Large-scale laboratory model test simulating rock mass uplift failure

NROCK 2023

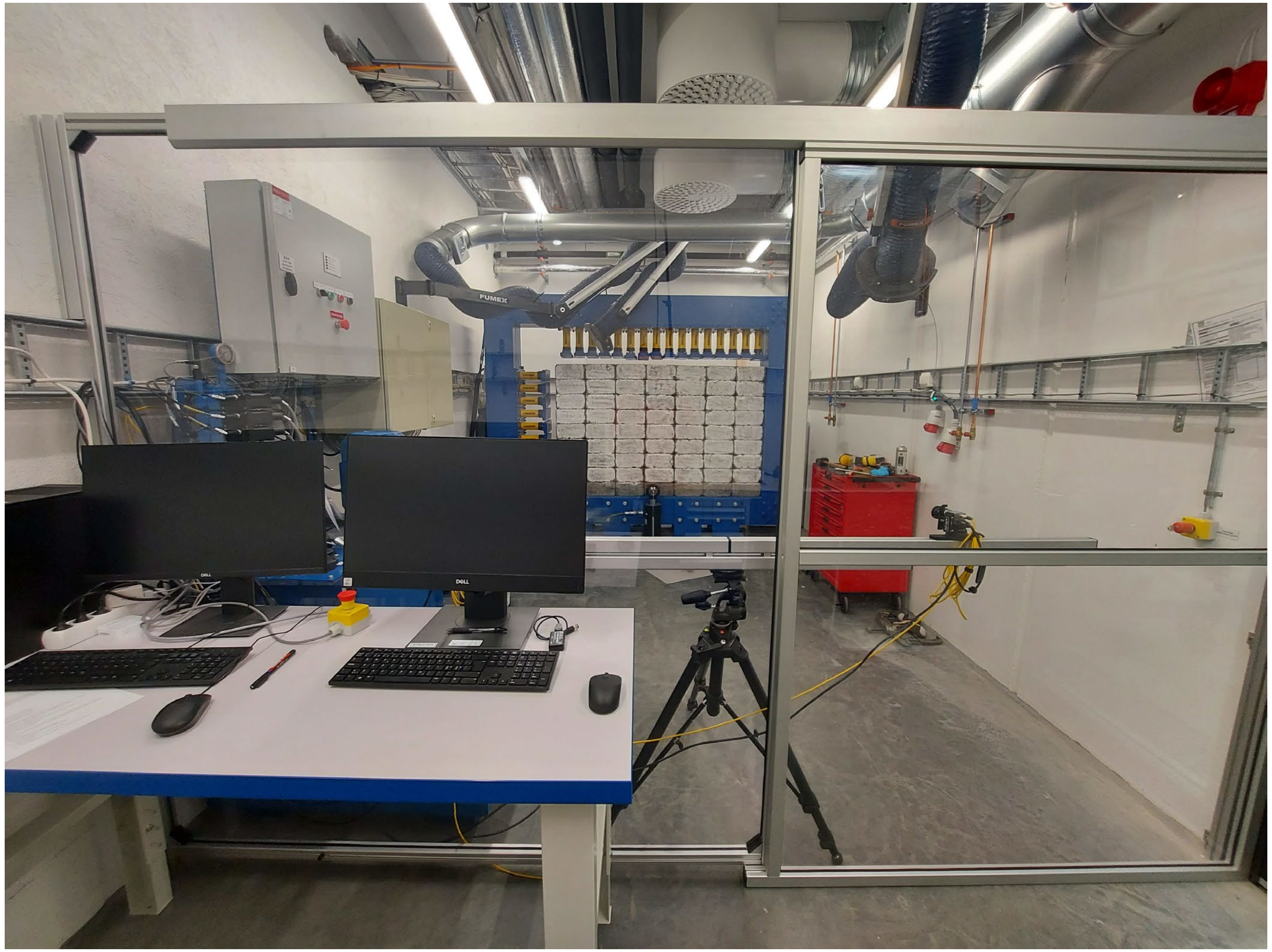
Bjarte Grindheim

Charlie Li

Are Håvard Høien

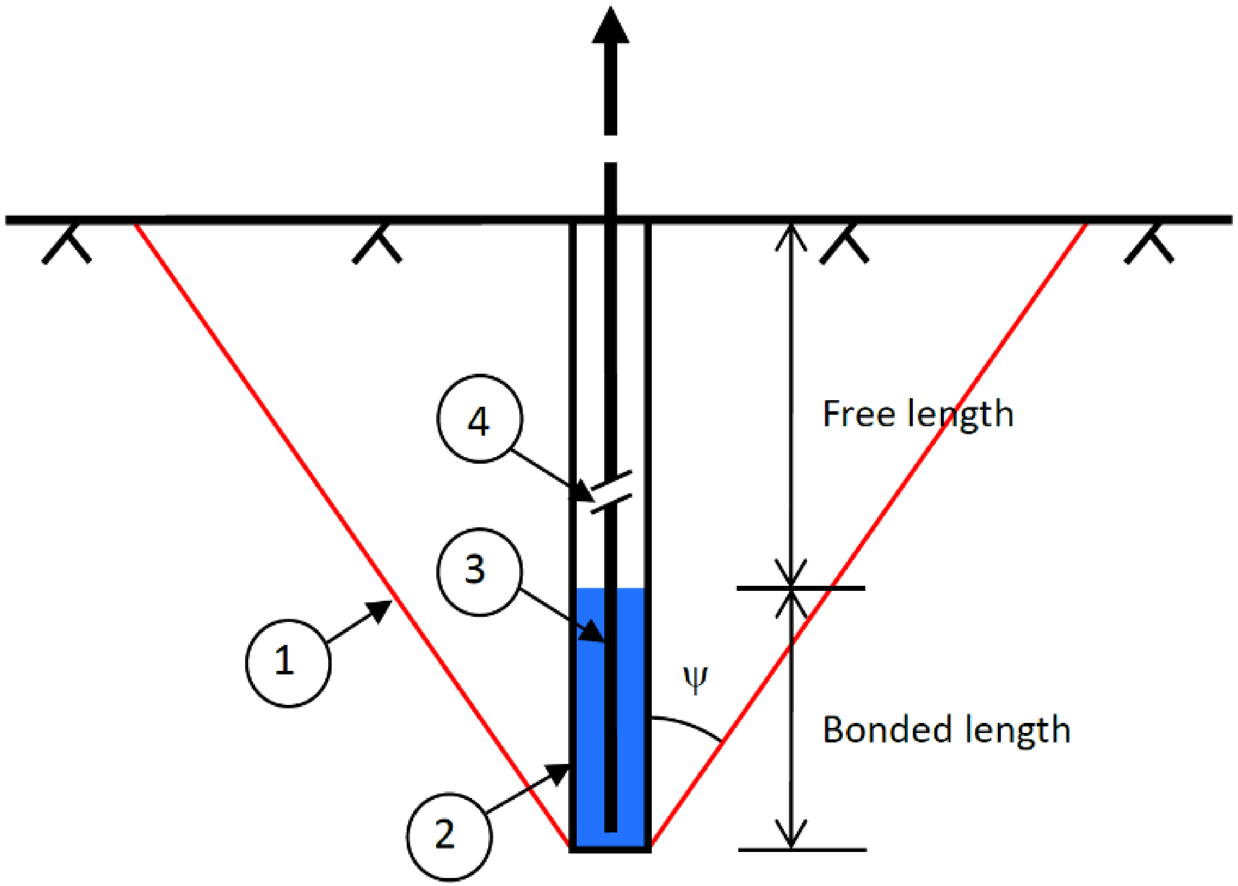
Contents

- Background
- Test setups
- Test procedure
- Test results and analysis
- Conclusions
- Further research
- References

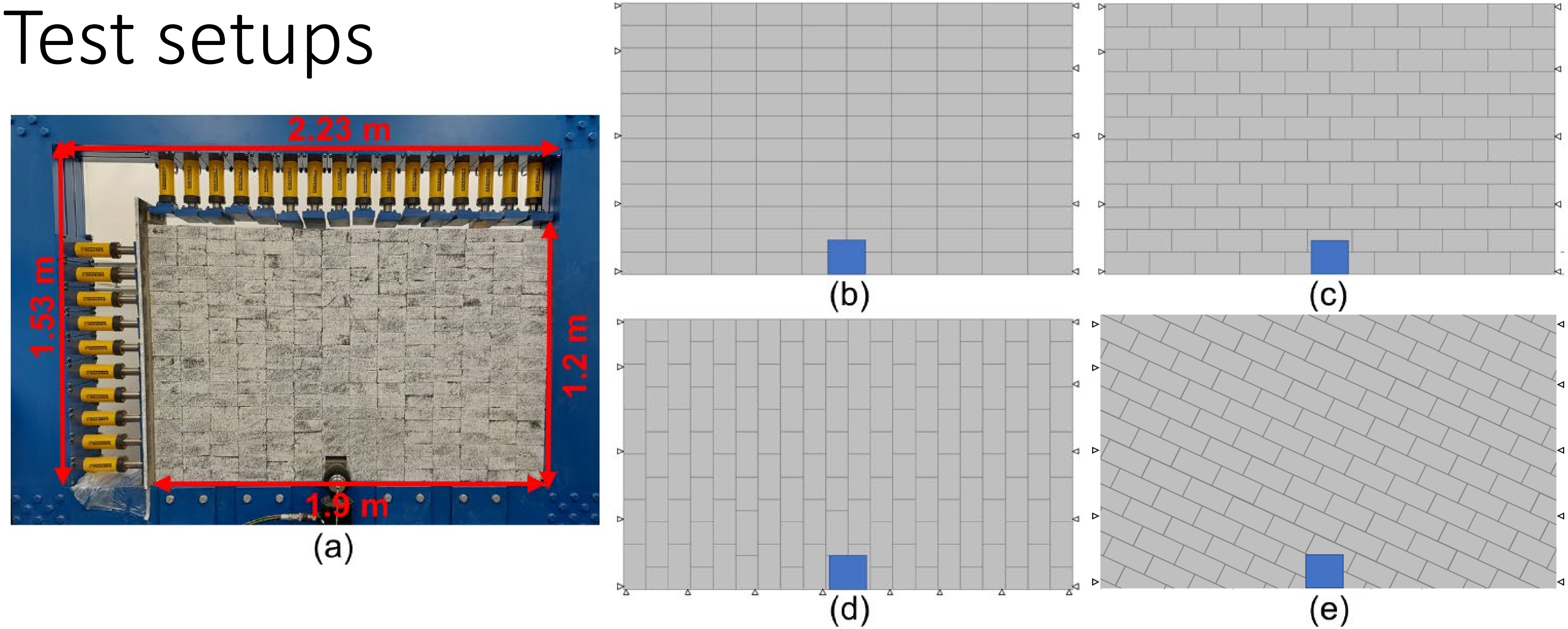


Background

- 4 principal failure modes of rock anchors:
    1. Rock mass uplift failure;
    2. Grout-rock interface failure;
    3. Tendon-grout interface failure;
    4. Tensile failure of the anchor steel.
- Review by Brown (2015) showed that the design against failure mode 1 is based upon simplified assumptions on the stress distribution and volume of rock influenced.
    - Resulted in an excessively conservative design and it represents a poor engineering practice.



Test setups

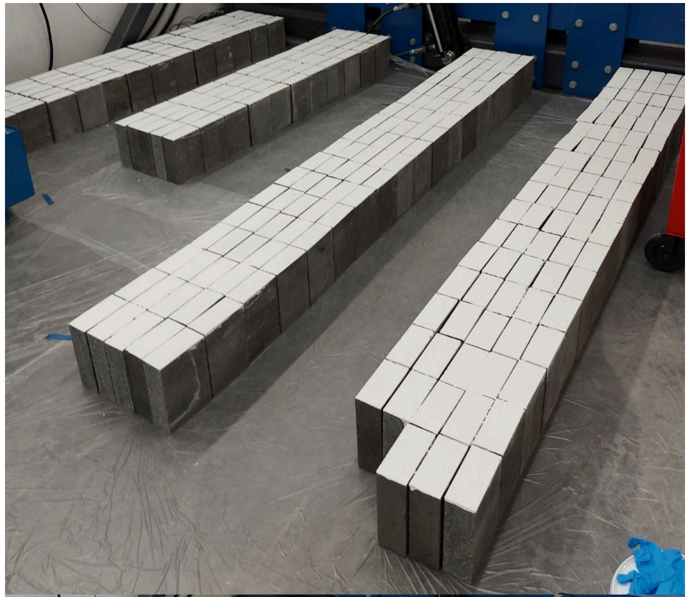


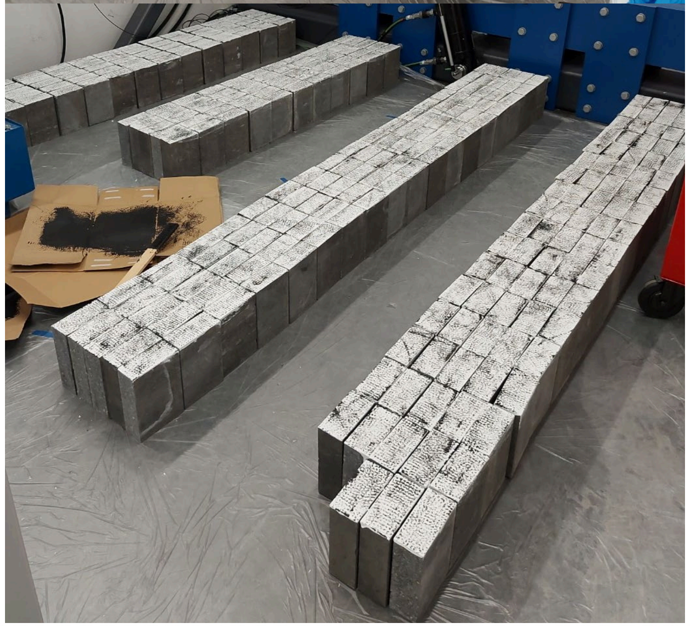
(a) (b) (c) (d) (e)

- 16 vertical and 10 horizontal cylinders with capacity of 142 kN each.
- 2 cylinders loading an anchor block with 225 kN capacity each, total anchor capacity 450 kN.

Materials and preparations

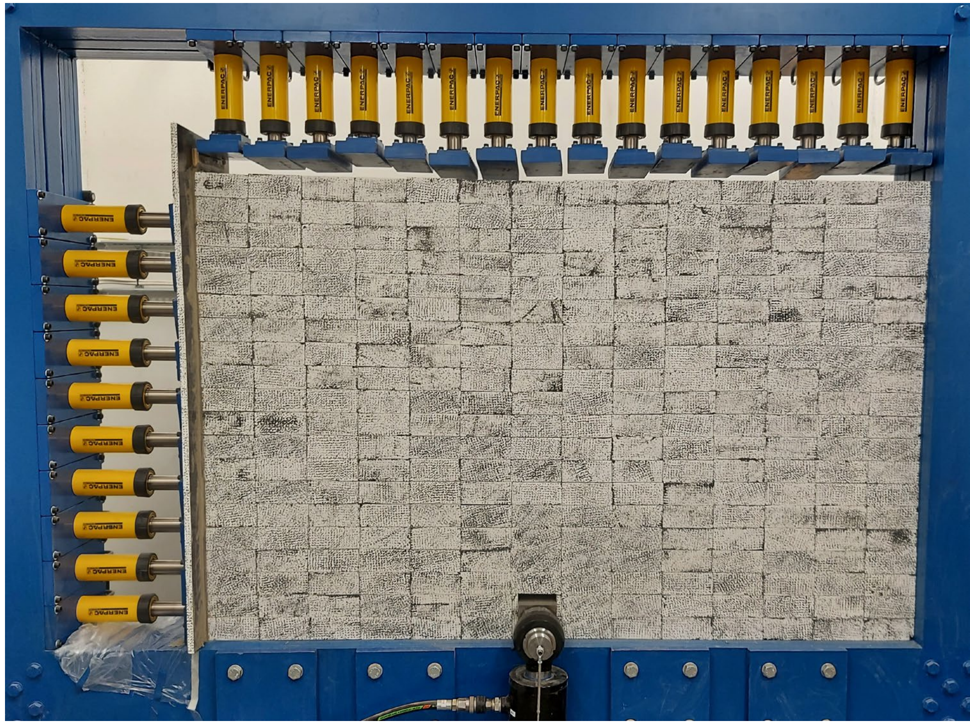
- The material used were concrete pavement blocks with measured properties:
  - UCS 43 MPa.
  - Young’s modulus 23 GPa.
  - Poisson’s ratio of 0.22.
- The pavement block were cut into dimensions 13 × 6 × 19 cm and 6.5 × 6 × 19 cm.
- The tests were monitored with Digital Image Correlation (DIC) cameras which required the blocks to be painted in a 50/50 black and white non-repetitive pattern.





Test procedure

- A total of 80 tests has been done in the testing rig. All the tests followed the same procedure:
  1. The blocks were placed in the frame with the wanted block pattern and height.
  2. The left side of the model was evened out with cementitious mortar and a wooden plate, the mortar was left to harden for a week.
  3. The wanted horizontal stress was applied to the blocks from the horizontal cylinders and then the valves were closed, to keep the model from deforming horizontally.
  4. A vertical stress was applied to the blocks from the vertical cylinders if a height higher than 1.2 m were to be simulated. The valves were left open to keep the stress constant and let the model deform vertically.
  5. If the tests were not run to failure a displacement limit of 25 mm was set on the system.
  6. The DIC capturing was started.
  7. The blocks were then loaded with a displacement rate of 0.5 mm/s with a force limit. The force limit was increased set to 50 kN for the tests not run to failure, and the test was stopped the force limit was reached or the displacement reached the limit of 25 mm. The failure tests were run to the end of the stroke of the pistons.
  8. The anchor was then unloaded slowly.
  9. The DIC capturing was stopped.
  10. The confining stresses were then removed.



Test results and analysis

Block pattern 1: Continuous horizontal and vertical joints.

Horizontal stress (MPa) \ Height (m)	0.6	0.9	1.2	4	8
0	Load 11.7 kN Disp. 25.2 mm	Load 16.1 kN Disp. 25.1 mm	Load 27.1 kN Disp. 25.1 mm	Load 45.1 kN Disp. 25.1 mm	Load 47.8 kN Disp. 18.5 mm
0.1	Load 14.9 kN Disp. 25.1 mm	Load 19.6 kN Disp. 25.1 mm	Load 33.3 kN Disp. 25.1 mm	Load 44.4 kN Disp. 25.1 mm	Load 47.0 kN Disp. 12.5 mm
0.5	Load 20.4 kN Disp. 25.1 mm	Load 31.7 kN Disp. 25.1 mm	Load 46.3 kN Disp. 18.5 mm	Load 46.1 kN Disp. 13.3 mm	Load 48.9 kN Disp. 10.0 mm
1	Load 23.6 kN Disp. 25.0 mm	Load 38.7 kN Disp. 25.2 mm	Load 46.0 kN Disp. 11.2 mm	Load 48.9 kN Disp. 9.6 mm	Load 49.0 kN Disp. 8.9 mm

Block pattern 2: Continuous horizontal and discontinuous vertical joints.

Horizontal stress (MPa) \ Height (m)	0.6	0.9	1.2	4	8
0	Load 14.1 kN Disp. 25.2 mm	Load 18.9 kN Disp. 25.1 mm	Load 16.3 kN Disp. 25.3 mm	Load 38.9 kN Disp. 25.2 mm	Load 43.0 kN Disp. 6.8 mm
0.1	Load 15.3 kN Disp. 25.0 mm	Load 20.5 kN Disp. 25.3 mm	Load 26.7 kN Disp. 25.1 mm	Load 43.1 kN Disp. 25.1 mm	Load 47.4 kN Disp. 5.8 mm
0.5	Load 20.3 kN Disp. 25.1 mm	Load 31.4 kN Disp. 25.1 mm	Load 44.7 kN Disp. 23.1 mm	Load 45.5 kN Disp. 11.7 mm	Load 47.8 kN Disp. 5.0 mm
1	Load 23.4 kN Disp. 25.1 mm	Load 40.4 kN Disp. 25.1 mm	Load 44.3 kN Disp. 12.6 mm	Load 45.5 kN Disp. 8.1 mm	Load 49.9 kN Disp. 4.9 mm

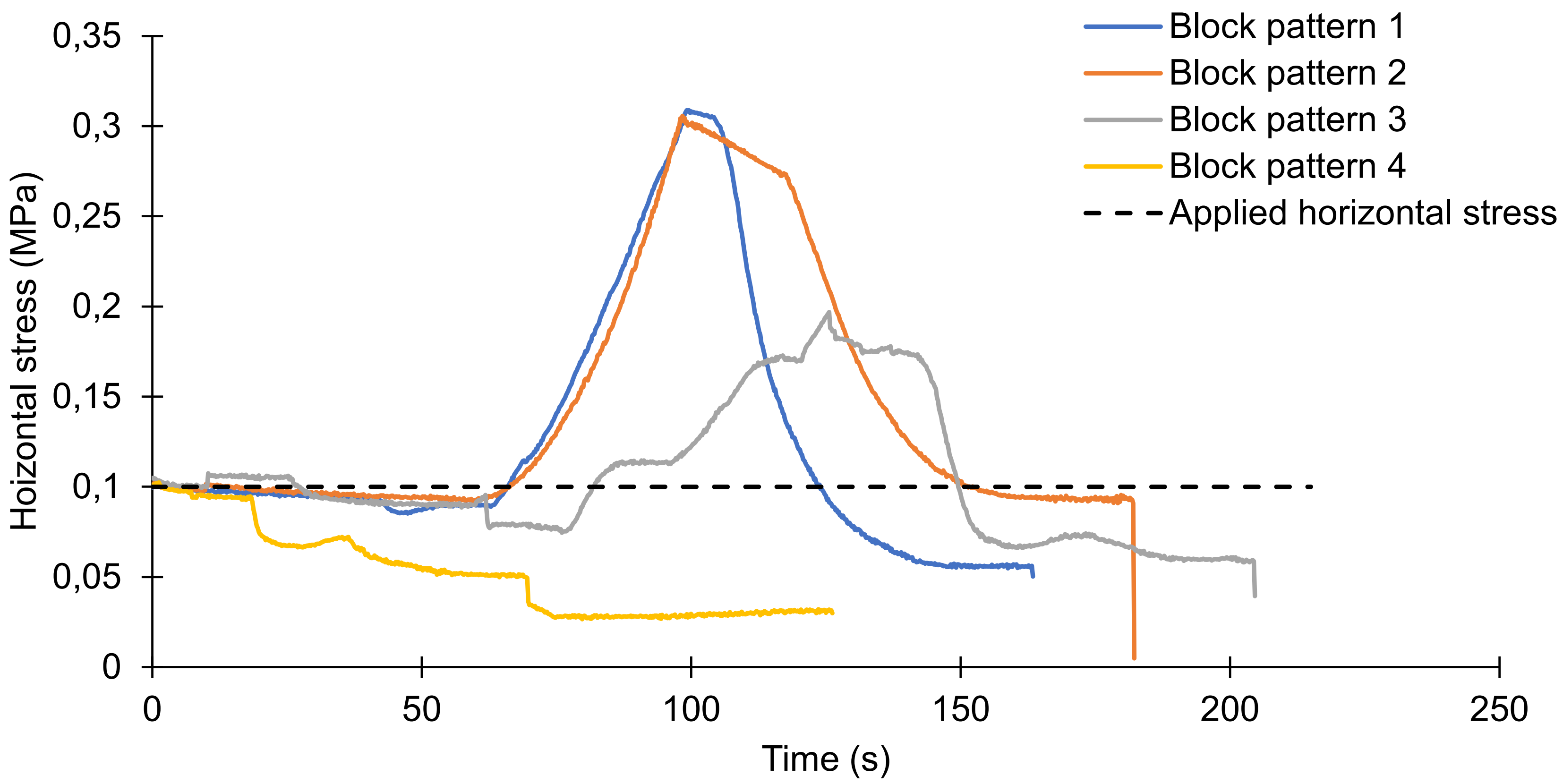
Block pattern 3: Discontinuous horizontal and continuous vertical joints.

Horizontal stress (MPa)	Height (m): 0.6	0.9	1.2	4	8
0	Load 12.9 kN Disp. 25.2 mm	Load 13.0 kN Disp. 25.3 mm	Load 15.0 kN Disp. 25.4 mm	Load 22.7 kN Disp. 25.2 mm	Load 29.6 kN Disp. 25.1 mm
0.1	Load 21.3 kN Disp. 25.2 mm	Load 39.4 kN Disp. 25.3 mm	Load 40.8 kN Disp. 25.1 mm	Load 46.2 kN Disp. 25.1 mm	Load 42.6 kN Disp. 25.2 mm
0.5	Load 39.7 kN Disp. 25.2 mm	Load 47.0 kN Disp. 3.6 mm	Load 50.2 kN Disp. 4.6 mm	Load 49.2 kN Disp. 2.6 mm	Load 47.6 kN Disp. 3.0 mm
1	Load 47.8 kN Disp. 5.3 mm	Load 46.0 kN Disp. 1.1 mm	Load 48.1 kN Disp. 1.3 mm	Load 46.7 kN Disp. 1.5 mm	Load 48.1 kN Disp. 1.3 mm

Block pattern 4: Continuous horizontal and discontinuous vertical joints rotated with 25°.

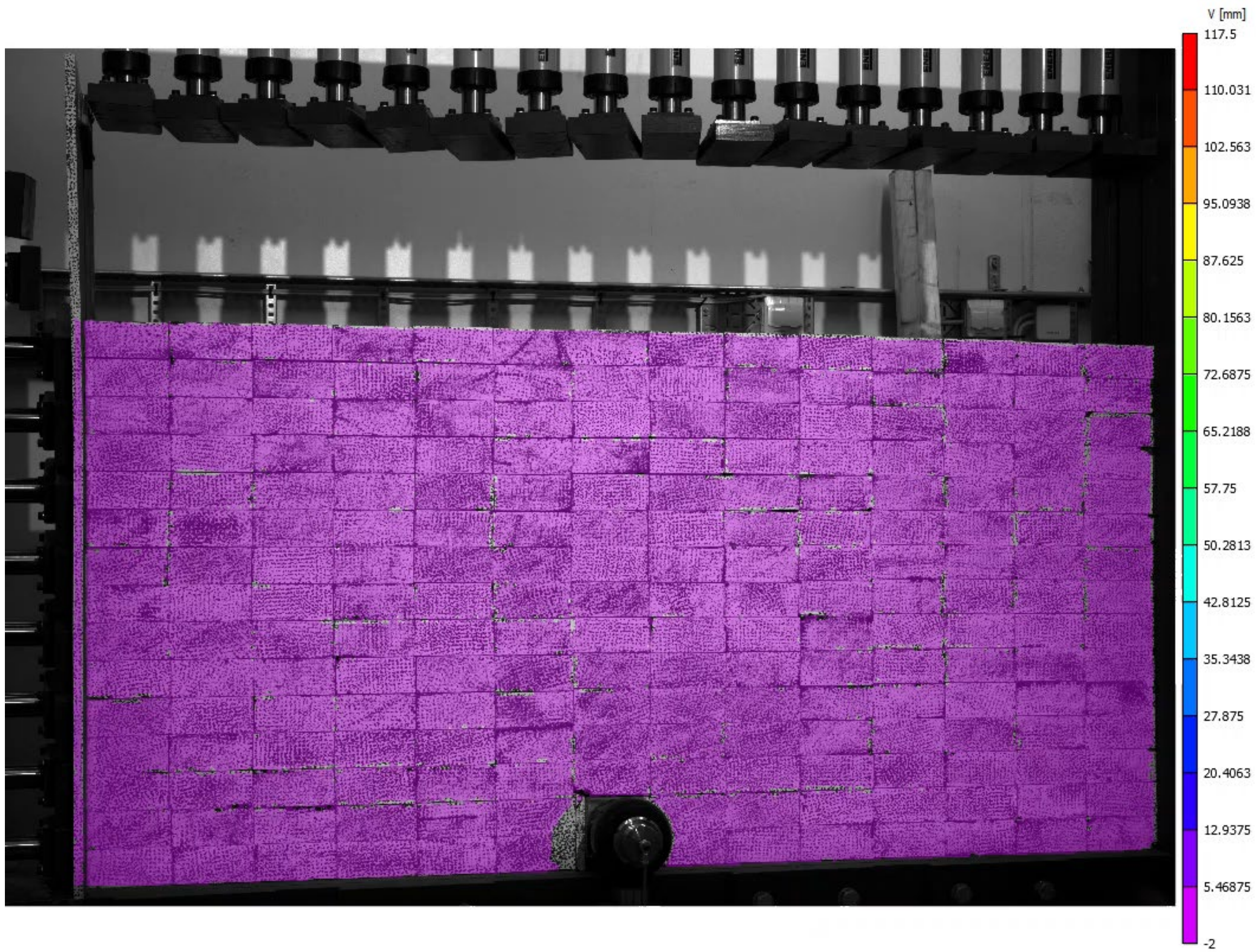
Horizontal stress (MPa)	Height (m): 0.6	0.9	1.2	4	8
0	Load 14.1 kN Disp. 25.5 mm	Load 16.6 kN Disp. 25.1 mm	Load 21.1 kN Disp. 25.1 mm	Load 45.2 kN Disp. 14.3 mm	Load 45.5 kN Disp. 3.9 mm
0.1	Load 14.0 kN Disp. 25.3 mm	Load 15.3 kN Disp. 25.2 mm	Load 24.1 kN Disp. 25.1 mm	Load 45.4 kN Disp. 12.2 mm	Load 46.3 kN Disp. 3.5 mm
0.5	-	-	Load 36.0 kN Disp. 25.1 mm	Load 46.4 kN Disp. 6.5 mm	Load 47.4 kN Disp. 2.5 mm
1	-	-	Load 46.3 kN Disp. 18.7 mm	Load 46.6 kN Disp. 7.5 mm	Load 45.5 kN Disp. 2.0 mm

Horizontal stress in the models



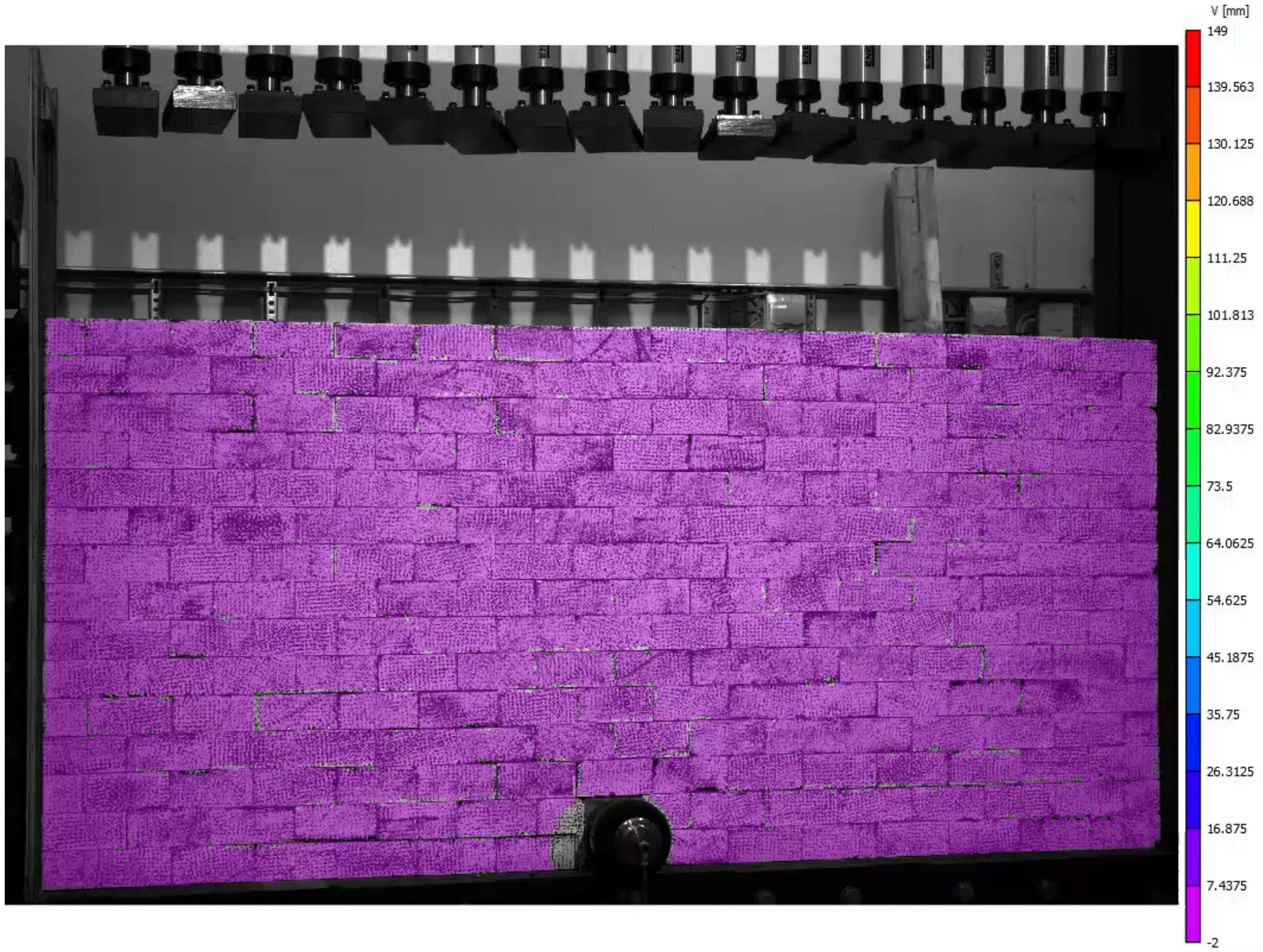
Failure of block pattern 1

- Load capacity: 29.7 kN.
- Apex angle: 120°.



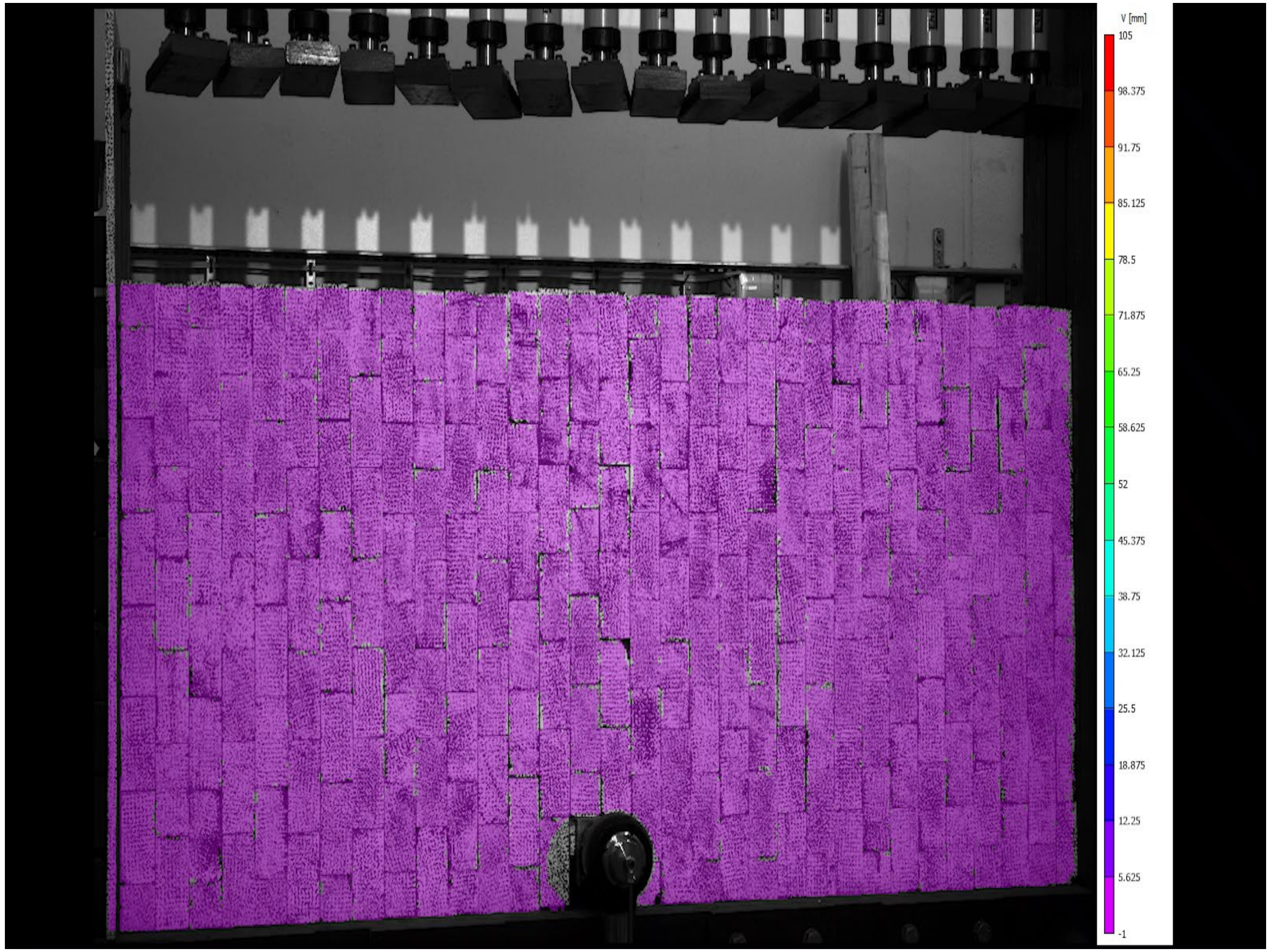
Failure of block pattern 2

- Load capacity: 33.8 kN.
- Apex angle: 100°.



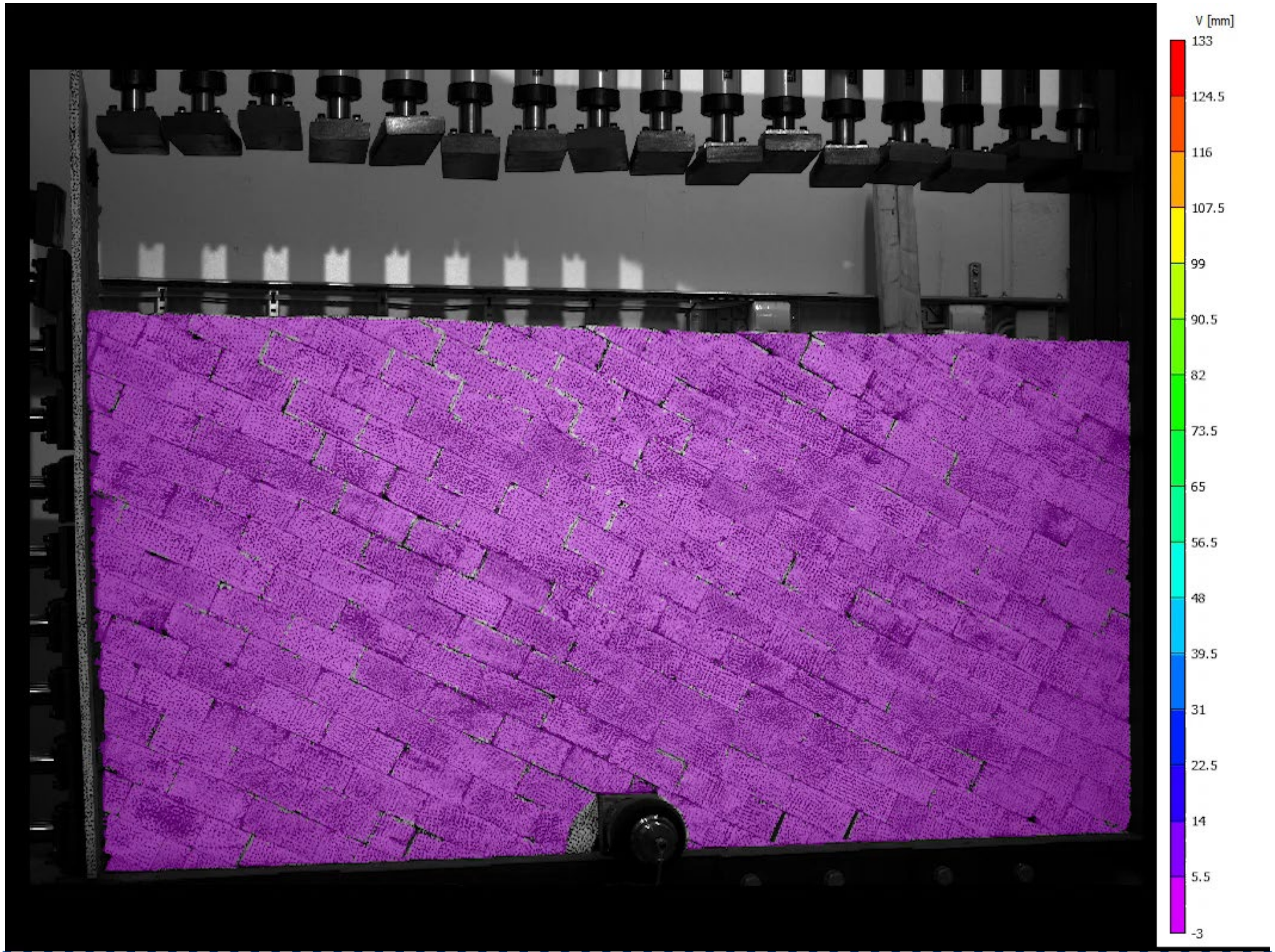
Failure of block pattern 3

- Load capacity: 75.2 kN.
- Apex angle: 90°.



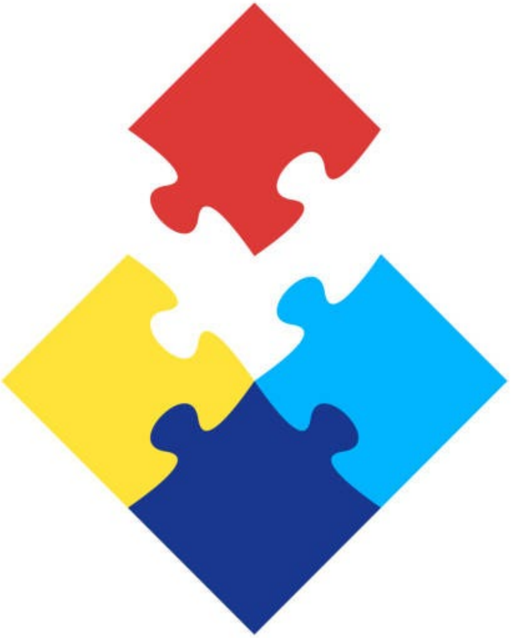
Failure of block pattern 4

- Load capacity: 19.4 kN.
- Apex angle: 140°.



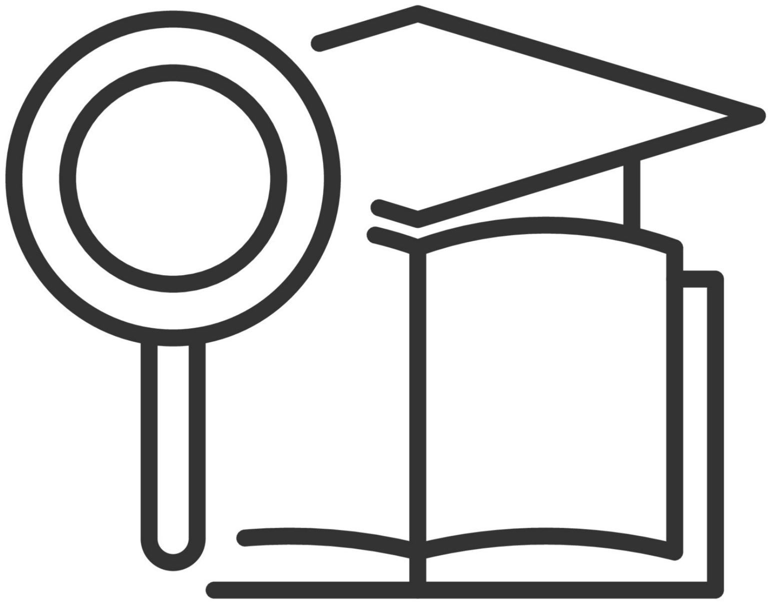
Conclusions

- A total of 80 two-dimensional block model tests were carried out in the laboratory to investigate load arching, the load capacity, and failure of different joint patterns.
- They showed an increase in horizontal stress (i.e., load arching) in the tests with horizontal and vertical joints.
- The vertical displacement was greatest in the direction normal or parallel to the joint sets.
- The block model capacity increased with both increasing horizontal and vertical stress.
- The joint patterns both affected the load capacity and failure shape.



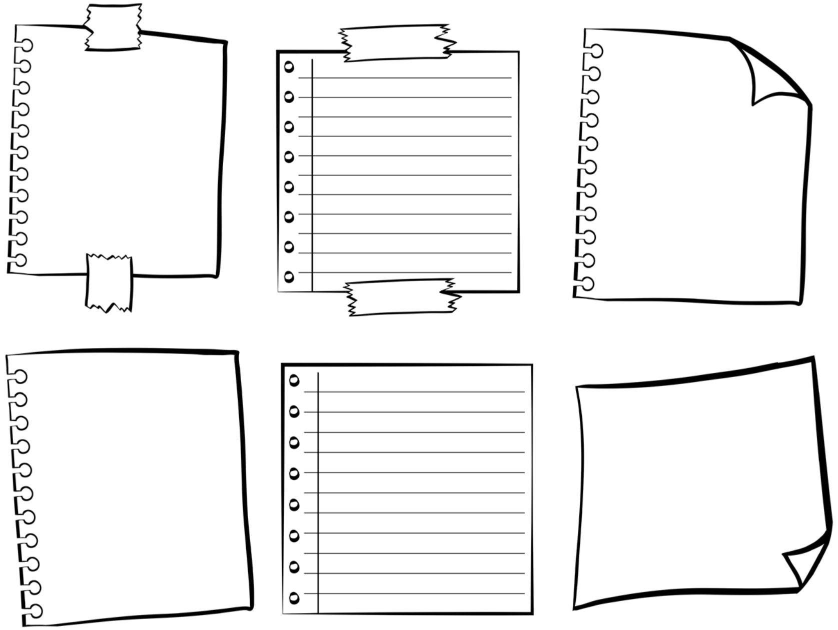
Further research

- It is necessary to test blocks of different sizes and materials to see how they affect the capacity, deformations, and stresses in the block models.
- The results should also be transferred to real scenarios, which can be done through numerical models calibrated on these test results.
  - The numerical models can also be used to test the effect of different materials through sensitivity analysis.



References

- Brown ET (2015) Rock engineering design of post-tensioned anchors for dams – a review. Journal of Rock Mechanics and Geotechnical Engineering 7(1):1-13, DOI https://doi.org/10.1016/j.jrmge.2014.08.001.



Once again, I want to acknowledge the help from our partners in this research project!

NBG NTNU THE ARCTIC UNIVERSITY OF NORWAY • UIT • Statens vegvesen SINTEF NGI

Multiconsult Norconsult NORSAR

Questions?

Thank you for pulling through my two rock anchoring presentations!