Numerical Modelling, instrumentation and construction sequence planning

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SINTEF Building and Infrastructure

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Norwegian Tunnelling Technology and Practice

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Numerical Modelling
is
“Rubbish-in & Rubbish-out”
or
“A useful tool for tunnel design”

?

OUTLINE

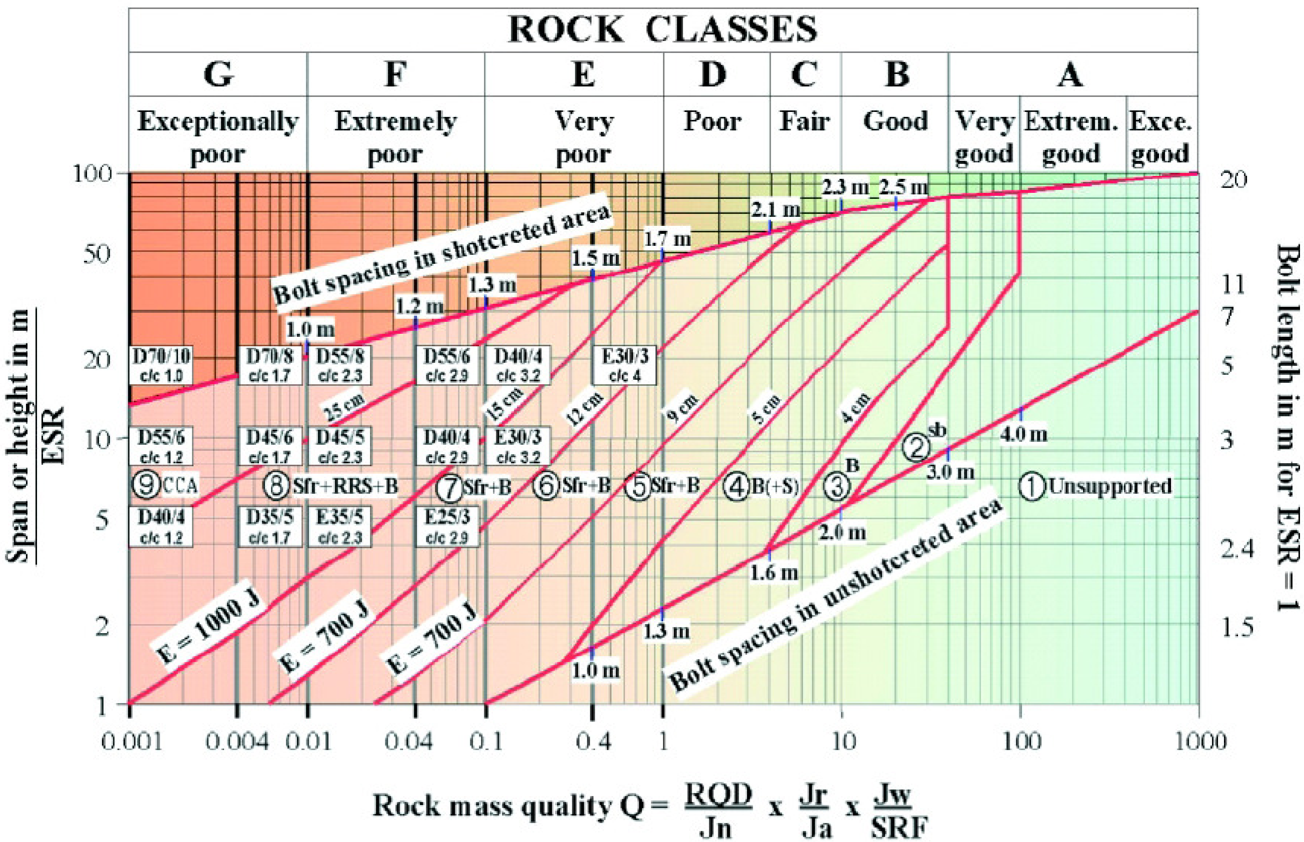
1. BRIEF INTRODUCTION TO TUNNEL SUPPORT DESIGN IN NORWAY
2. COMMON NUMERICAL METHODS FOR TUNNEL SUPPORT ANALYSIS
3. AN EXAMPLE
4. DISCONTINUUM METHODS
5. MODELLING OF SPECIAL SUPPORTS
6. CONCLUSIONS

BRIEF INTRODUCTION TO TUNNEL SUPPORT DESIGN IN NORWAY

TUNNEL SUPPORT DESIGN METHOD

- Personal experience of the design engineer
- Empirical approach
  - Rock mass classification (Q – System)
  - Completed projects
- Verification and optimization with numerical analysis (possible modifications)
- Follow-up numerical analyses based on real geological conditions and the monitoring result

Tunnel Support Design Based on Rock Mass Classification Q –System



REINFORCEMENT CATEGORIES

1) Unsupported
2) Spot bolting, **sb**
3) Systematic bolting, **B**
4) Systematic bolting, (and unreinforced shotcrete, 4-10 cm), **B(+S)**
5) Fibre reinforced shotcrete and bolting, 5-9 cm, **Sfr+B**
6) Fibre reinforced shotcrete and bolting, 9-12 cm, **Sfr+B**
7) Fibre reinforced shotcrete and bolting, 12-15 cm, **Sfr+B**
8) Fibre reinforced shotcrete > 15 cm + reinforced ribs of shotcrete and bolting, **Sfr+RRS+B**
9) Cast concrete lining, **CCA**

COMMON NUMERICAL METHODS FOR TUNNEL SUPPORT ANALYSIS

Preparation of numerical analysis

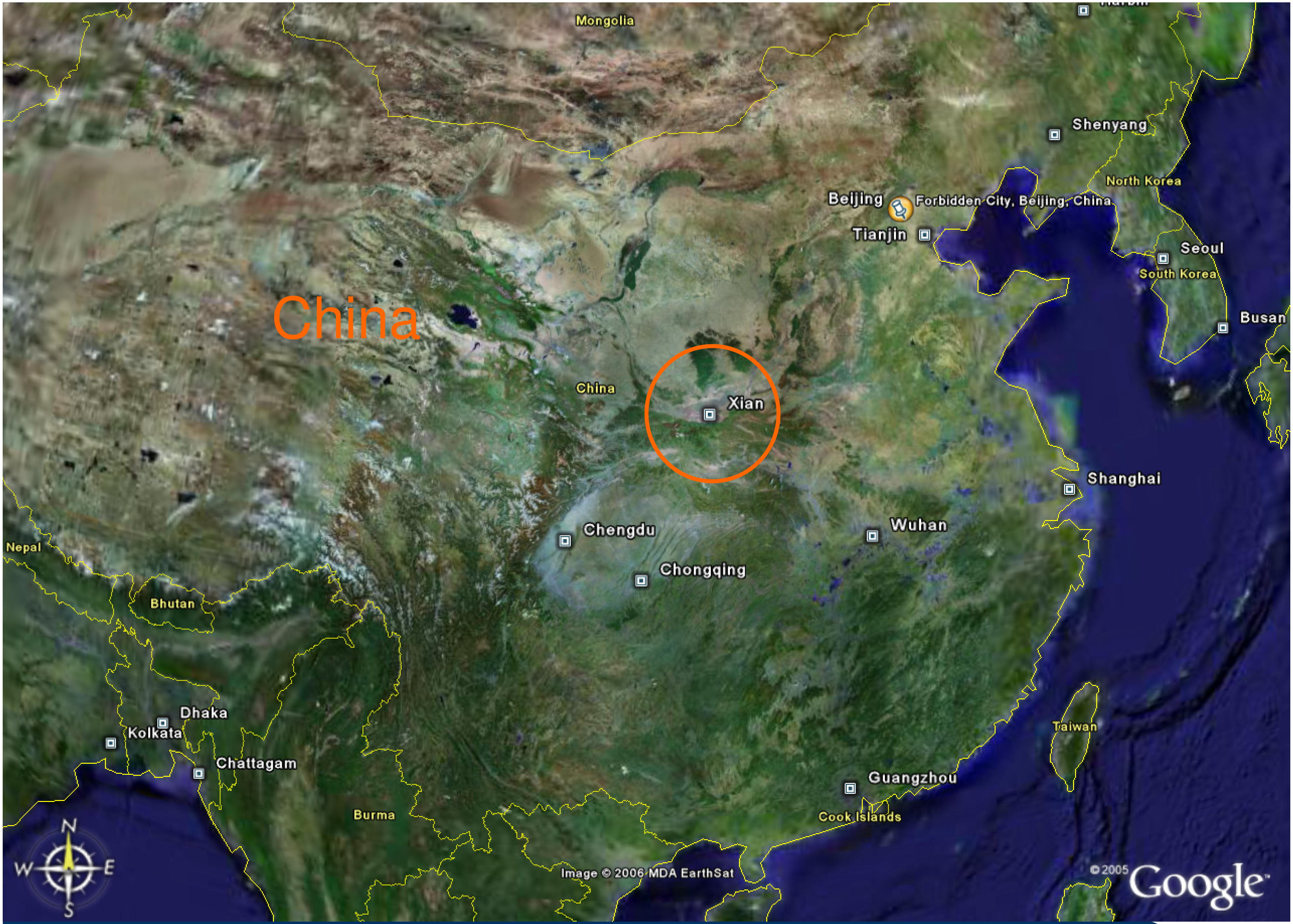
- Selection of fundamental methods
  - Continuum modelling or
  - Discontimuum modelling
- 2-D analysis is normally performed; 3-D analysis is carried out when necessary
- Selection of codes – computer program
  - Low cost commercial codes are preferred
  - For continuum modelling: Phase2, Flac/Flac3D, ABAQUS
  - For discontinuum modelling: UDEC, DDA, PFC

Preparation of numerical analysis

- Material model and parameters
  - For continuum modelling
    - M-C or H-B: c, ϕ and ψ; s, m
    - Site investigation, simple lab test and rock mass classification system, empirical equations for conversion
  - For discontinuum modelling
    - Joint systems: mapping
    - M-C model: ϕ_p, ϕ_r, c, ψ Direct shear test
    - B-B model: JCS, JRC, ϕ_r, Tilt tests, joint profiling test, Schmitt hammer
    - Joint stiffness: K_n, K_s

AN EXAMPLE

Rock Support Design for the Special Lighting Caverns of the Qinling Highway Tunnel, Shaanxi, China


China
Mongolia
Shenyang
North Korea
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Forbidden City, Beijing, China
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Chengdu
Wuhan
Chongqing
Nepal
Bhutan
Dhaka
Kolkata
Chattagam
Burma
Guangzhou
Cook Islands
Taiwan
Image © 2006 MDA EarthSat
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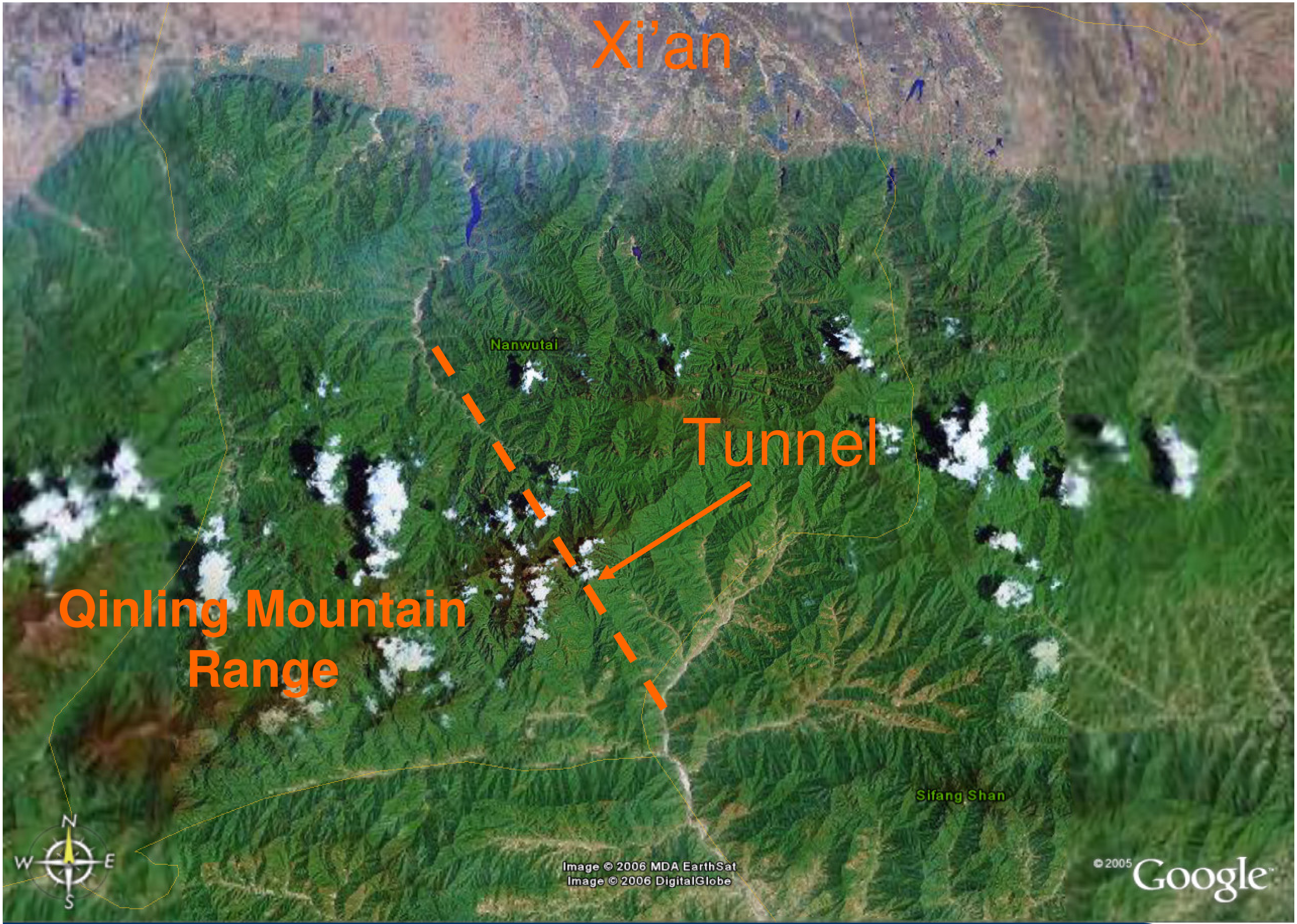
Xi'an
Nanwutai
Tunnel
Qinling Mountain Range
Sifang Shan
N
W
E
S
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Project background

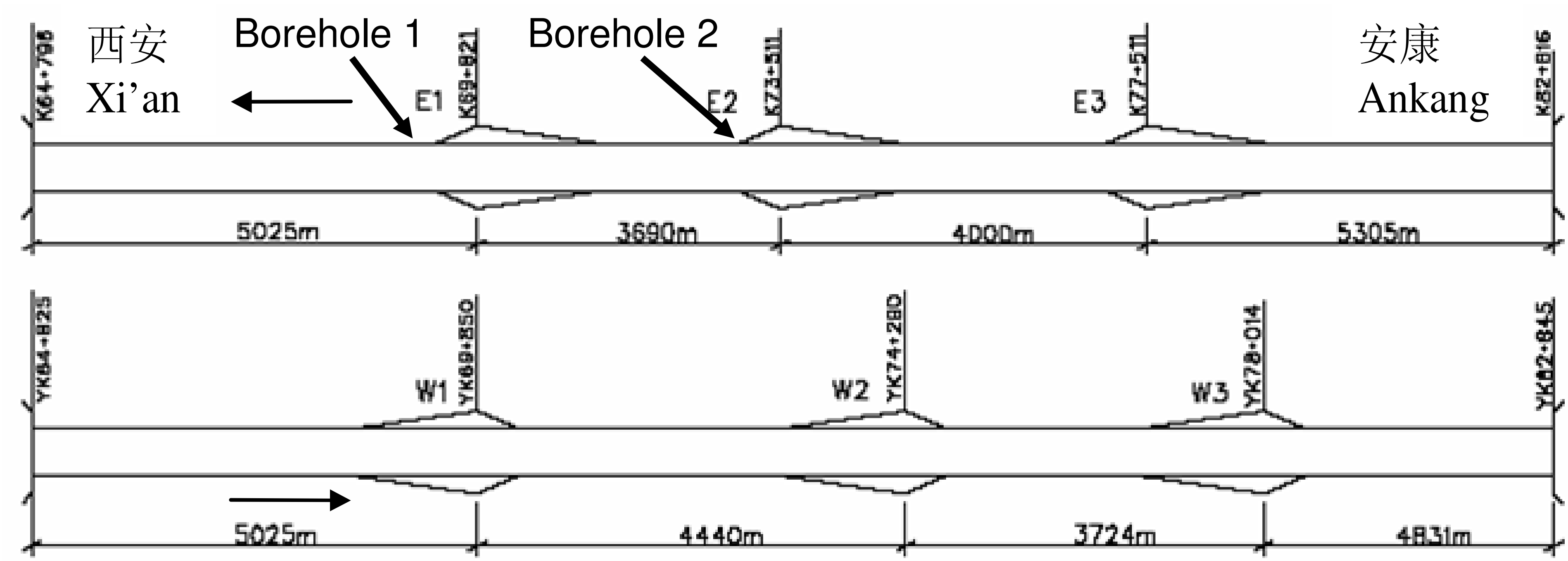
- World's longest two tube road tunnel (18 km)
- Two lanes each tube
- Special lighting caverns for driving safety purpose: monotony and anxiety
- Main features
  - High in-situ rock stresses (overburden up to 1800 m)
  - Mainly granitic gneiss
  - Minimum pillar width between tunnels only 8 m

Rock support design steps

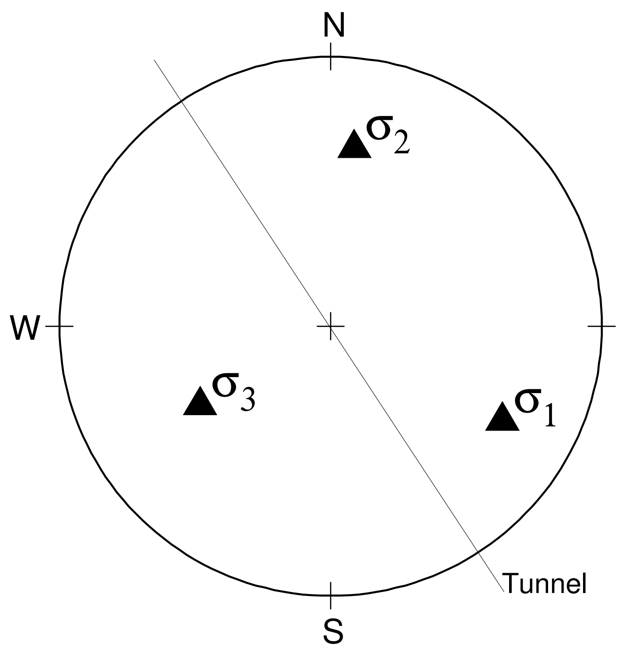
- **Site geological and rock mechanics data**
  - Data provided by client
  - Own site inspection
  - Performing rock stress measurements
  - Estimate of rock mass classification index
- **Empirical design**
  - Based on Q-system
  - Referring to Lærdal tunnel
- **Numerical modelling to verify the empirical design**
  - 3D modelling with FLAC3D: General analysis with focus on the 3D effects
  - 2D modelling with Phase2: Detailed study of entire construction sequence and functioning of each support element
- **Design of construction sequence and monitoring system**

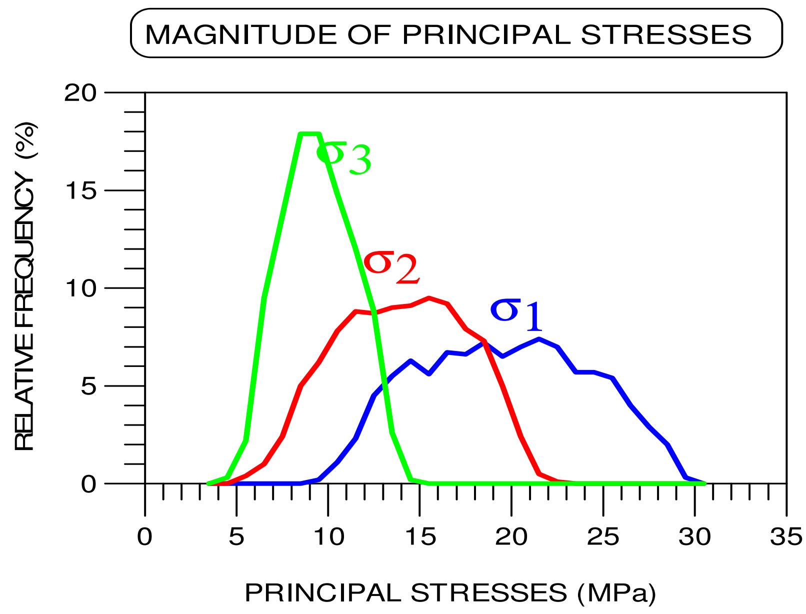
Tunnel and cavern outline

- 6 caverns, 3 in each tube
- Rock stress measurements at two locations



Rock stress measurement results - Borehole 1





σ1 = 19.6 MPa
σ2 = 14.0 MPa
σ3 = 9.4 MPa

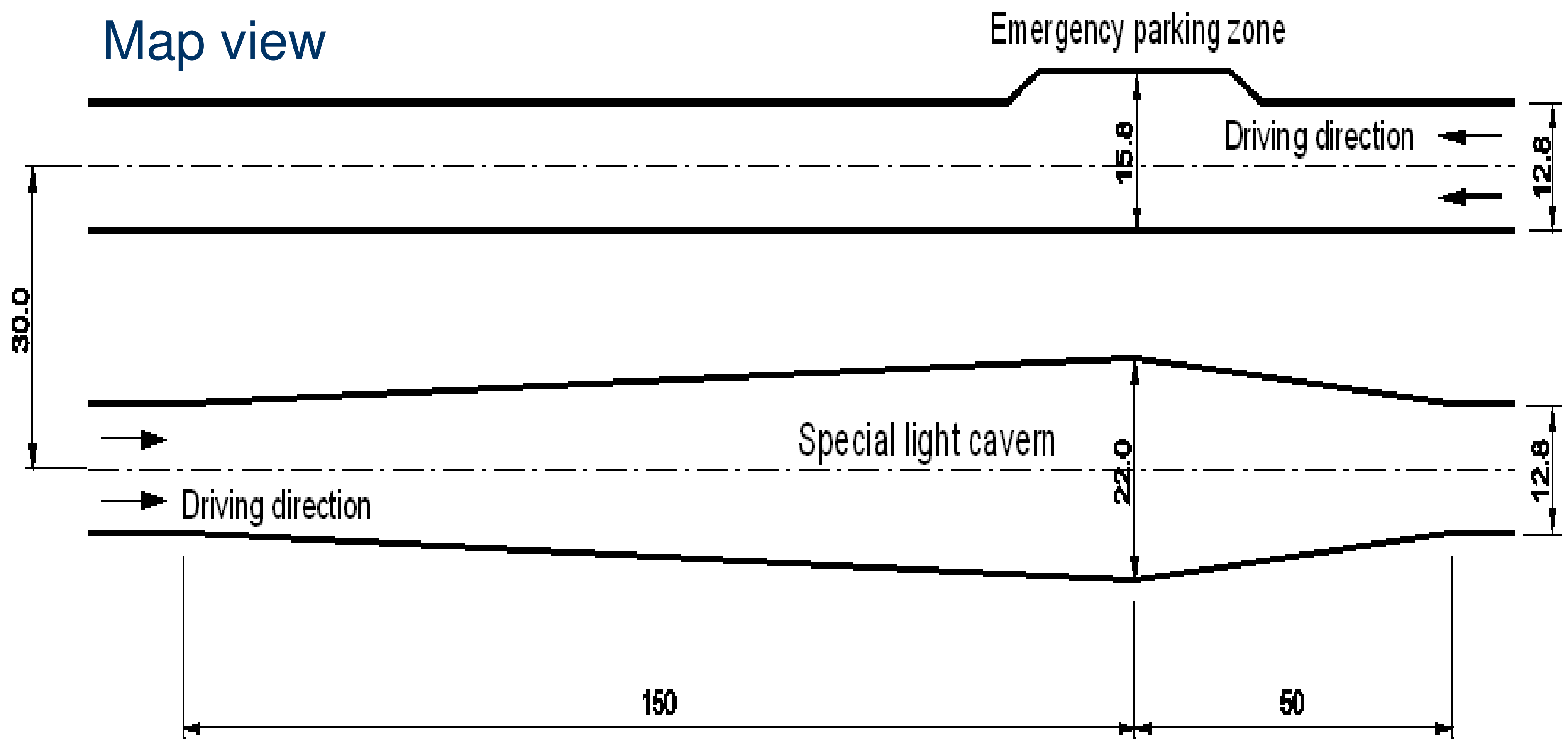
Two major stresses are relatively horizontal

Rock stress measurement results - Borehole 2

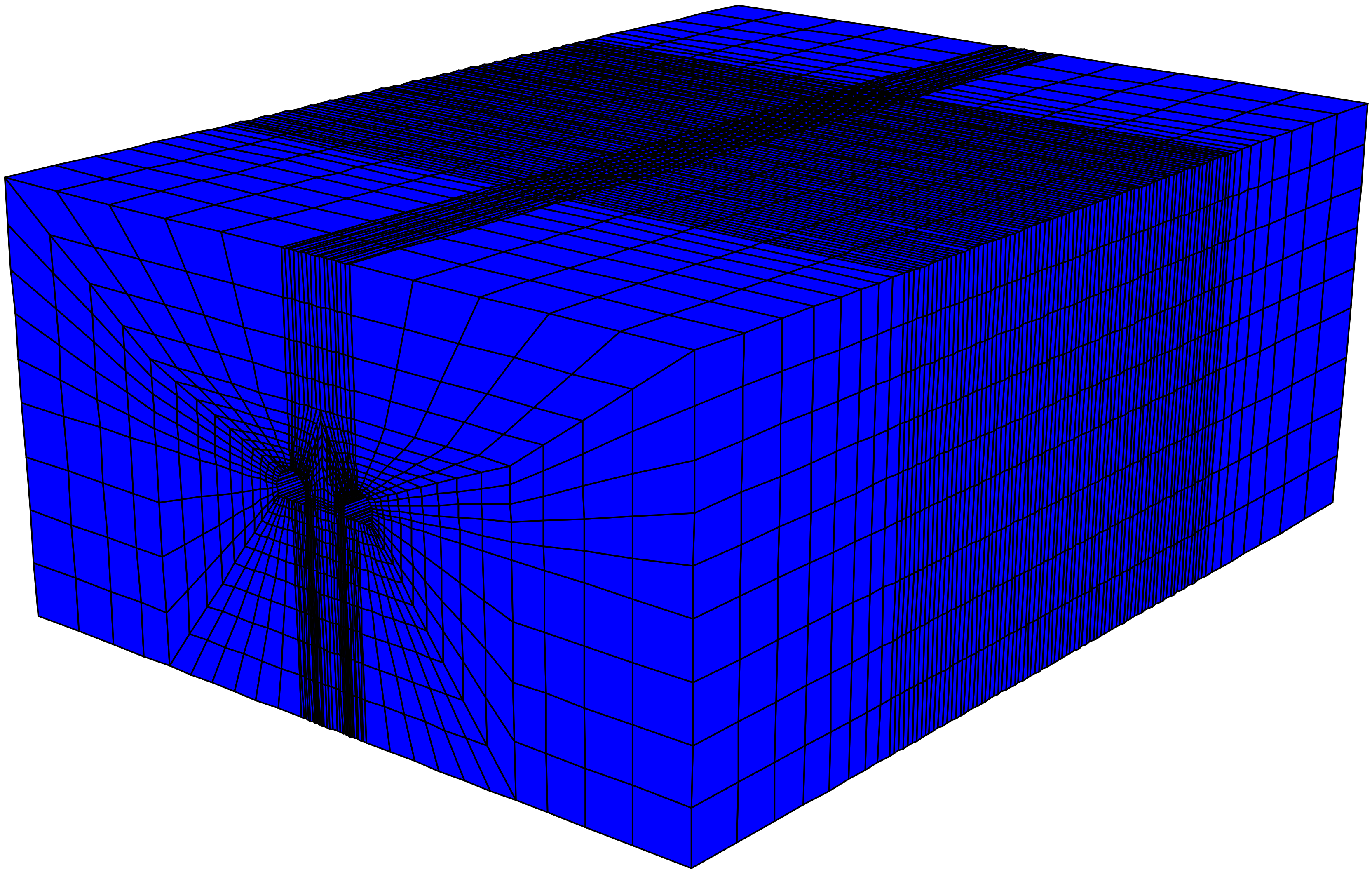
- Heavy core disking made 3D measurements impossible
- 2D Doorstopper measurements successfully performed
- Vertical stress: ~45 MPa

Cavern geometry

Map view

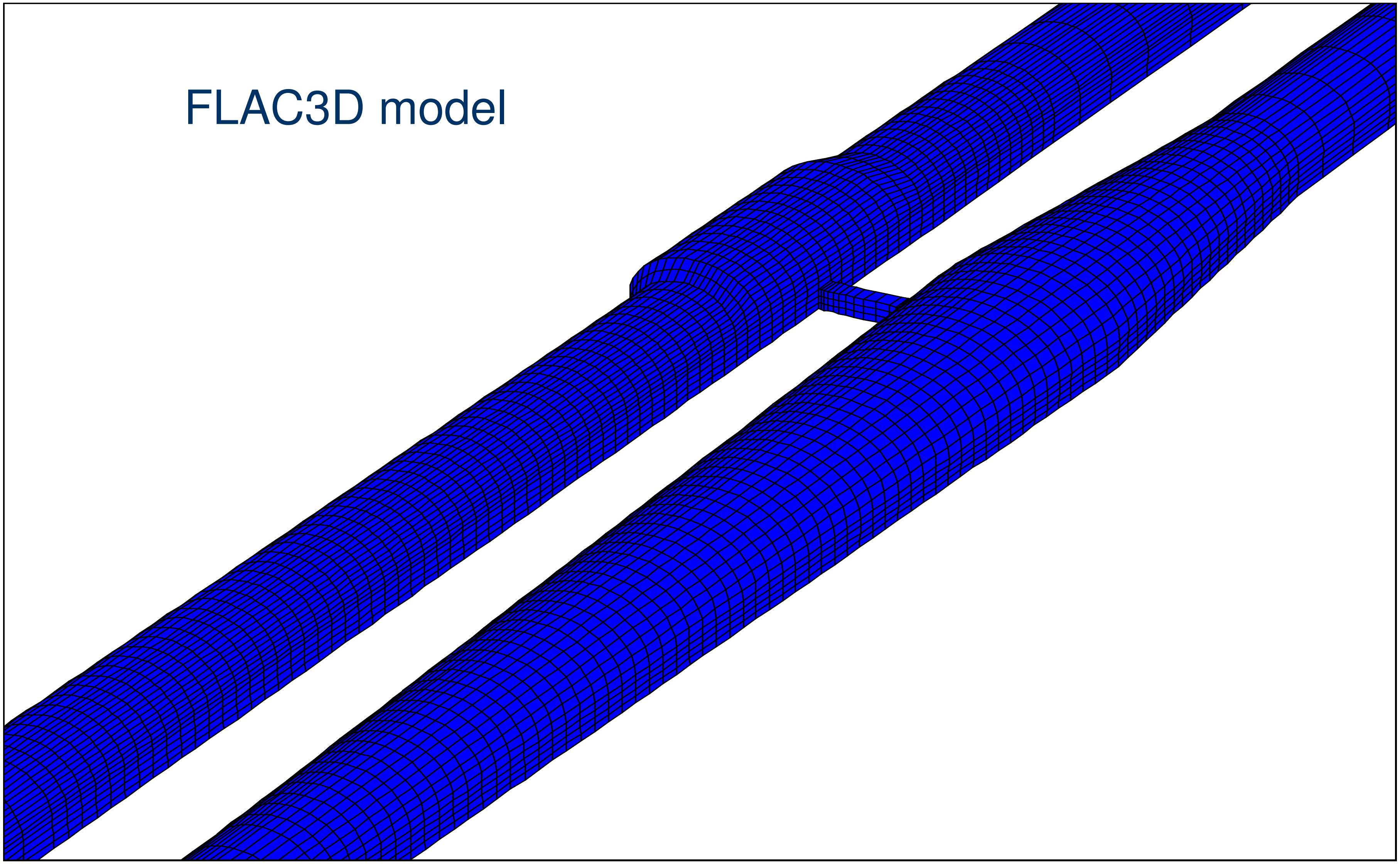


3D FLAC3D Model

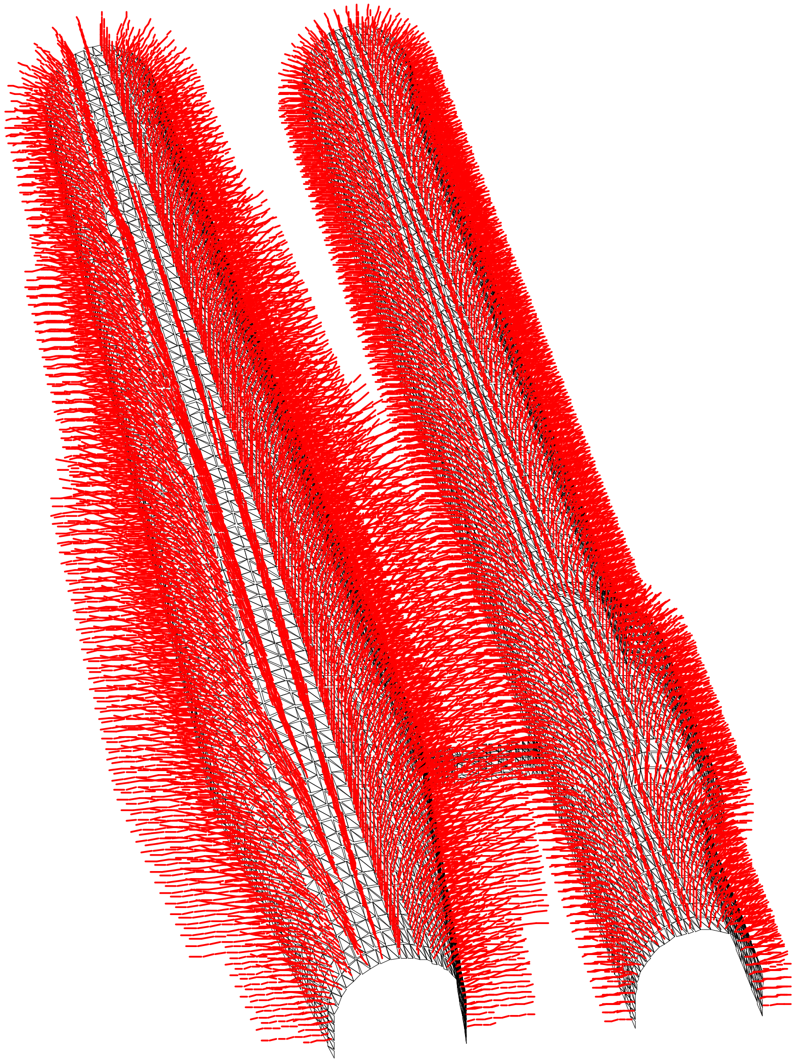


3D FLAC3D Model

FLAC3D model

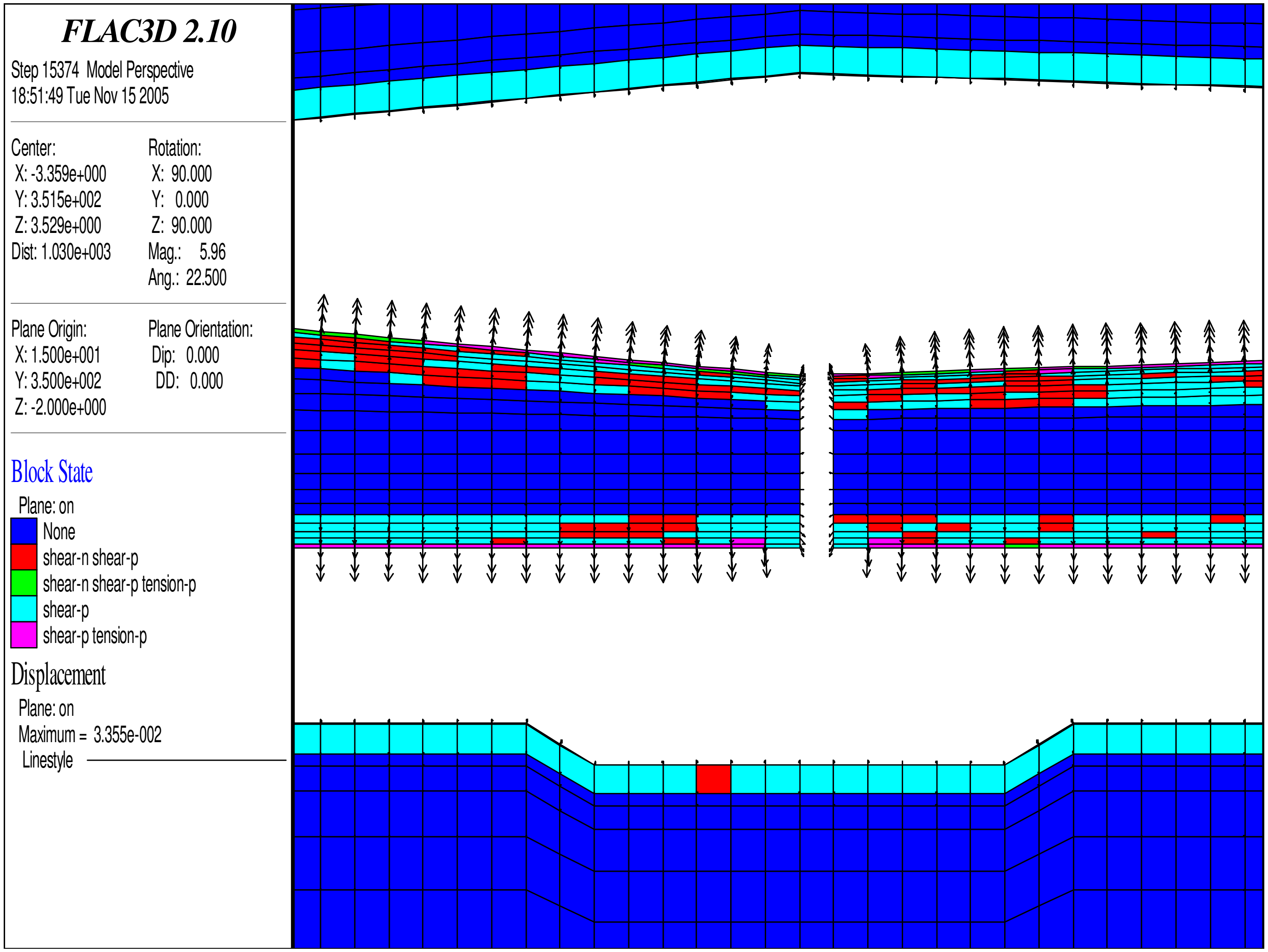


3D FLAC3D Model

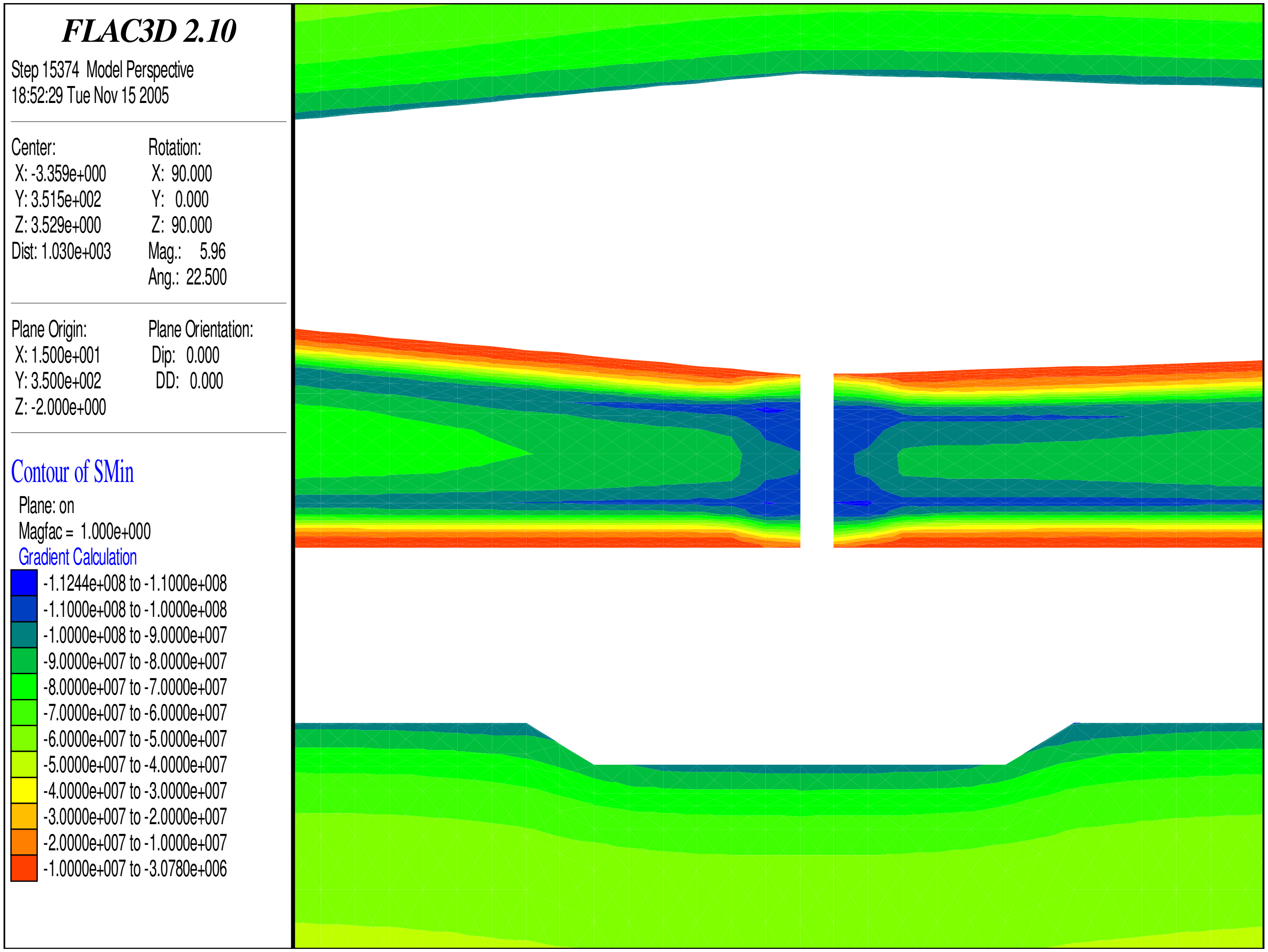


3D numerical results, high overburden

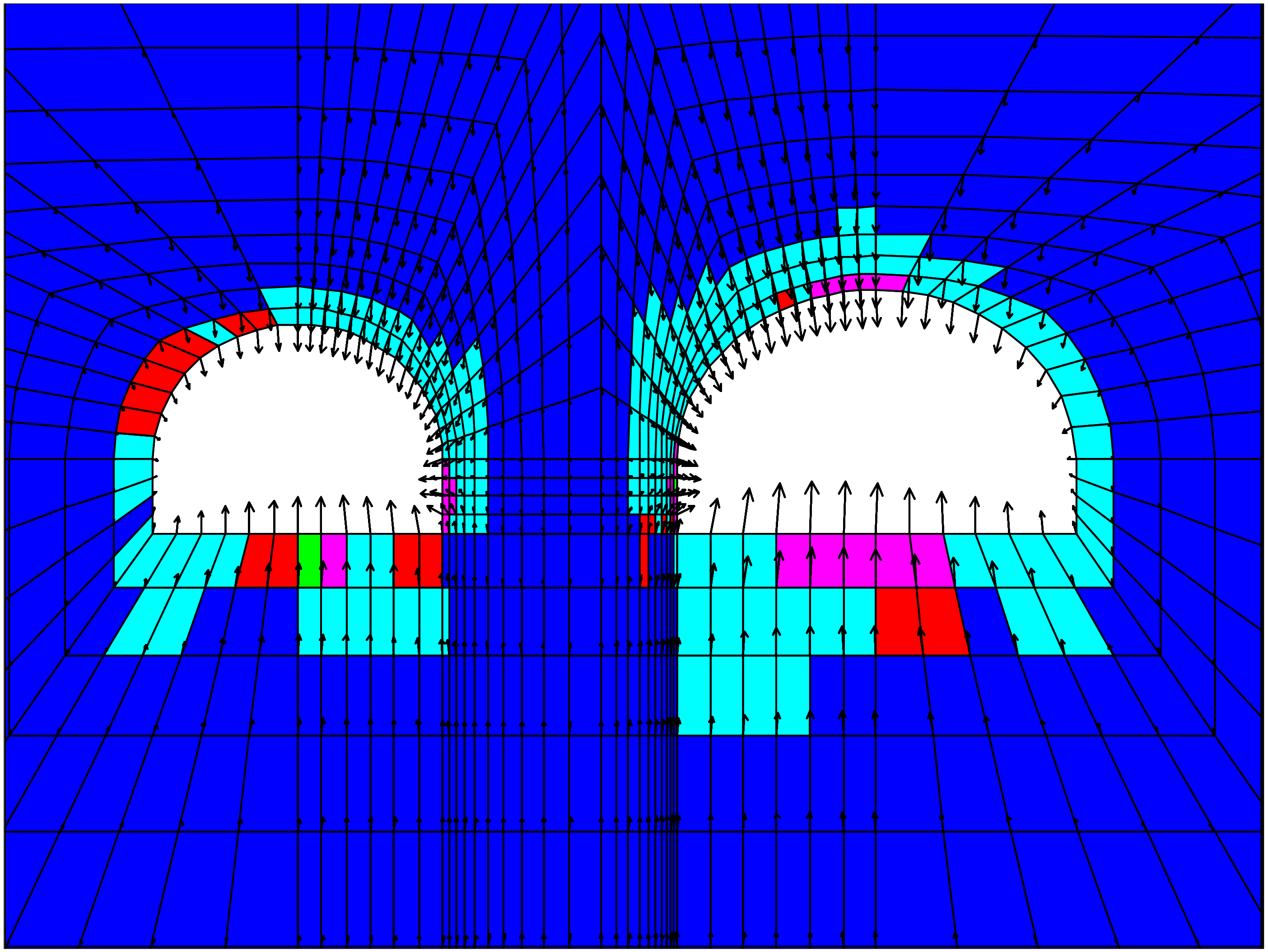
E2-W2 result – Yielding and displacement – plan view



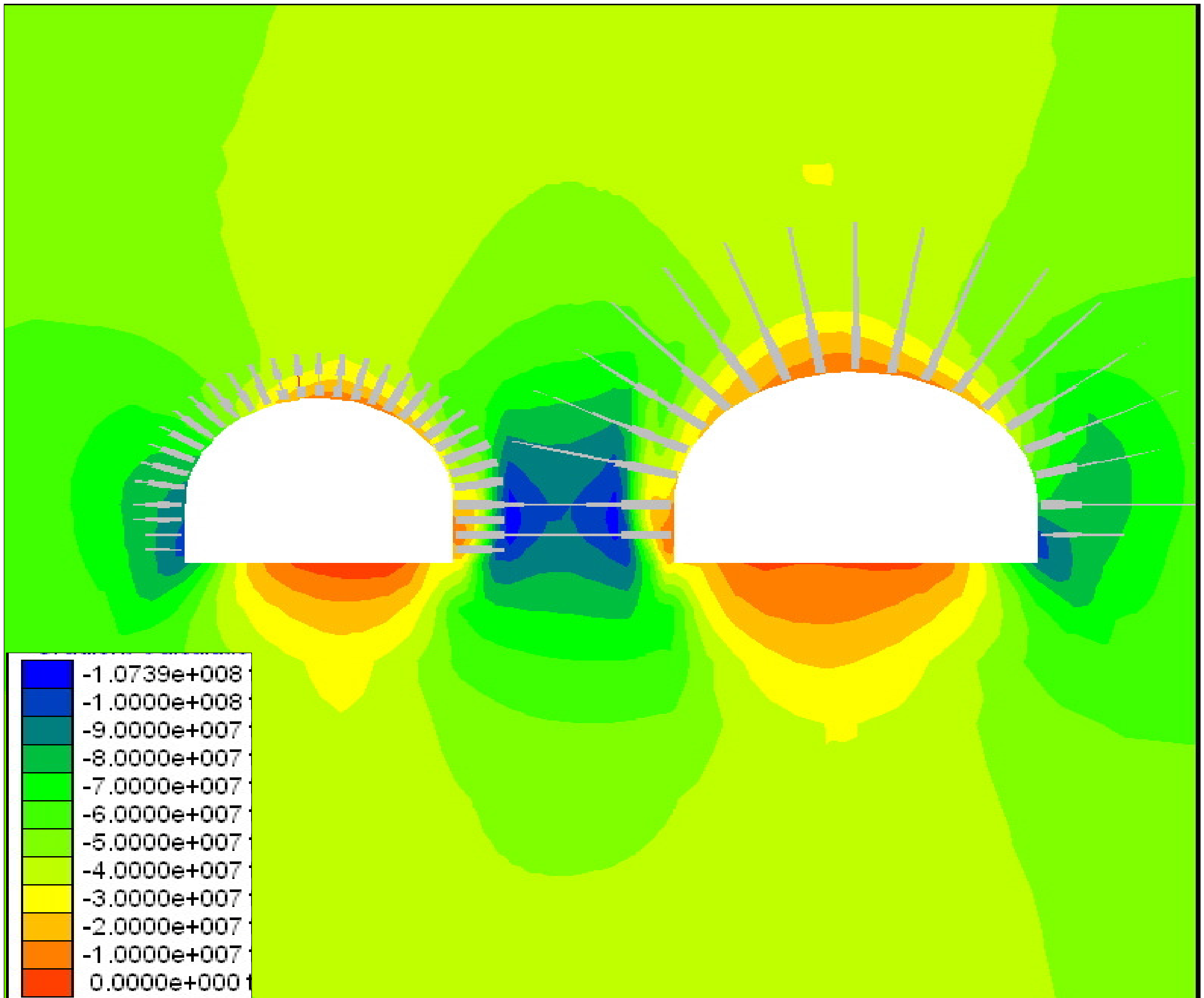
3D numerical results, high overburden
E2-W2 result – Major principal stress



3D numerical results, high overburden

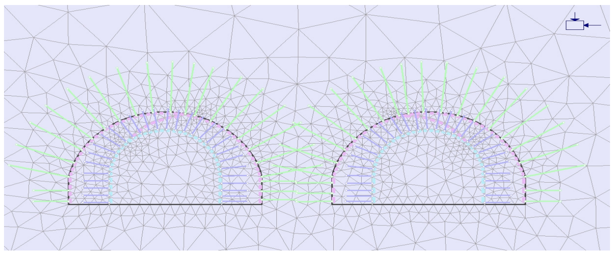


3D numerical results, high overburden

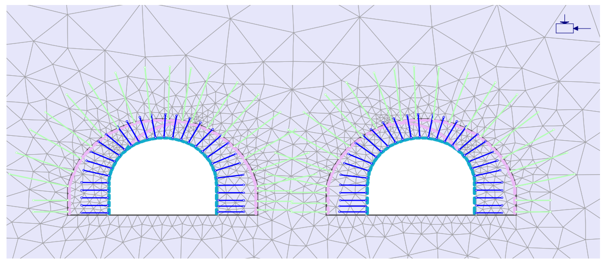


2D Numerical modelling

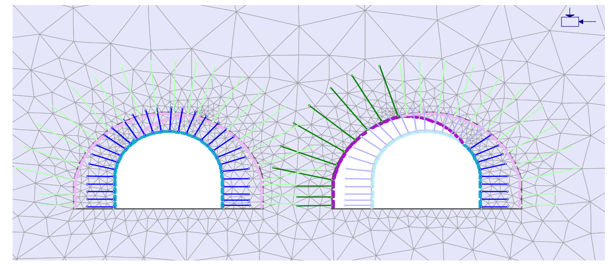
Stage 1



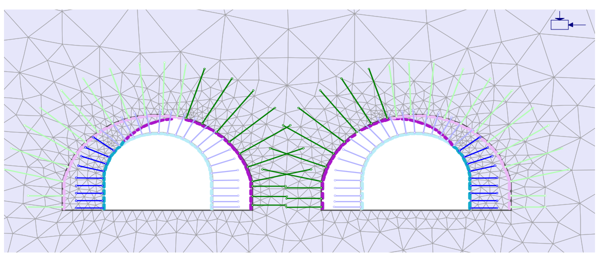
Stage 2



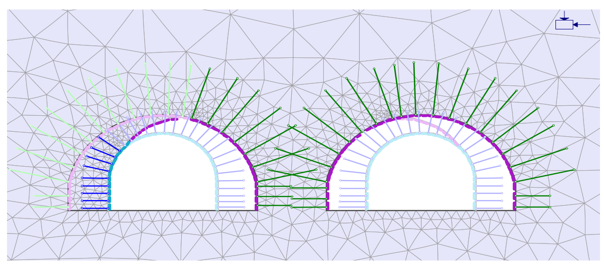
Stage 3



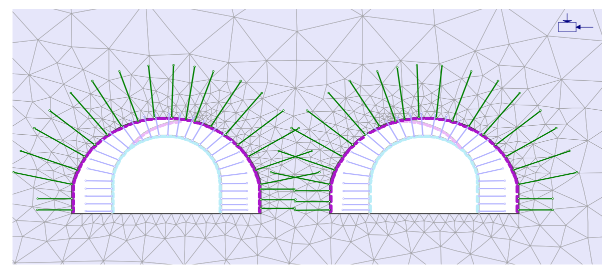
Stage 4



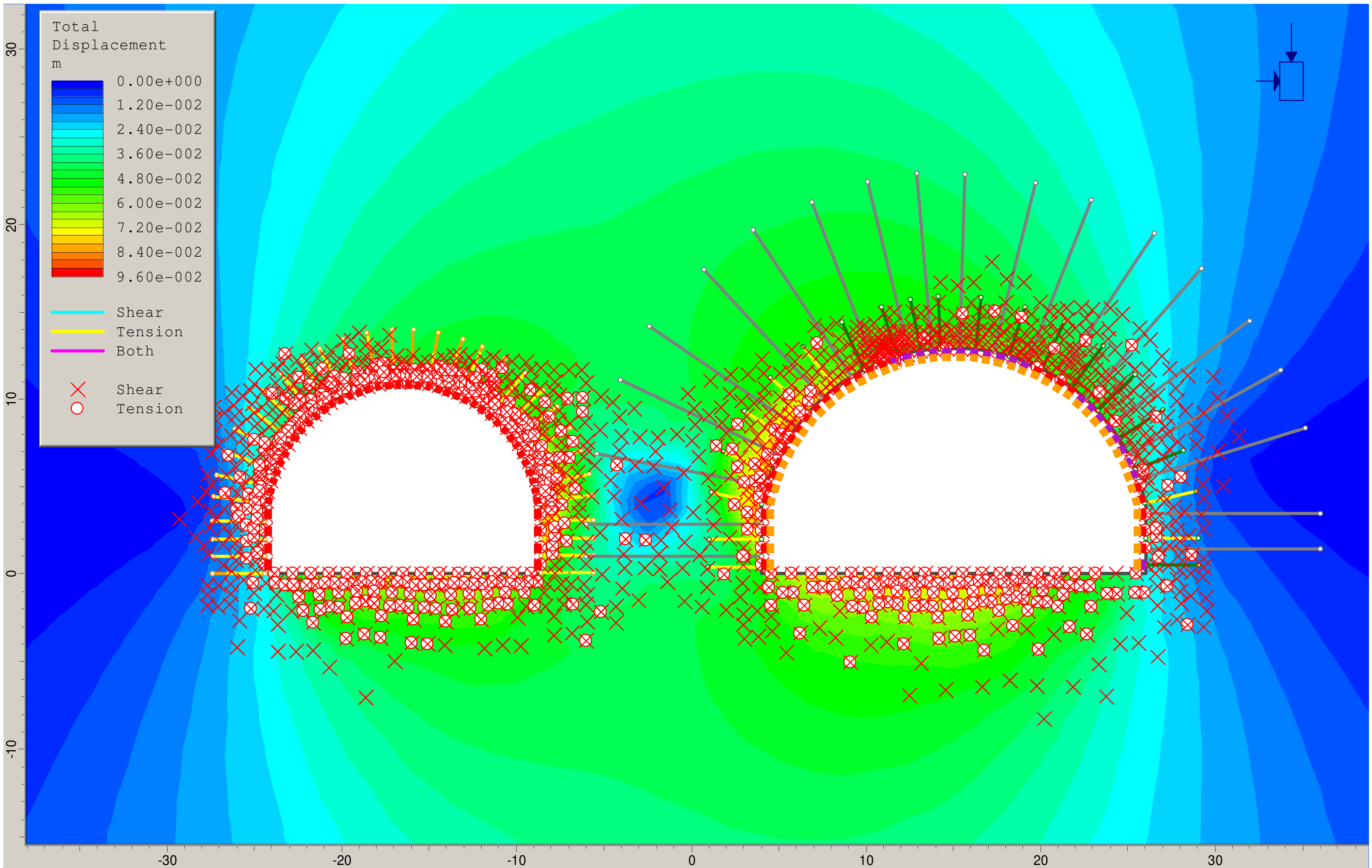
Stage 5



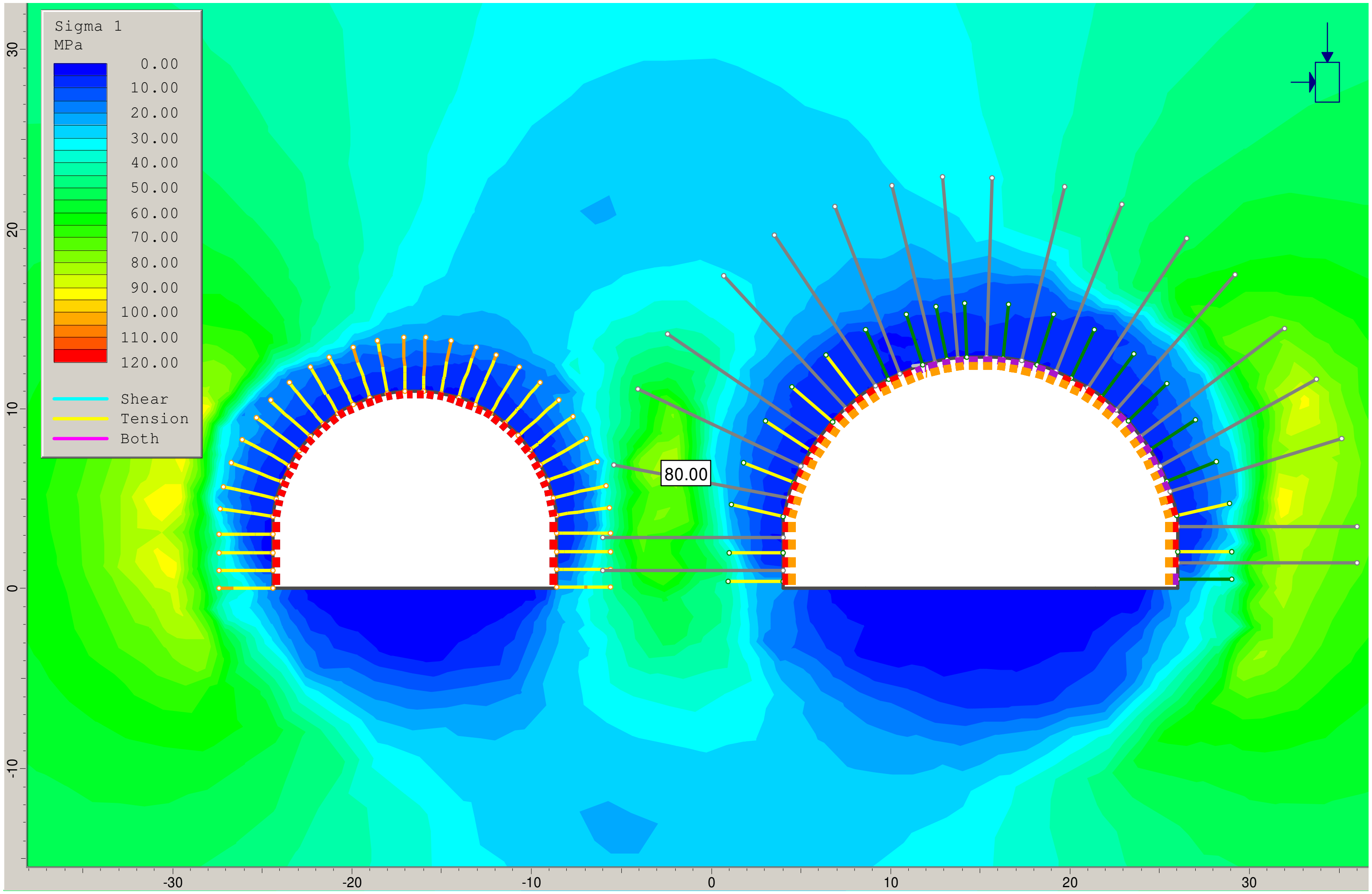
Stage 6



2D numerical results, 1600m overburden



2D numerical results, 1600m overburden



Rock support summary
- caverns E1, W1, E3 and W3

- Excavation in 2 stages, first inner part and then the outer part.
- A layer of 15 cm shotcrete and 20 mm diameter 7/4 m long fully grouted bolts in 2x2 m patterns installed right after each excavation stage.
- This is the permanent support.

Rock support summary - caverns E2 and W2

- Excavation in 2 stages, first inner part and then the outer part.
- The support is divided to temporary support and the permanent support
- The temporary support consists of 6 cm shotcrete and 3 m long end-anchored bolts in 2x2 m patterns which are installed right after each excavation stage.
- The permanent support consists of 24 cm shotcrete and 20 mm diameter 10 m long end-anchored bolts in 2x2 m pattern which is installed 3-4 days after the temporary support.

Specification of construction sequence

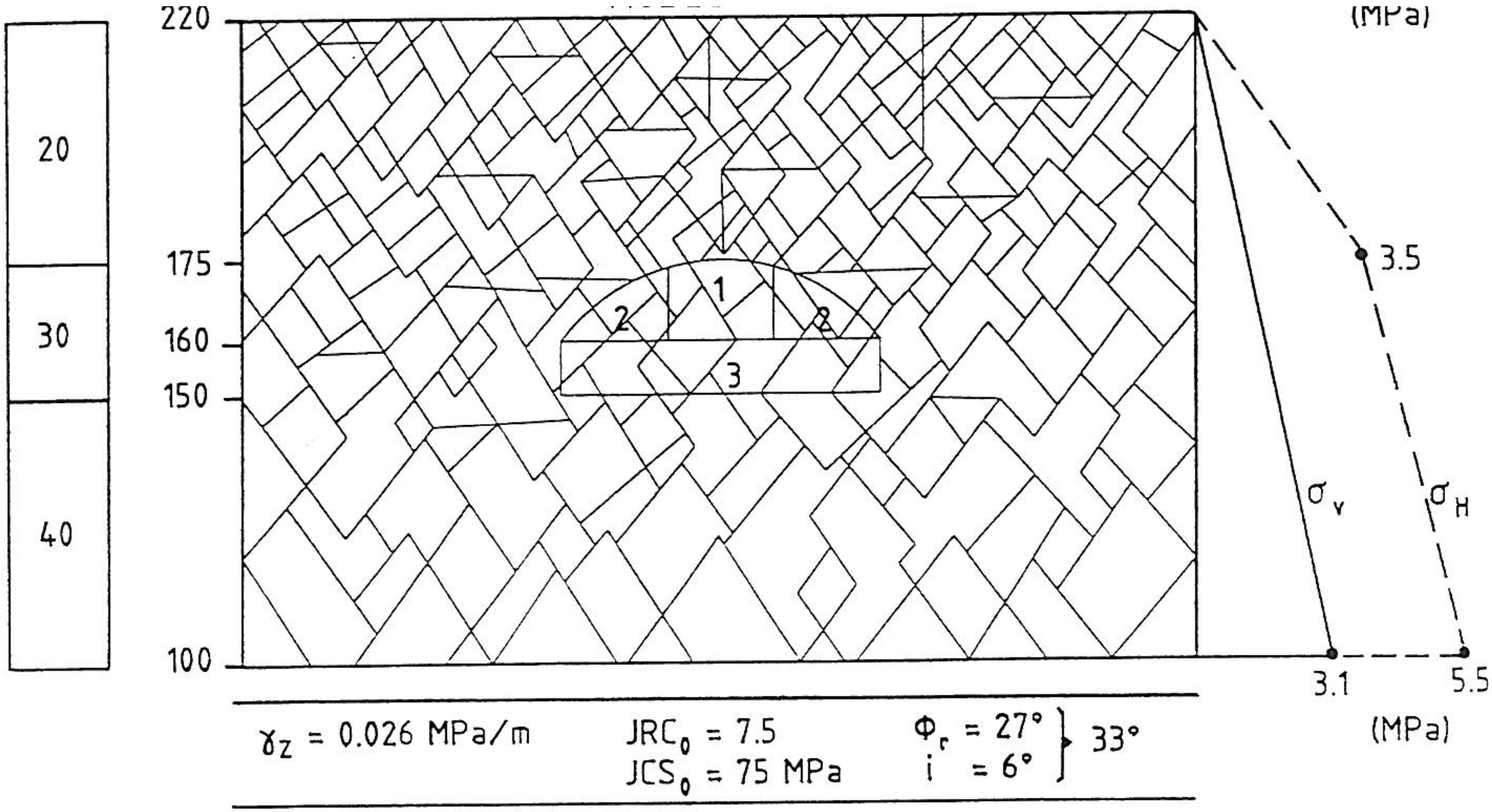
1) Slashing of the left hand side of the tunnel to reach full height and full width of the cavern constituting approximately half the full size of the cavern, as shown in Figure 7 with step 1.
2) Before mucking out after the last blasting, 3 m long holes shall be drilled in a 2x2 m pattern in the final wall and roof areas as described in point (i) above. The holes shall be equipped with protection to prevent sprayed concrete to clog the holes.
3) The newly excavated surface of the wall shall be manually scaled to remove loose rock before being sprayed with an initial layer of fibre-reinforced shotcrete, building up a layer of 60 mm.
4) End-anchored rock bolts with length of 3m (polyester cartridges shall be used for anchoring) shall be inserted in the pre-drilled holes and the steel plates shall be mounted outside the wet shotcrete. The nuts shall be tightened only loosely, so that the bolts are not pre-stressed.
5) The muck from the last blast round is removed and points (iii) and (iv) above are repeated. It is important that the rock bolts and shotcrete are installed all the way down to the floor level.

Specification of construction sequence

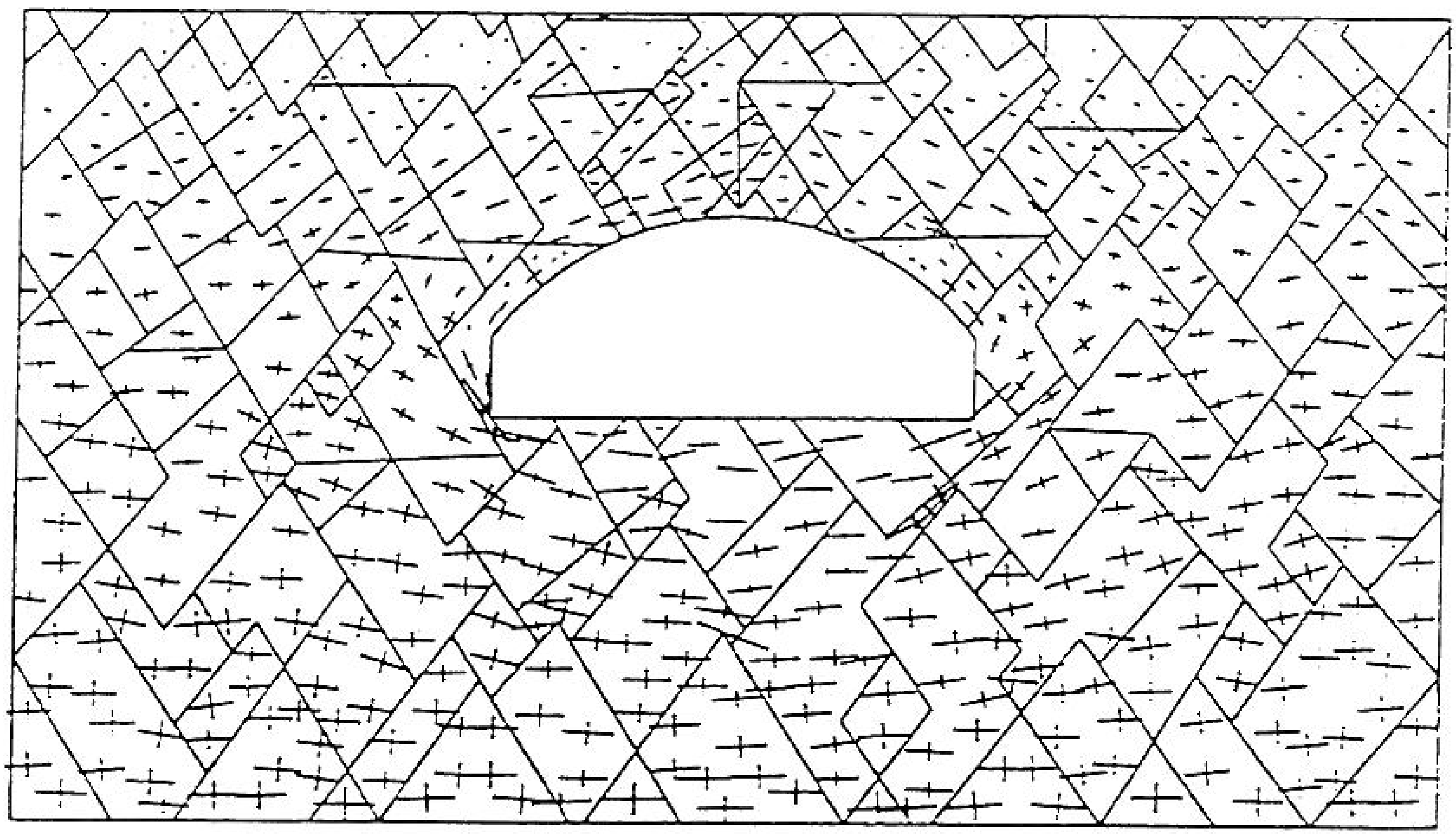
6) Excavation of the right hand side of the tunnel to the full height and width of the caverns, blast rounds shall be parallel to the tunnel axis.
7) Installation of permanent rock support in the remaining part of the tunnel, i.e. the wall and roof on the right hand side as was the last part to be excavated. The installation of rock support shall follow the same procedure as described above in points (ii), (iii) and (iv).
8) When the sprayed concrete has cured for 3-4 days the installation of permanent rock support may start. 10 m long steel bars shall be installed in a pattern of 2x2 m to fill in between the existing rock bolts. Use end-anchored rock bolts with polyurethane cartridge. 10 m long bolts towards pillar and roof, 7 m long on the other side of the cavern. Stepwise reduction of bolt lengths towards regular tunnel cross section.
9) Apply fibre-reinforced sprayed concrete to build up the permanent shotcrete layer. The thickness of the shotcrete layer shall be 300 mm totally.

DISCONTINUUM MODELLING
UDEC, DDA & PFC

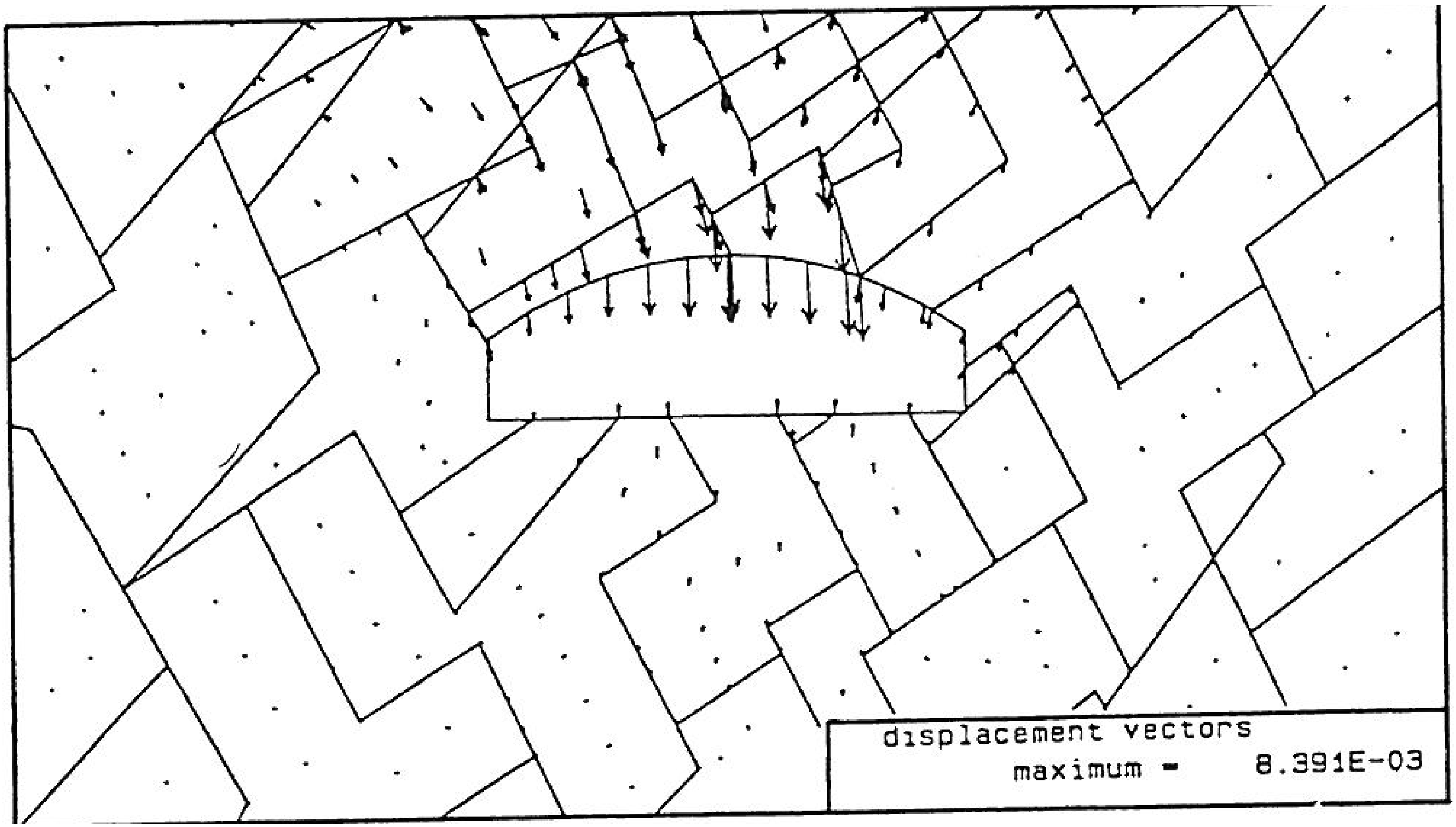
UDEC Modelling of Gjøvik cavern



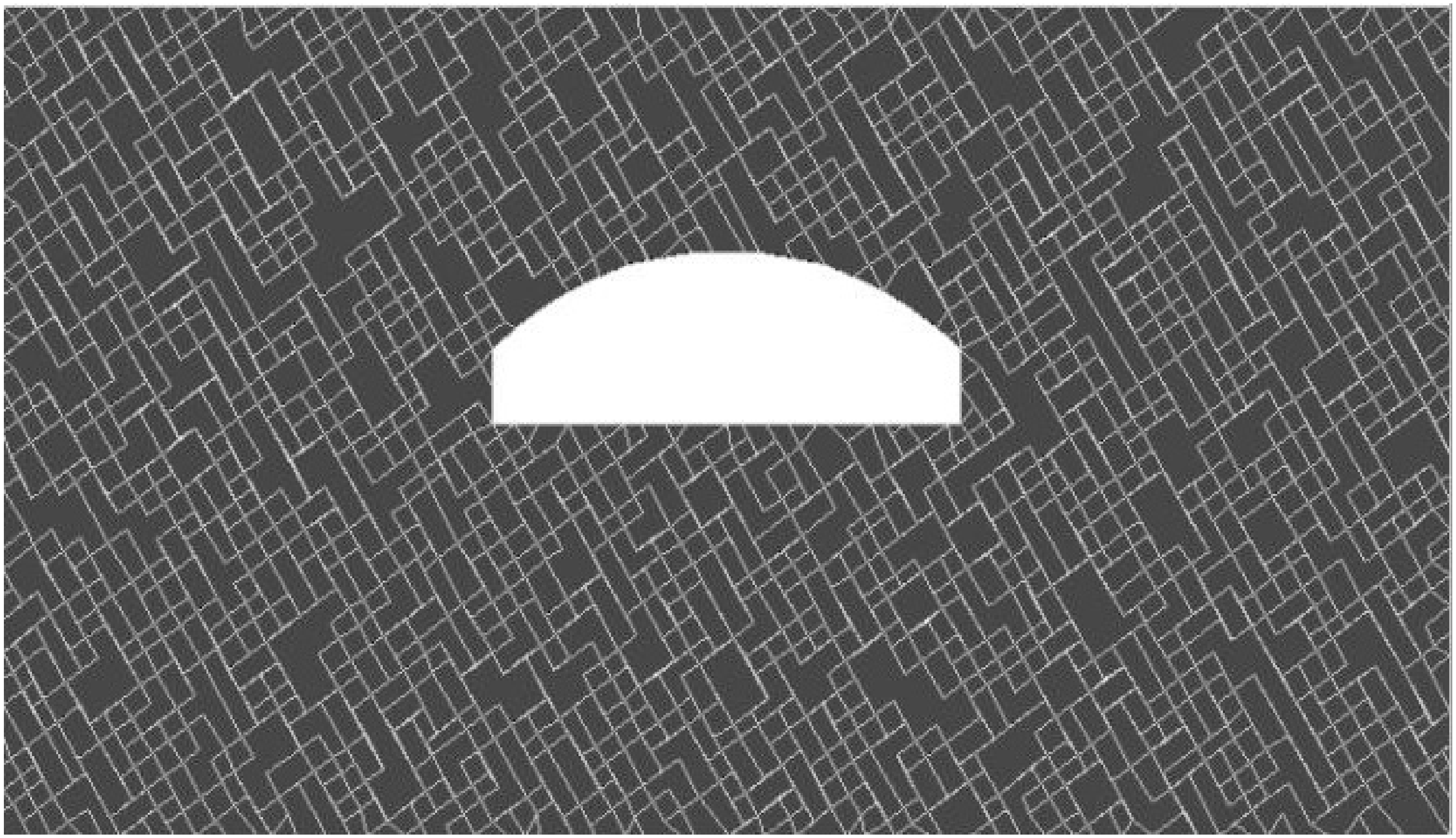
UDEC Modelling of Gjøvik cavern



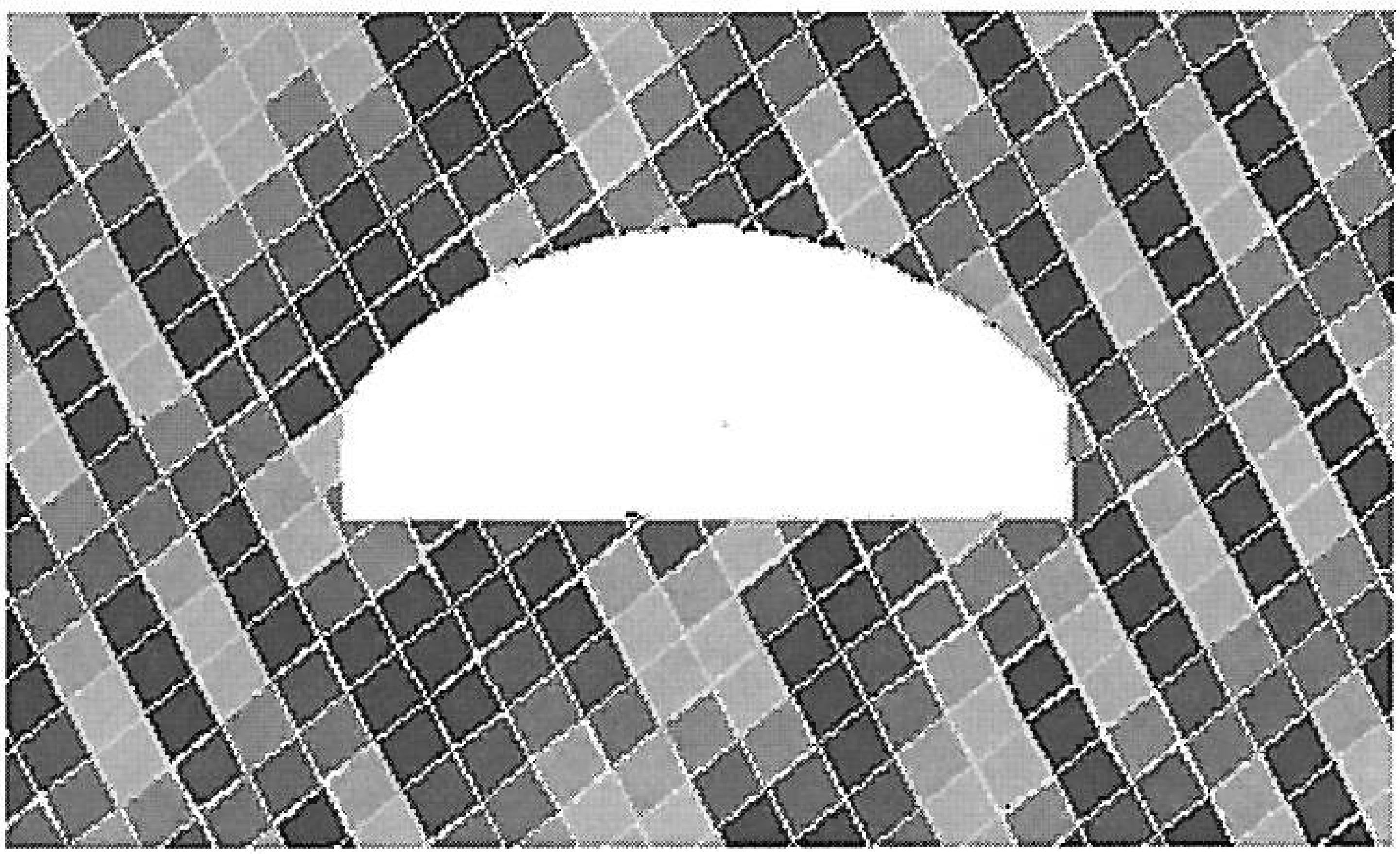
UDEC Modelling of Gjøvik cavern



DDA Modelling of Gjøvik cavern



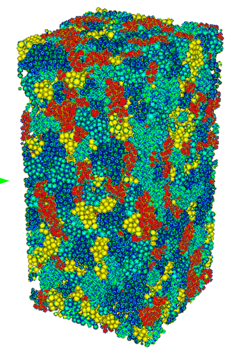
DDA Modelling of Gjøvik cavern



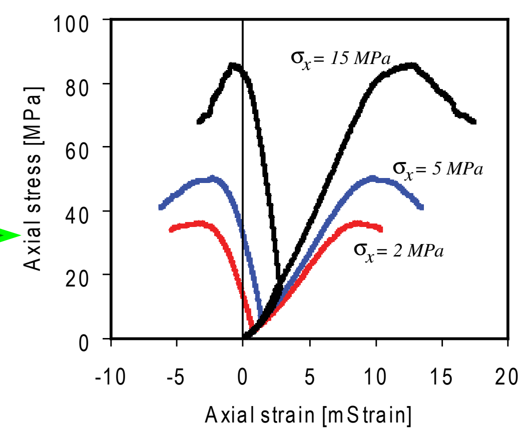
Rock characterization by PFC simulation

small piece of rock

X-ray tomography



Numerical model



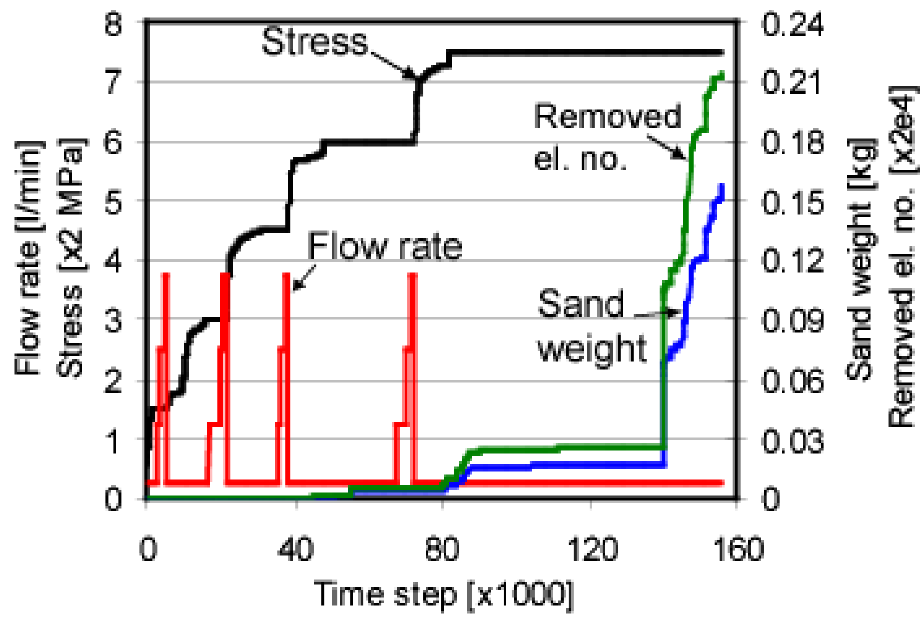
Numerical testing

Compute rock mechanical and petrophysical properties (elastic moduli, wave velocities, permeability, relative permeability, etc...) as functions of stress, stress history and stress path...

Dynamic modeling with hydro-mechanical coupling

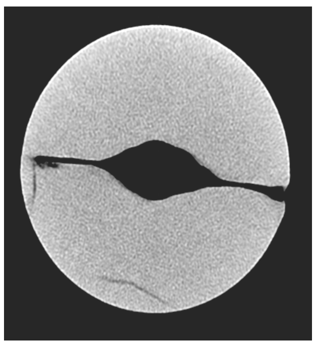
Application example: sand production prediction

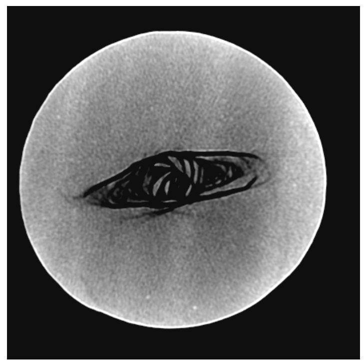
Predict volumetric sand production as a function of effective stress, flow rate and time.

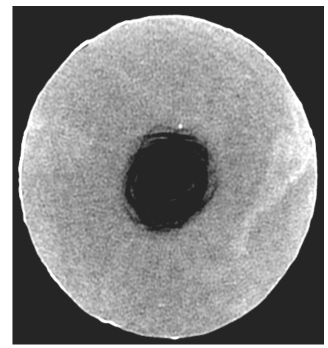


Dynamic modeling with hydro-mechanical coupling

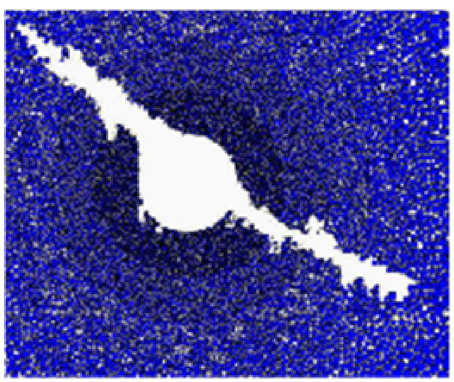
Application example: sand production mechanism in different rocks

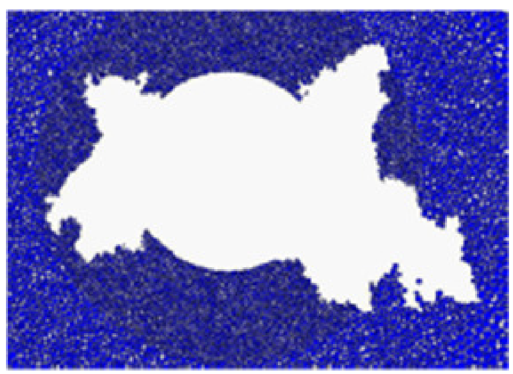


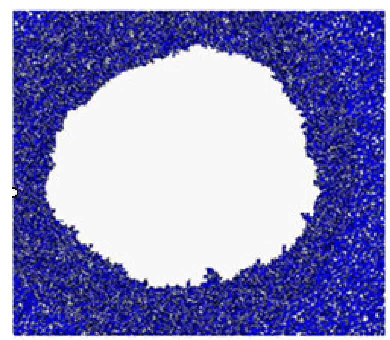




Lab observation



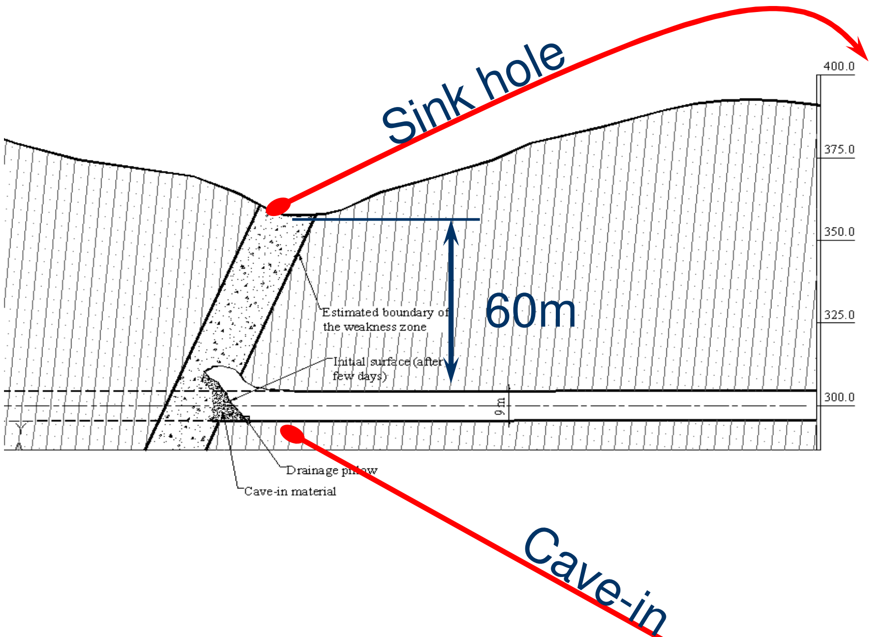




Numerical simulation

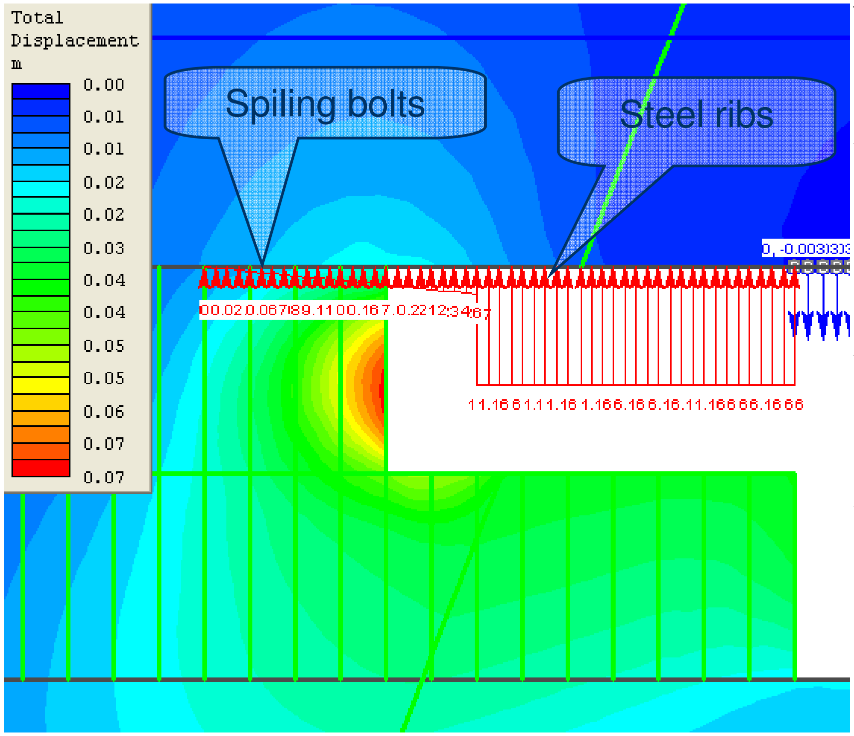
Modelling of Special Rock Support

Modelling rock support by spiling bolts



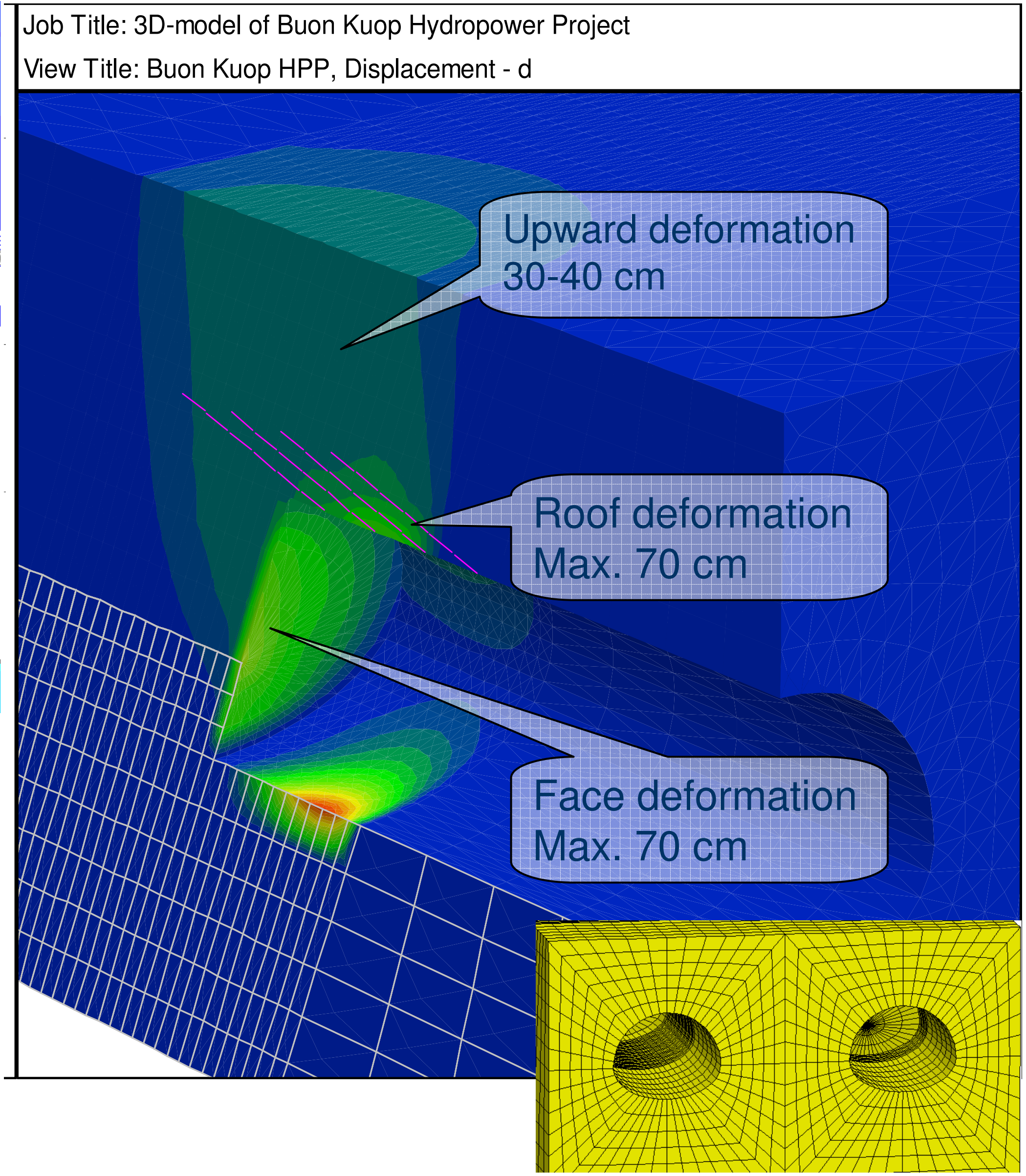
- A serious cave-in has happened
- No probe drilling
- Material flows in with water
- Weakness zone is about 15-20 m wide

2D and 3D models with spiling bolts, steelrib, shotcrete



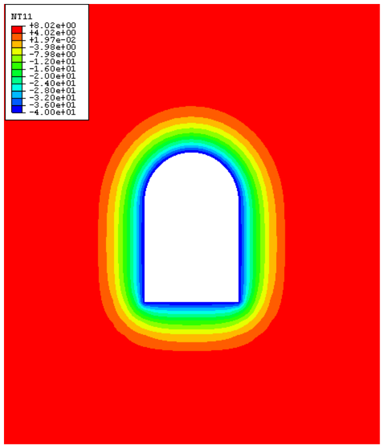
The tunnel failure has been analysed using 2D and 3D models, including many excavation and support methods.

A important academic goal after the analyses is the more realistic model to describe the behaviour and support action of spiling bolts.

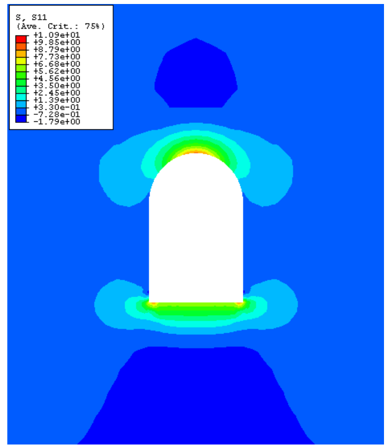


Modelling of temperature evolution and thermal Stress for gas storage cavern

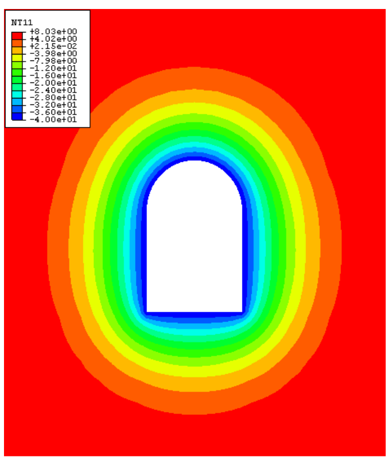
A



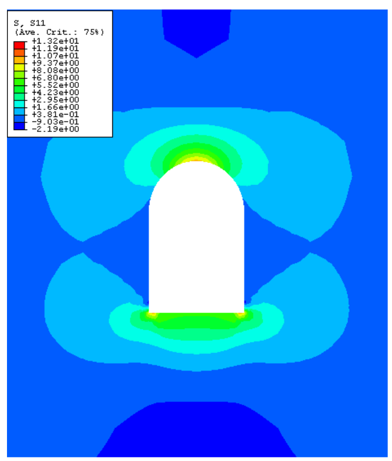
C



B



D



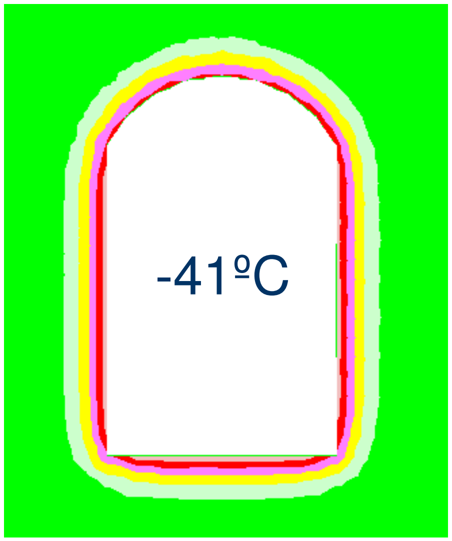
(A) Temperature distribution 150 days after cooling-down

(B) Temperature distribution 3 years after cooling-down

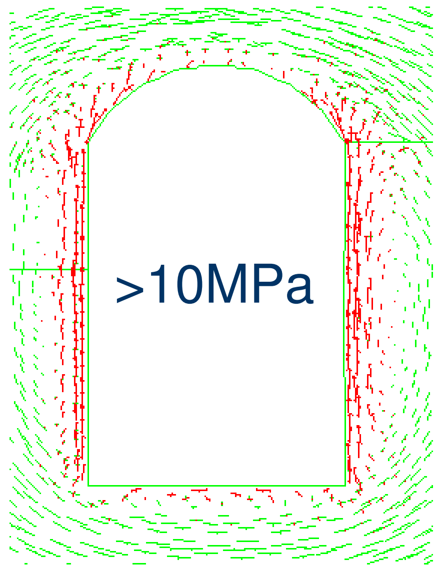
(C) Distribution of major principal stress 150 days after cooling-down (Max. 10.9 MPa)

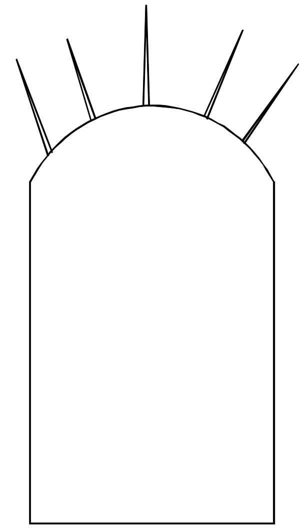
(D) Distribution of major principal stress 150 days after cooling-down(Max. 13.2 MPa)

Temperature gradient **Tensile thermal stress** **Rock cracking**



+10ºC





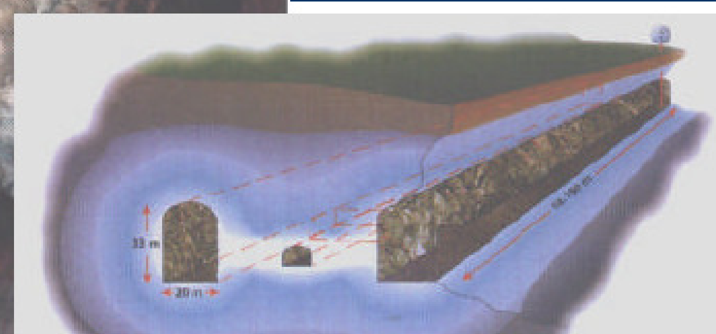
Ground water inflow

Gas leakage

Kårstø propane caverns excavation

Before excavation

- Ground water observation wells
- Borehole extensometers for each cavern



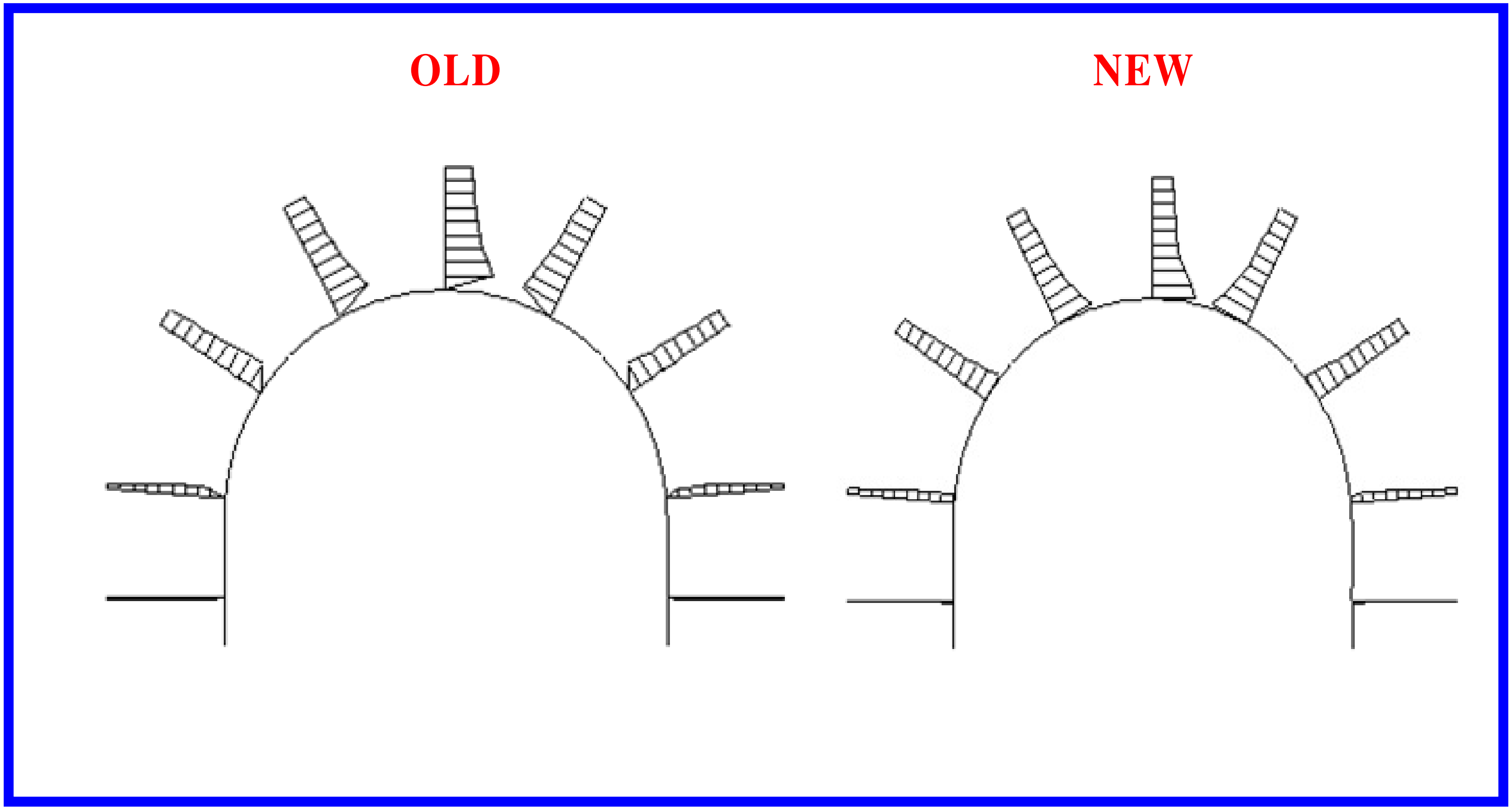
Frostzone 35m after 10 years of operation

Conclusions

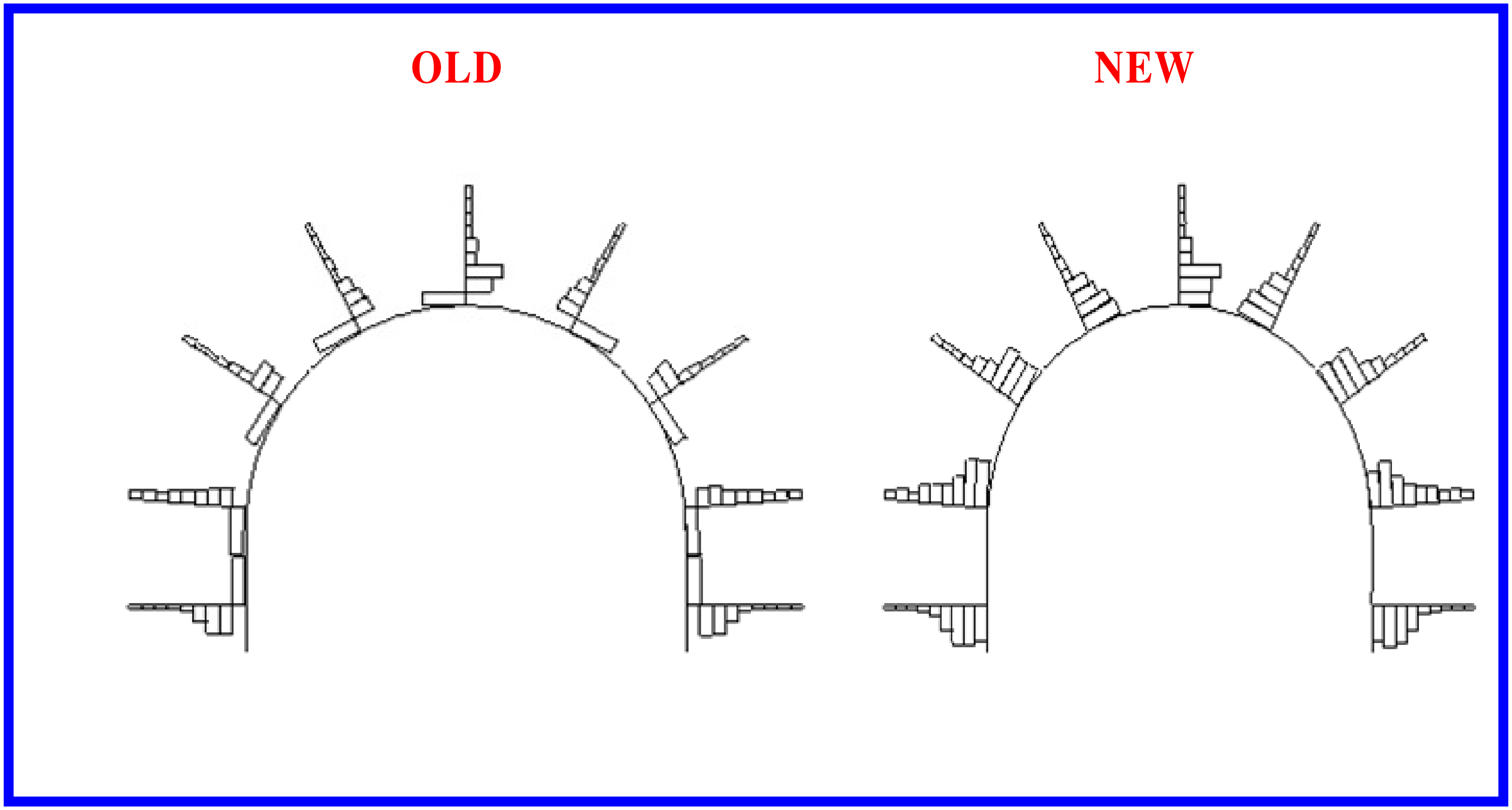
- If used properly the numerical modelling can be a useful tool for rock mechanics analysis and tunnel rock support design
- If the input data is rubbish the outcome is not only rubbish it also misleading

- **Even the input is correct the output may also be wrong, due to bugs in the software.**
- **All software have bugs!**
- **Judge your computation result based on your engineering experience!**

Comparison of old and new analyses - Axial displacement of bolts



Comparison of old and new analyses
Axial force of bolts



Numerical modelling is an excellent tool for design optimization

- Tunnel route/geometry/depth/spacing
- Tunnel rock support and construction sequence
- Operation mode for facility caverns such as gas storage