Task 2 Cavern Study

Ground model and 3D cavern layout

5 December 2011

Matt Sykes
Eden Almog
Alison Barmas
Yung Loo
Agnieszka Mazurkiewicz
Franky Waldron

ARUP

Requirements Document

Matt Sykes

ARUP

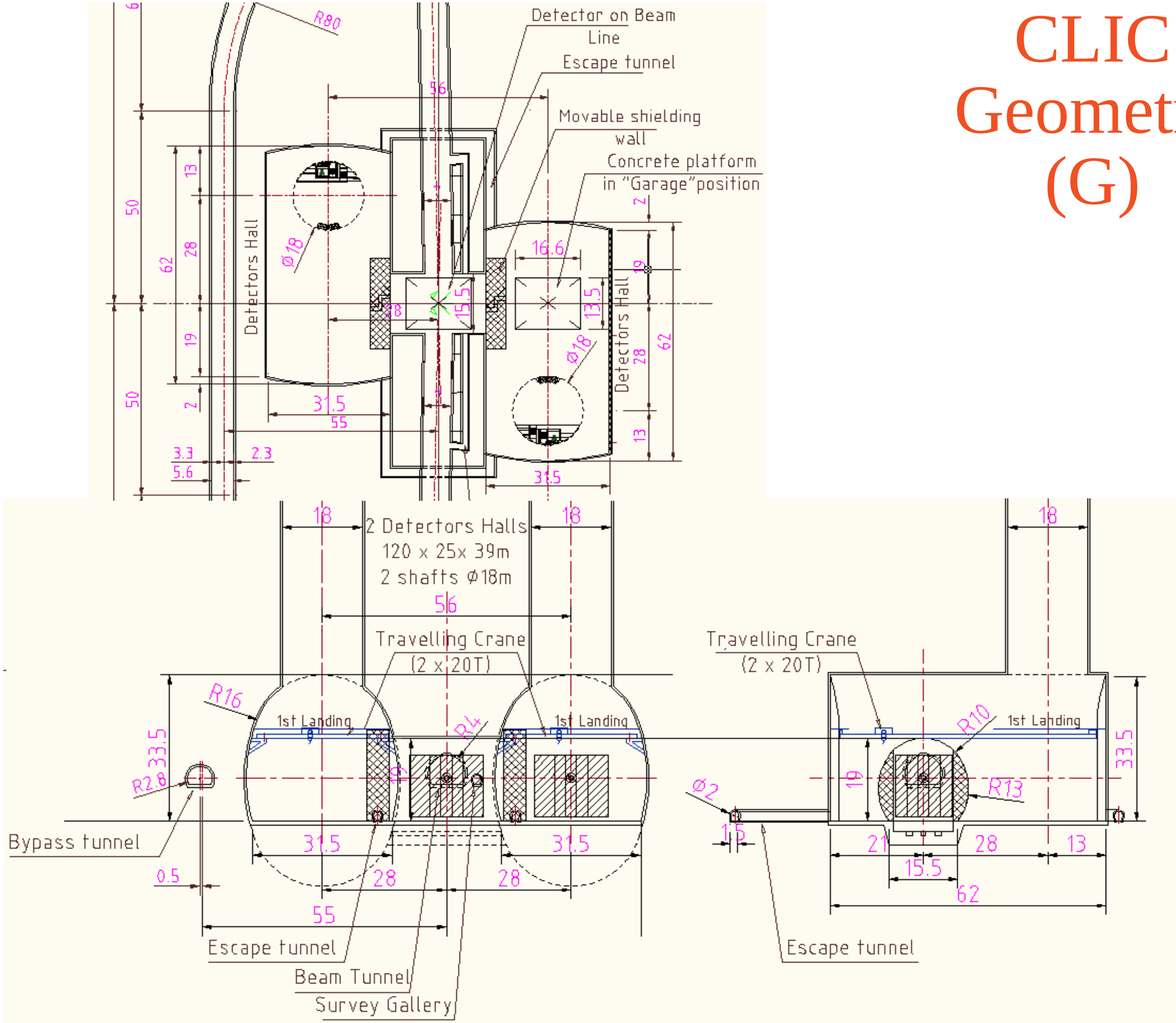
This presentation…

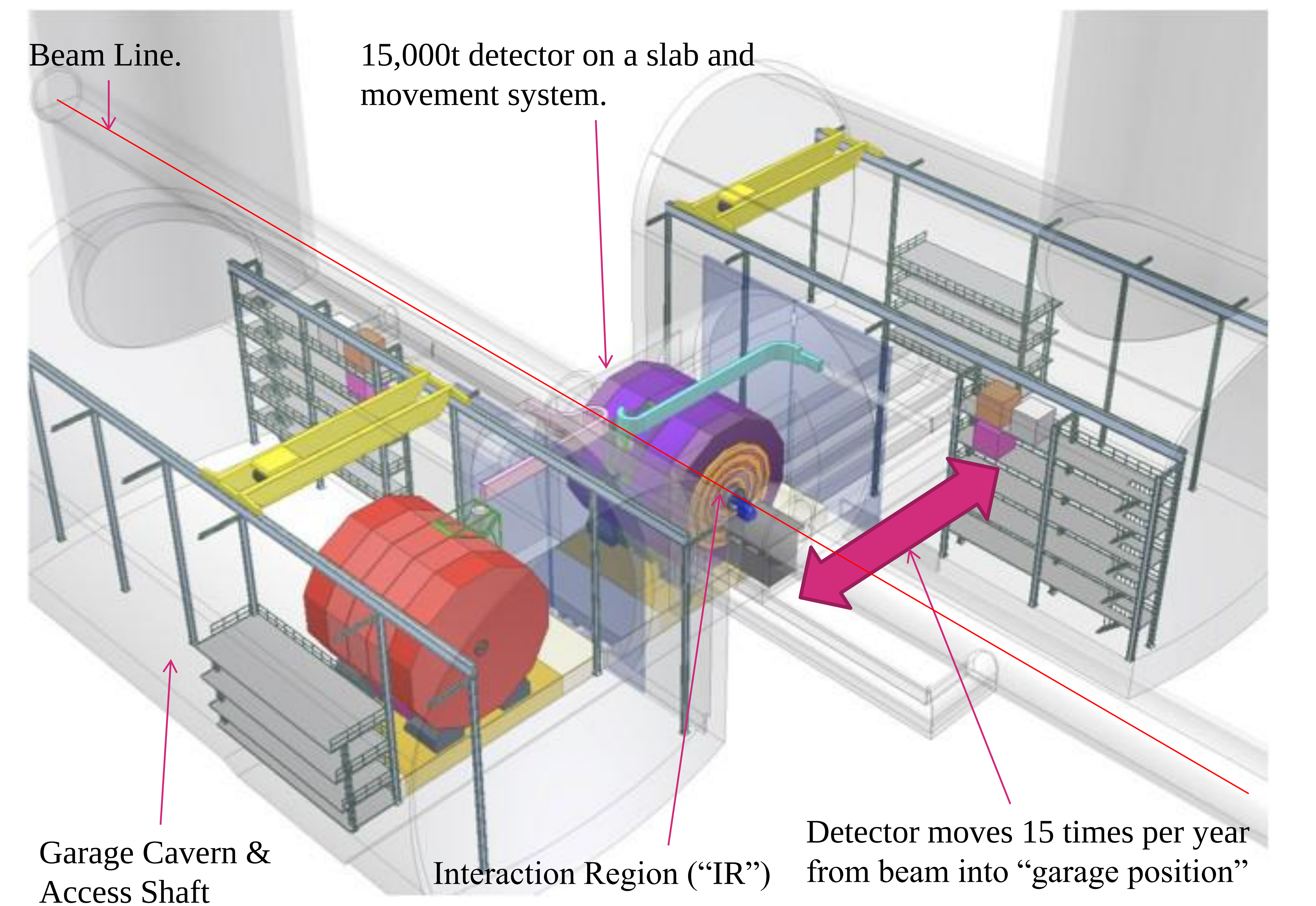
1. General Overview
2. Task 2 Study Summary
3. Stress analysis and ground yield
4. Construction sequence
5. CERN Molasse Geological model
6. Short term behaviour – Small strain stiffness
7. 2D Finite Element analysis of interaction cavern
8. 3D bedded-spring model of interaction cavern
9. Conclusions and recommendations

General Overview

ARUP

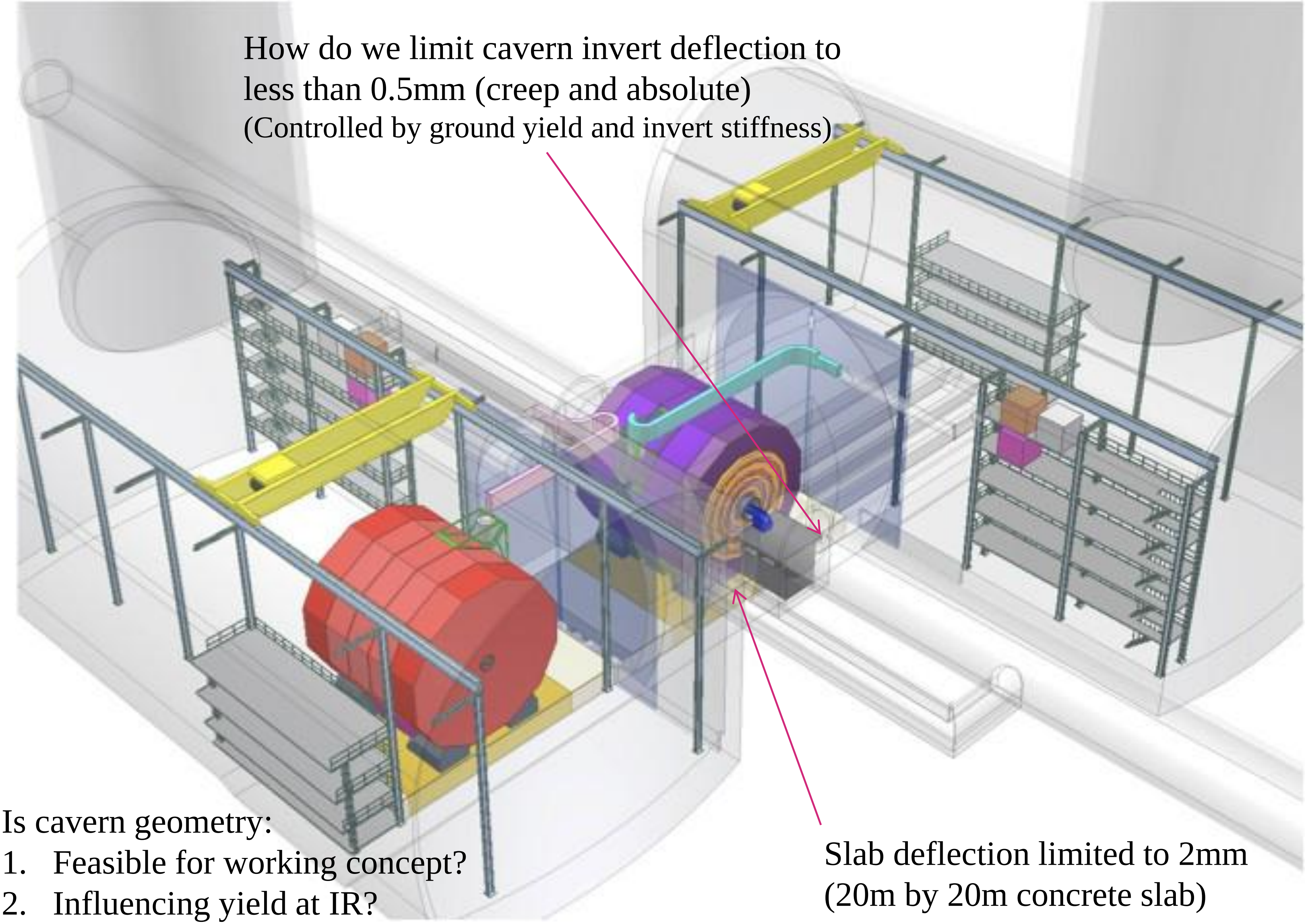
CLIC Geometry (G)




Beam Line.
15,000t detector on a slab and movement system.
Garage Cavern & Access Shaft
Interaction Region ("IR")
Detector moves 15 times per year from beam into "garage position"

ARUP

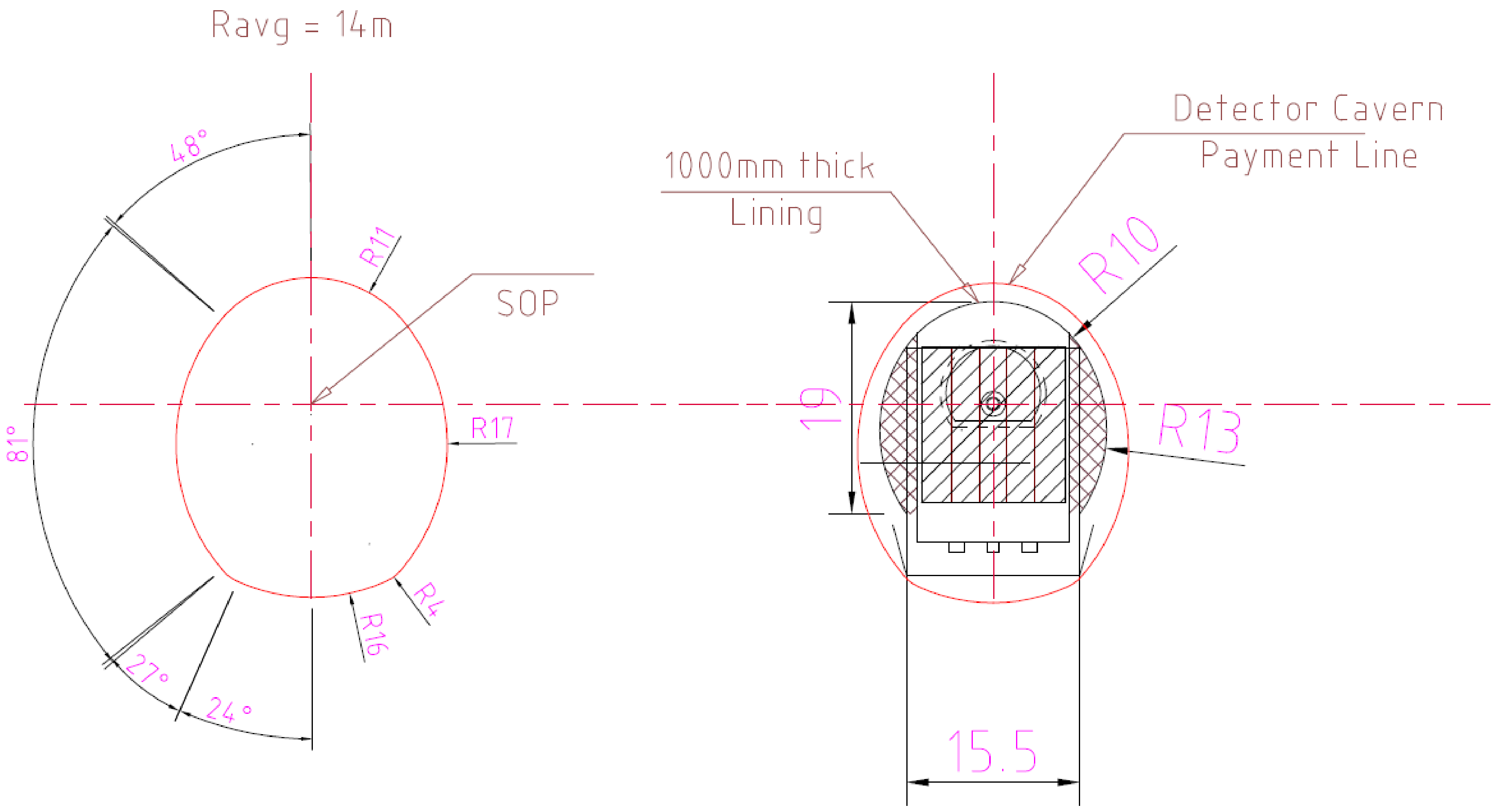
How do we limit cavern invert deflection to less than 0.5mm (creep and absolute)
(Controlled by ground yield and invert stiffness)



Slab deflection limited to 2mm
(20m by 20m concrete slab)

Is cavern geometry:
1. Feasible for working concept?
2. Influencing yield at IR?

Interaction Cavern Outline Geometry (G)



ARUP

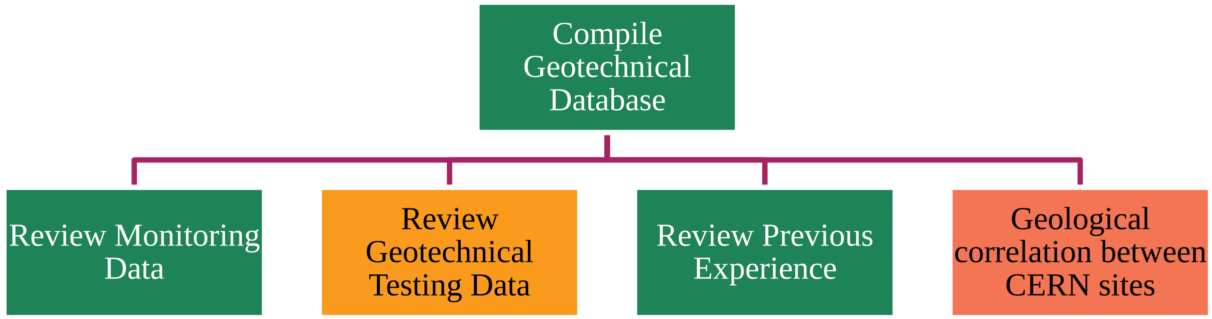
Task 2 – September Presentation

Completed

Underway

Not Started

Geotechnical Review



Cavern Design

ARUP

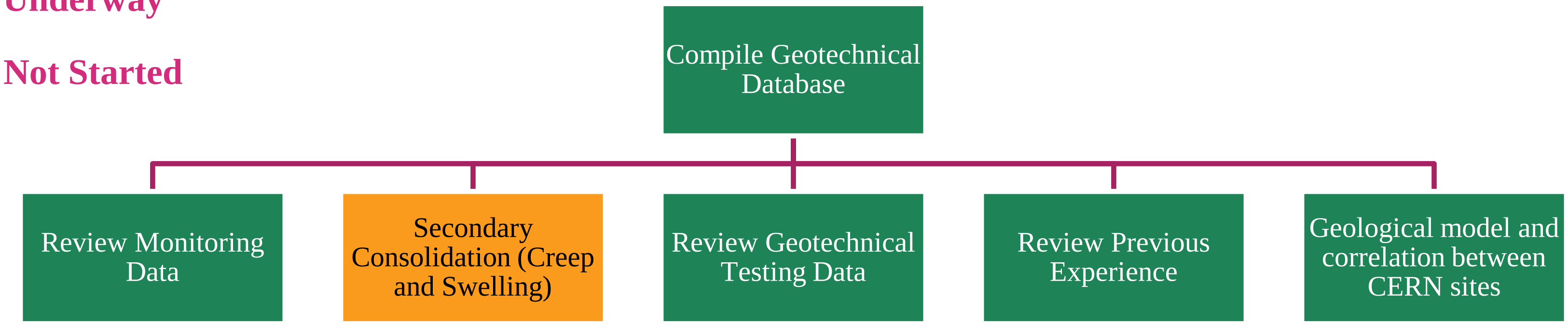
Task 2 – Study Summary

Completed

Underway

Not Started

Geotechnical Review



Cavern Design

ARUP

Stress Analysis and Ground Yielding

ARUP

Boundary Element Modelling (3D Stress Analysis)

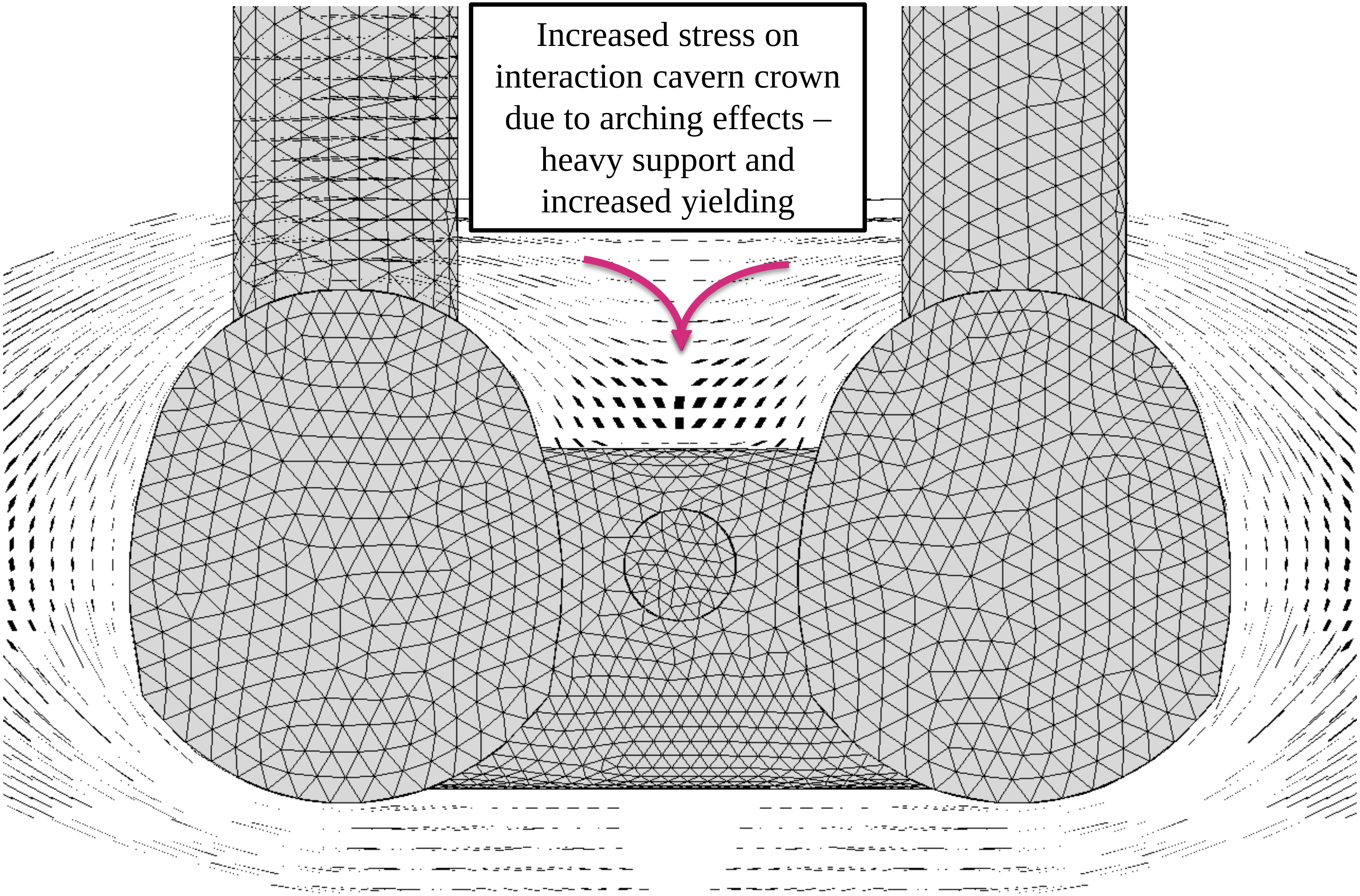
Linear elastic stress analysis in *Examine3D.*

Indication of how stress manifests at the interaction of the cavern's boundary and the ground.

Analyses carried out comparing Layout G and a layout where the caverns are pushed apart by 5m.

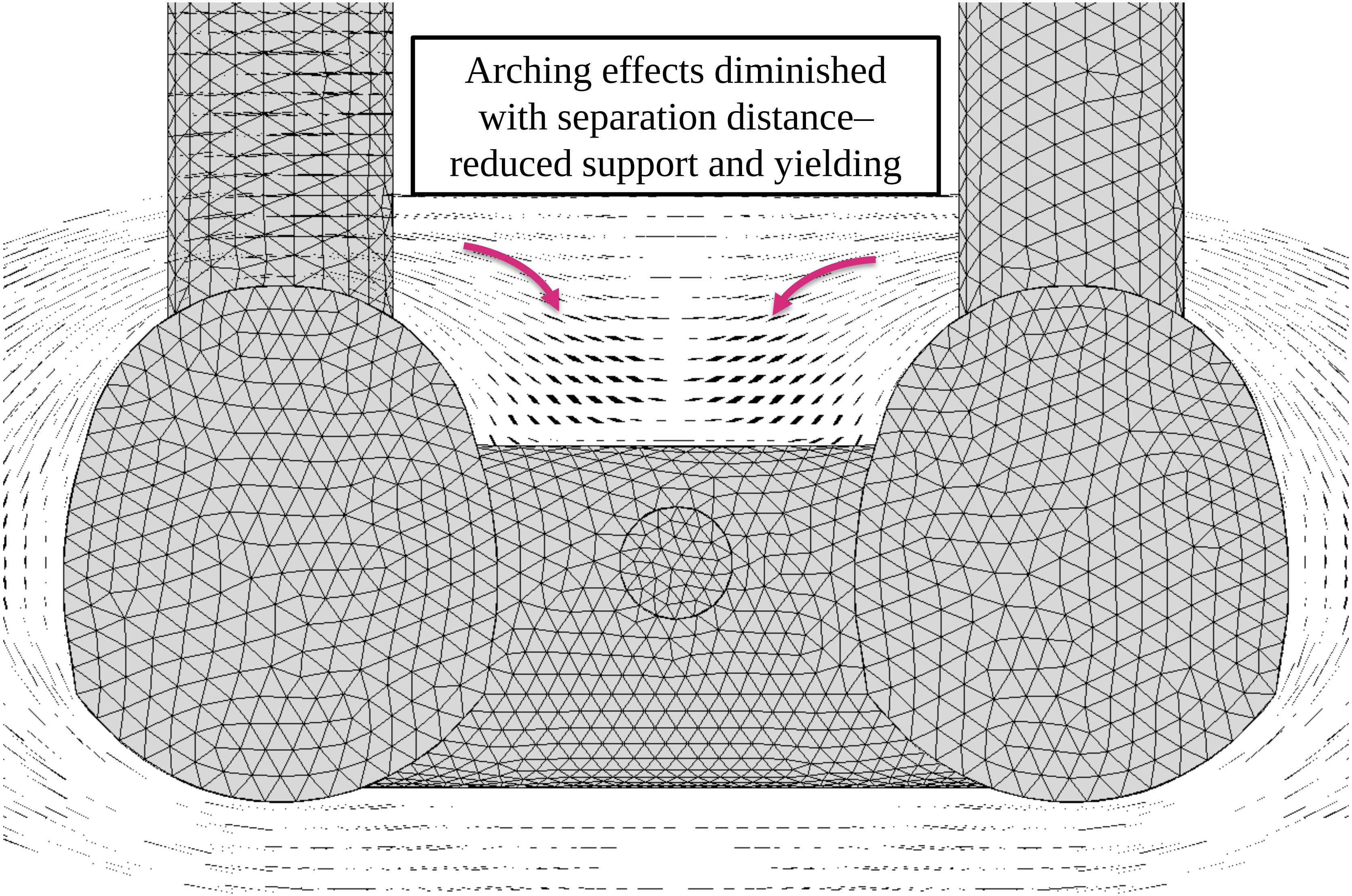
Effective strength criteria used to estimate rock mass yielding.

Layout G – Principal Stress Trajectories



ARUP

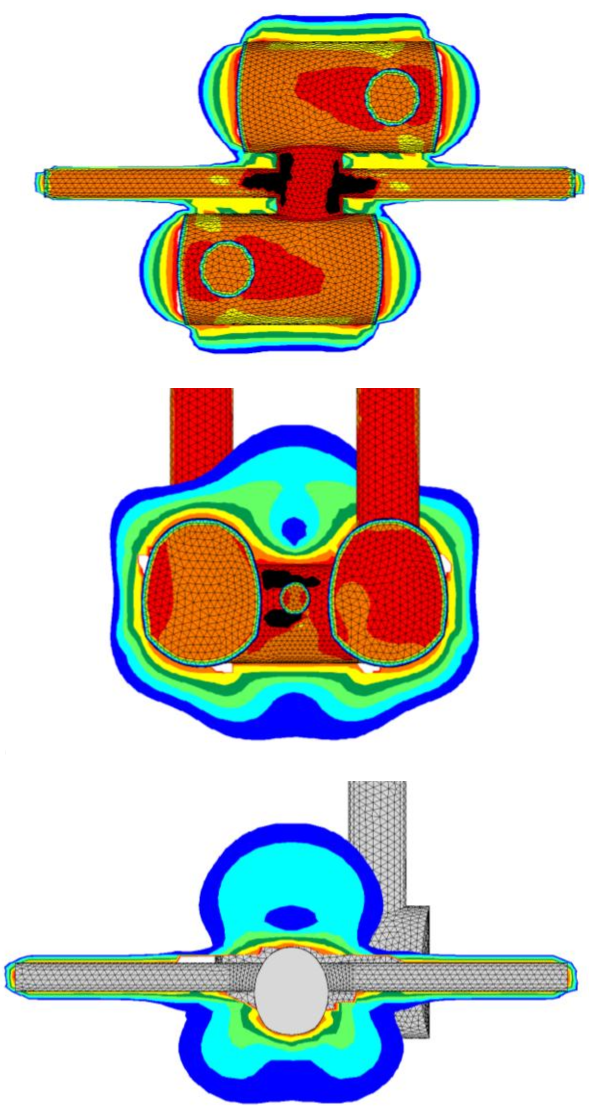
Layout G + 10m – Principal Stress Trajectories



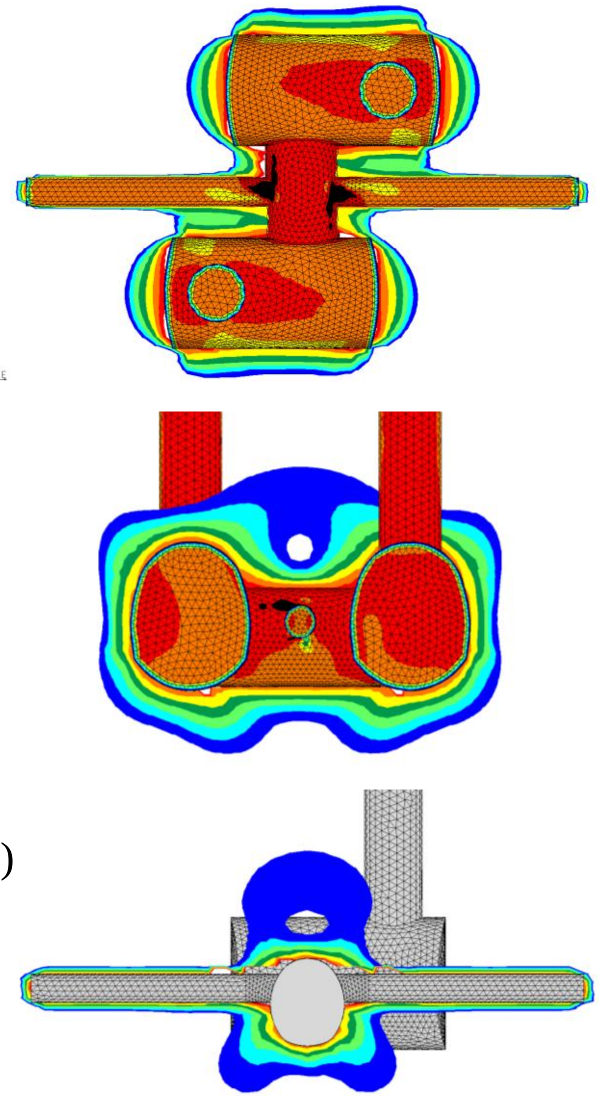
ARUP

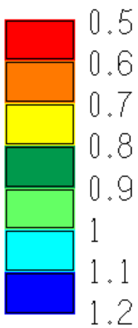
Contours of Overstress

Geometry G



Geometry G + 10m

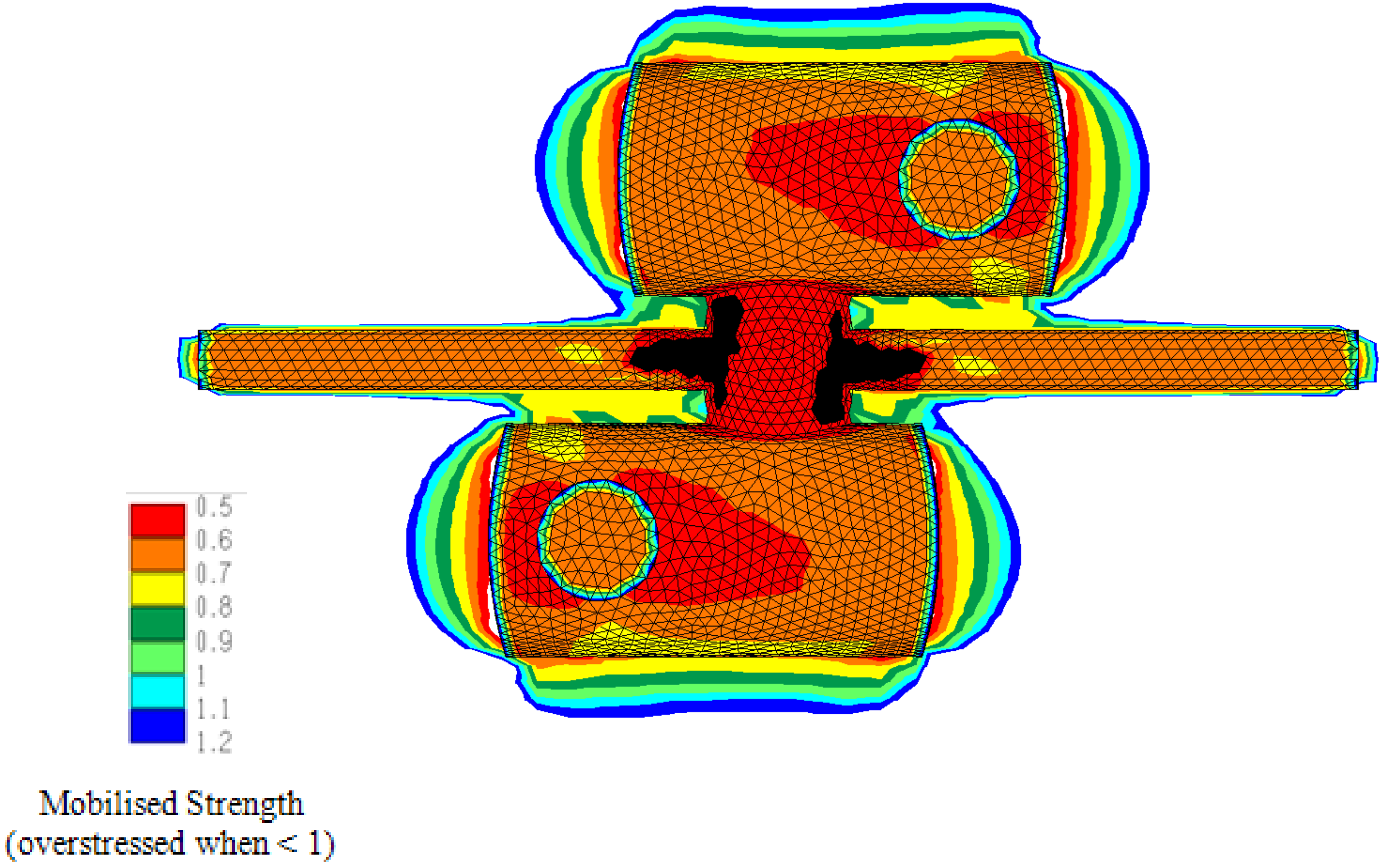




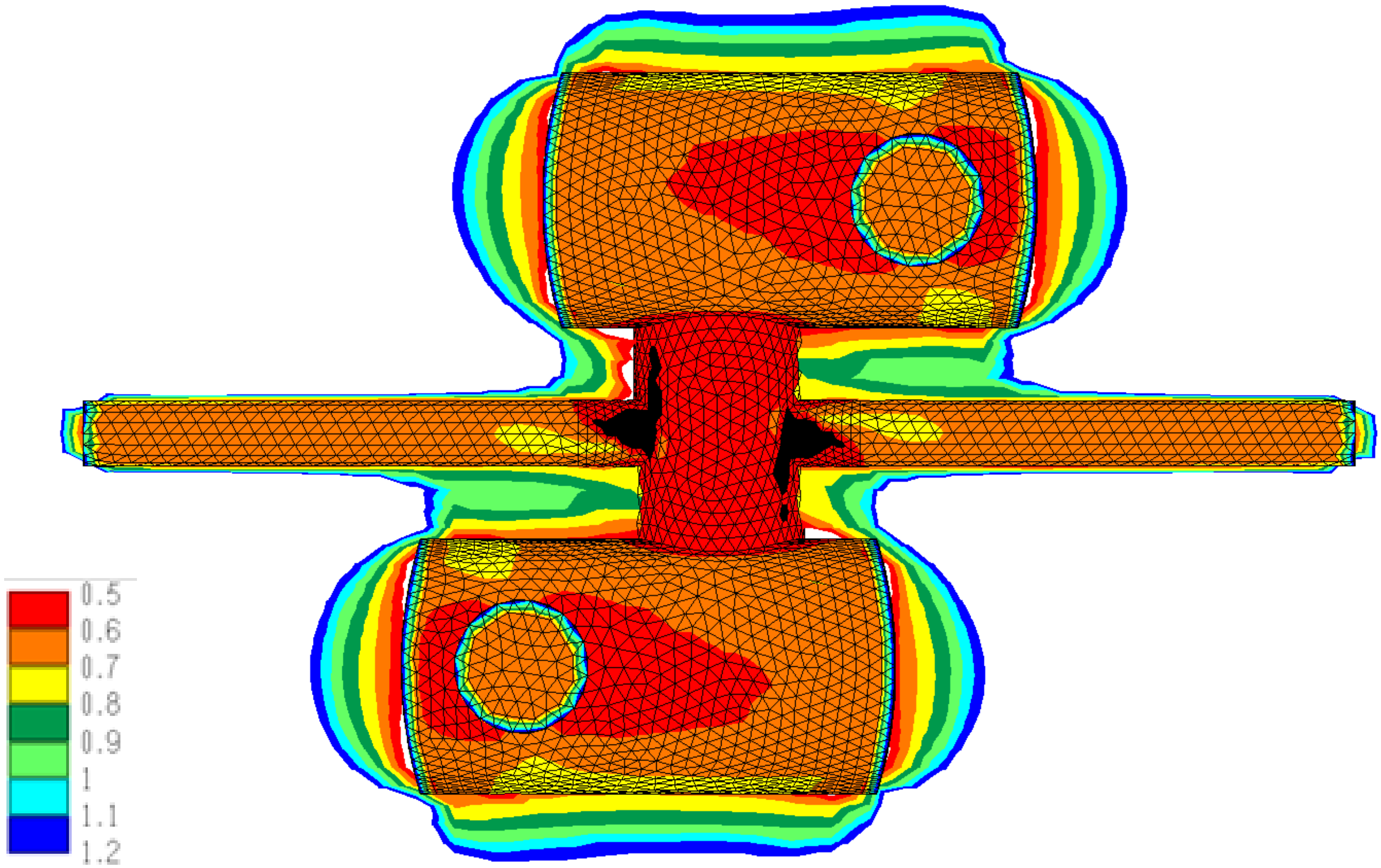
Mobilised Strength
(overstressed when < 1)

ARUP

Layout G

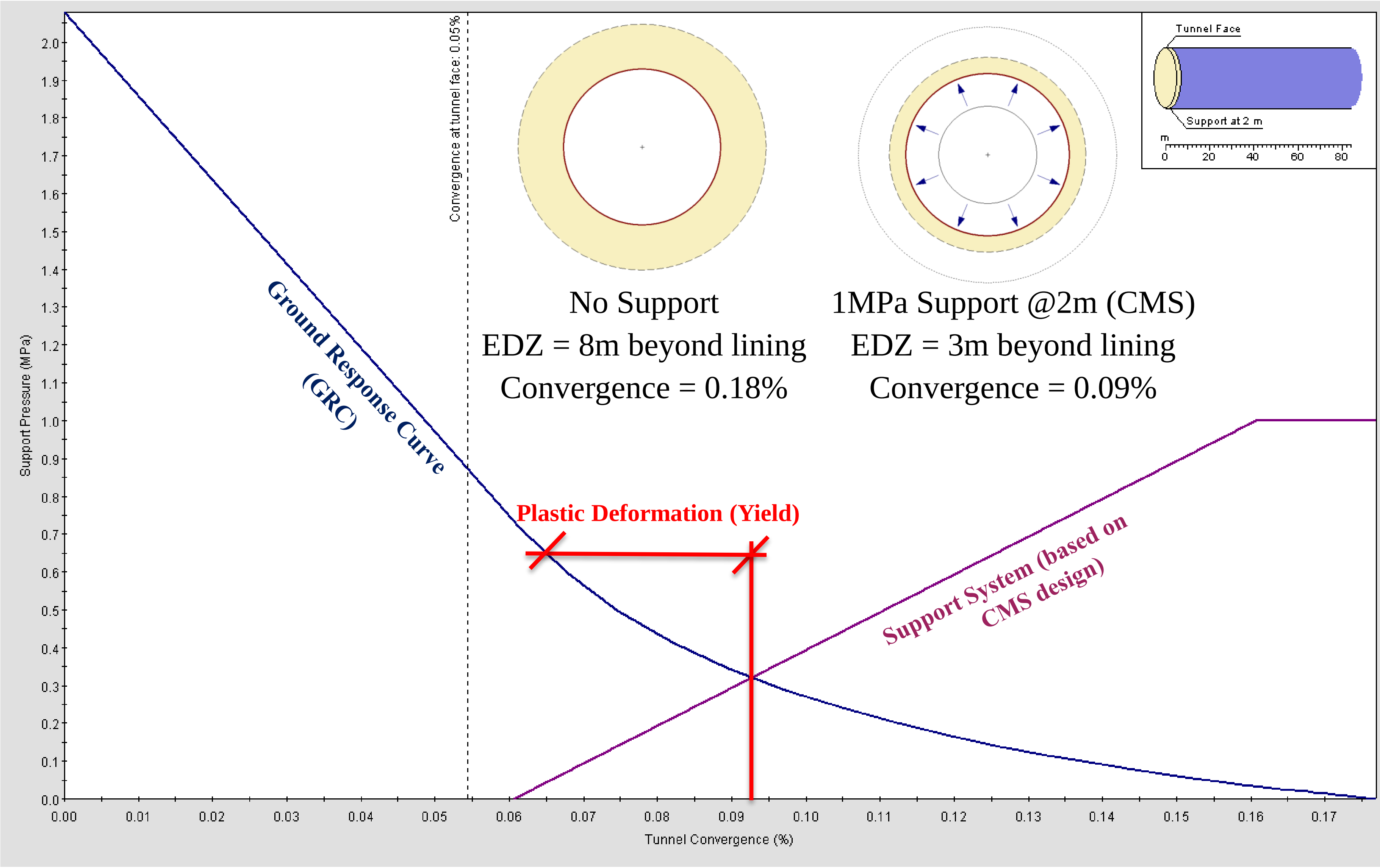


Layout G + Interaction Cavern Enlargement



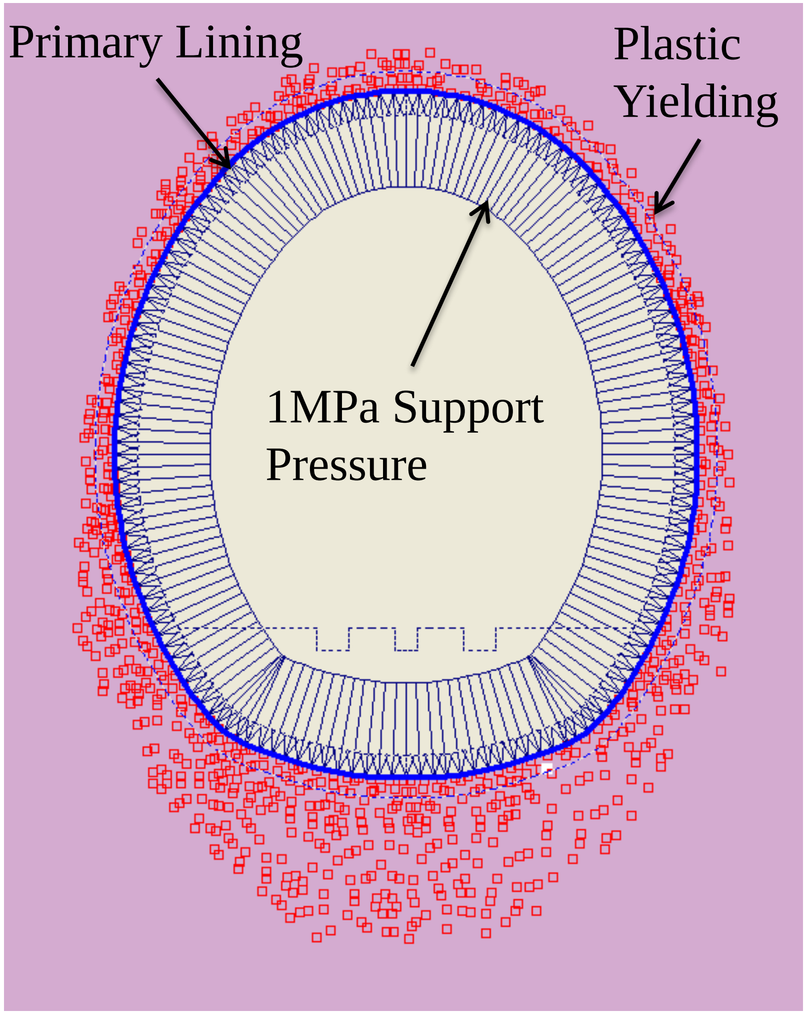
Mobilised Strength
(overstressed when < 1)

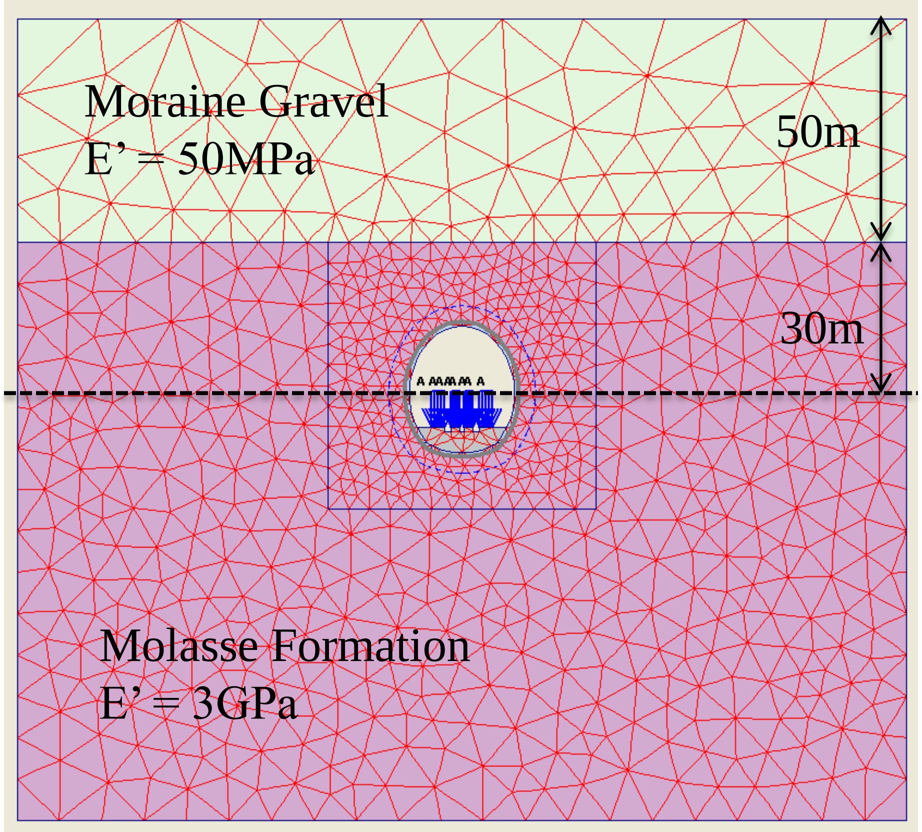
SCL Support Design



Final convergence: 0.09%, FS: 3.12
Convergence at tunnel face: 0.05%, Convergence at support: 0.06%

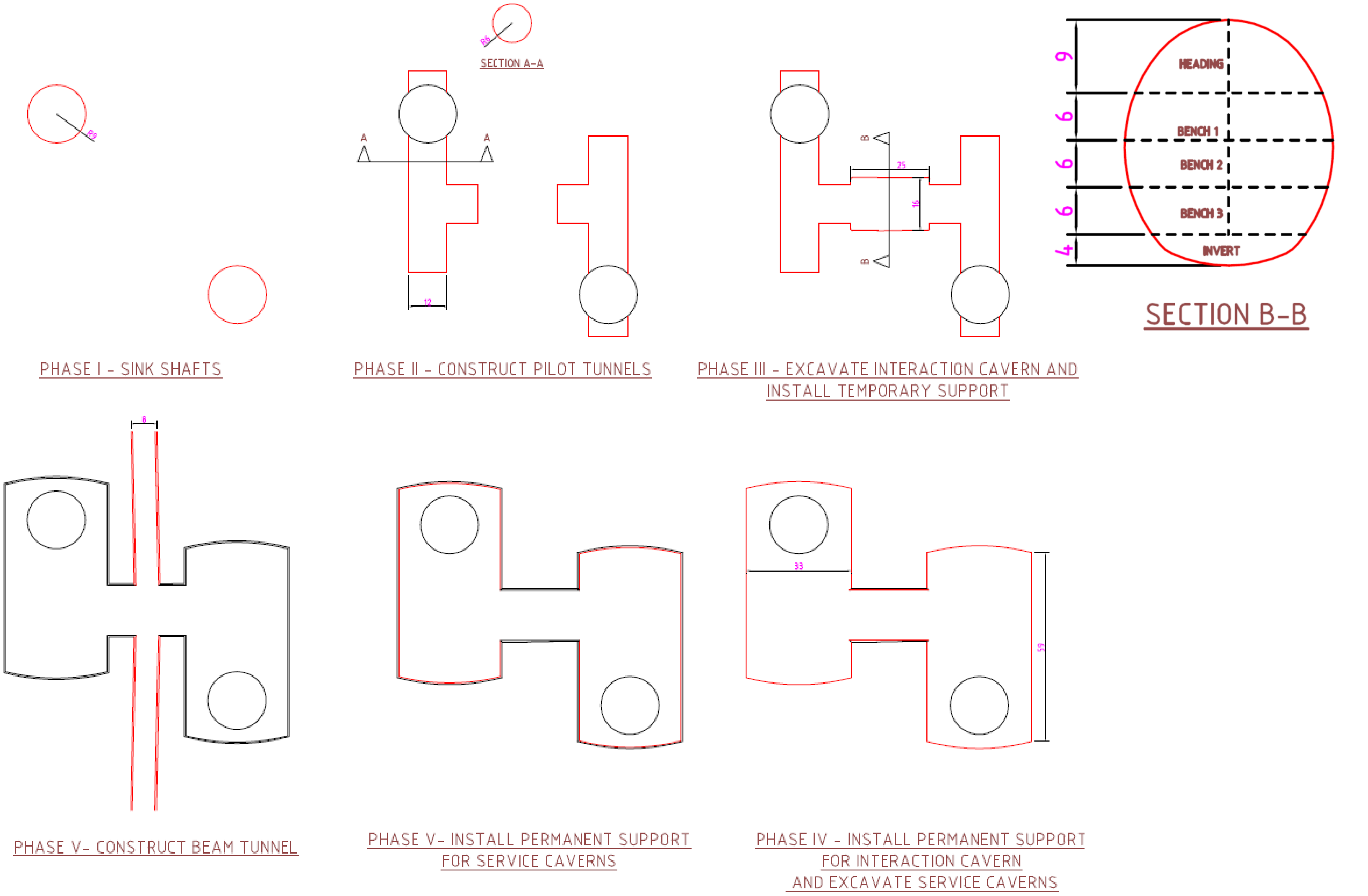
Conservative 2D FE analysis





ARUP

Construction Sequence



ARUP

Ground Model Development

Alison Barmas/ Yung Loo/ Franky Waldron

ARUP

Outline

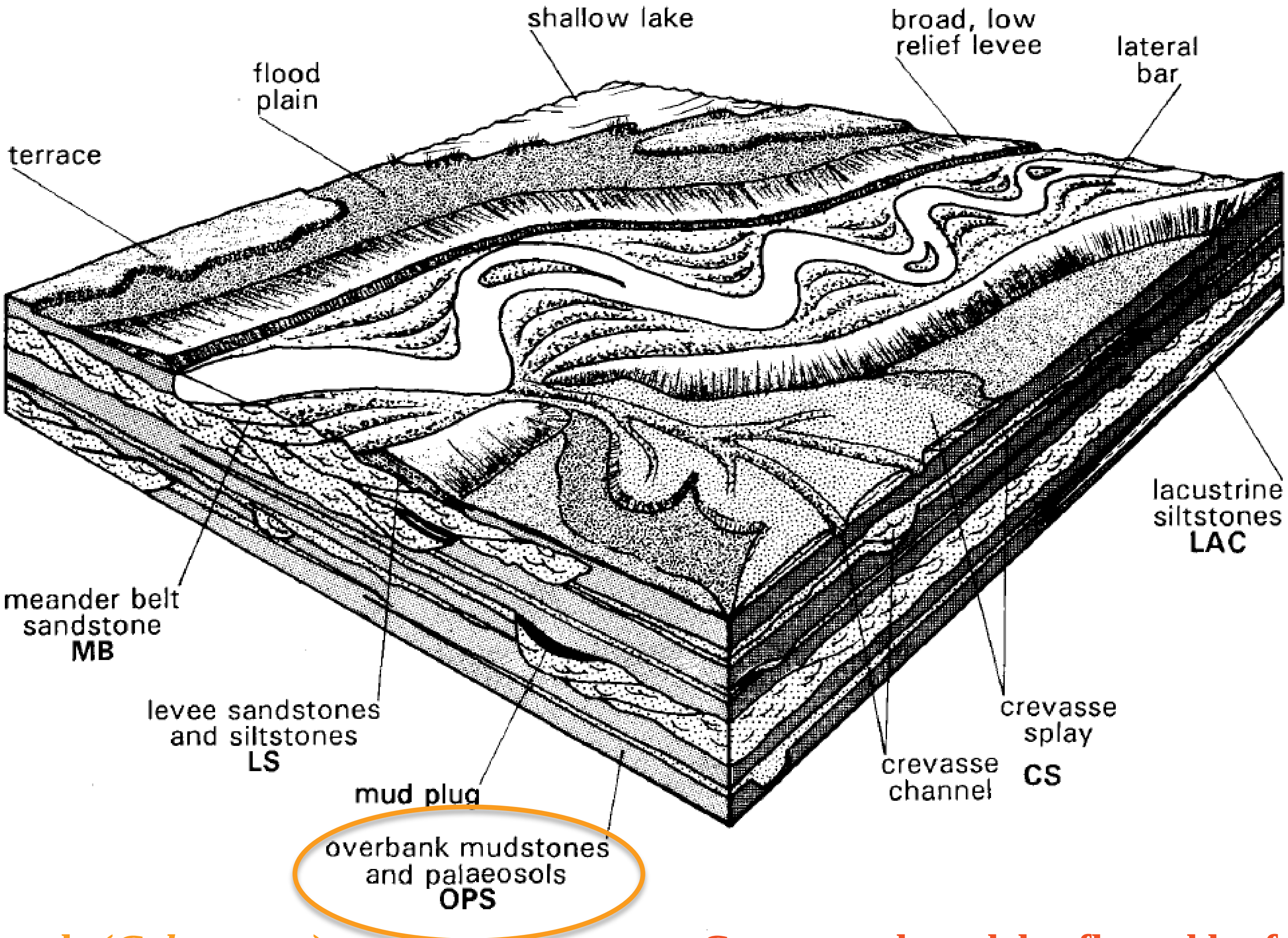
1. Review of new data - Geoconsult Report & GSG Face log data
2. Influence of Geological interpretation to the Cavern Design
3. Geophysical Interpretation using Point 5 data
4. Interpretation of small strain stiffness from P-wave data
5. Recommendations

CMS Point 5 Data Sources

- CERN reports for Point 5 (CMS) including borehole logs, in situ and laboratory testing
- Geoconsult (May 2003) Geological Factual Report and shaft and face logging
- Published geotechnical literature for the correlation of down hole geophysics in Sedimentary basin deposits
- DataPlot and RockWorks15 for 3D modelling of the available geophysics data

Depositional Environment

Lateral and vertical variability



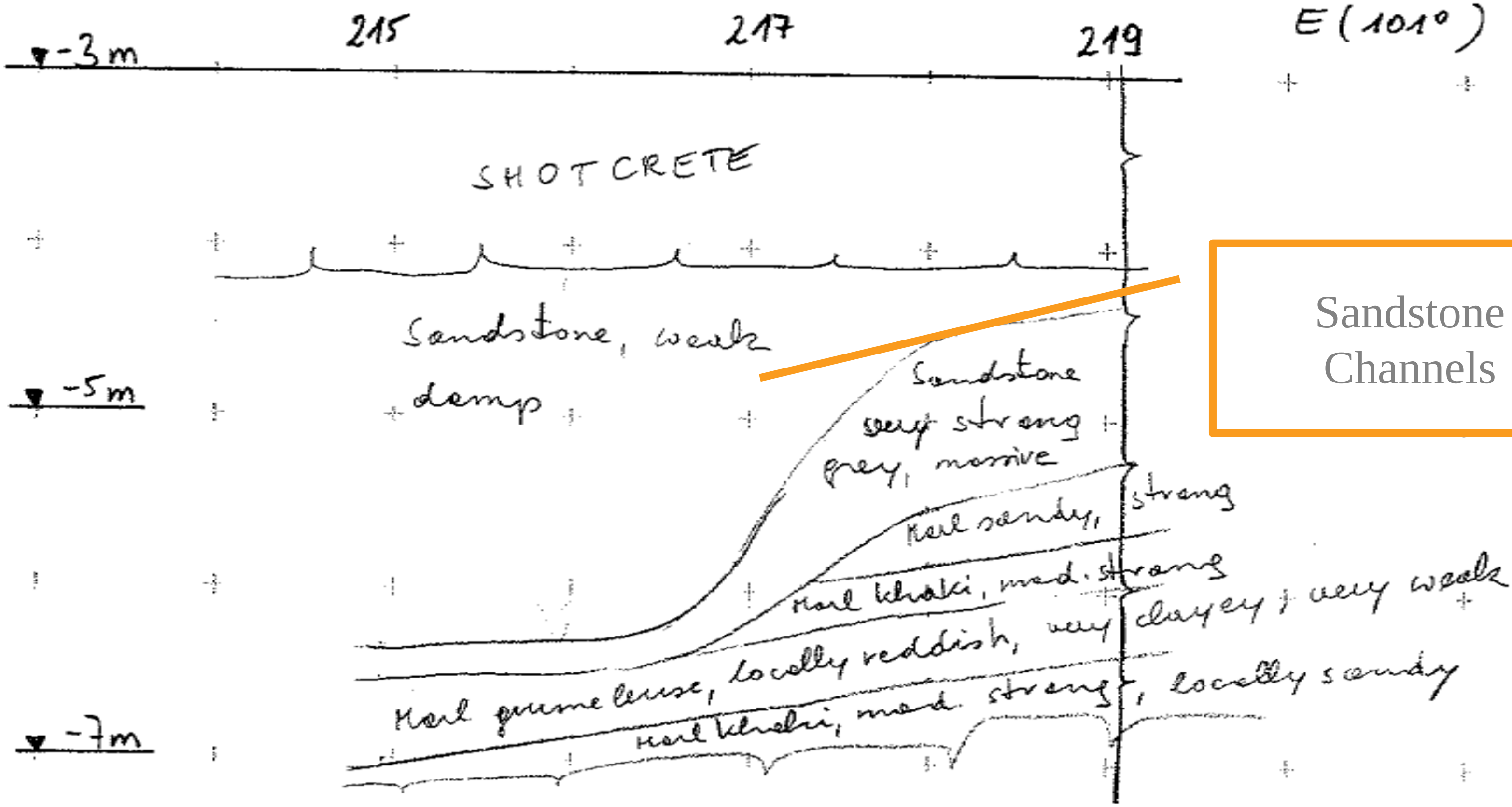
Paleosols (*Calcareous*)
Potential Marker beds

Conceptual model reflected by face logging

ARUP

Confirmation of Depositional Features

- Examples from Point 5 GSG Face logs



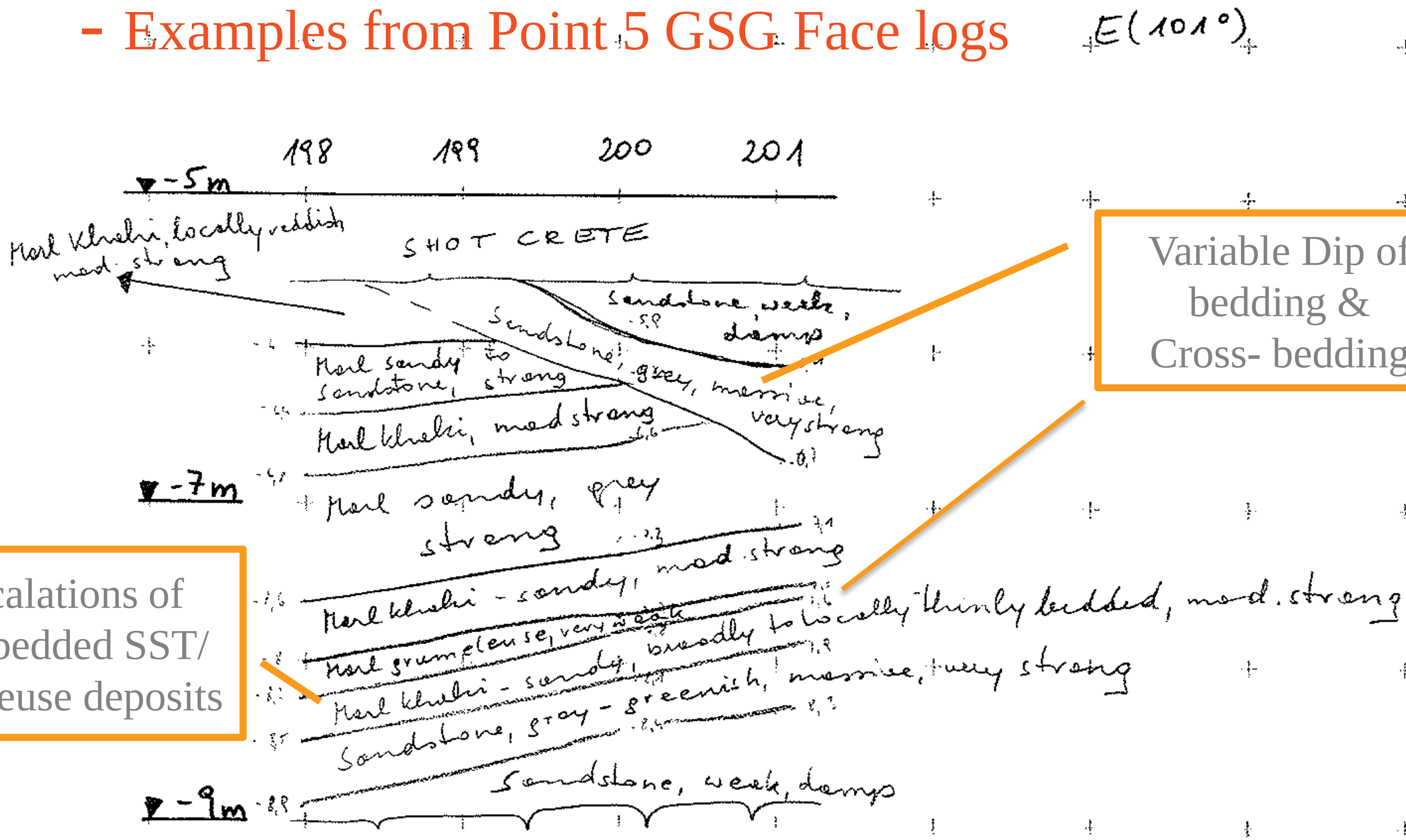
Sandstone Channels

Pillar Ch. 215 – 219m

ARUP

Confirmation of Depositional Features

- Examples from Point 5 GSG Face logs

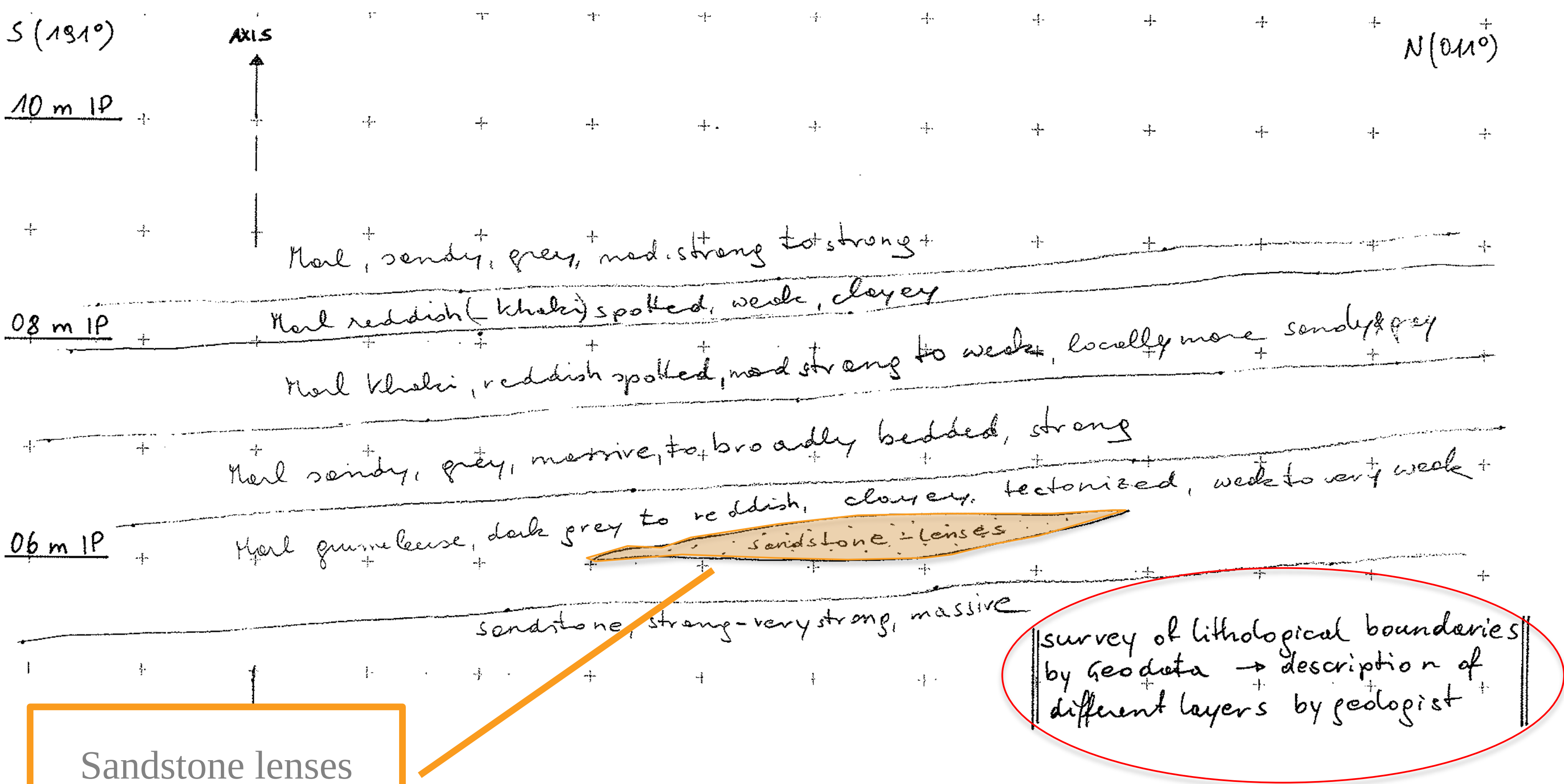


Variable Dip of bedding & Cross- bedding

Intercalations of thinly bedded SST/ Grumeleuse deposits

Pillar Ch. 198-201m

UCX 55 West Head Wall - Chainage 170.5 – 172.5

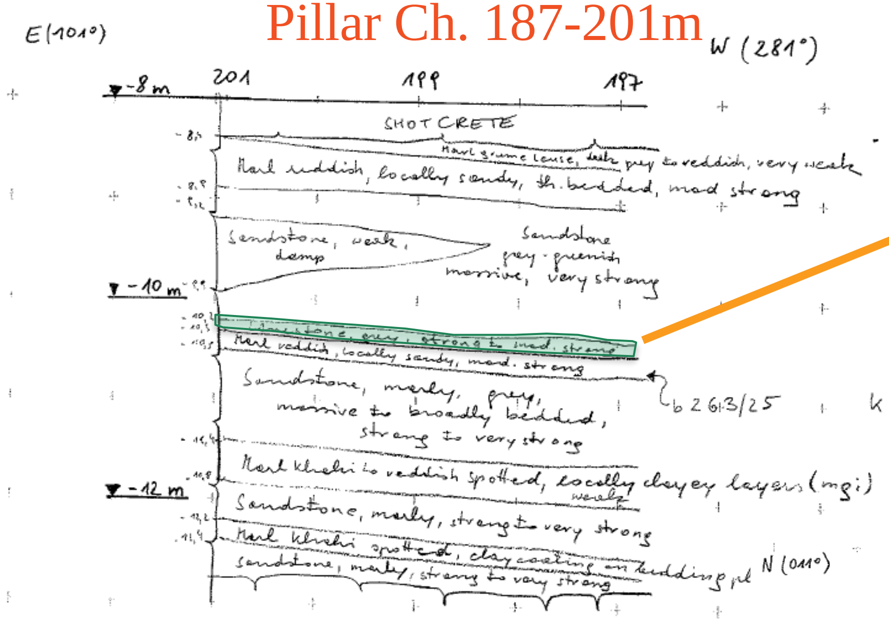


Sandstone lenses

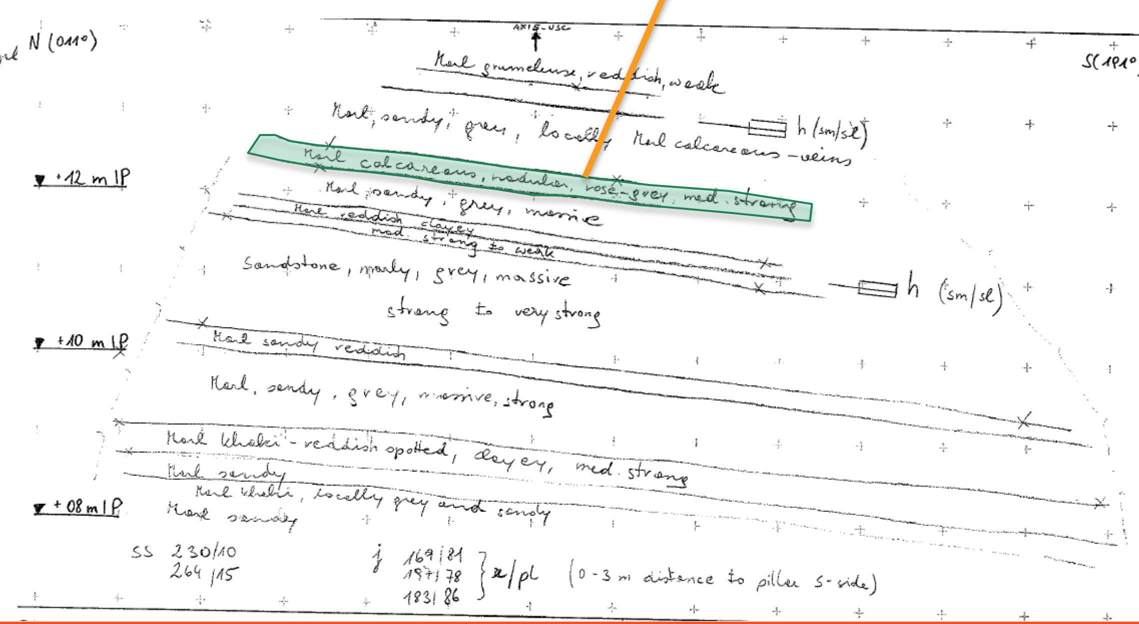
ARUP

Confirmation of Depositional Features

Pillar Ch. 187-201m



Calcareous Horizons/ Paleosol development

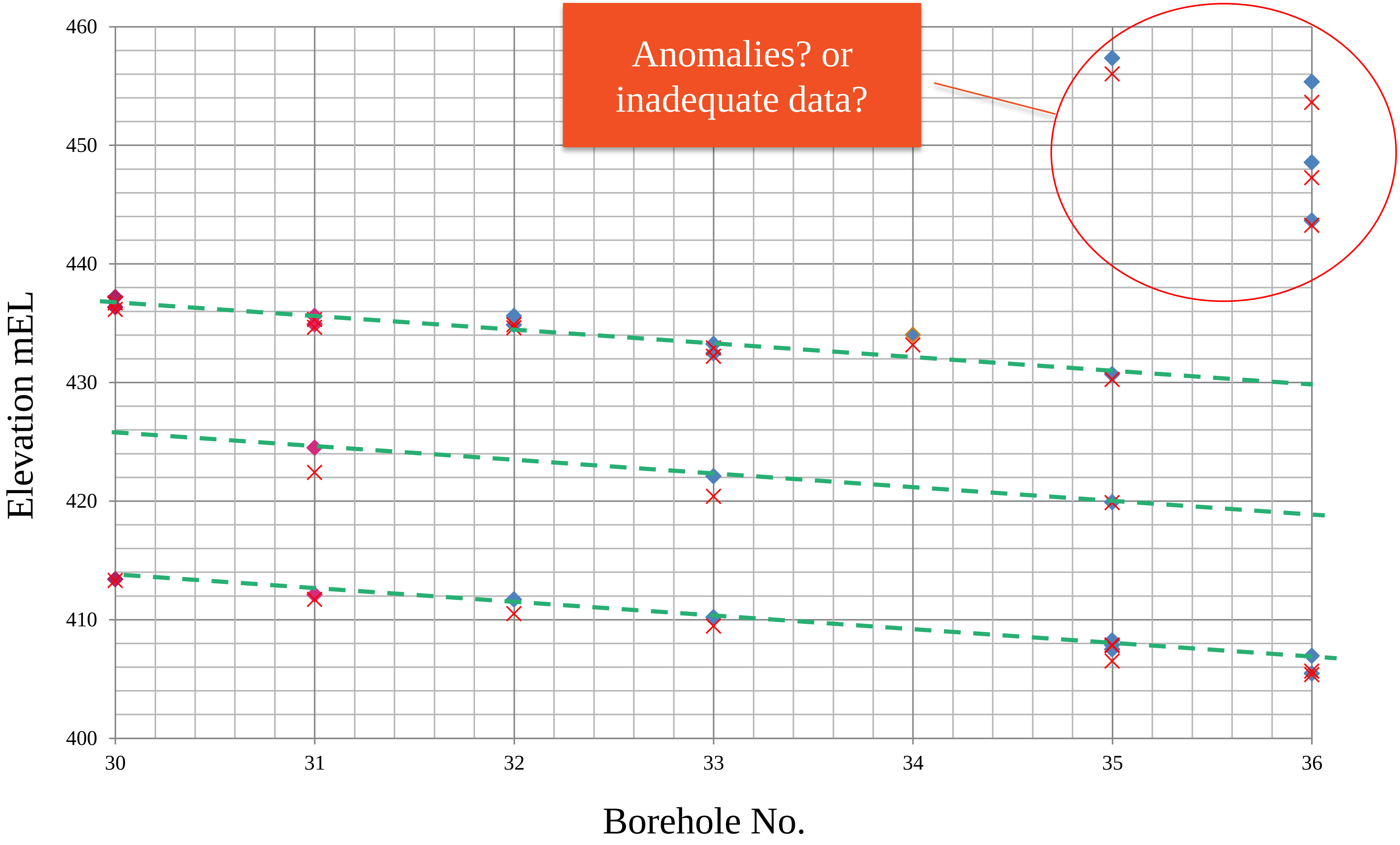


USC 55 Ch. 197.51m

ARUP

Calcareous & "Limestone" from Point 5 BH data

Data shows an approximation of the top and base of calcareous horizons from BH descriptions



ARUP

Geoconsult Report and Face mapping

Key Comments:

- Allocation of strength parameters to the stratigraphical layers is different from predictions

- Rock mass has a pronounced Time dependent behaviour

ARUP

Geoconsult Report and Face mapping

Details:

1. Detailed geological mapping from excavations shows the encountered

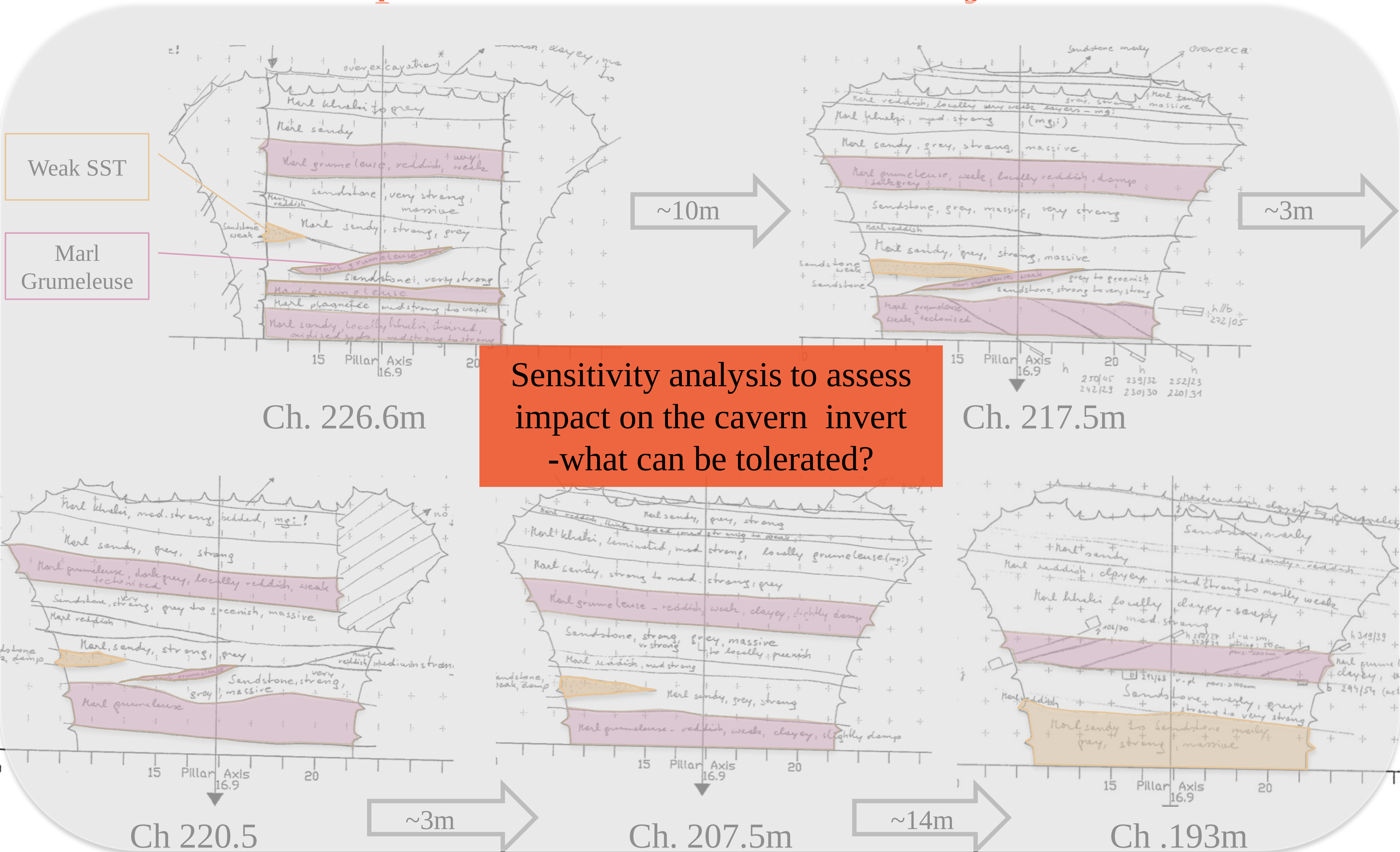
   strength parameters differ from borehole predictions.
2. Rock mass **less competent** than predicted
3. Anticipated SST layers were not the expected quality & actually marly SST/ sandy MARL (questions the reliability of borehole logs to verify geophysics).
4. Anticipated SST **encountered as lenses** not as persistent layer

   (as we predicted in CSM from depositional environment)
5. Marl Grumeleuse layers in sidewalls were thicker than anticipated and poorer quality

How does this affect the approach to the design?

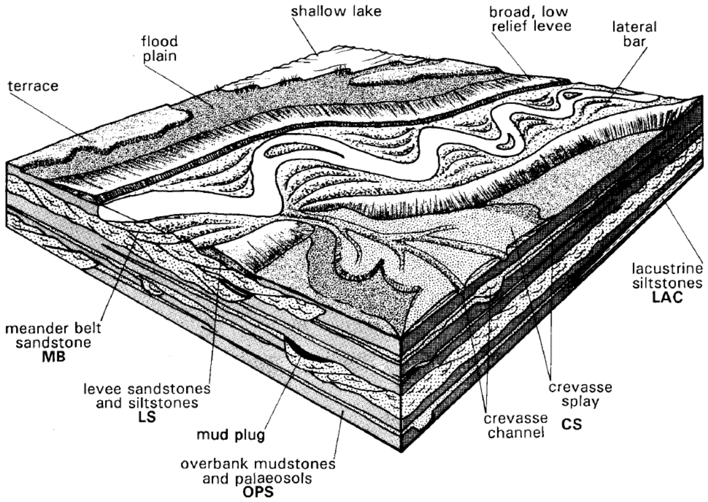
ARUP

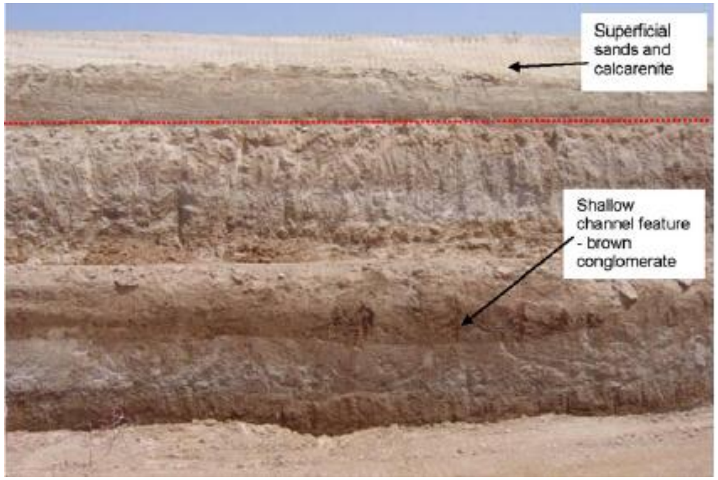
Pillar Example of Lateral Variability over ~35m

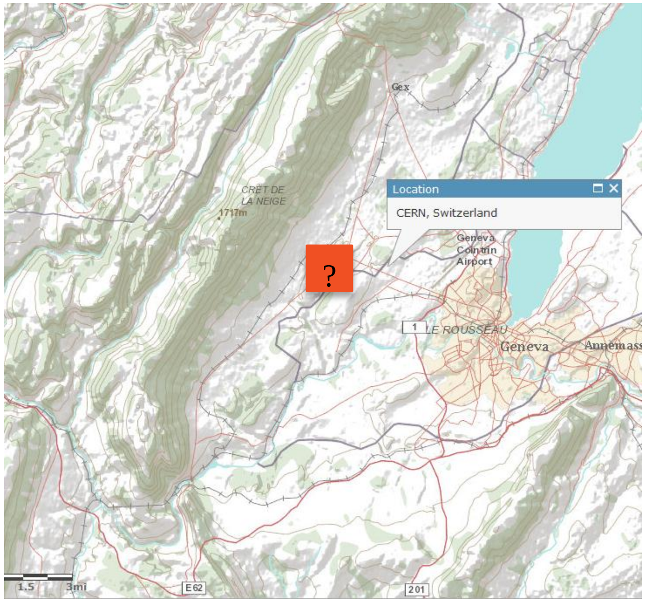


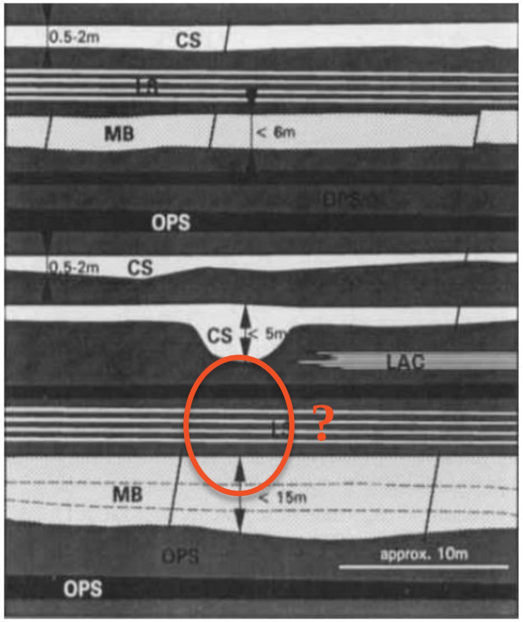
Sensitivity analysis to assess impact on the cavern invert -what can be tolerated?

Cavern design approach must account for Scale



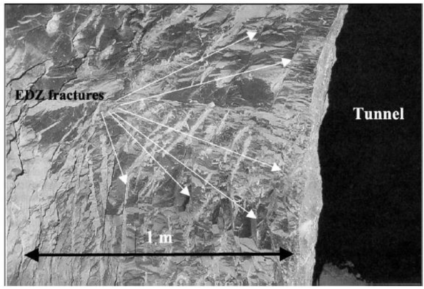






Optimise depth & invert conditions

Target the detail!

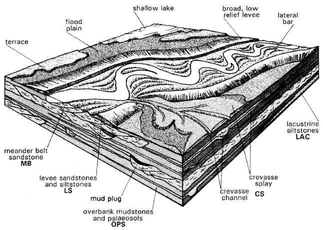


ARUP

Geological Interpretation with scale

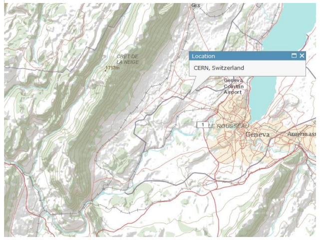
Regional

- Large scale understand the Depositional Environment
- Predict behaviour, sedimentary structure and variability
- Model affects of large scale variability in terms of the affect on cavern feasibility



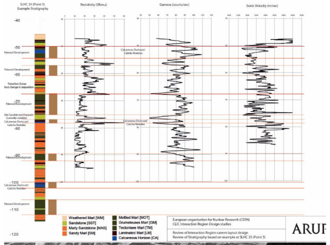
Local

- Develop Conceptual Model from existing Site Data/ Plan Site Selection
- Favourable stress orientation for caverns
- Set-up 3D Conceptual model (Elevation data, existing information for planning SI)



Site Specific

- Characterisation of stratigraphy and Engineering parameters from detailed investigation using a suite of boreholes, in-situ and laboratory testing and monitoring.
- Development of 3D Conceptual model to include all new data sets



Micro

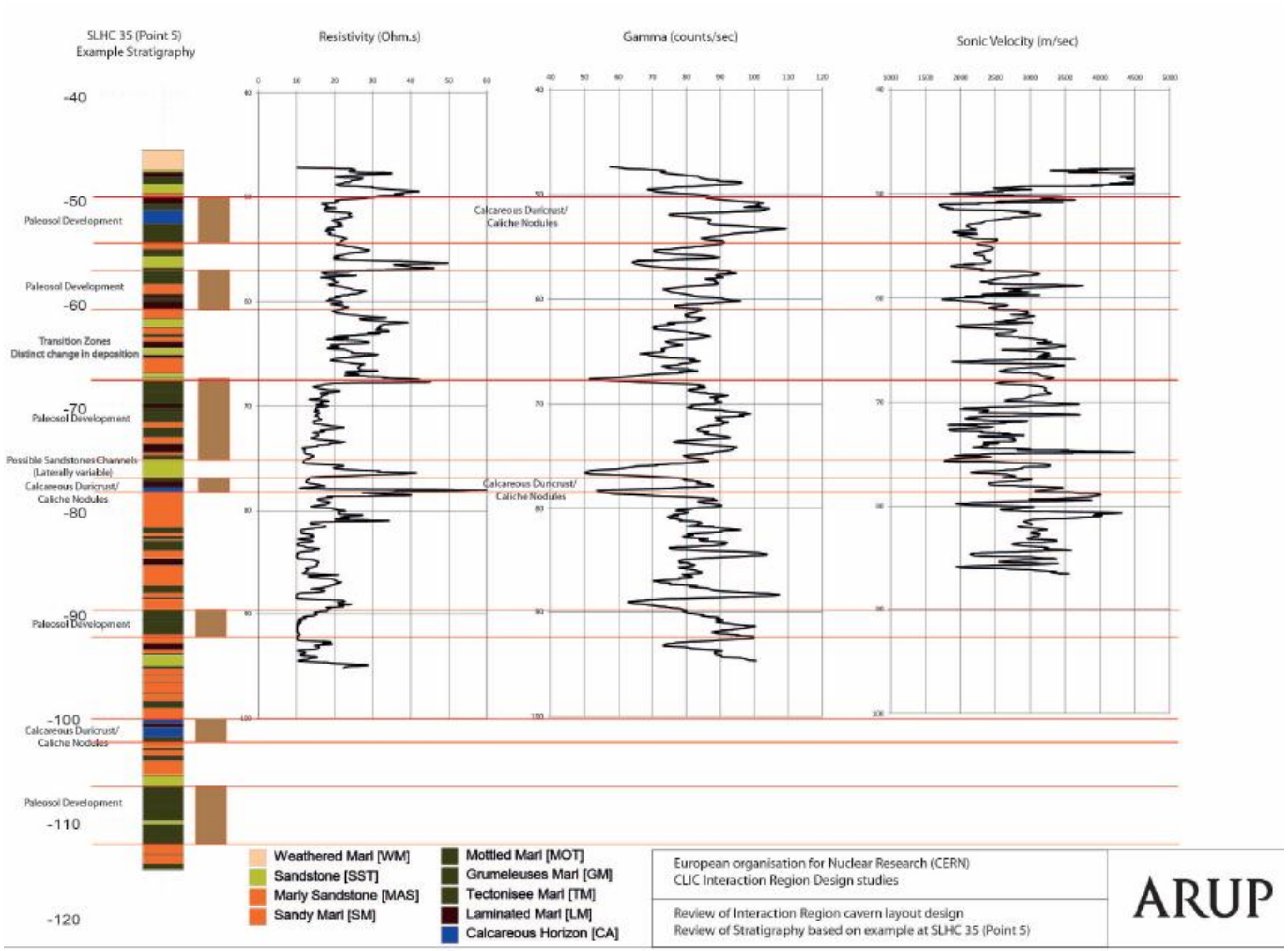
- Optimisation of depth and invert conditions based on interpretation and influence of mineralogy/ sedimentary structure/ lithofacies models and predicted behaviour
- **Target the detail!**

.. verification during excavation!

Geophysical Interpretation

ARUP

Initial approach to geophysics in July …



ARUP

Geophysical Interpretation at CMS Point 5

Natural Gamma

Stratigraphy

Determination of proportion of clay/ alteration zones

Electrical Resistivity

Sub-surface structure

Resistivity – depth profile

Gamma-Gamma

Density

Medium-energy gamma rays using Compton scattering method.

Different aims
Complimentary tools

Sonic velocity

Small Strain Stiffness

Measurement of P-waves

Characterisation of Seismic Facies

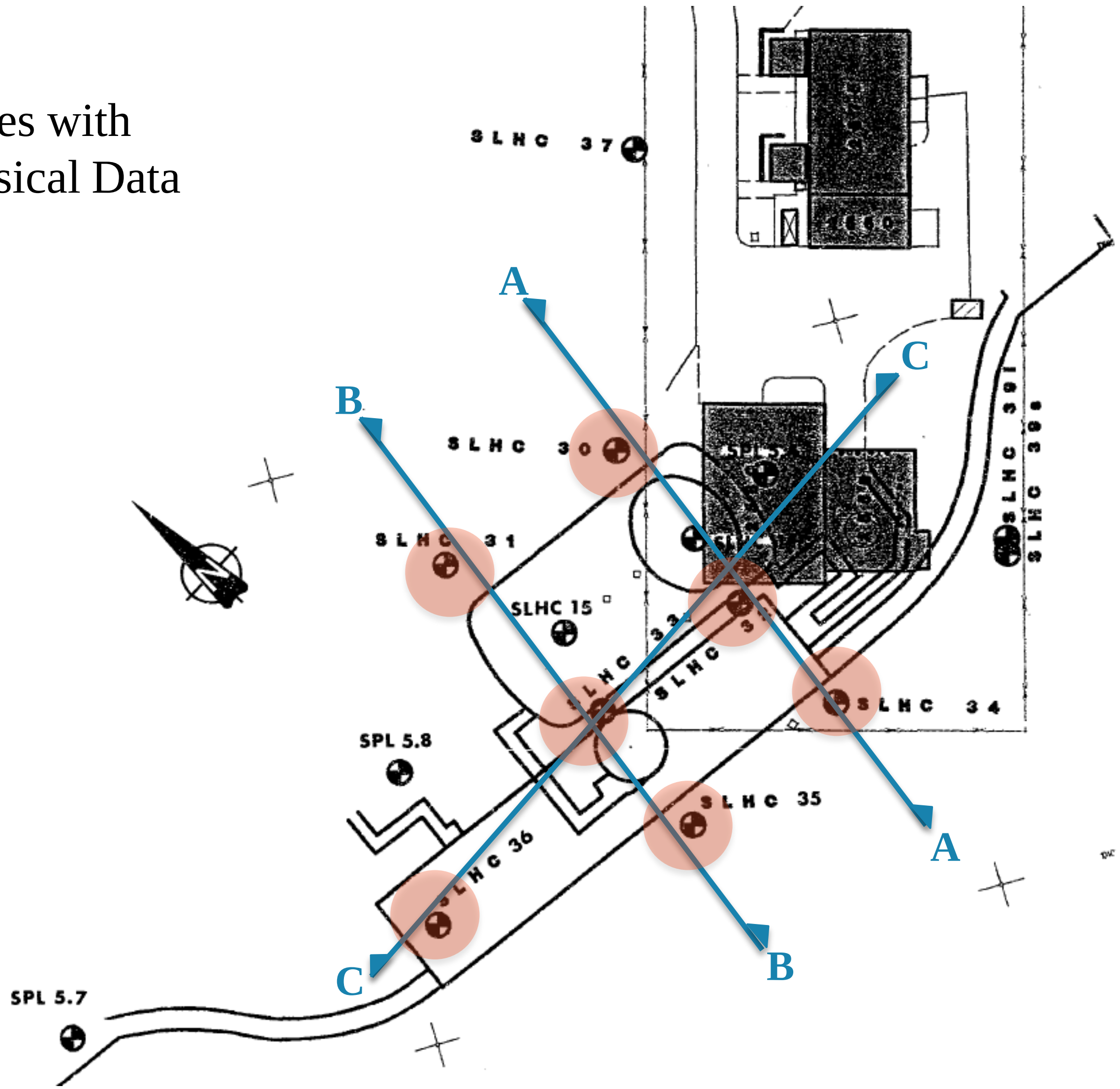
Create sections from digitised data from 7 boreholes BH30 to BH36

3D RockWorks Model of Data for each method

ARUP

Plan of Point 5 BHs showing analysis sections

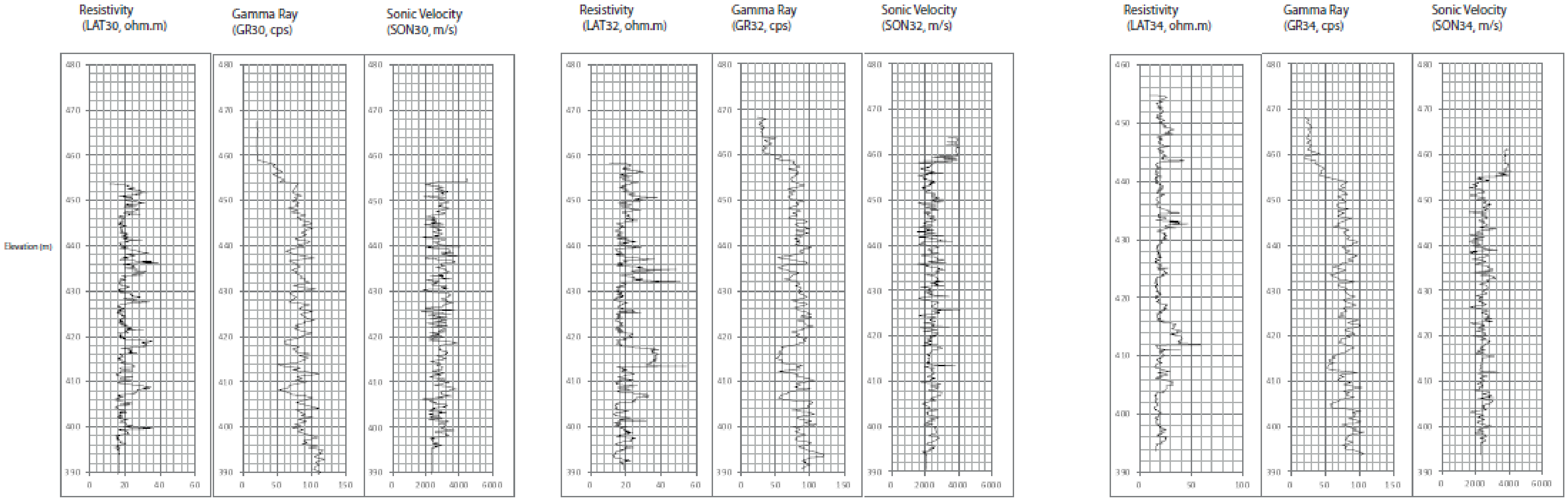
Boreholes with Geophysical Data



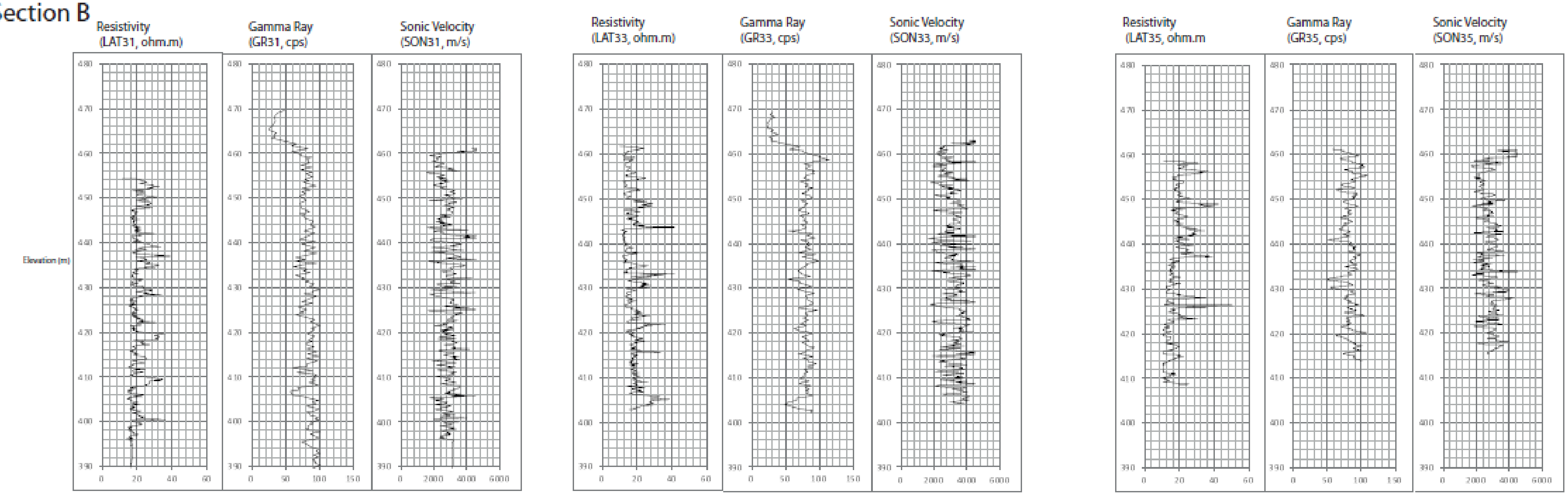
ARUP

Geophysical Data for Point 5 A-A & B-B

Section A

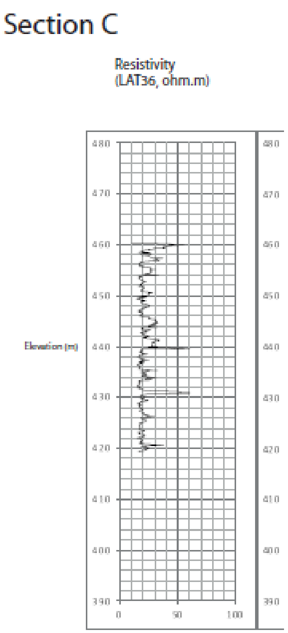


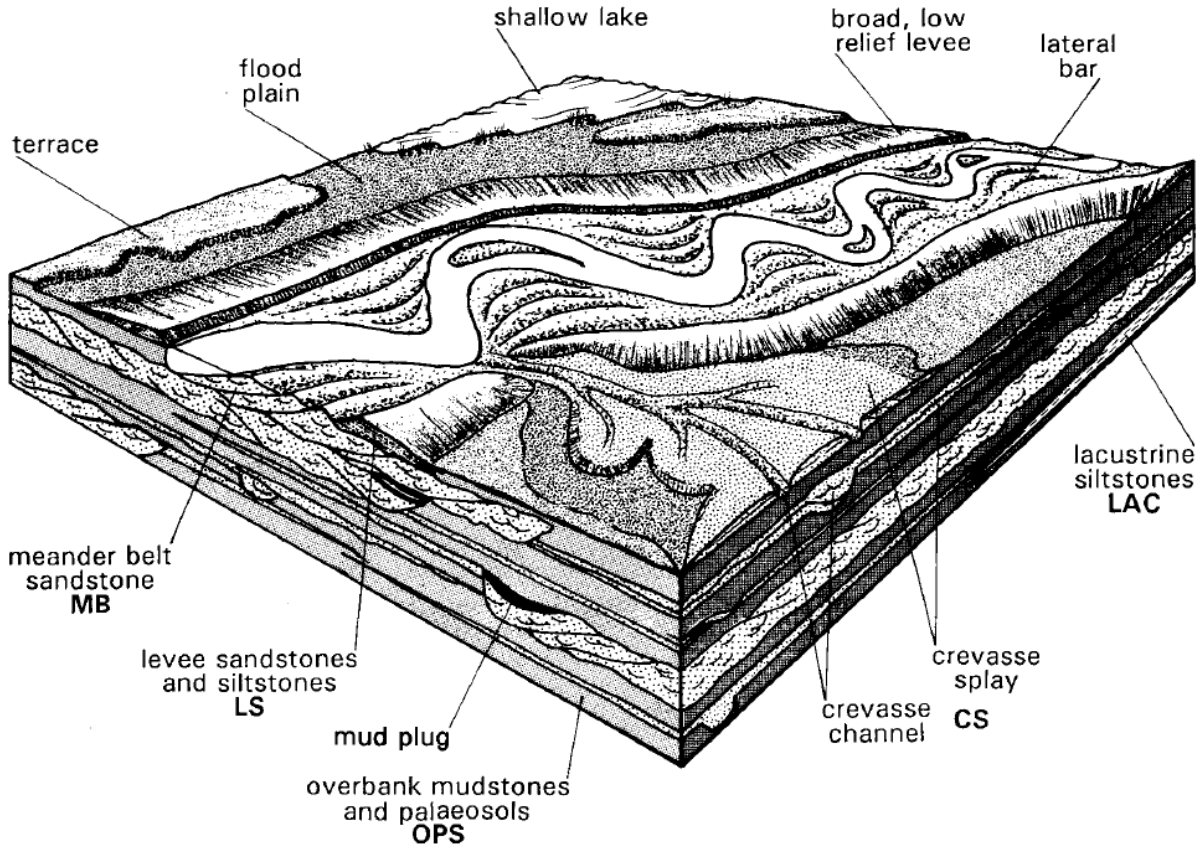
Section B

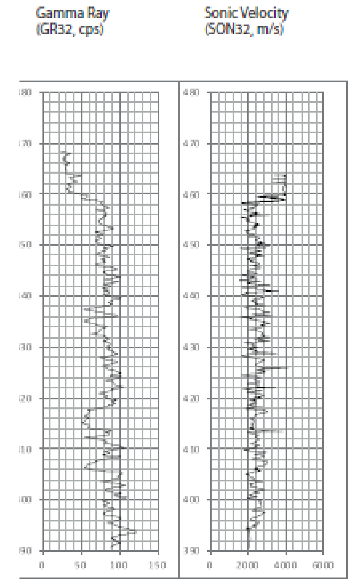


ARUP

Geophy





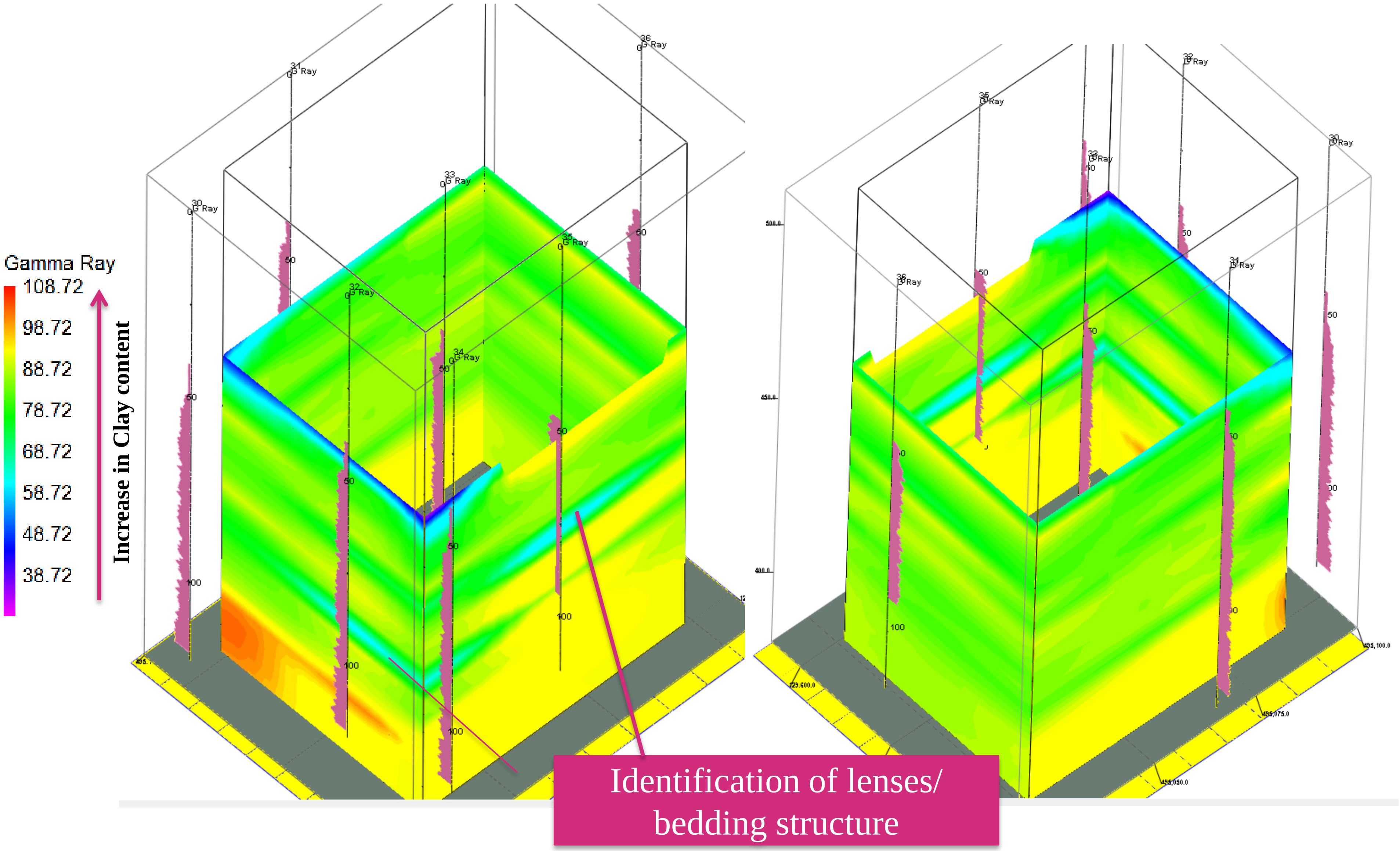


Difficult to visualise variations

Natural Gamma in Rockworks

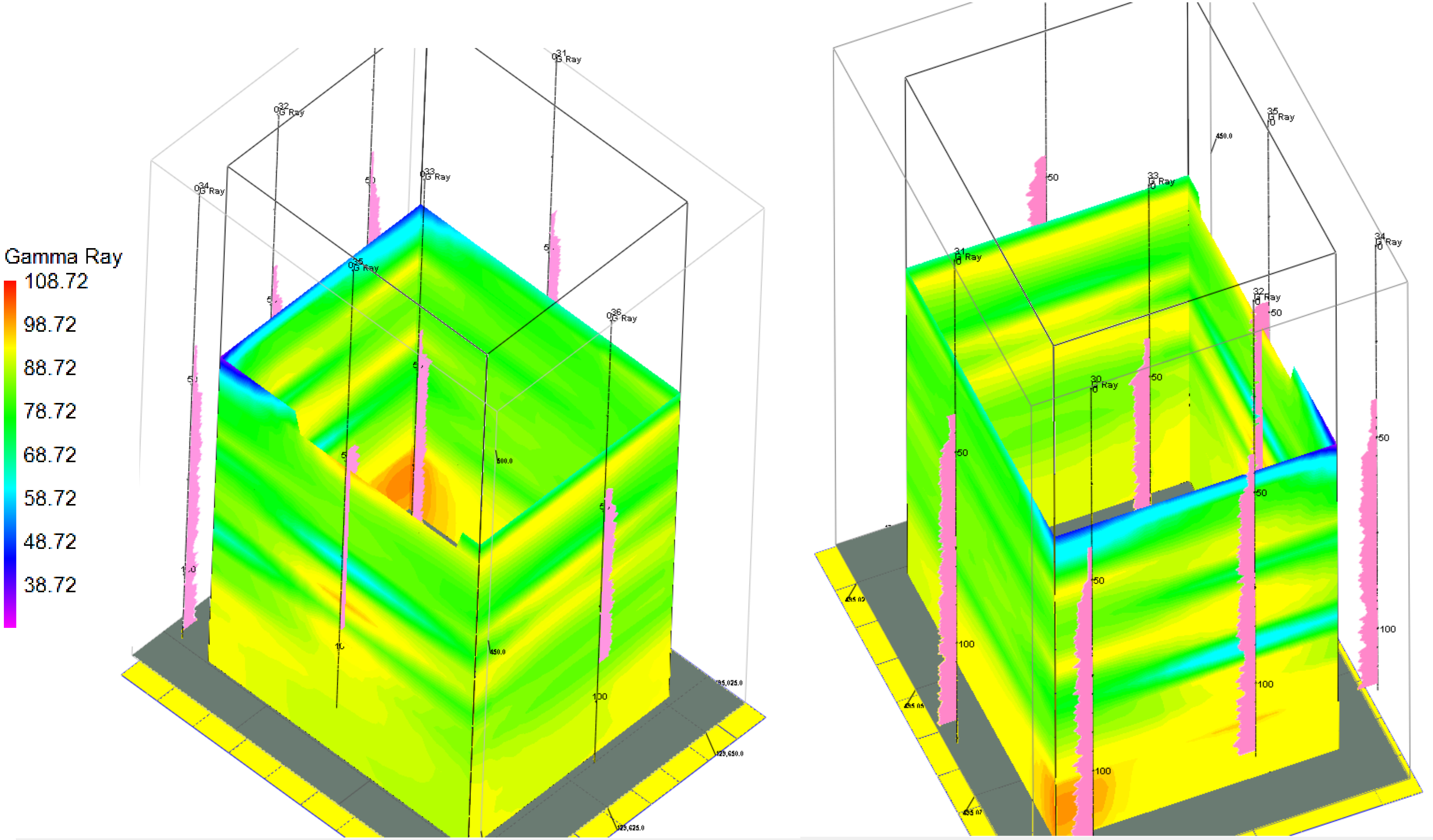
Evaluate stratigraphy

Natural Gamma model slides



ARUP

Natural Gamma model slides



ARUP

Limitations

- Quality of data

  (correlations/ digitizing)

- Amount of Data (no. Of BHs)

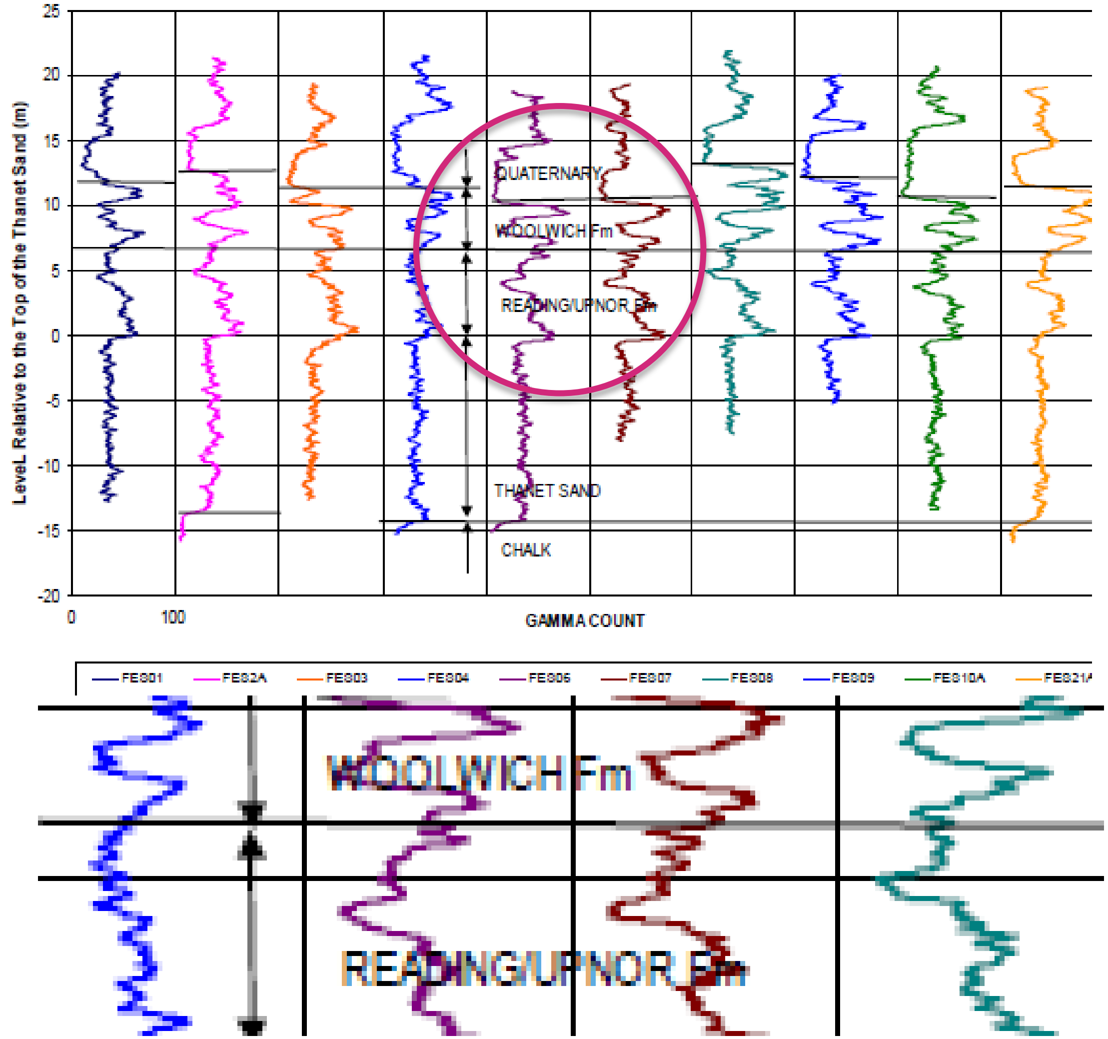
  accuracy of interpolation between boreholes / edge effects/ change in detail of results/ incorporate cross hole data in future

- Persistence of horizons

  lack of confidence in BH descriptions

BUT it can be achieved ...

Stratigraphy - what detail are we looking for?

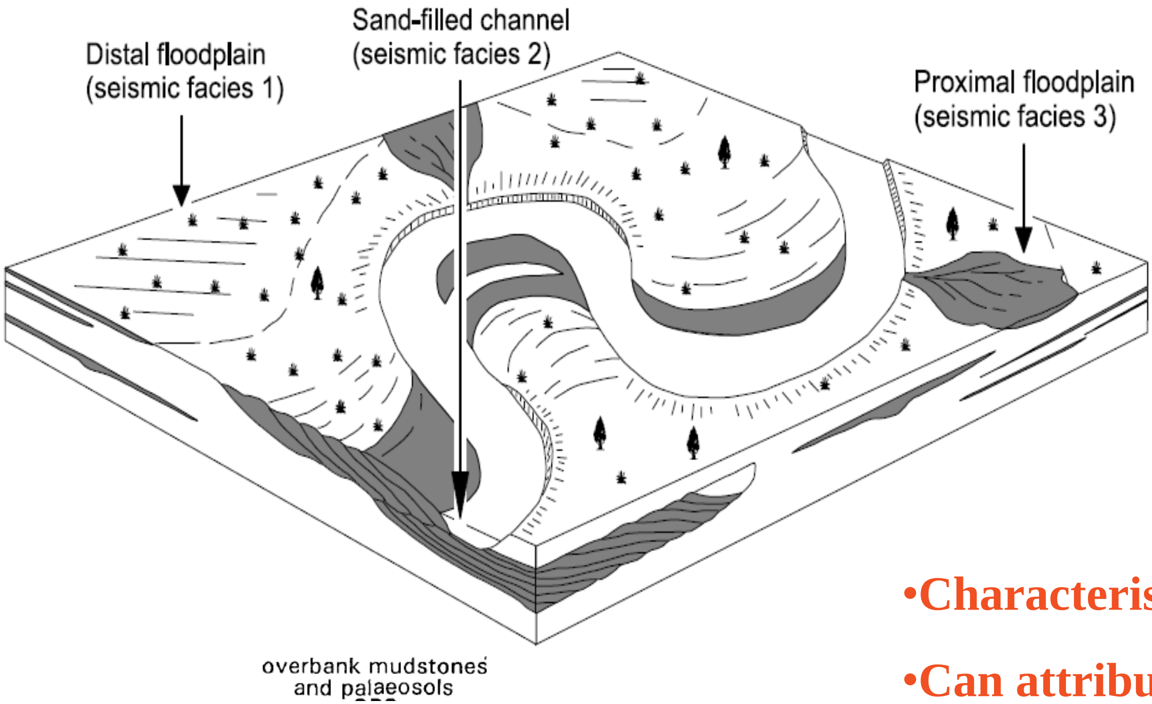


ARUP

Sonic Logging in RockWorks

P-wave output to determine seismic facies

Seismic Facies



- Seismic facies 1: poorly reflective, low amplitude, discontinuous reflections;
- Seismic facies 2: fairly reflective, high amplitude, continuous reflections;
- Seismic facies 3: highly reflective, high amplitude, moderately continuous reflections.

Example in Lower Freshwater Molasse From Morend, Pugin and Gorin (1998)

•Characterise facies based on reflection

•Can attribute small strain stiffness to seismic facies models using P-wave correlations

•Add stratigraphy model from natural Gamma, Resistivity and Boreholes

ARUP

Seismic Limitations

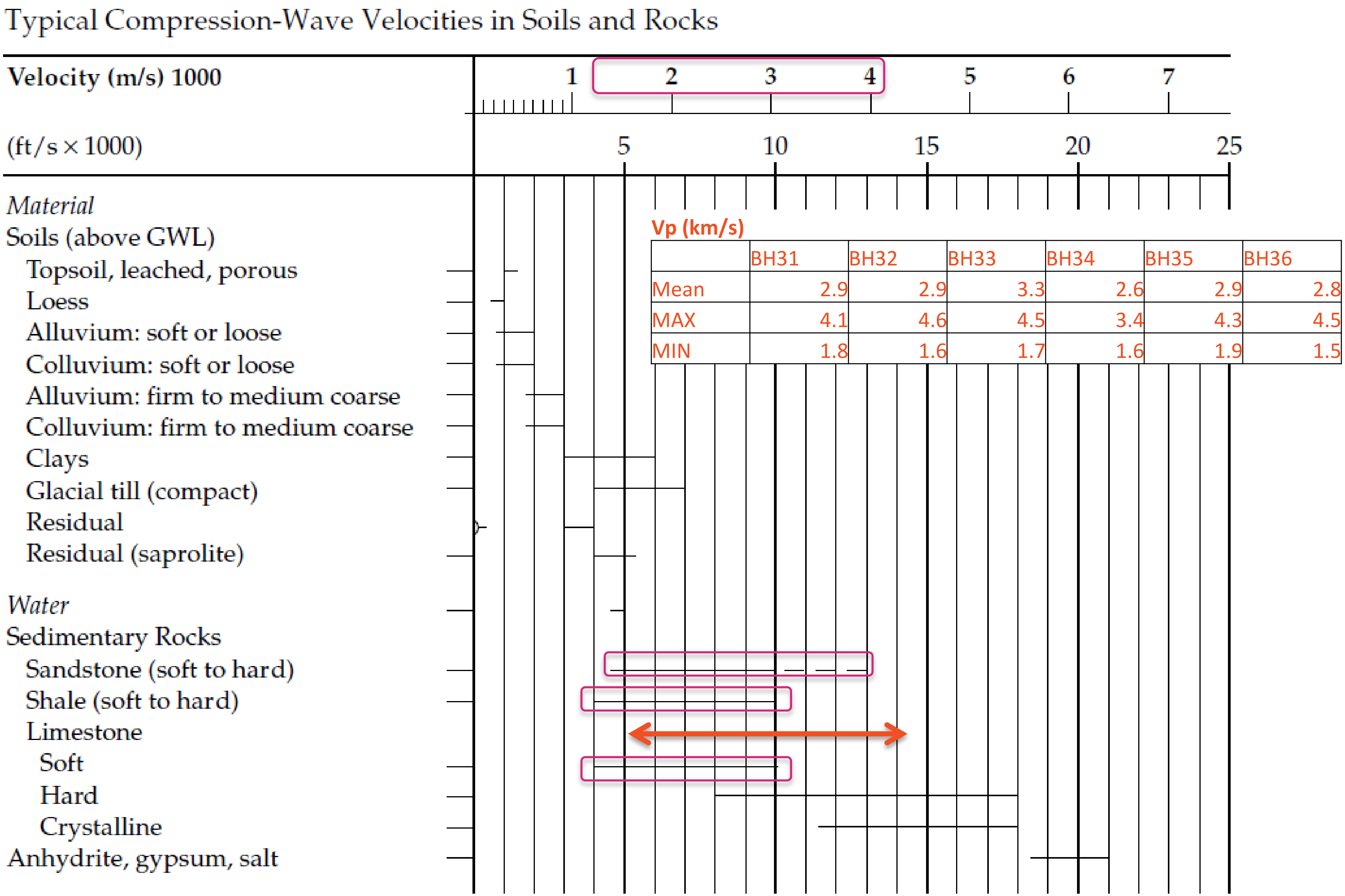
- Intercalated/ thinly bedded deposits can be difficult to pick up using Vp depending on resolution of data

  Seismic resolution often thinner than bedding thickness/ lithological change

- Limited ability to develop ‘signature’ values for each lithology

  materials can vary within the same range hence adoption of a statistical mean for development of parameters at this stage.

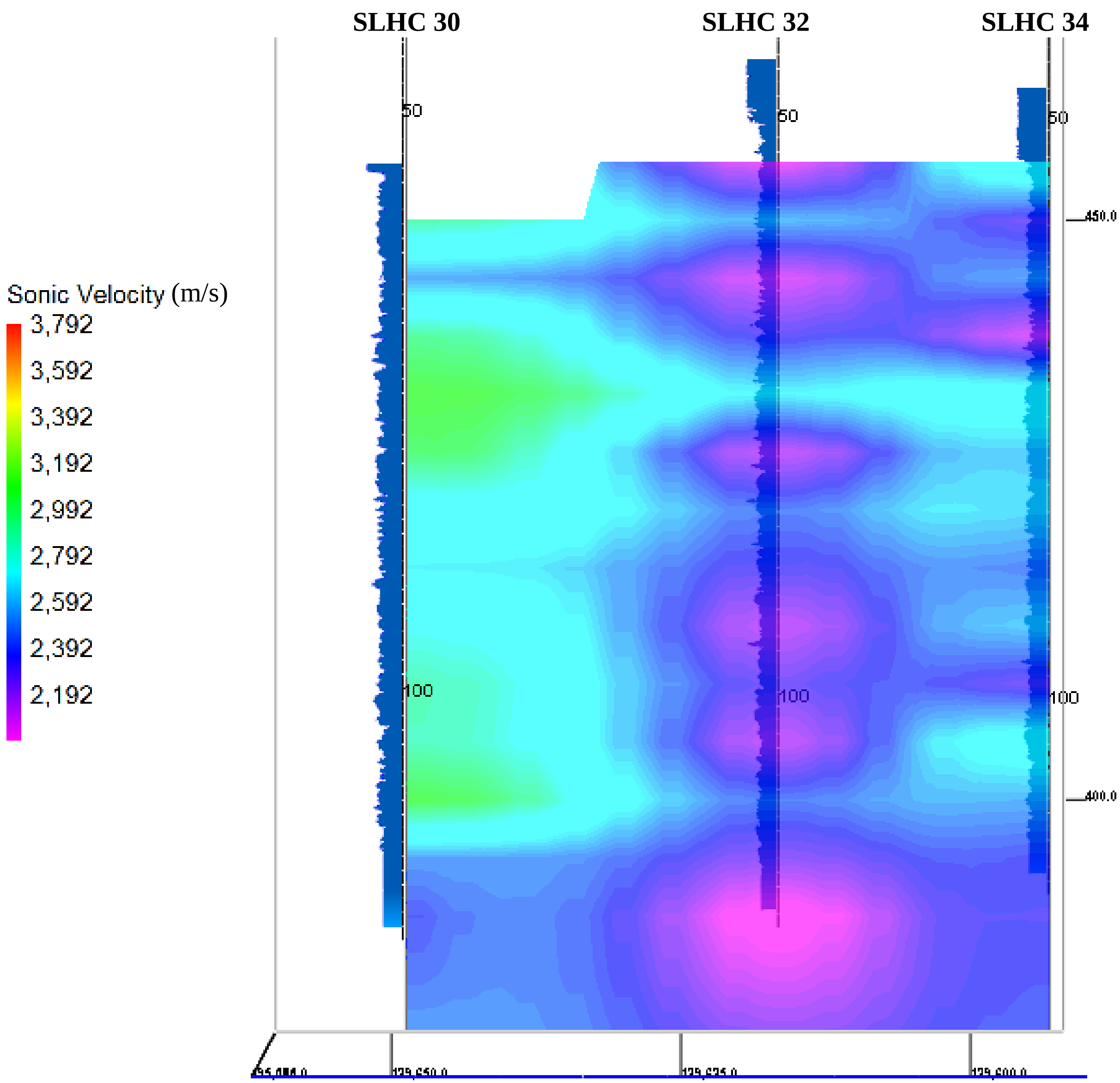
Typical P-Wave Velocities



Vp (km/s)

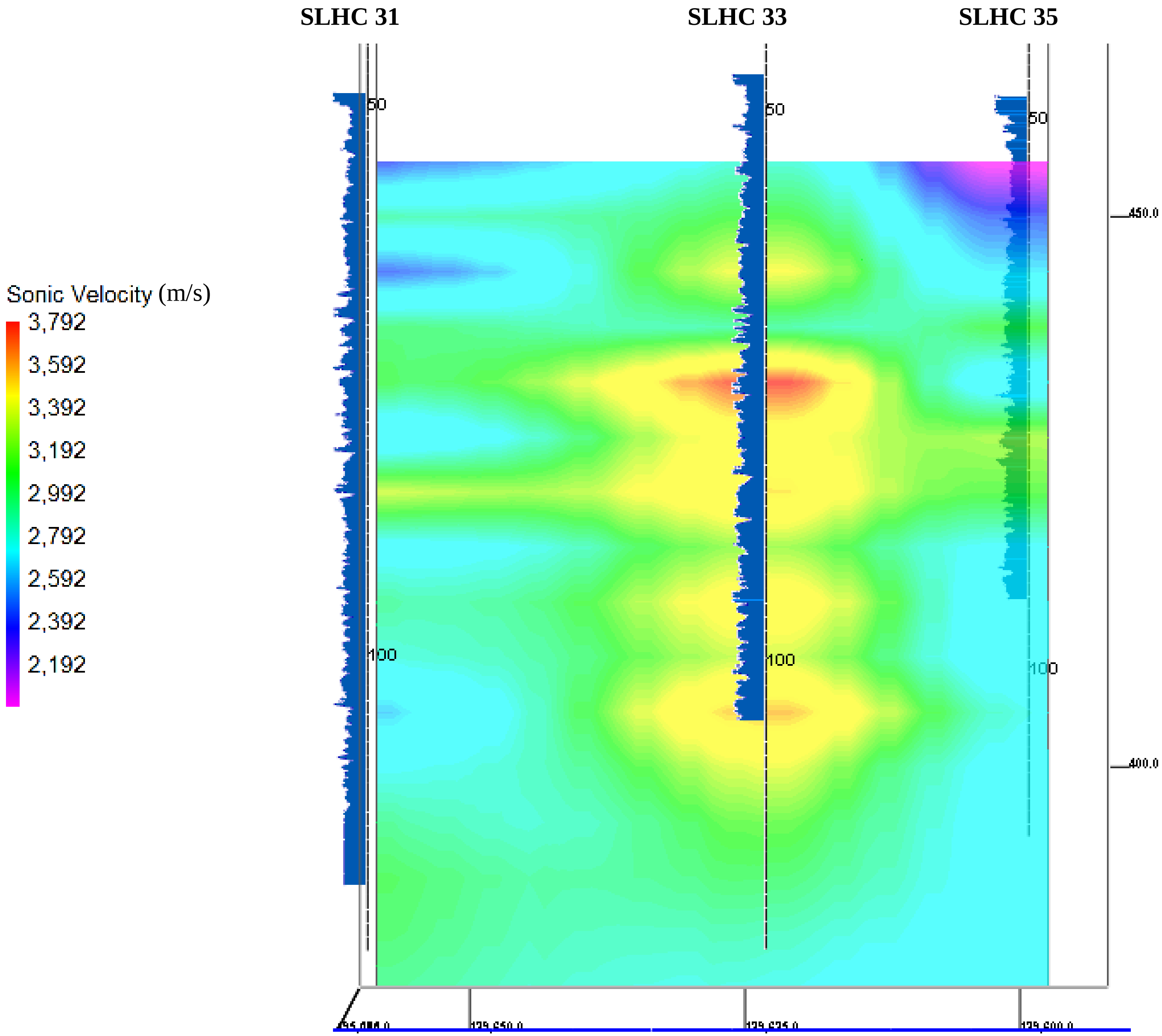
	BH31	BH32	BH33	BH34	BH35	BH36
Mean	2.9	2.9	3.3	2.6	2.9	2.8
MAX	4.1	4.6	4.5	3.4	4.3	4.5
MIN	1.8	1.6	1.7	1.6	1.9	1.5

Sonic Velocity – Section A

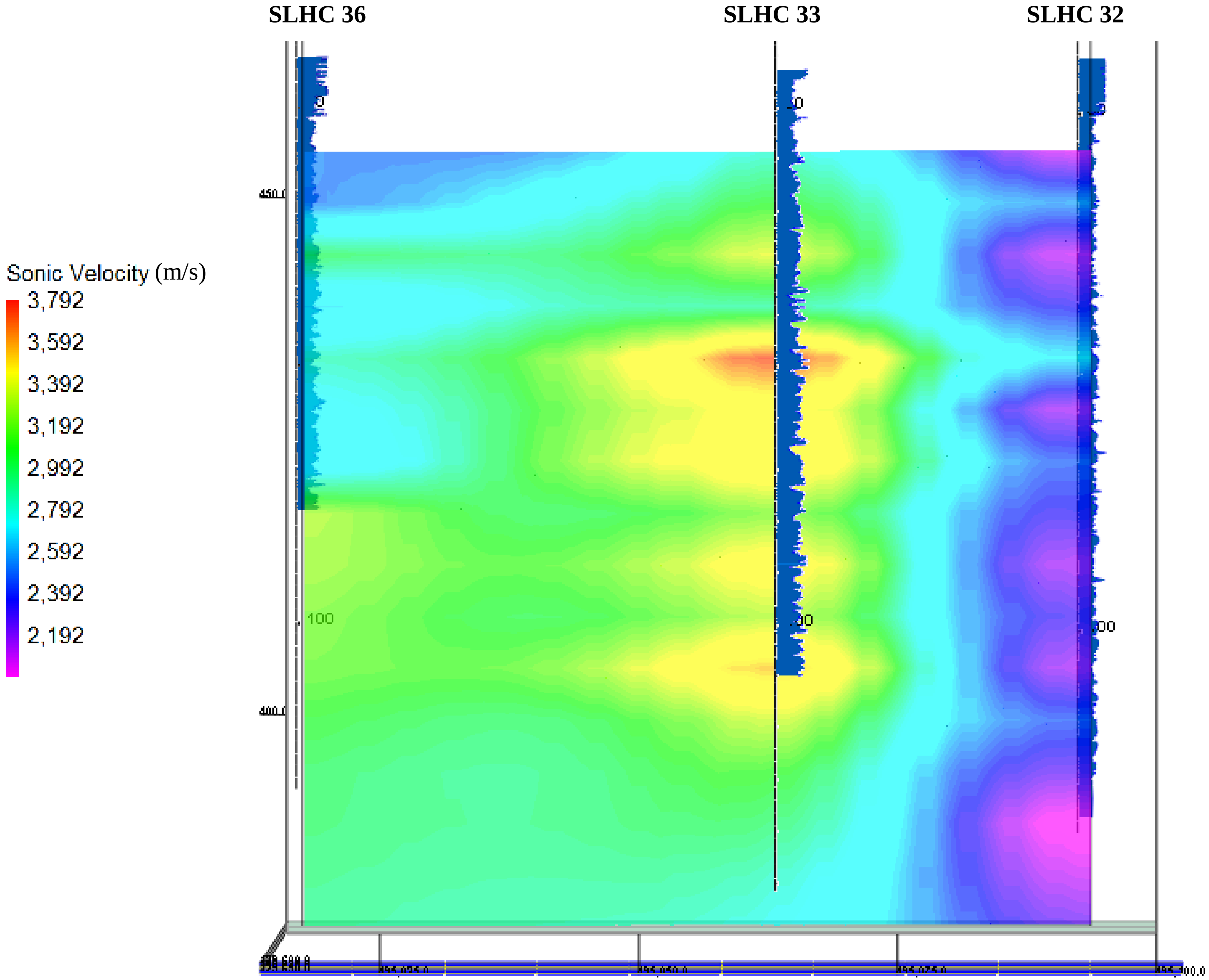


ARUP

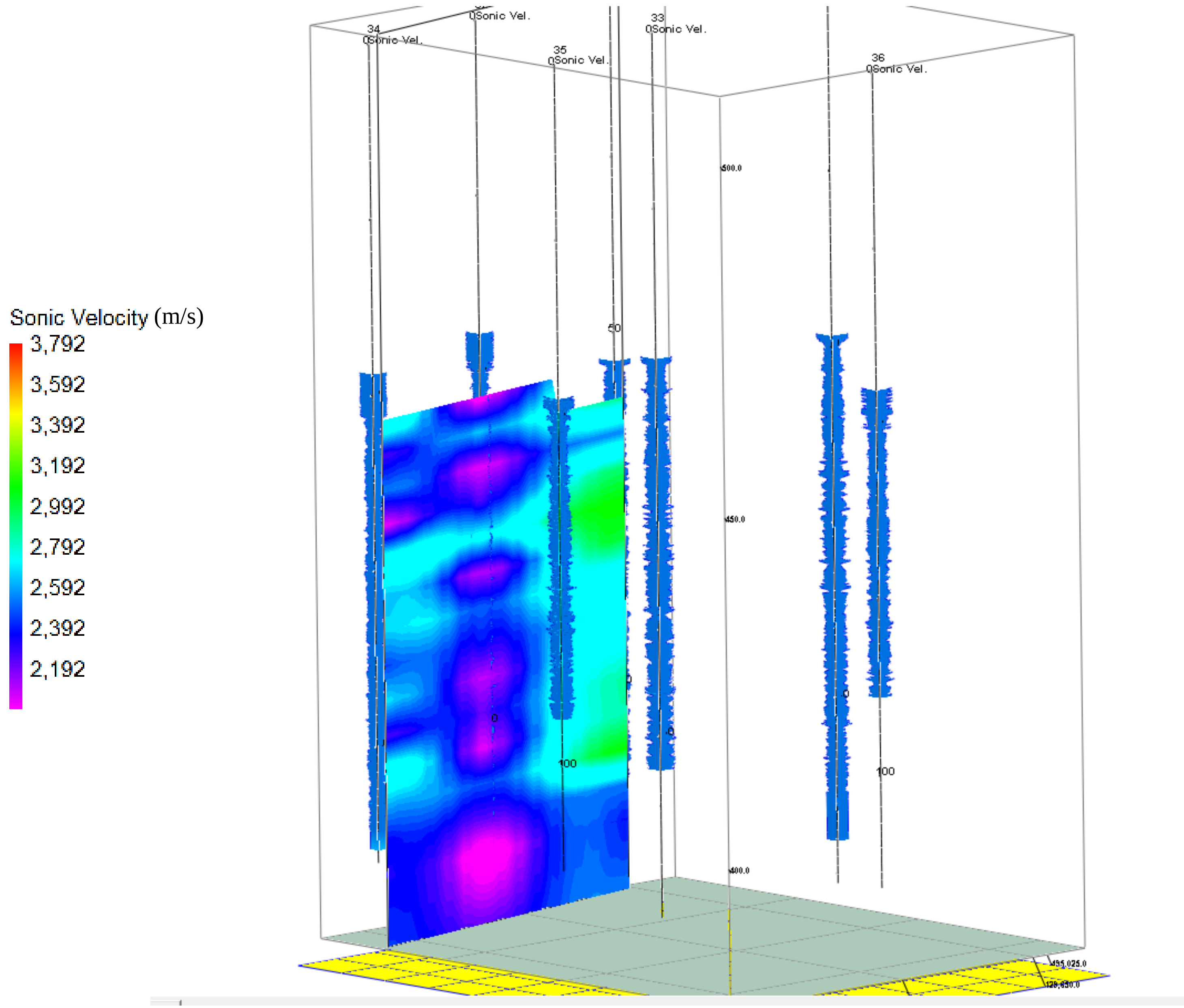
Sonic Velocity – Section B



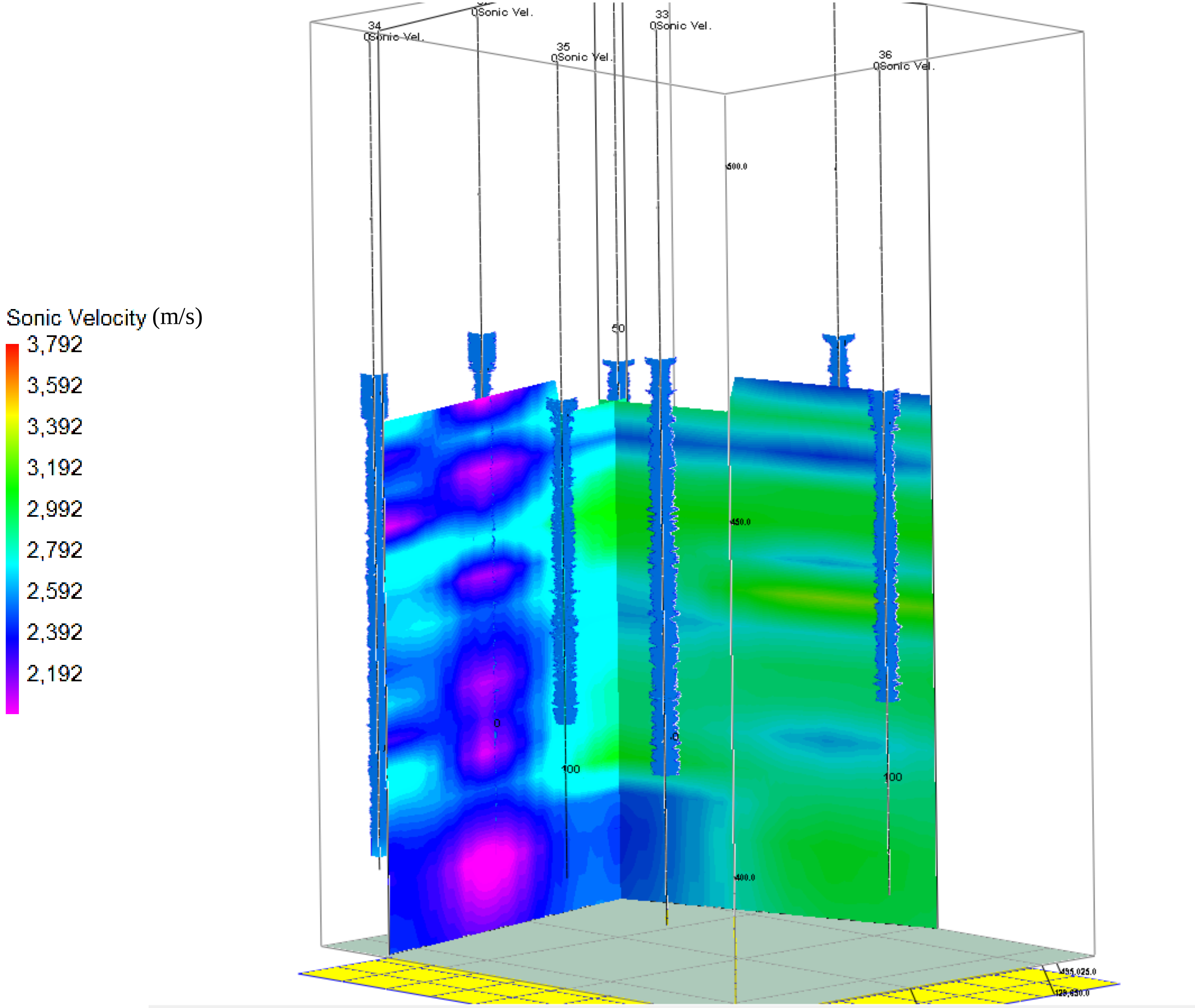
Sonic Velocity – Section C



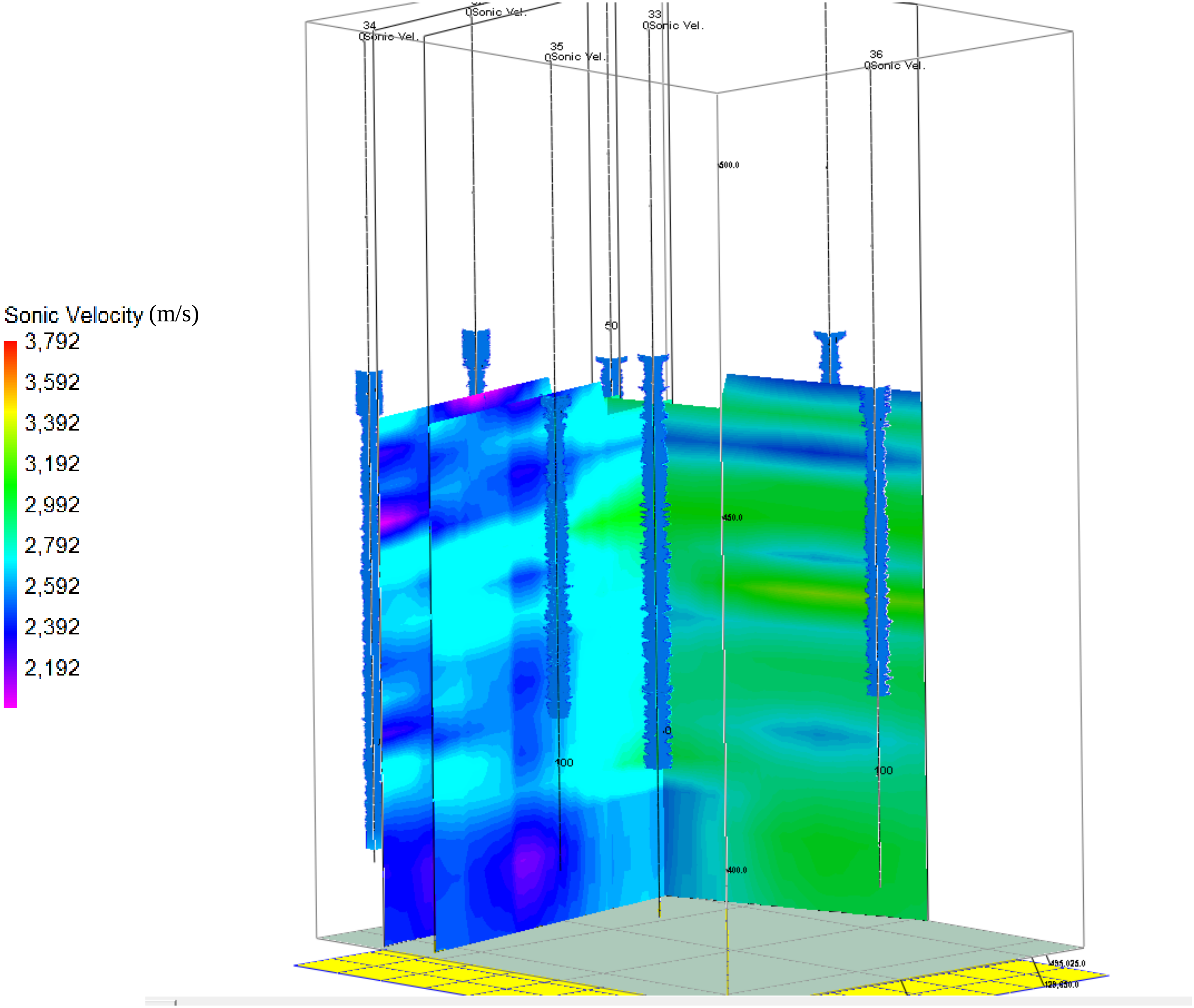
ARUP


Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
0Sonic Vel.
35
0Sonic Vel.
33
0Sonic Vel.
36
0Sonic Vel.
500.0
450.0
400.0
50
100
100

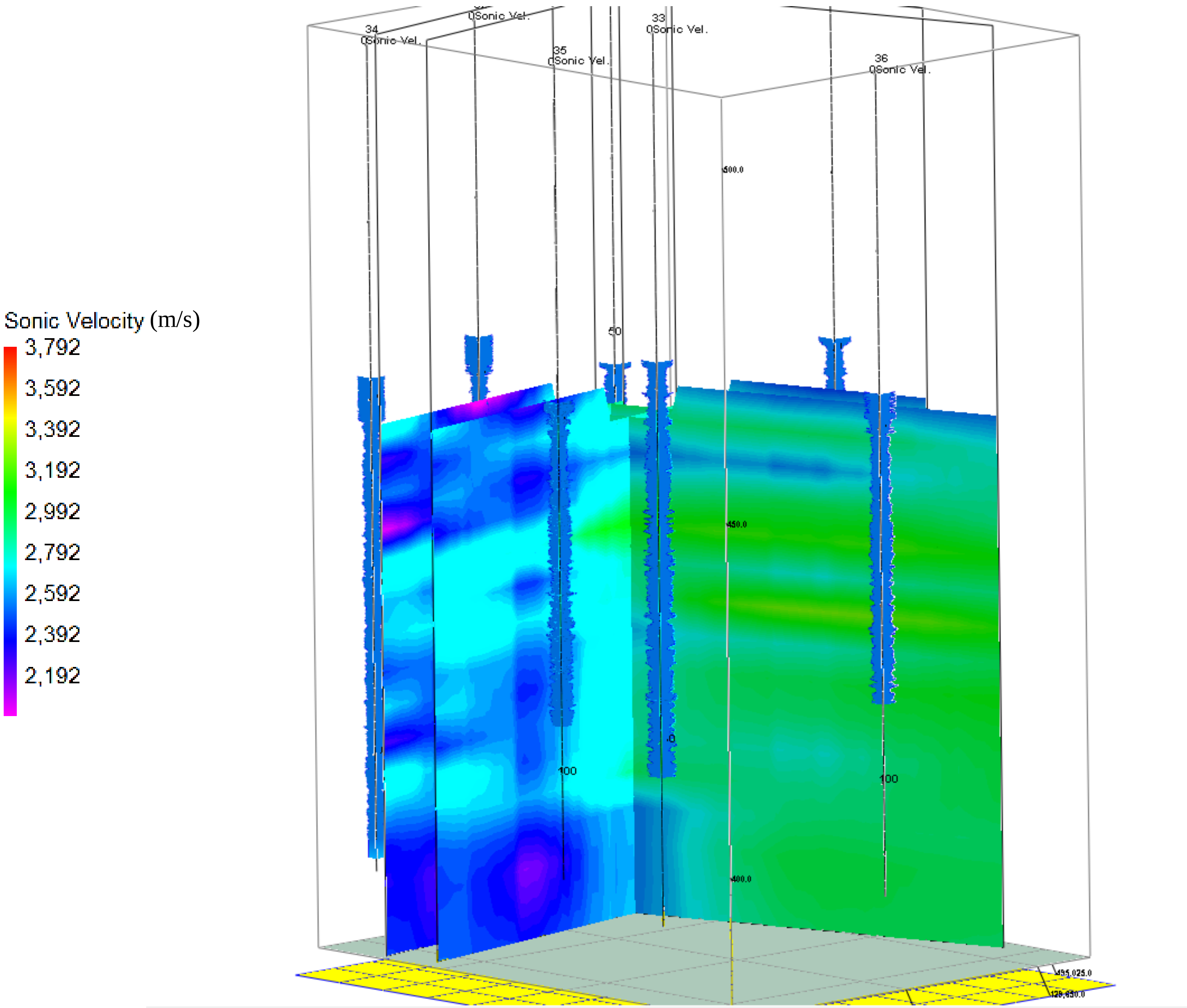
ARUP

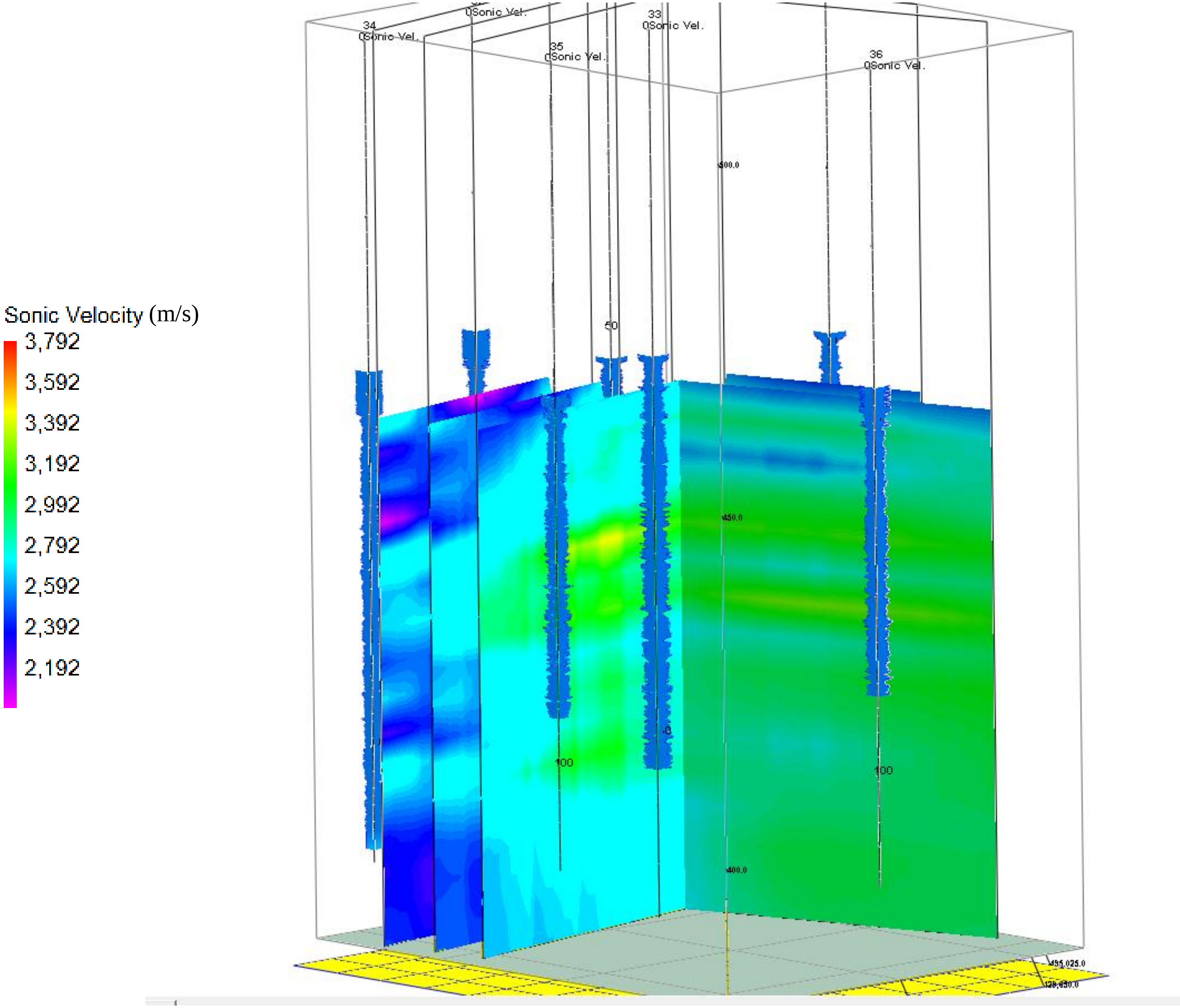

Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
0Sonic Vel.
35
0Sonic Vel.
33
0Sonic Vel.
36
0Sonic Vel.
500.0
50
450.0
0
100
0
100
400.0

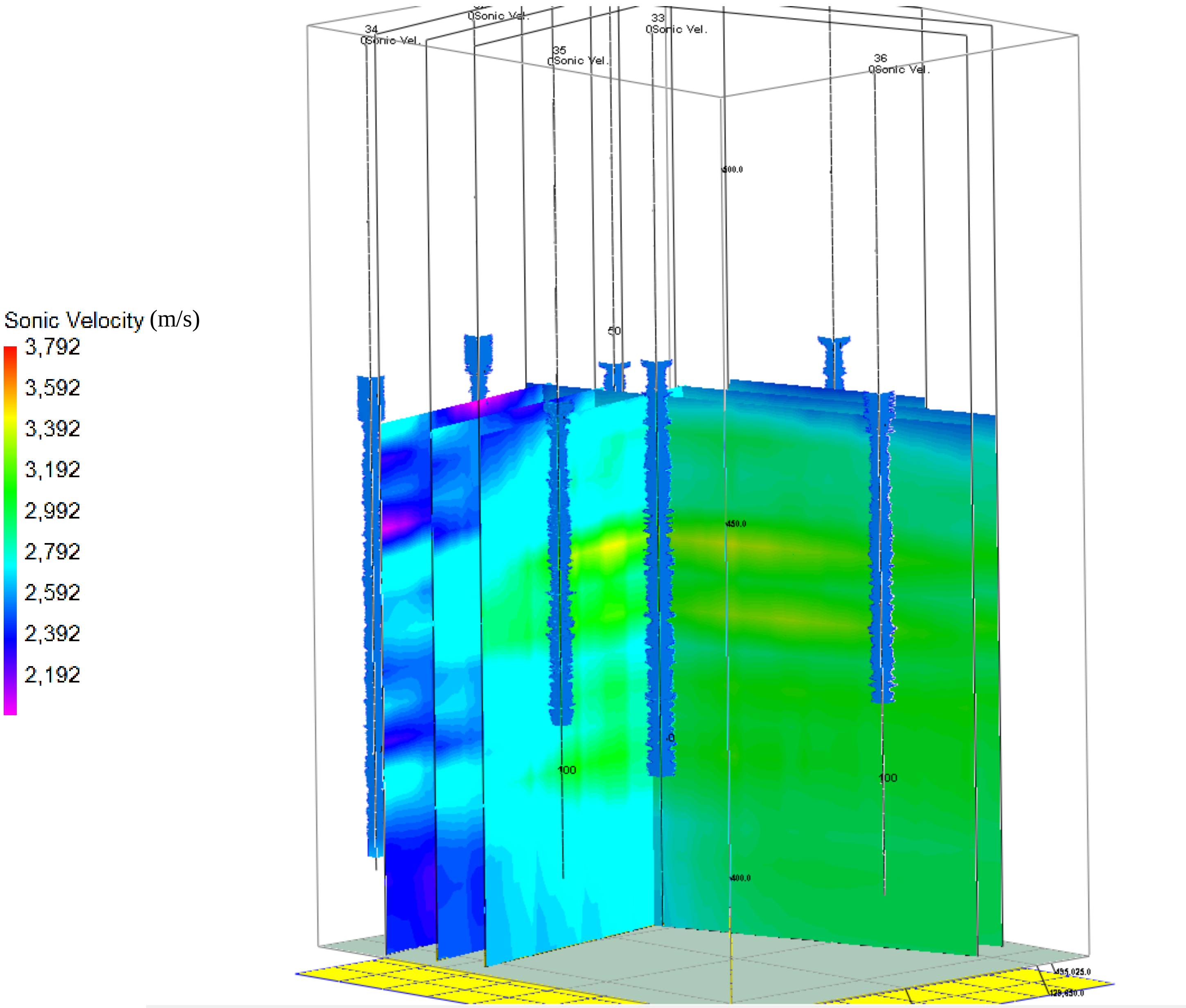
ARUP

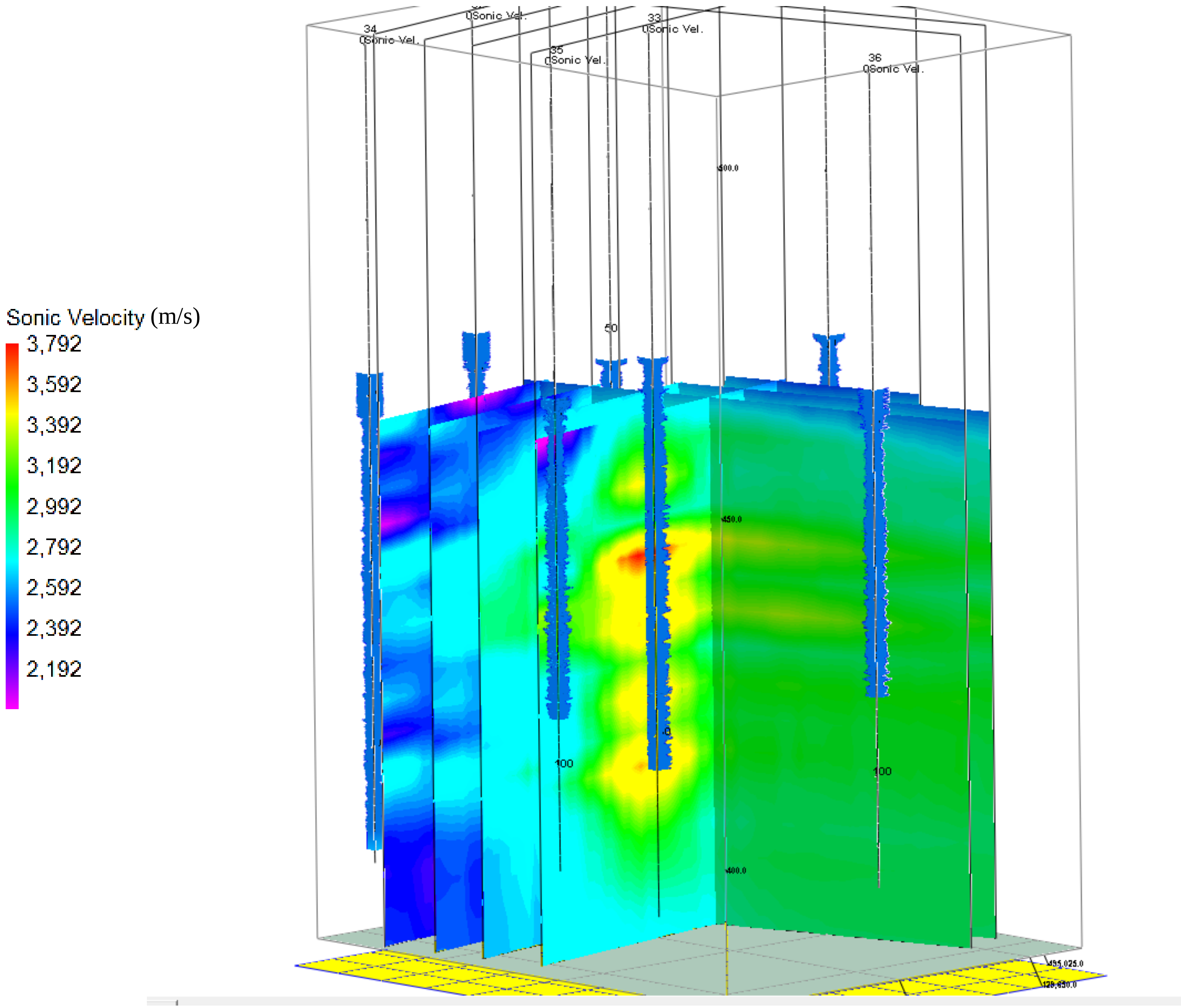

Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
35
0Sonic Vel.
33
0Sonic Vel.
36
0Sonic Vel.
50
100
100

ARUP

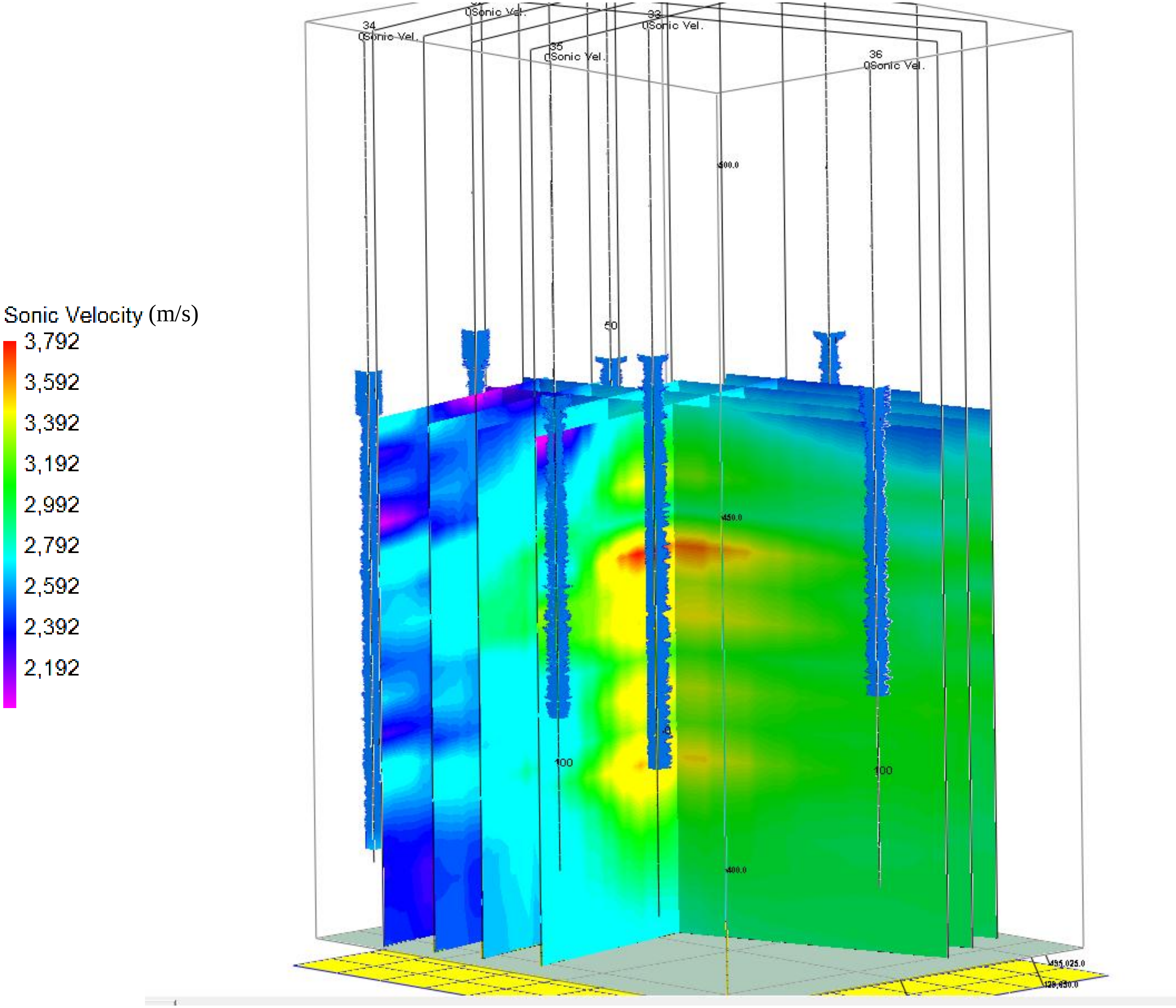

Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
0Sonic Vel.
33
0Sonic Vel.
35
0Sonic Vel.
36
0Sonic Vel.
500.0
450.0
400.0
50
100
100


Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
33
0Sonic Vel.
35
0Sonic Vel.
36
0Sonic Vel.
50
100
100

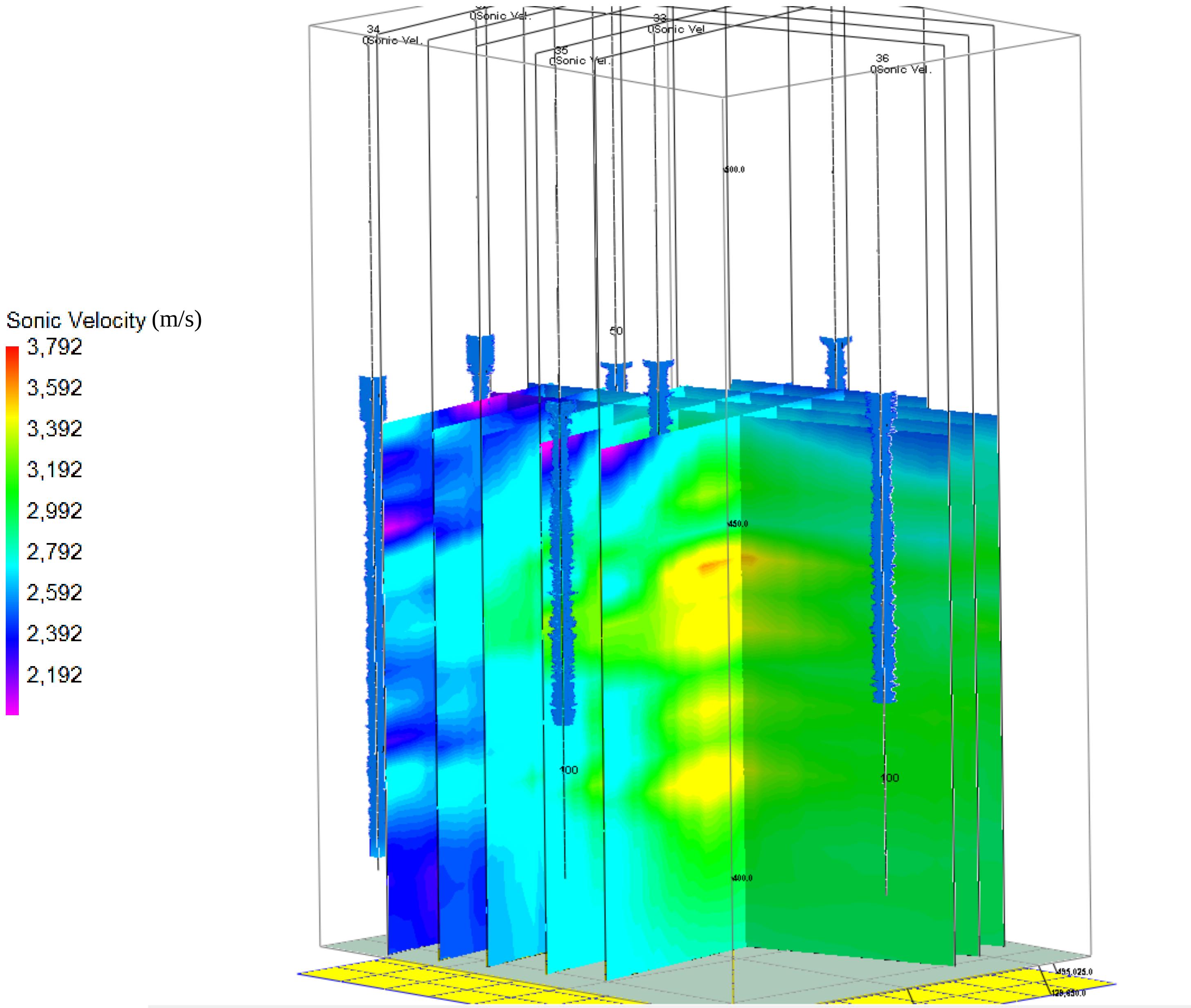

Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
33
0Sonic Vel.
35
0Sonic Vel.
36
0Sonic Vel.
500.0
50
450.0
100
100
400.0


Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
33
0Sonic Vel.
35
0Sonic Vel.
36
0Sonic Vel.
50
100
100

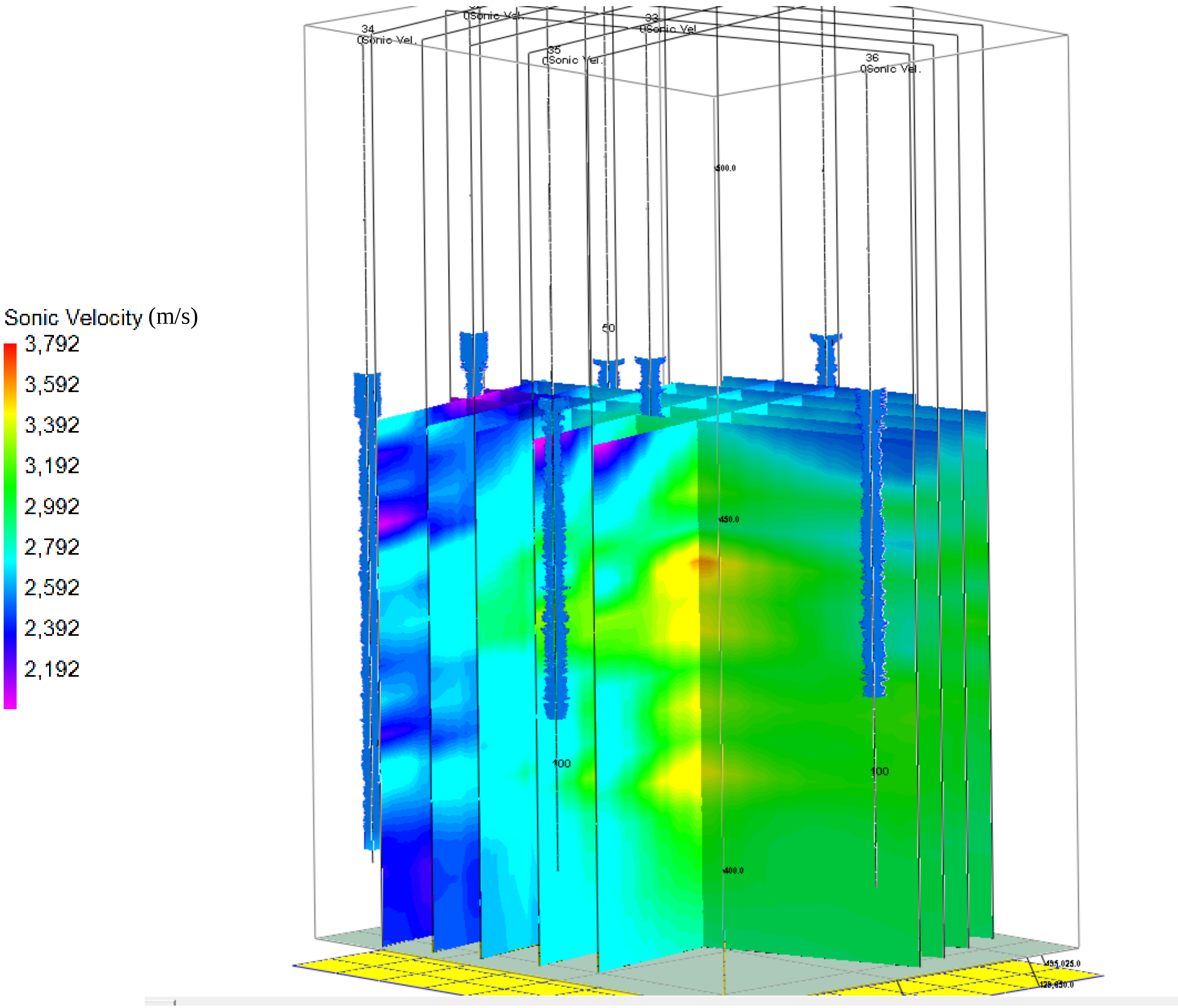
ARUP

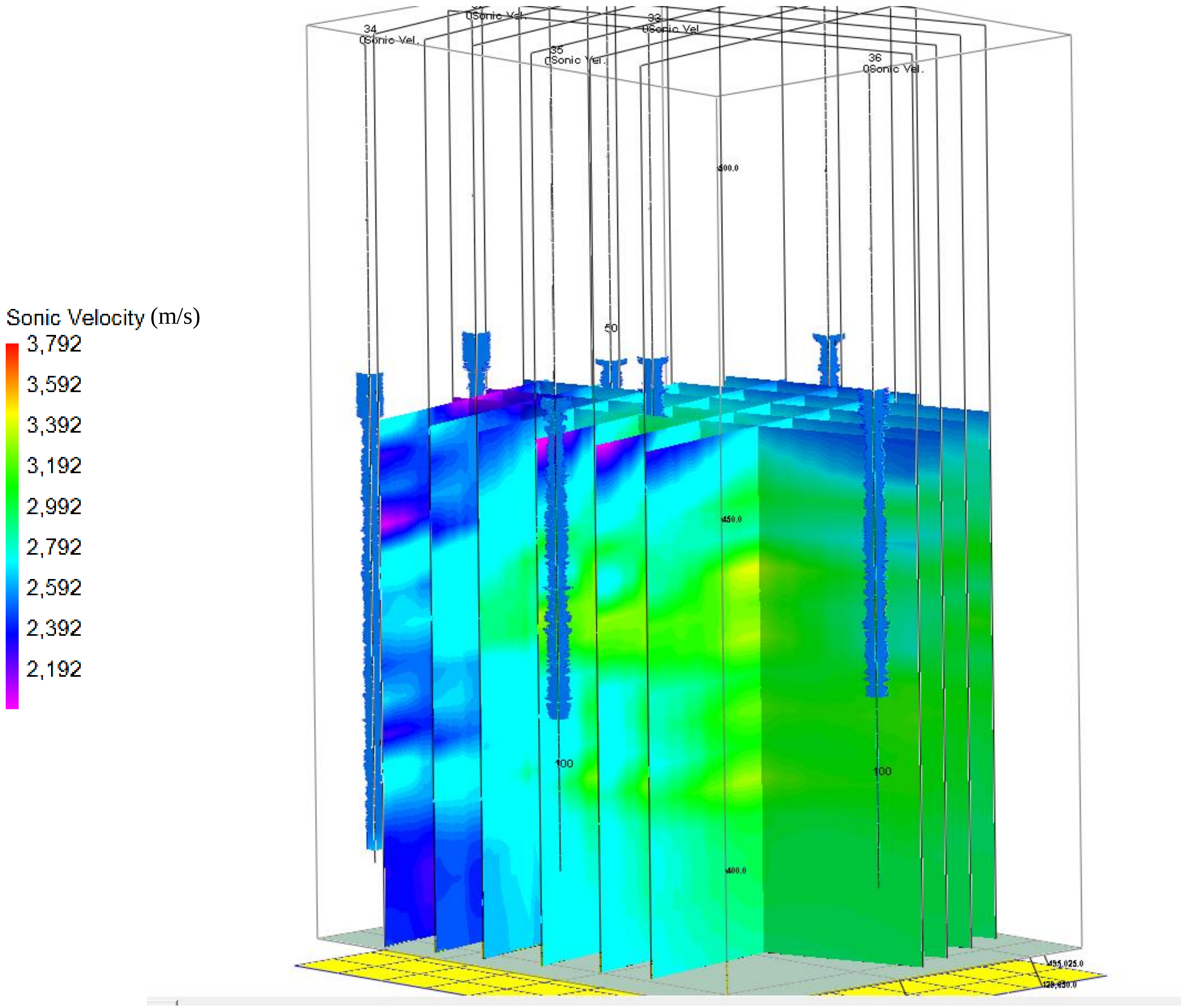

Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
Sonic Vel.
35
Sonic Vel.
36
Sonic Vel.
100
100

ARUP

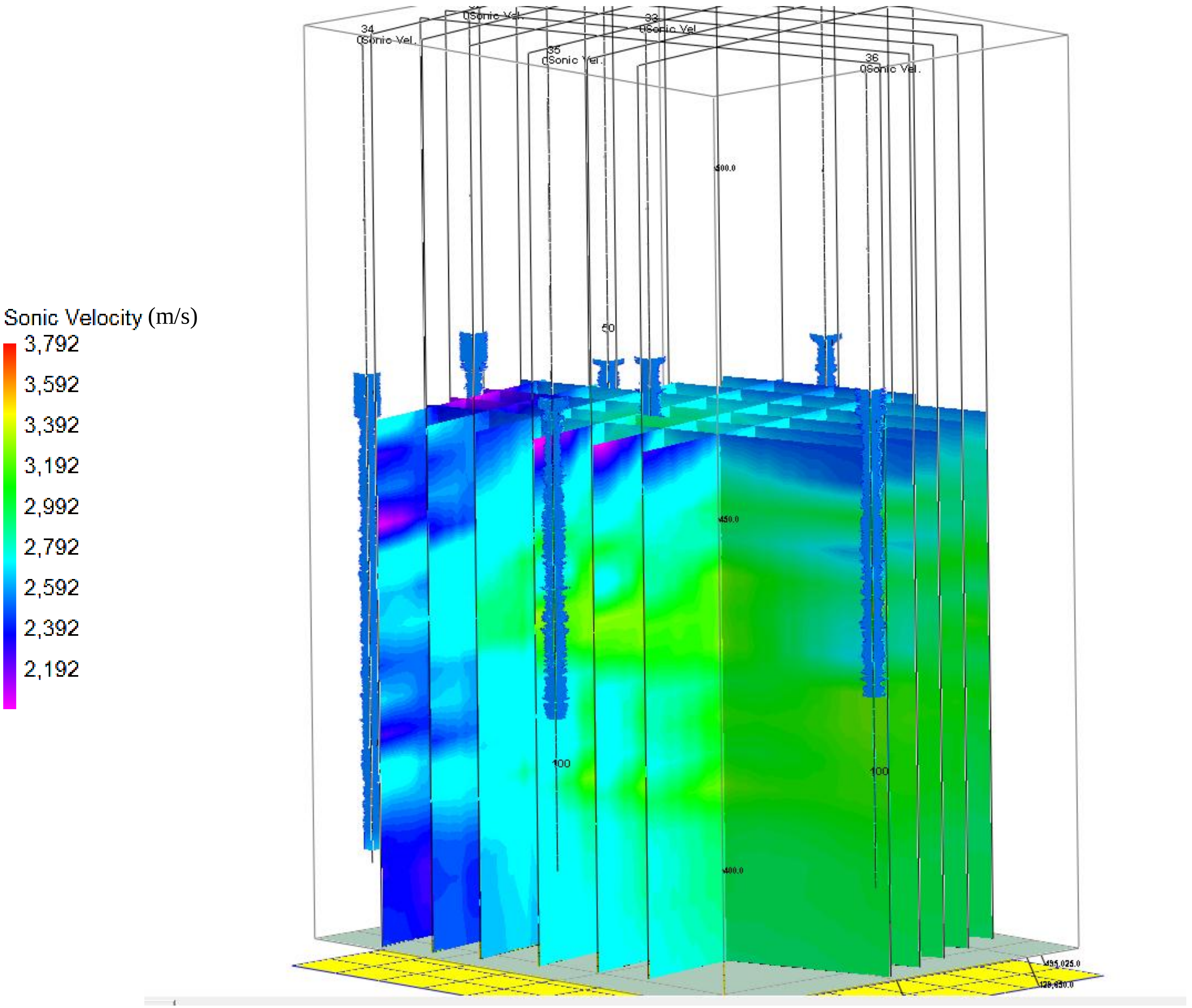

Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
35
0Sonic Vel.
36
0Sonic Vel.
50
100
100

ARUP

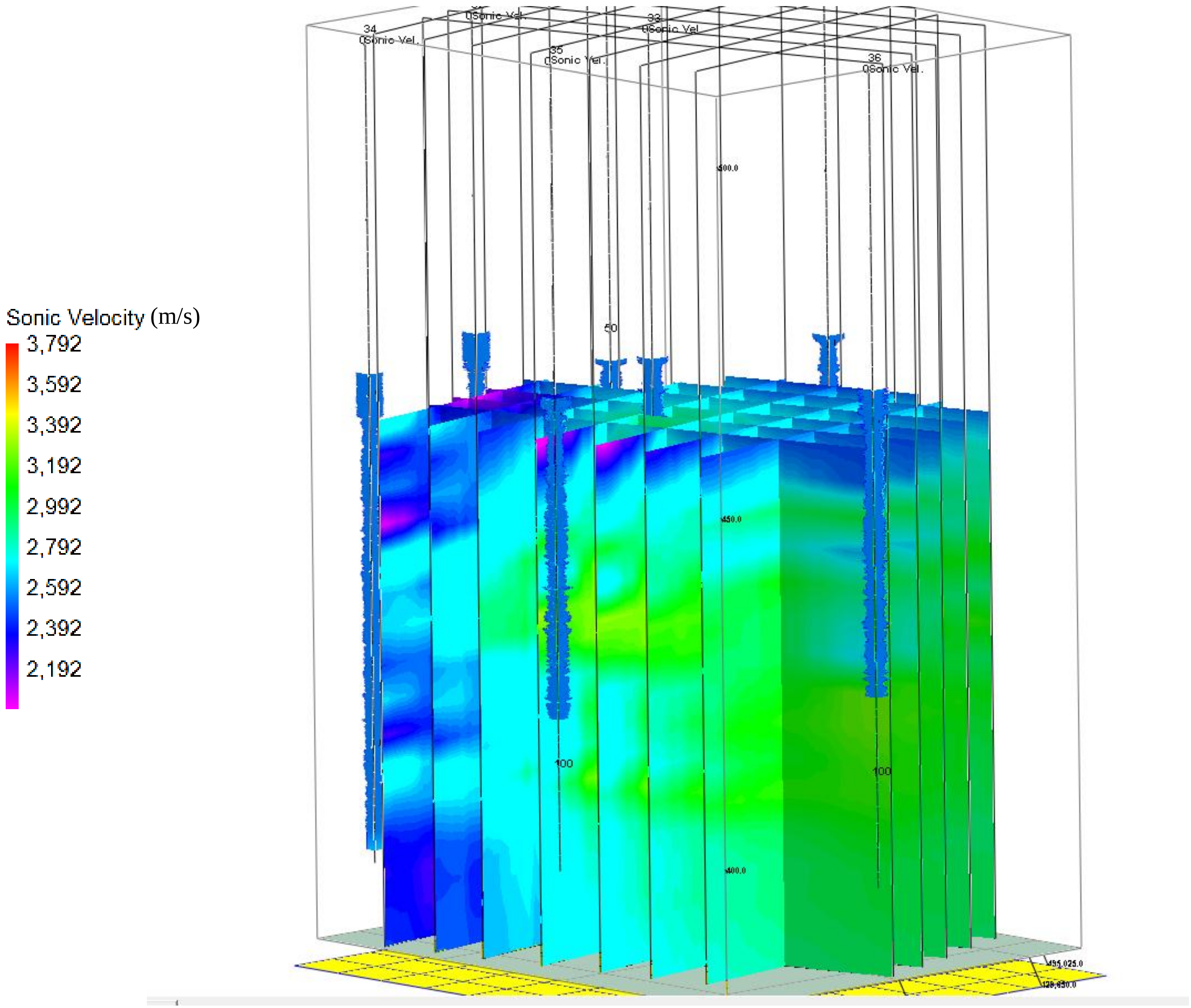

Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
35
0Sonic Vel.
33
0Sonic Vel.
36
0Sonic Vel.
500.0
50
450.0
100
100
400.0

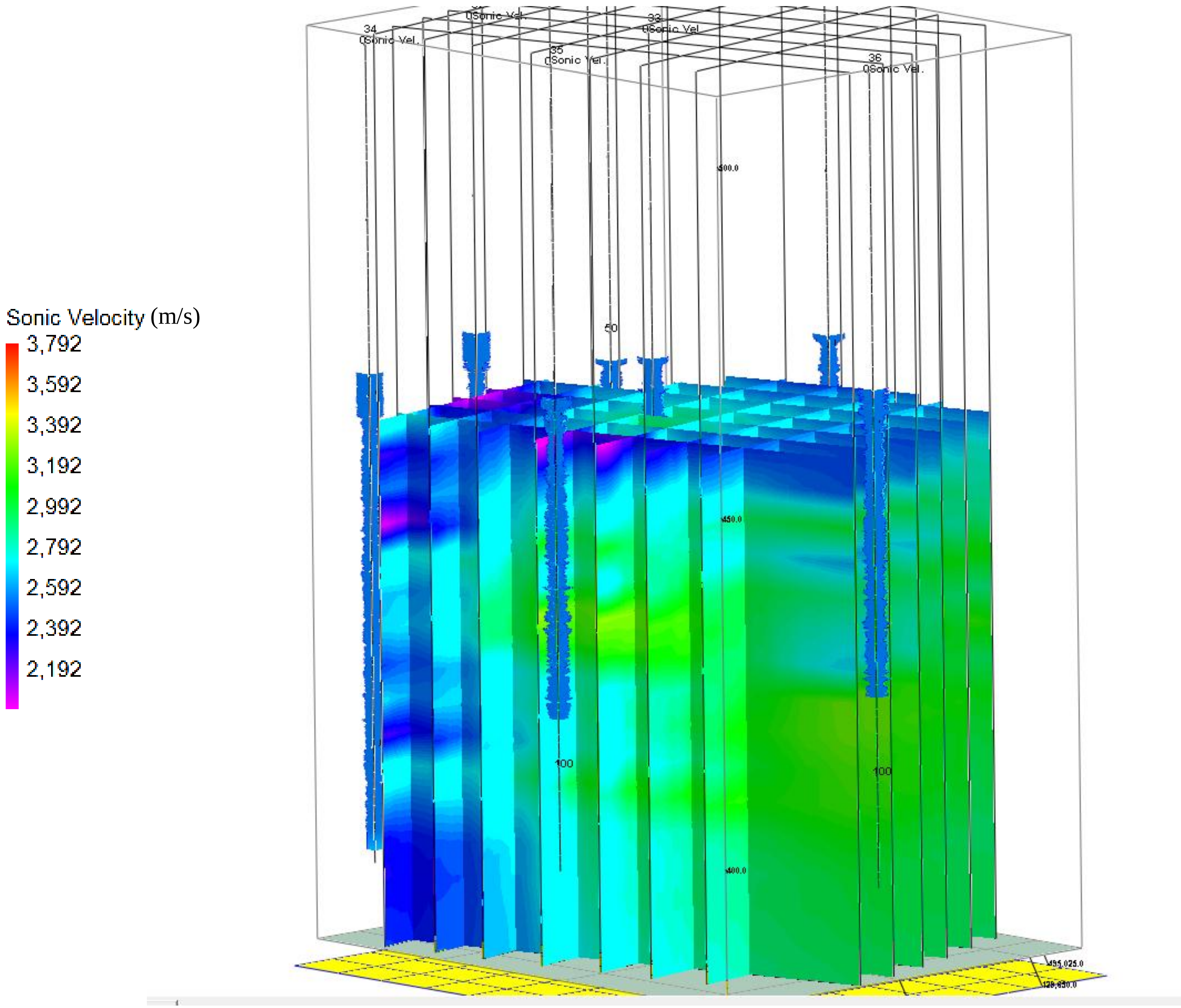

Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
33
0Sonic Vel.
35
0Sonic Vel.
36
0Sonic Vel.
50
100
100

ARUP

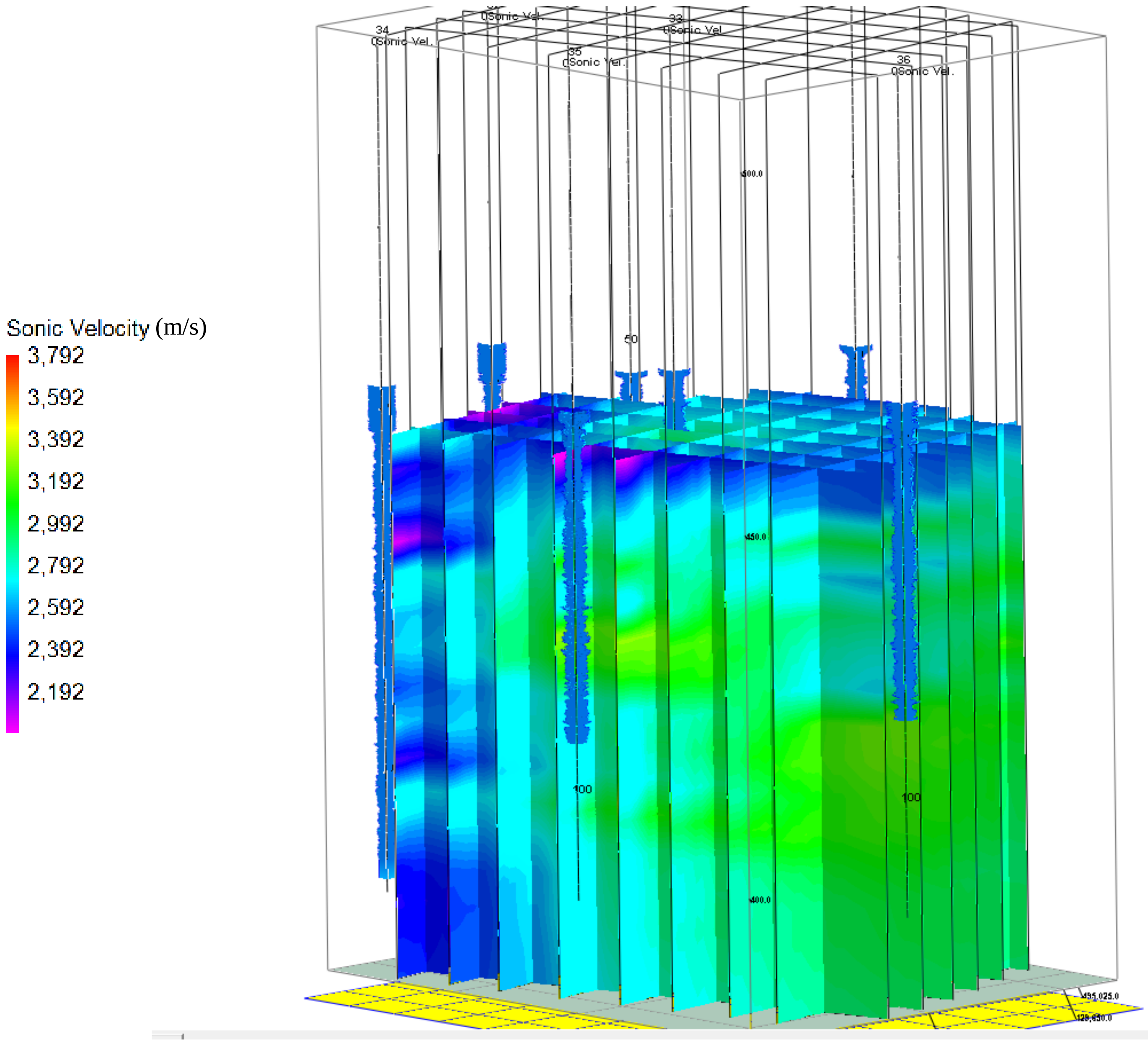

Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
33
0Sonic Vel.
35
0Sonic Vel.
36
0Sonic Vel.
50
100
100

ARUP

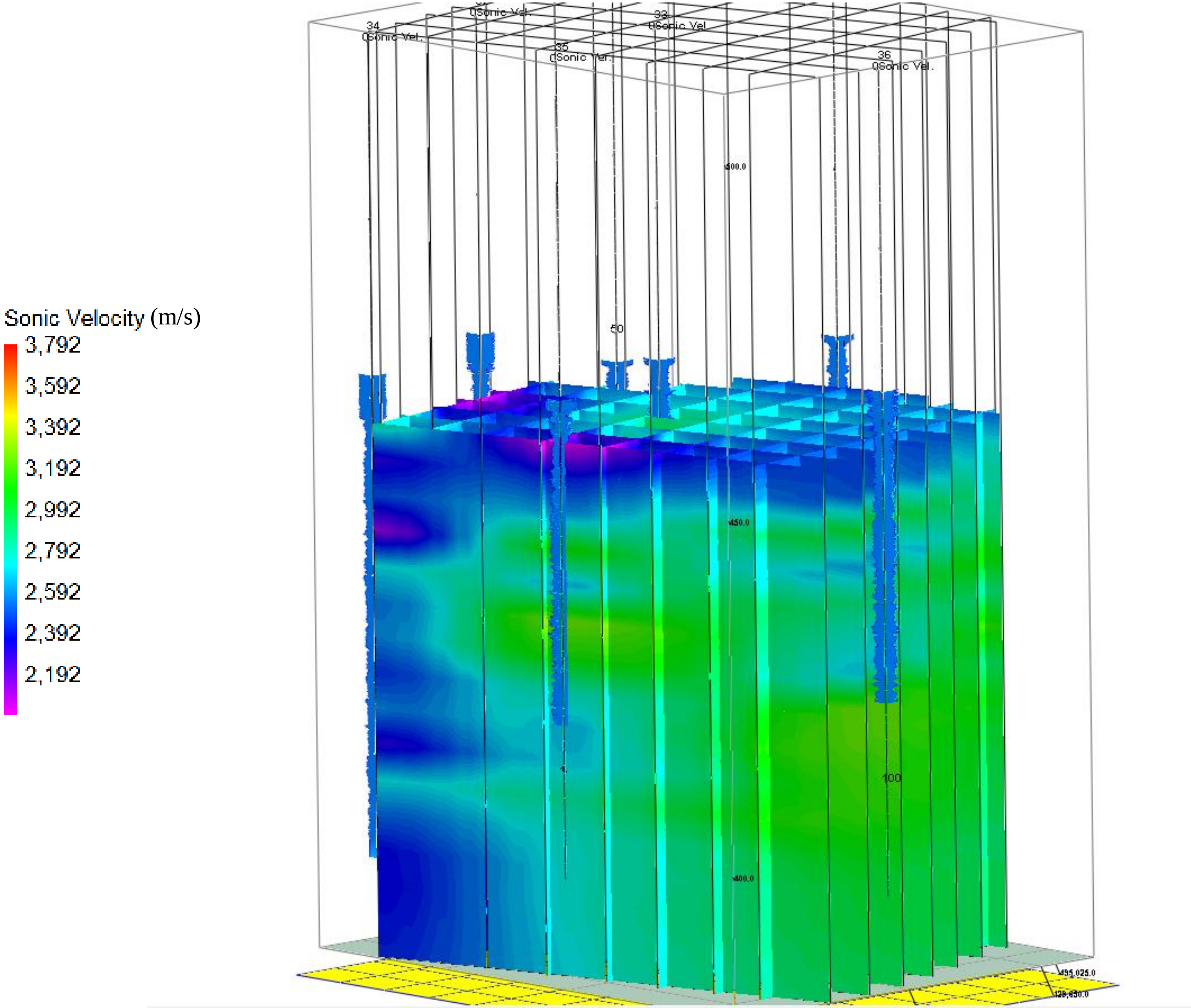

Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
35
0Sonic Vel.
33
0Sonic Vel.
36
0Sonic Vel.
50
100
100

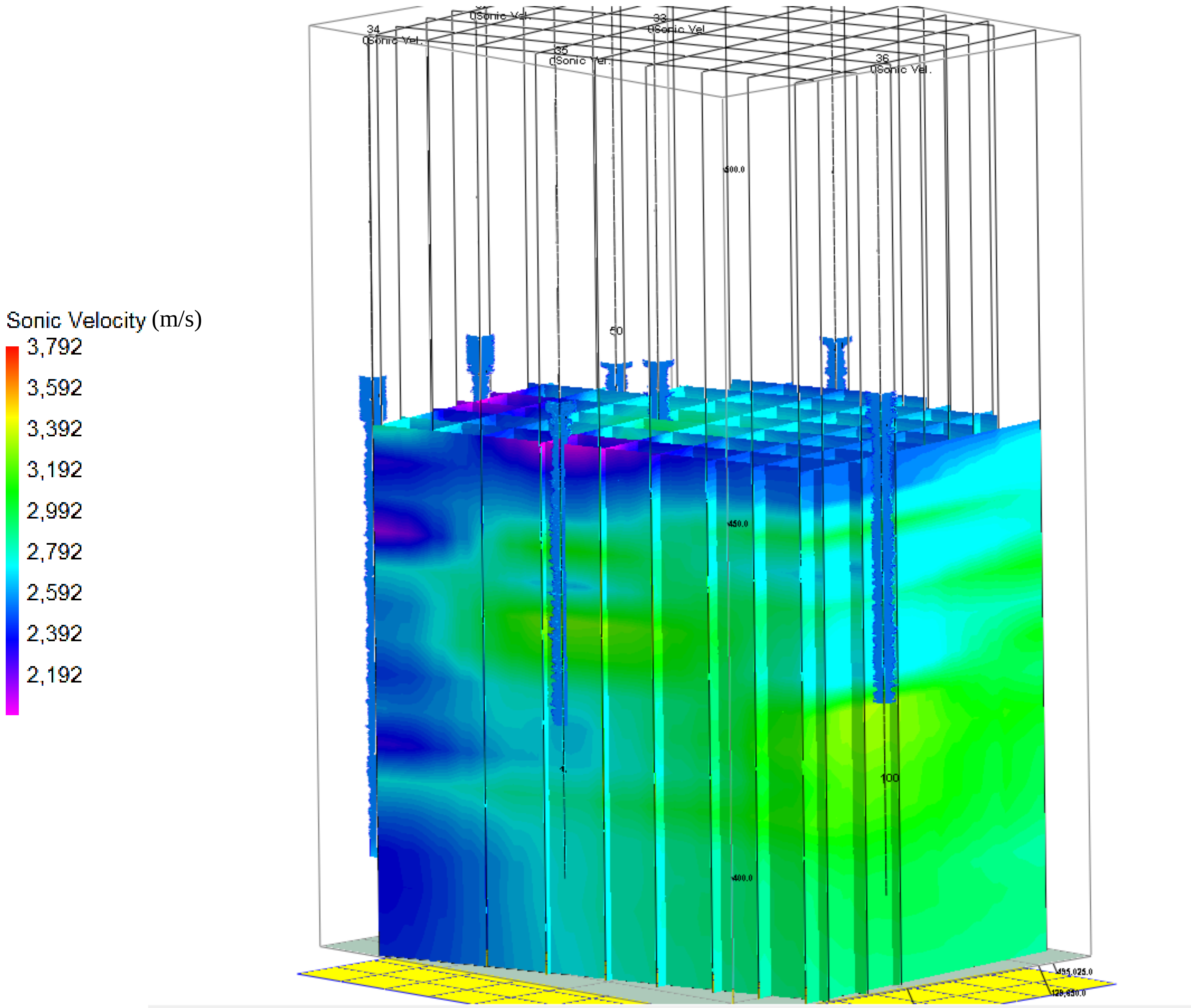


Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192


Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
34
0Sonic Vel.
33
0Sonic Vel.
35
0Sonic Vel.
36
0Sonic Vel.
50
100
100

ARUP


Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
50
100


Sonic Velocity (m/s)
3,792
3,592
3,392
3,192
2,992
2,792
2,592
2,392
2,192
50
100
500.0
450.0
400.0

Small Strain Stiffness

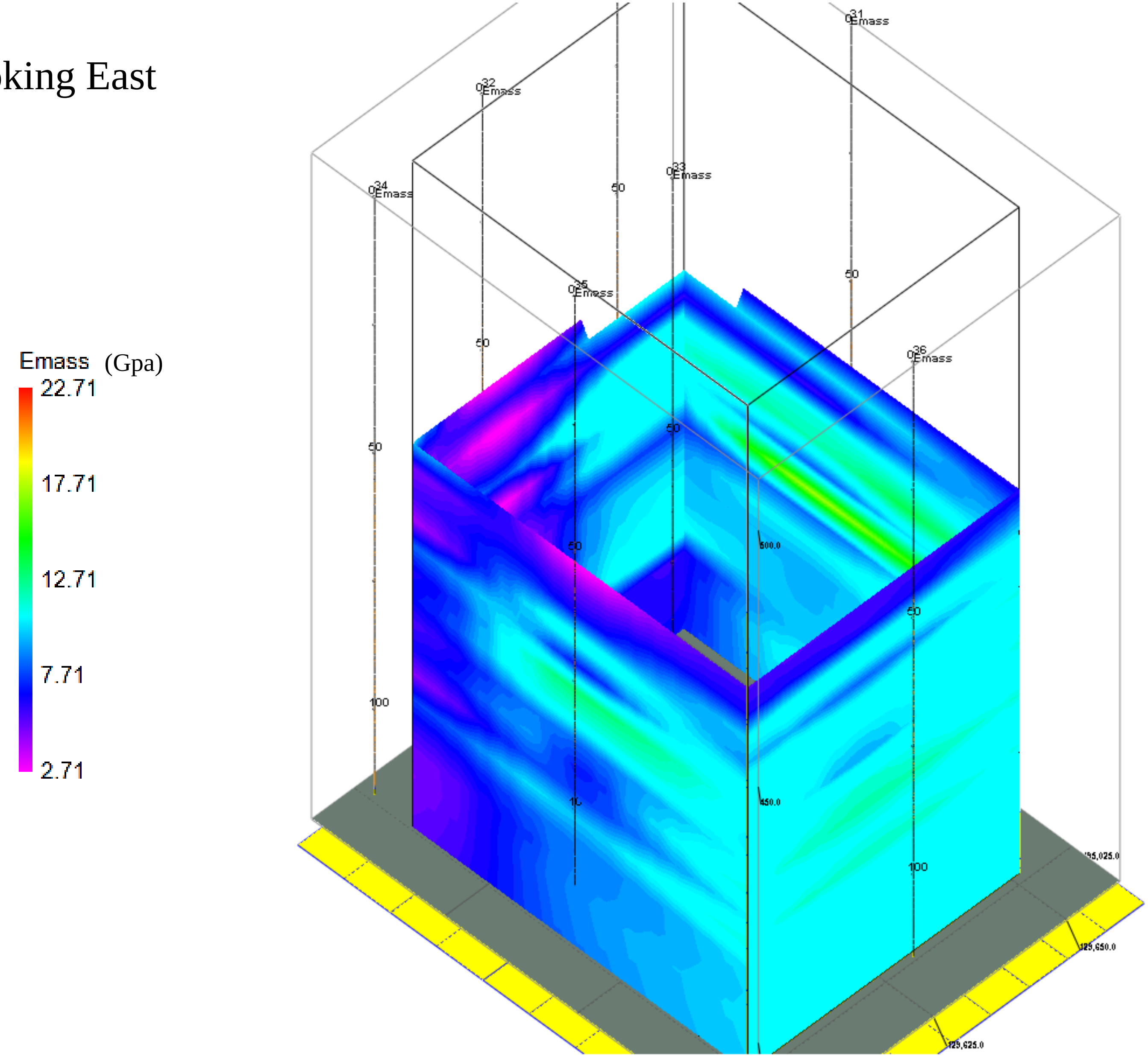
ARUP

Statistical Approach for Small Strain Stiffness

- Calculation of small-strain stiffness from Sonic Velocity Data (using Barton 2002)
- Determination of Conservative Assessed Mean (CAM)
- Current approach to analyse range and CAM for Geotechnical & Structural Models

(Example for BH 30 using Barton 2002)	Vp m/s	E_{mass} Small strain Young's Modulus (Gpa)
CAM	2606.6	5.2
Mean	2871.5	6.5
Standard Dev.	441.6	2.1
Maximum	4094.5	15.8
Minimum	1756.7	2.6

Looking East



ARUP

Conclusions & Further Ideas

- Assess sensitivity of design to thickness and frequency of weak/ grumuleuse horizons
- Targeted geophysics at Calcareous horizons as potentially most laterally persistent horizons - marker beds.
- Optimisie tunnel depth following site selection based on Detailed logging and Geophysical models.
- Development of 3D Model for interpretation all data sets
- Use of Seismic data to define critical small strain stiffness to predict yield behaviour in Geotechnical & structural models

2D FE Geotechnical Modelling

Eden Almog

ARUP

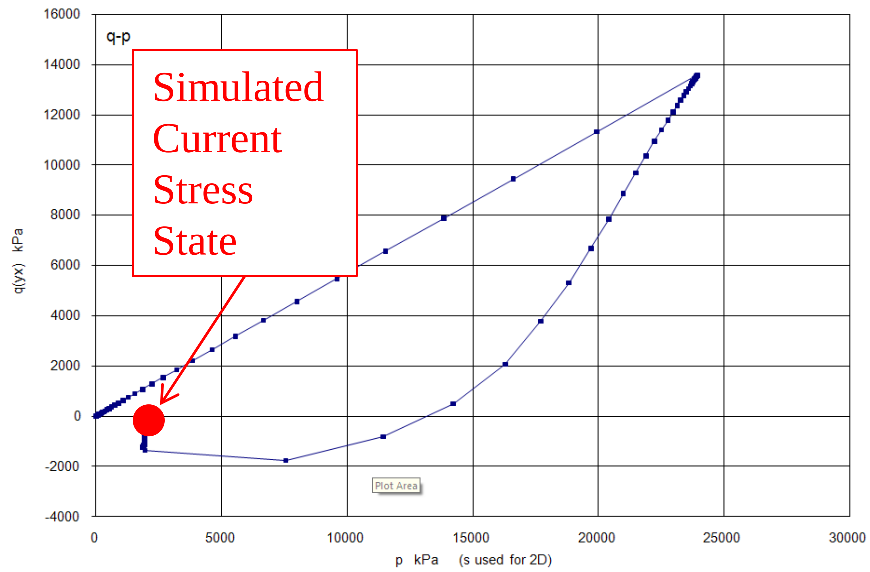
Stress History and Ground Parameters

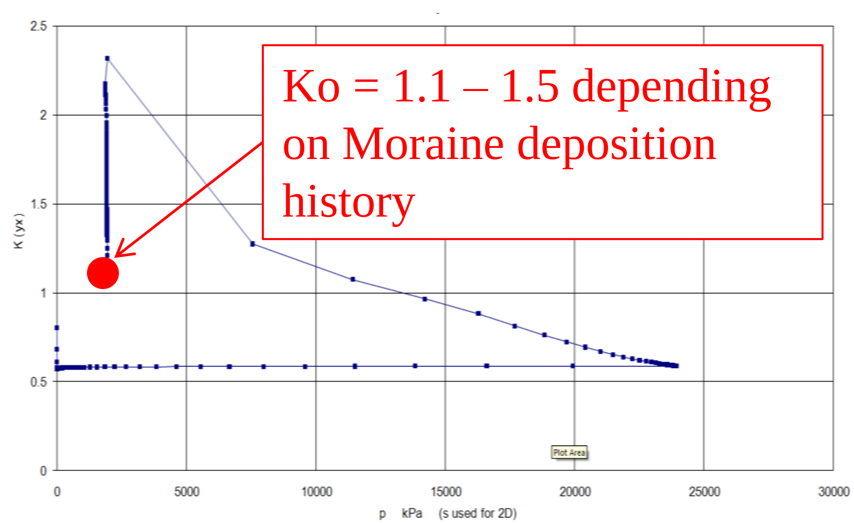
Assumed stress path:

Stage	Name	Cavern Depth (m)	Soil Effective Weight (kN/m^3)	Vertical Effective Stress (kPa)
1	Deposition of Molasse Rocks (2km)	2060	16	33000
2	Erosion	60	16	1000
3	Assumed deposition of 20m Moraine deposits	80	11	1200

Soil mass parameters:

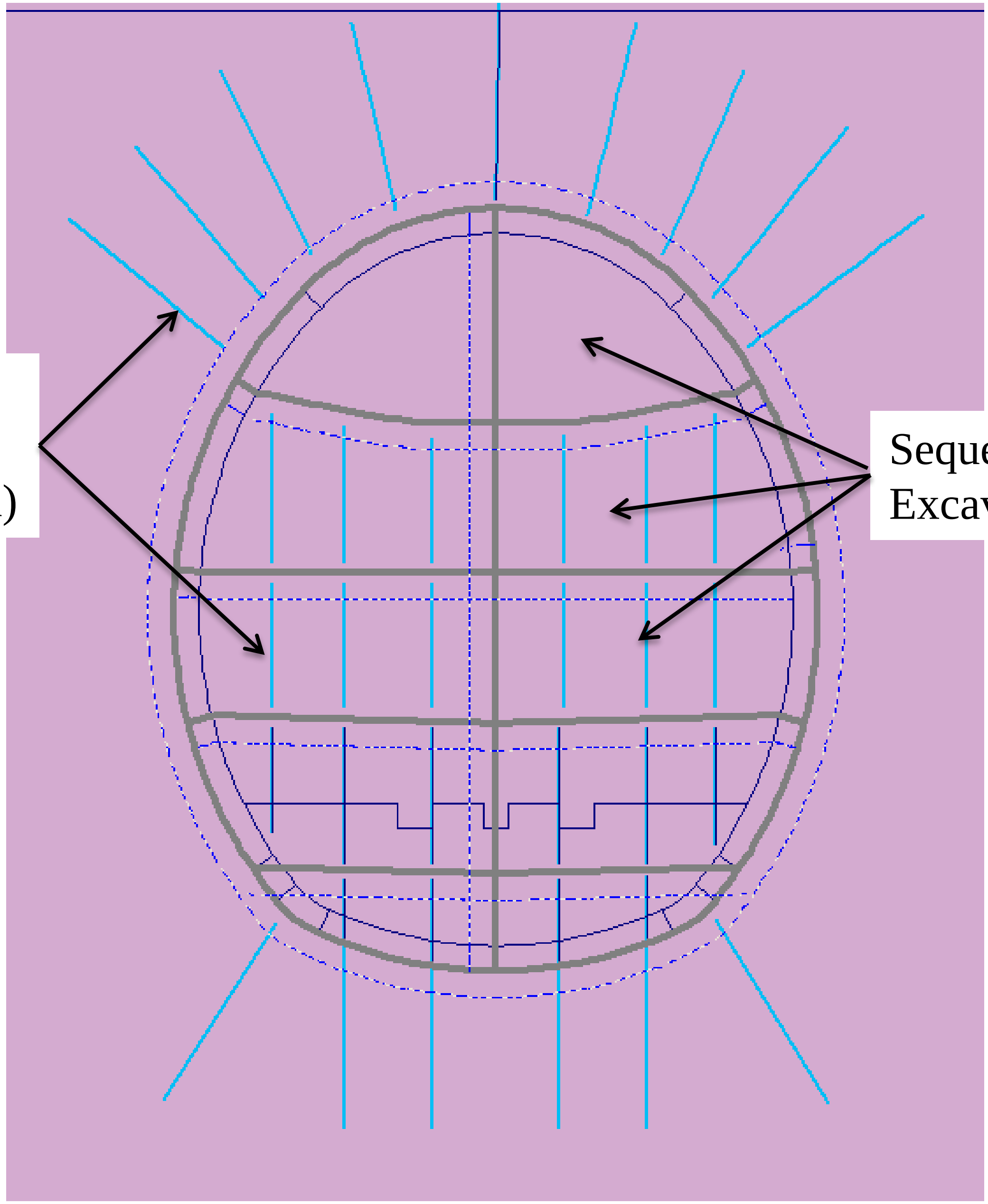
Name	γ [kN/m^3]	k [m/s]	ν [-]	E_{mass}' (LB) [kN/m^2]	c' [kN/m^2]	ϕ' [°]
Molasse Rock Mass	23	1.00E-09	0.2	2800000	220	35
Moraine Gravel	23	1.00E-05	0.25	50000	0.01	35





ARUP

Detailed 2D FE Analysis



Other features:

-Molasse drained behaviour with steady state seepage forces

-Stress relaxation per stage

-Shotcrete hardening with time

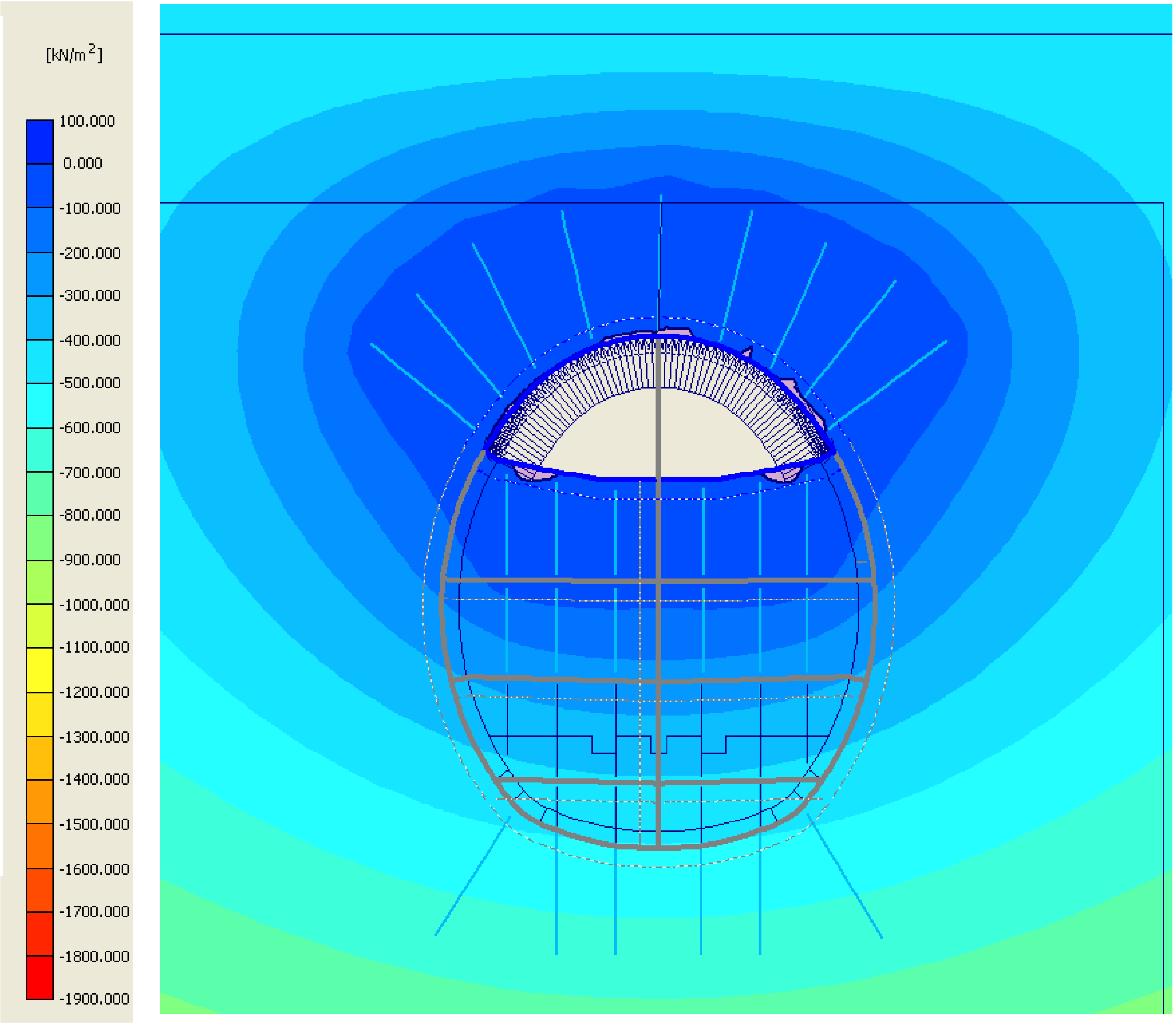
Example – Top Heading Excavation

Ground water modelling

-Reduced pore-pressure around excavation to minimise yielding

-Low permeability coupled with relatively high stiffness with slow construction require drained analysis (little excess pore pressures)

-Steady state seepage but with very low flow rate due to low permeability



ARUP

Example – Top Heading Excavation

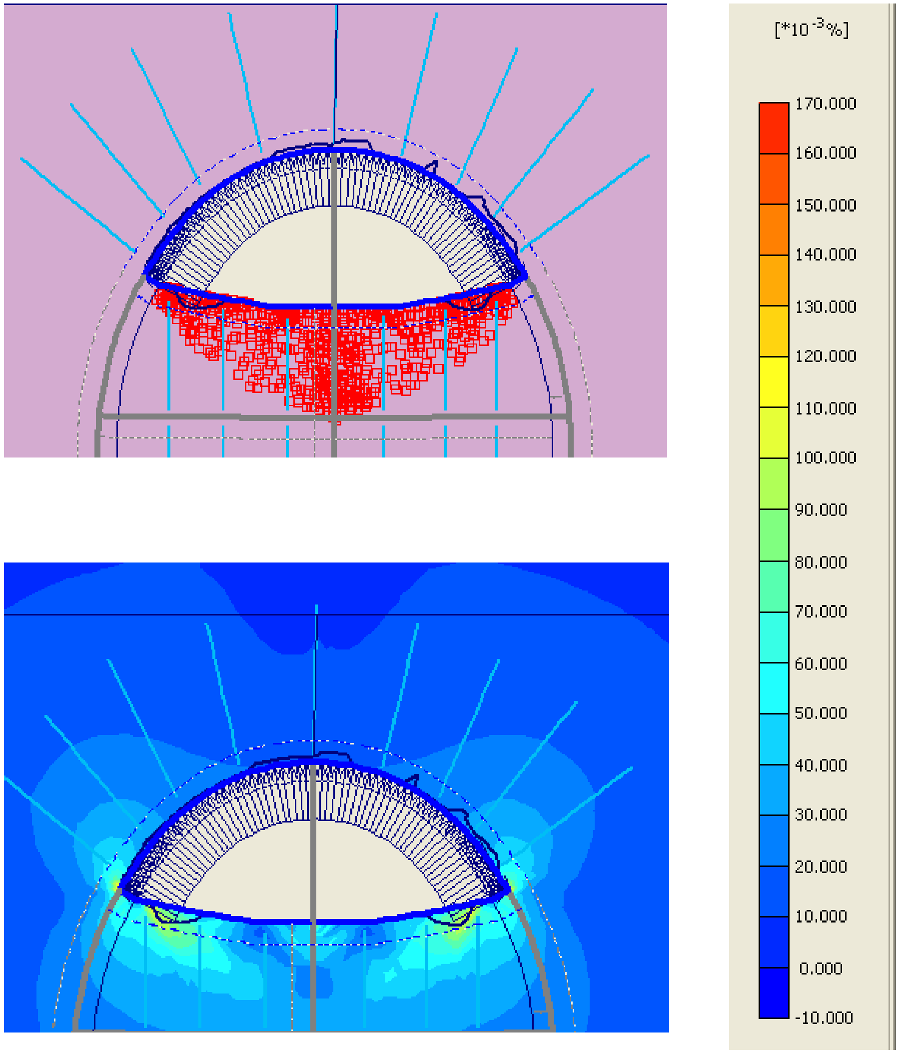
Ground Yielding

-Full face heading excavation is conservative

-Radial support minimises yielding.

-Most yielding occurs at invert and can be reduced by further sequencing and curvature

-Shear strains values acceptable and no slip surfaces generated (global FoS = 3.5)

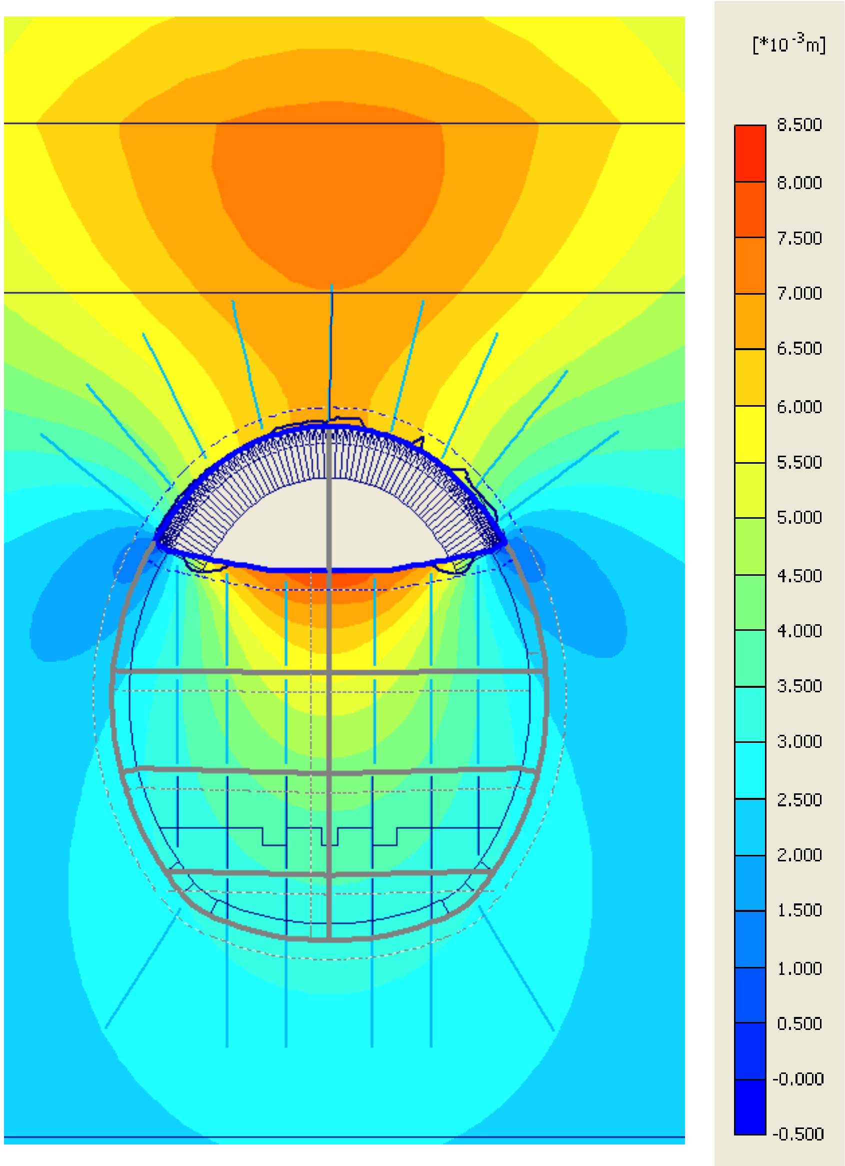


Example – Top Heading Excavation

Ground Deformations

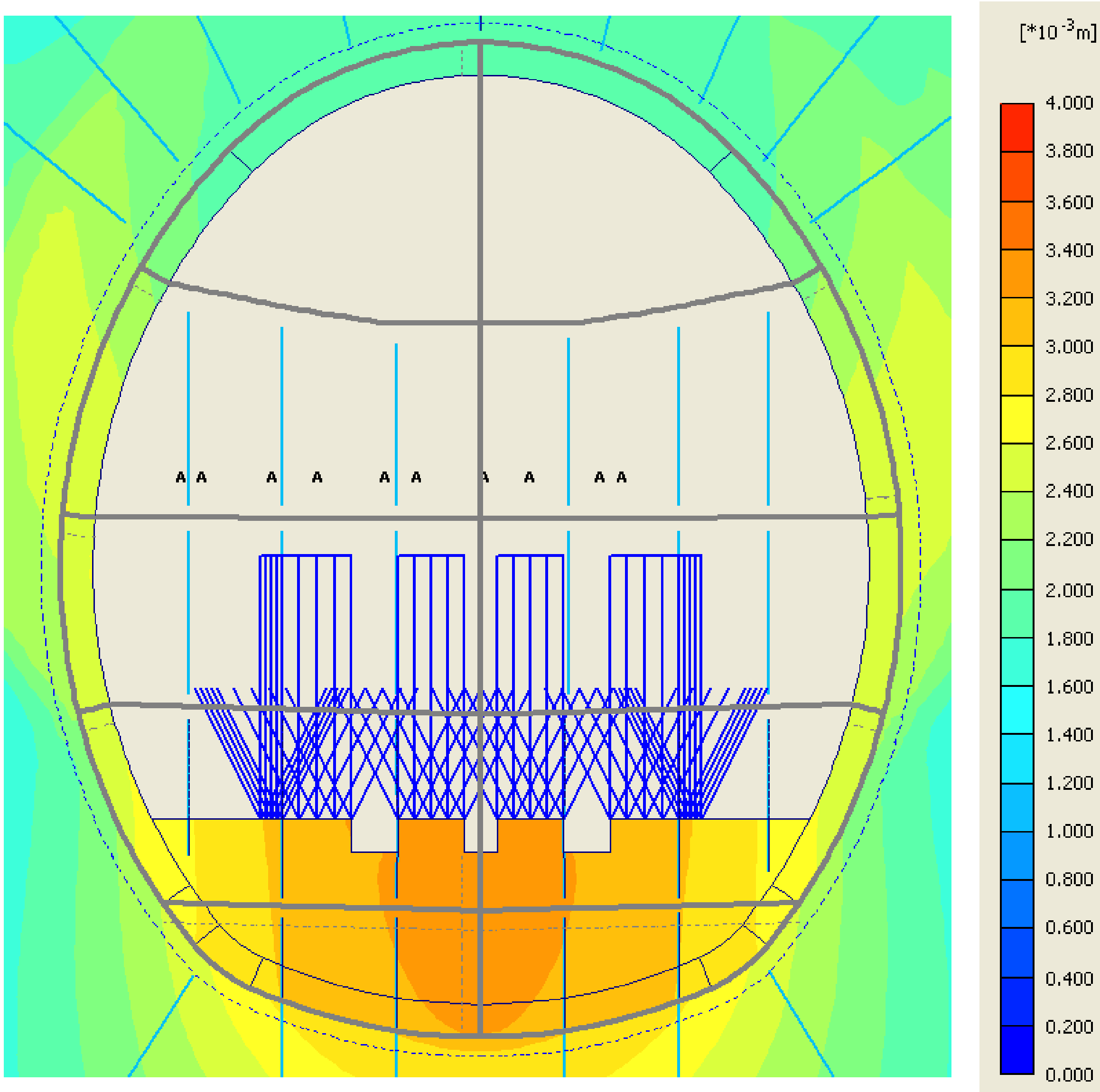
-Invert deformations are in accordance with measured displacements at CMS.

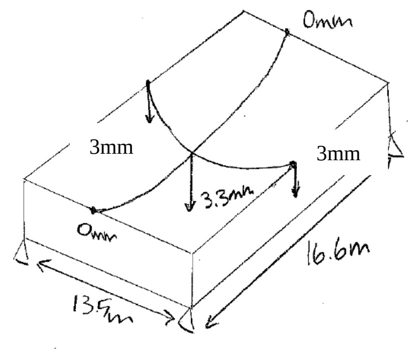
-Maximum tunnel convergence = 0.2% which is acceptable



ARUP

2D Invert Deformations





Longitudinal: 3.3mm / 16.6m = 0.2mm/m x 20m = **4mm/20m > 0.5mm/20m**.

Transversal: 3.3mm-3 mm / 13.5m = 0.023 x 20 = **0.45mm/20m < 0.5mm/20m**.

Unacceptable invert deformation in longitudinal direction. Highlights the need to consider 3D structure effects

3D Bedded Spring Model

Agnieszka Mazurkiewicz

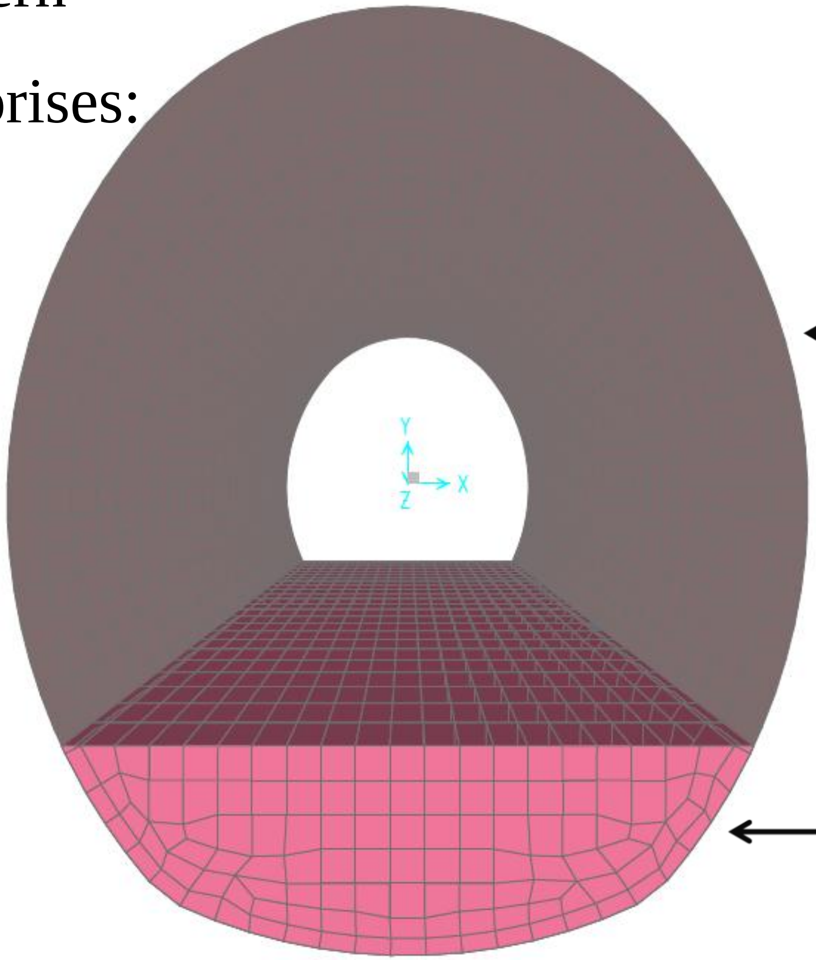
ARUP

3D Finite Element Analysis
Structural Design

Interaction Cavern

3D-model comprises:

- Lining
- Invert Slab



Lining

Thickness: 1.0m

Concrete C50/60

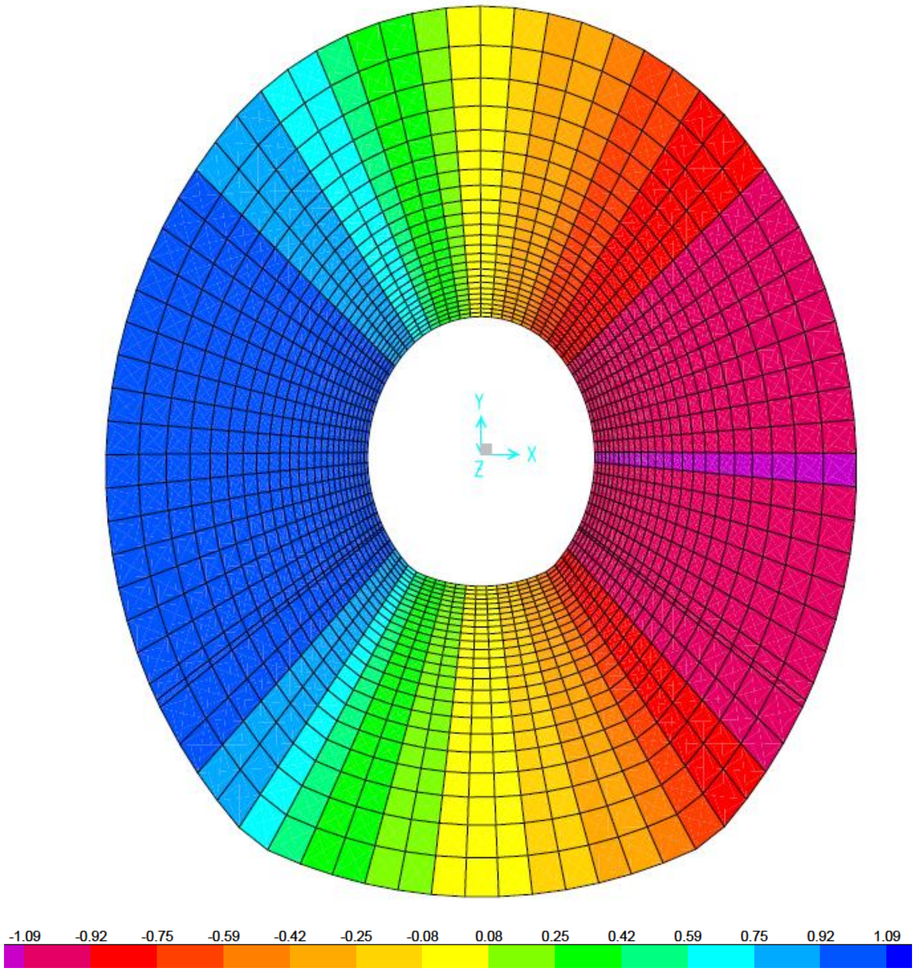
Invert Slab

Thickness: 5.6m

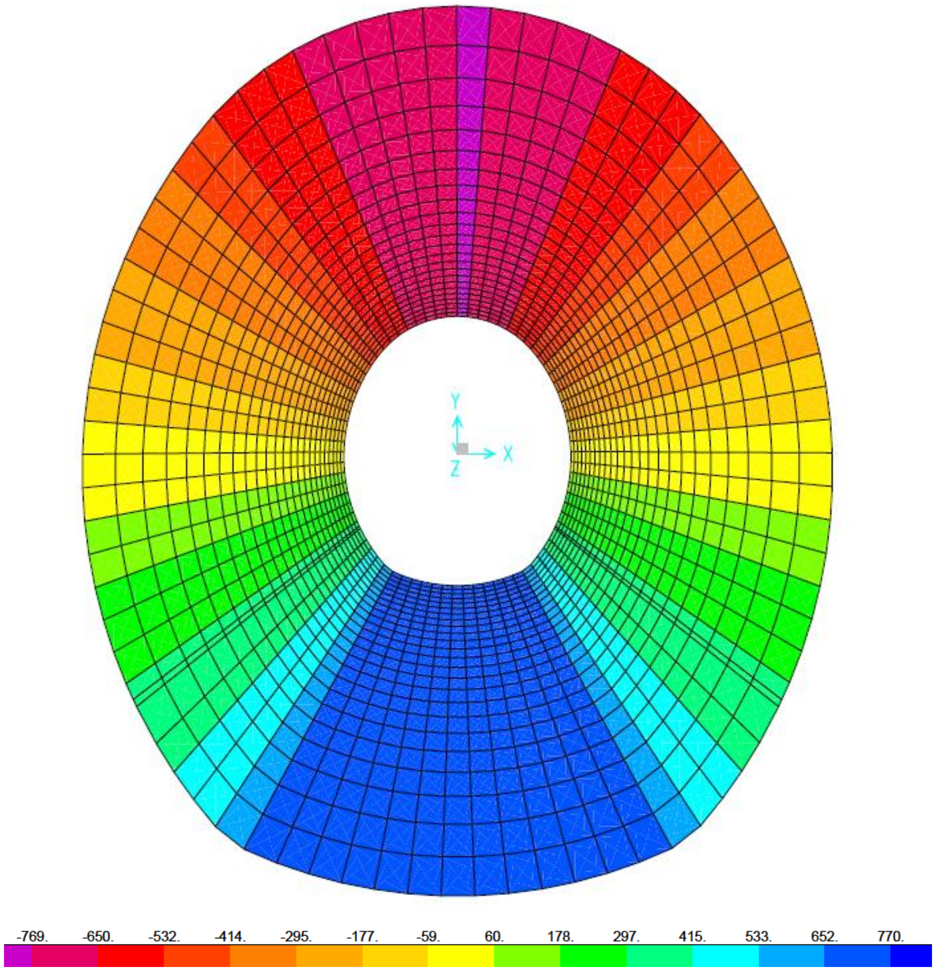
Concrete C50/60

Ground Pressure (Including Stress Arching)

Max Horizontal Pressure: 1090 kPa

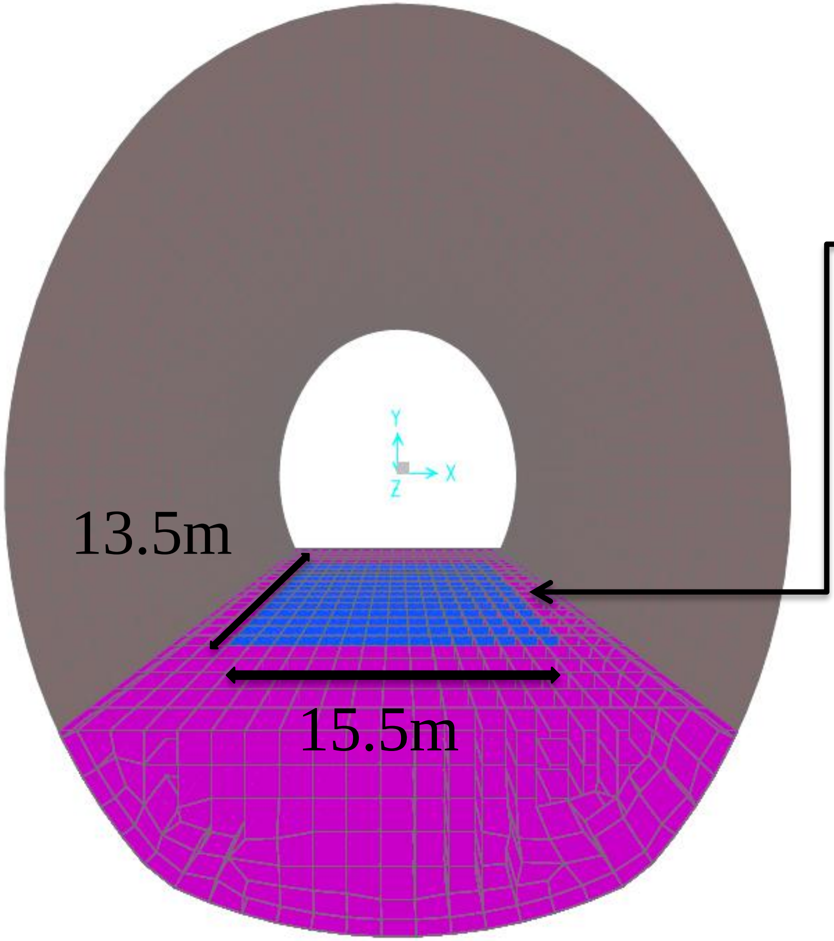


Max Vertical Pressure: 770 kPa



ARUP

Moving Slab Distributed Load

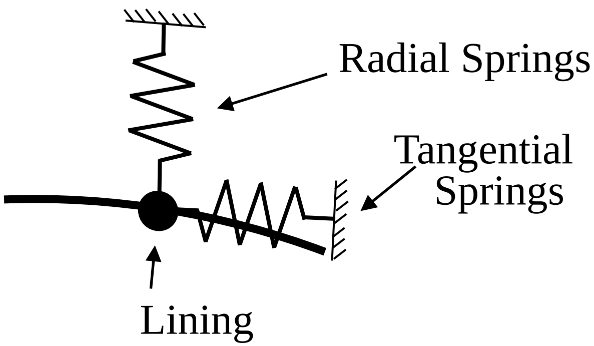


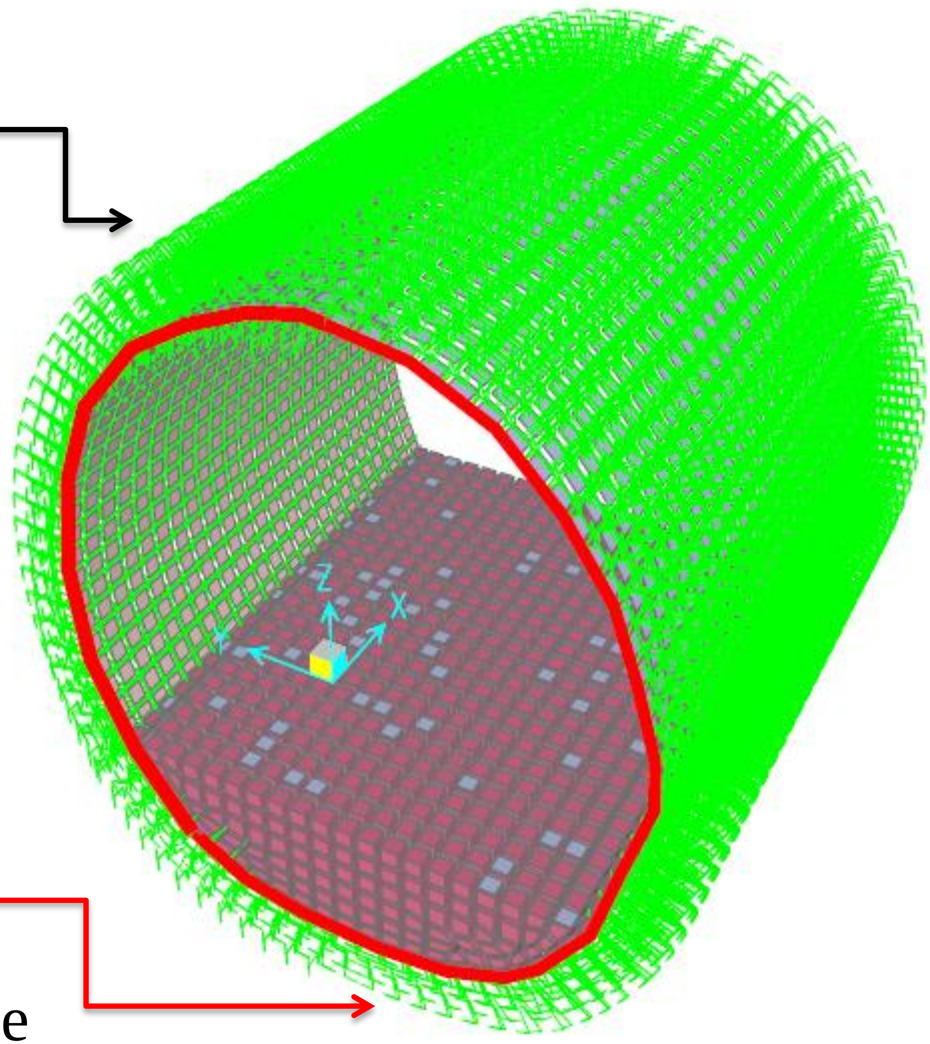
800 kPa

Moving slab distributed load applied in the middle of the cavern span

Boundary Conditions

Springs represent ground stiffness



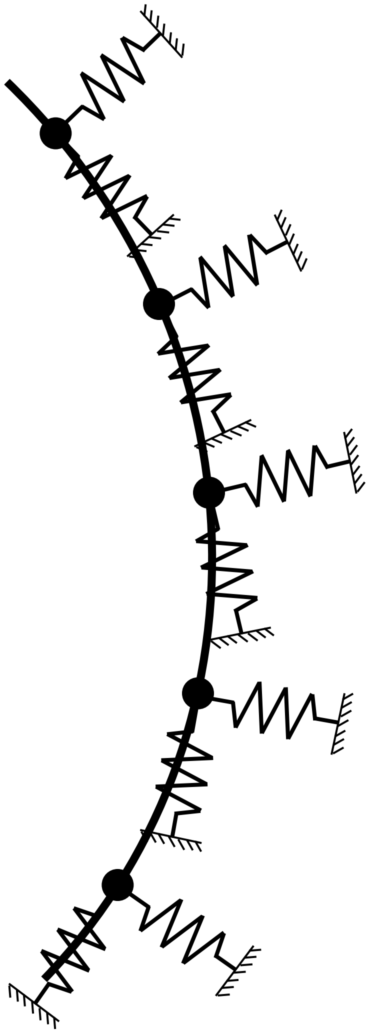


Pinned connection at interaction cavern and the service caverns interface

Boundary Conditions

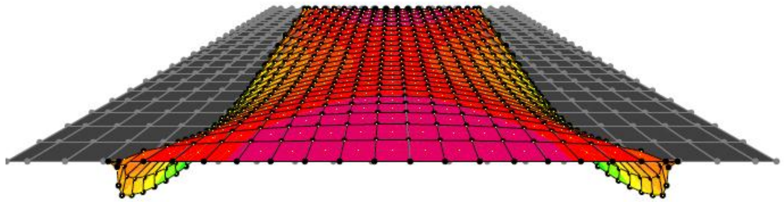
Three following ground stiffness has been investigated in order to evaluate the ground-structure interaction:

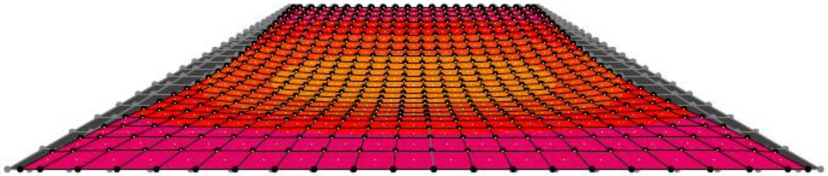
- 2D FE non-linear model stiffness:
  - Radial Springs: 100 kPa/mm
- 2x FE model stiffness
  - Radial Springs: 200 kPa/mm
- 3x FE model stiffness
  - Radial Springs: 300 kPa/mm



ARUP

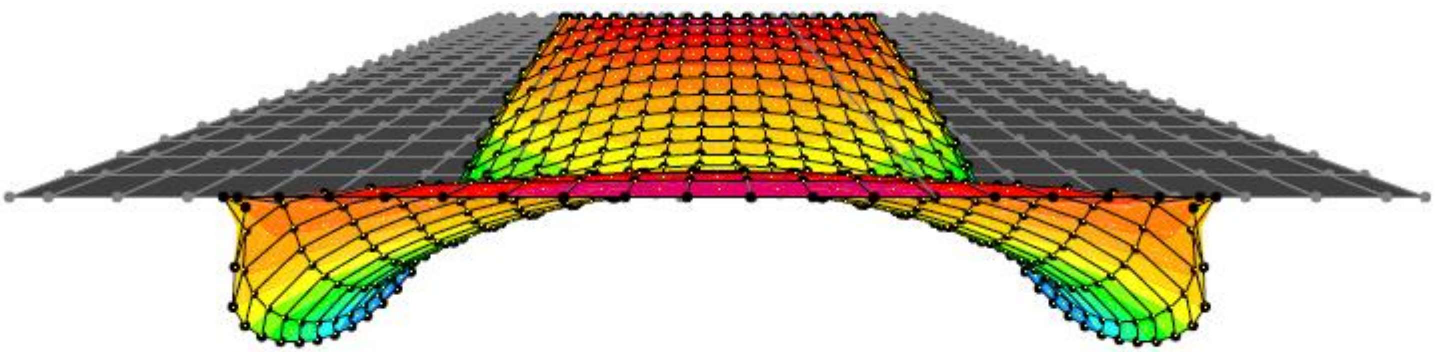
Serviceability Limit State Analysis
Invert Slab Deformed Shape





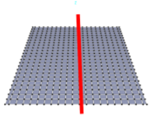
Ground Pressure + Moving Slab +

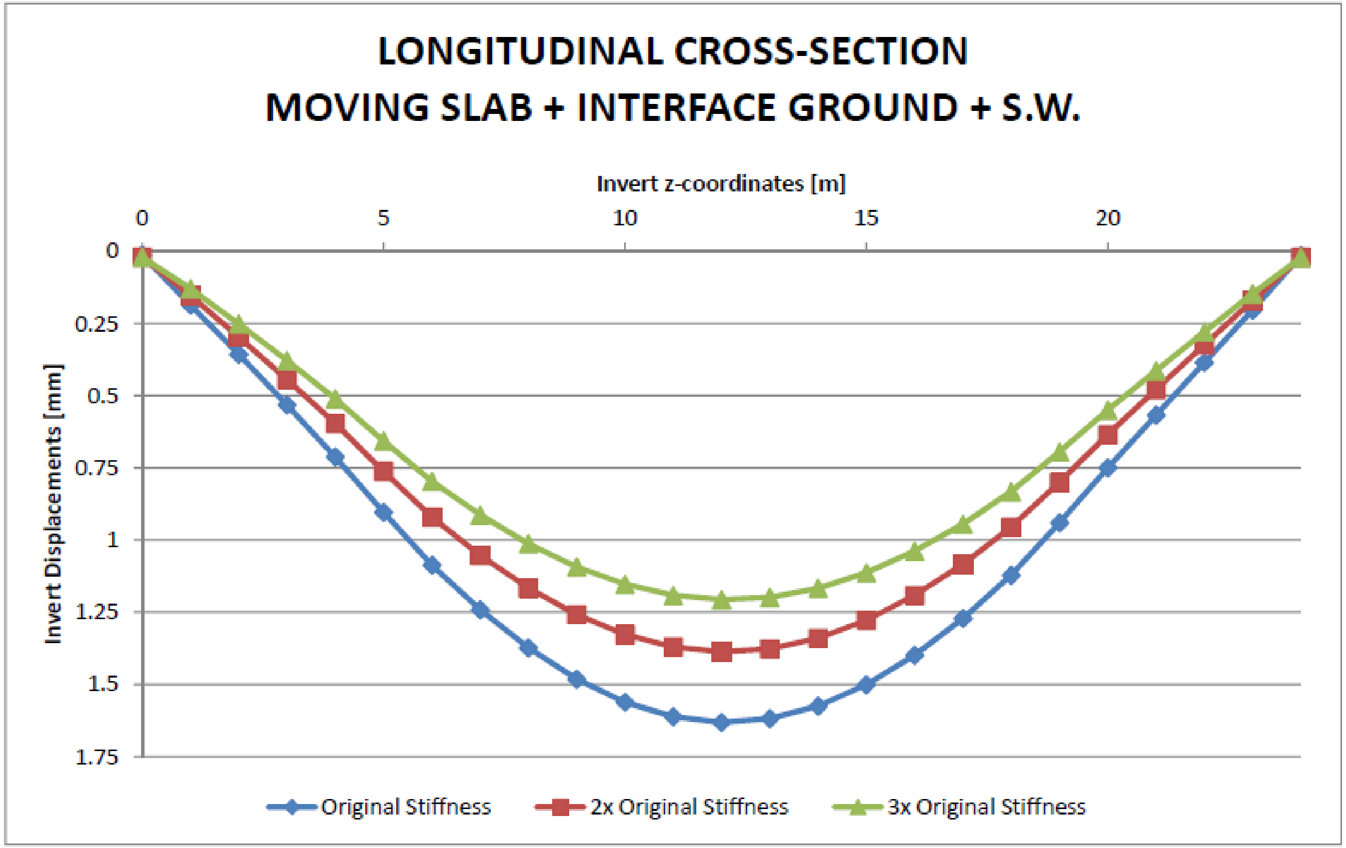
+ Self Weight



Final Deformation

Longitudinal Cross Section

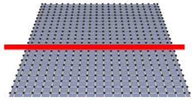


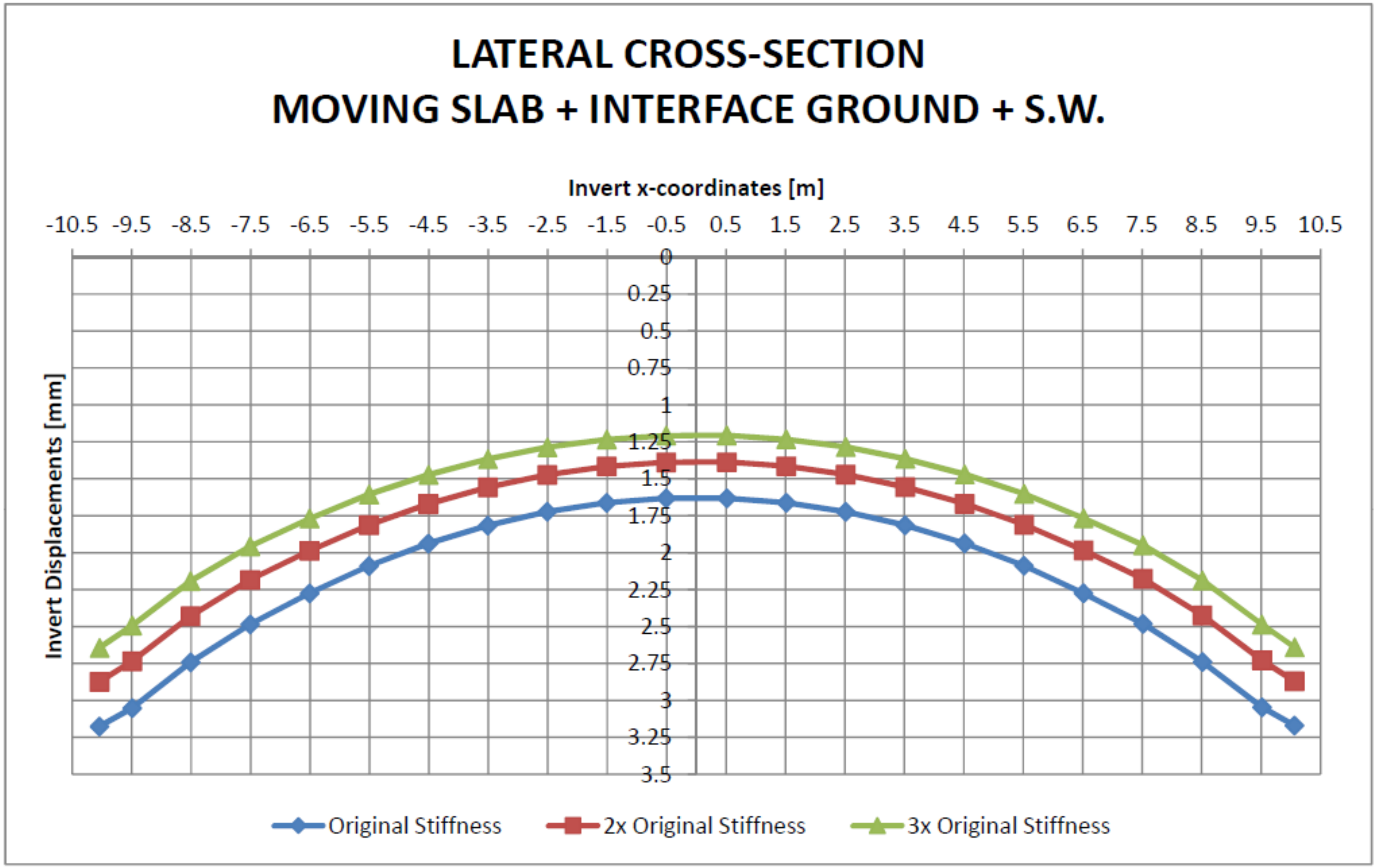


2D FE model stiffness	2x FE Stiffness	3x FE Stiffness
1.6 mm	1.4 mm	1.2 mm

ARUP

Lateral Cross Section





2D FE model stiffness	2x FE Stiffness	3x FE Stiffness
1.55mm	1.5mm	1.44mm

ARUP

Conclusions and Recommendations

ARUP

Interaction Cavern – Conclusions & Recommendations

Assuming a conservative “full face” construction sequence invert static deformations exceed acceptable limits.

This depends on extent of yielding around cavern during construction (i.e. EDZ). An appropriate construction sequence should limit this.

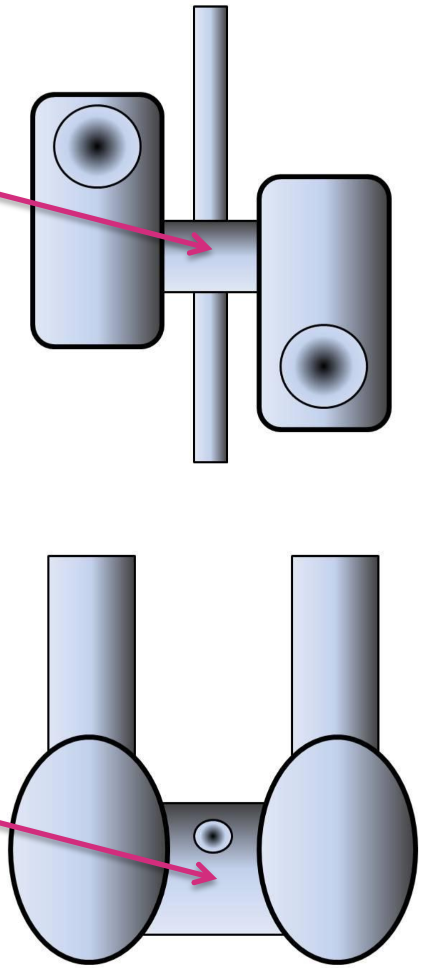
EDZ expected to be larger than the simulated in the 2D FE models due to 3D stress arching resulting from service caverns.

Construction of shaft and interaction cavern prior to service caverns sequence would limit soil yielding at the invert.

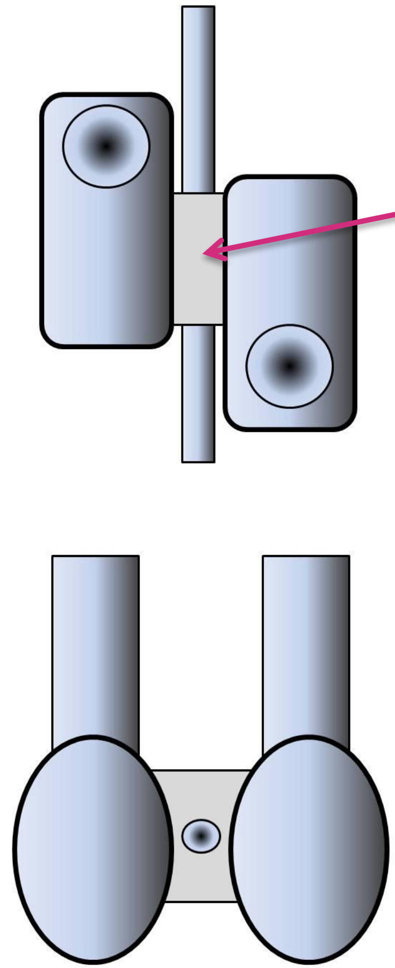
But...significant support will be required!

Alternatives to consider...

Revision G



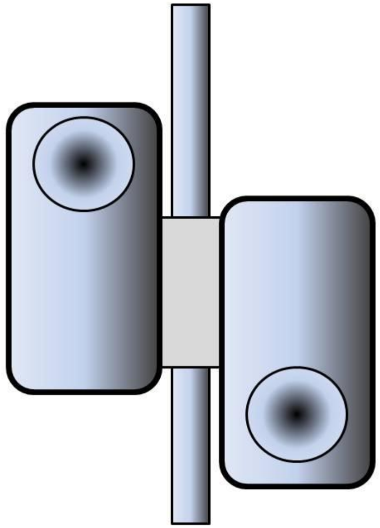
Caverns Moved Closer

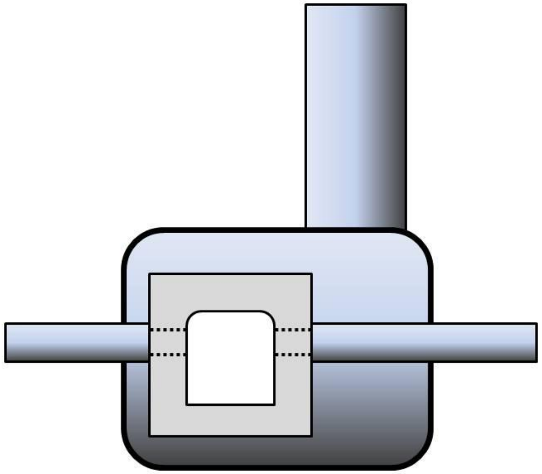


ARUP

Potential Advantages:

- **Reduces lining stress around caverns**
- **Slab foundations likely to be extremely stiff**
- **Vertical walls at IP, machine/detector interface can be optimised**
- **Slab size potentially independent of detector width**
- **Minimum travel time and umbilical lengths**





Section A-A