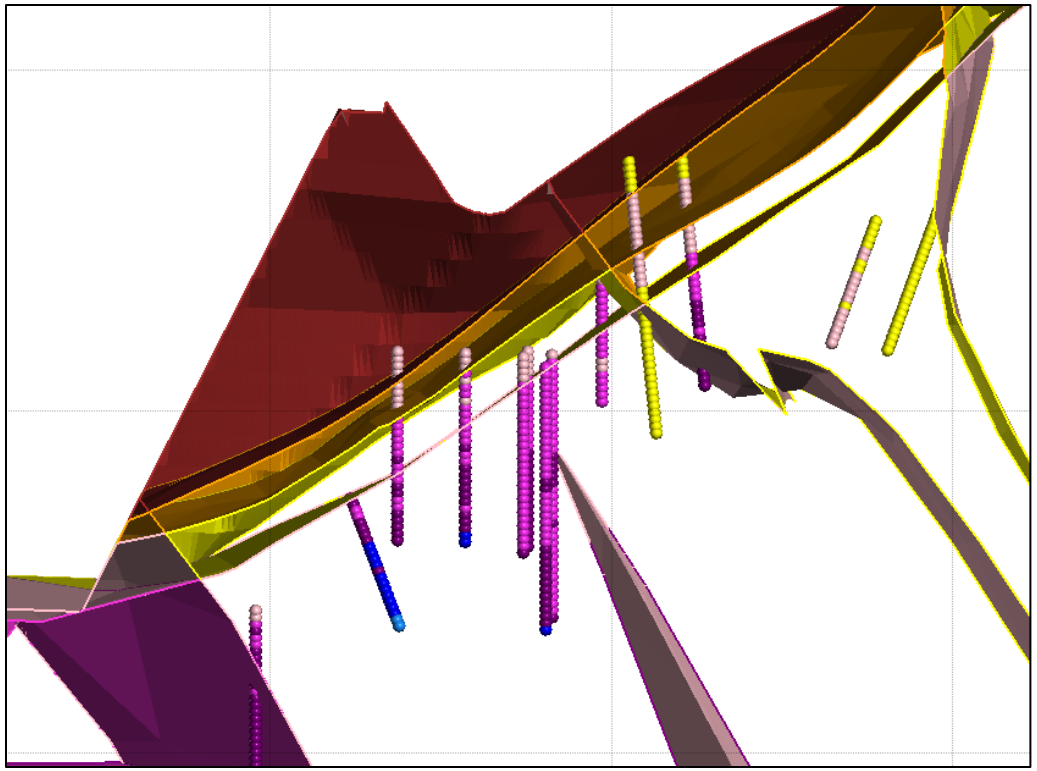
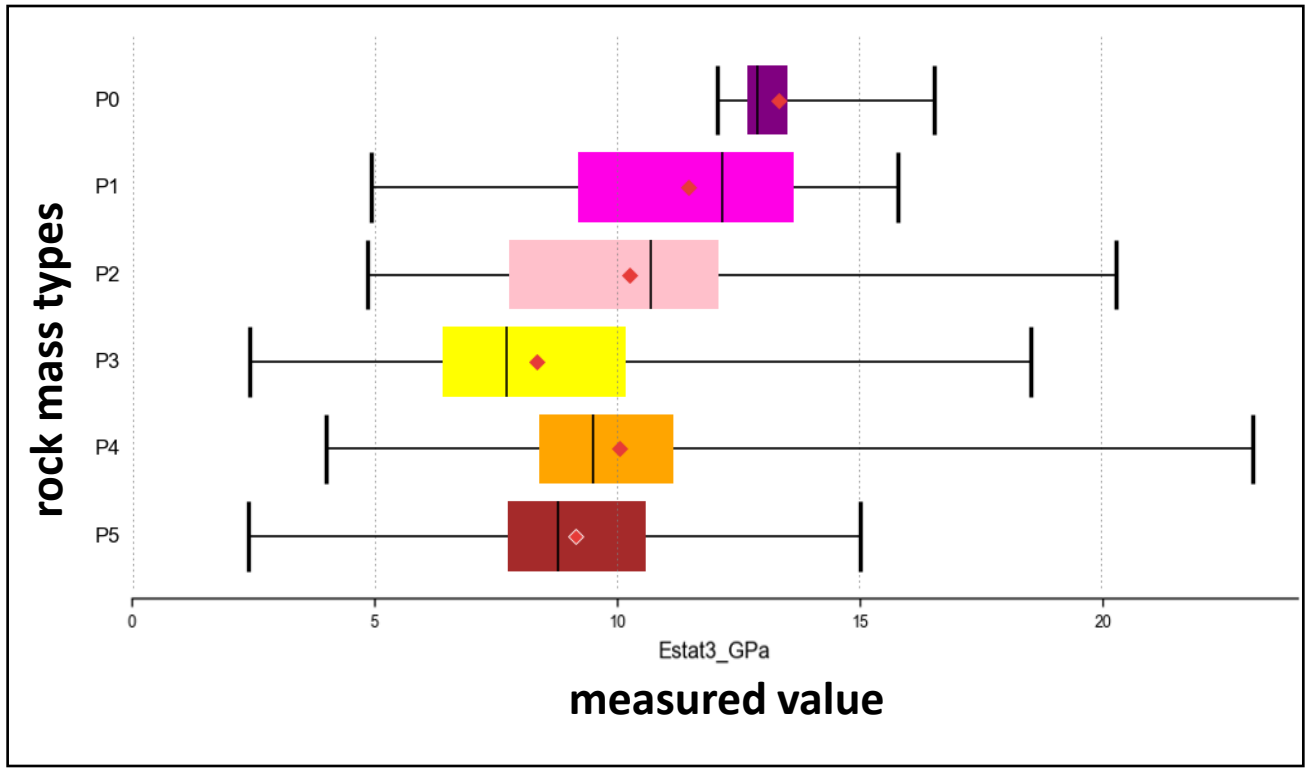
## Analysis of test results vs. rock mass model

Test results are grouped according to their position in the post-grout geotechnical model





# Yusufeli arch dam: digital ground model – data handling and applications

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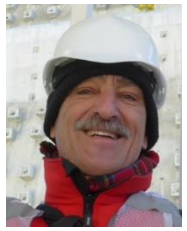
# Thank you for your attention!

Details on digital modeling approach and rock mass classification schema:.

ICOLD 2019: Innovative 3D ground models for complex hydropower projects

ISRM congress 2023: 275 m high Yusufeli arch dam – Geotechnical modelling during construction

Presentation at RMCC 2024 October in Oslo



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