Full-scale pullout tests of rock anchors in limestone testing rock mass uplift failure

NROCK 2023

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Contents

Background

- Rock anchors are high-capacity reinforcement measures.
- Consists of a steel tendon, anchor head and a bond length.
    - Between the anchor head and the bond length the tendon is free to elongate.
- They are used to stabilise large scale infrastructures.

(Li, 2020)

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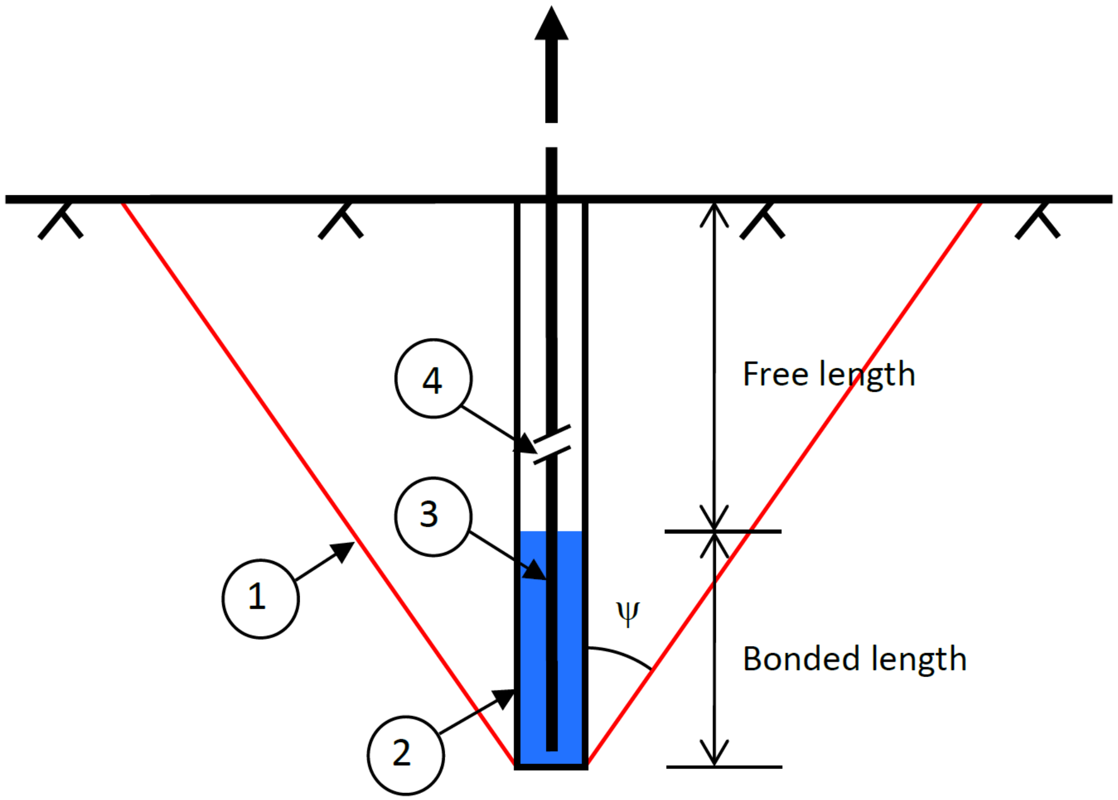
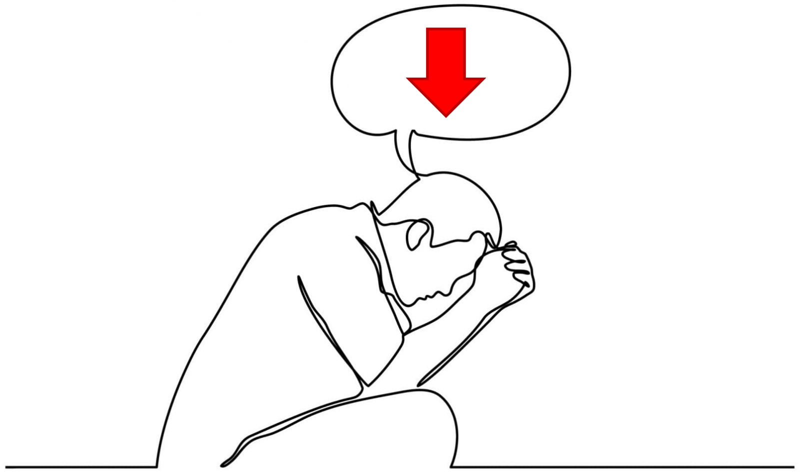
Failure modes of rock achors

- In literature there are four principal failure modes of rock anchors:
    1. Rock mass uplift failure;
    2. Grout-rock interface failure;
    3. Tendon-grout interface failure; and
    4. Tensile failure of the anchor steel.



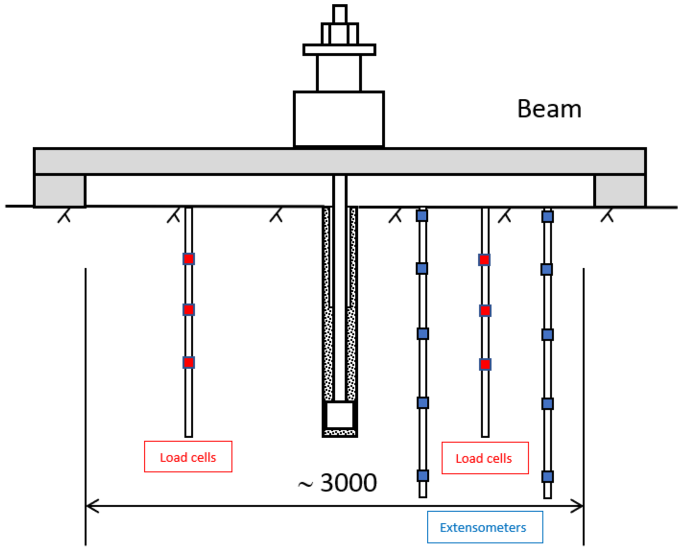
Deficiencies with current design method against rock mass uplift failure

- A review by Brown (2015) listed several deficiencies with the current design method:
  - Induced stresses from the anchor in the overlying rock mass is not considered.
  - All tests with rock mass failure has been with shallow anchors.
  - The effect of rock mass anisotropy on stresses and failure shape is not included.
  - The usage of a “theoretical” failure cone to calculate the rock mass capacity based upon presumptive and back calculated shear and tensile strength values is questionable.



Test setup

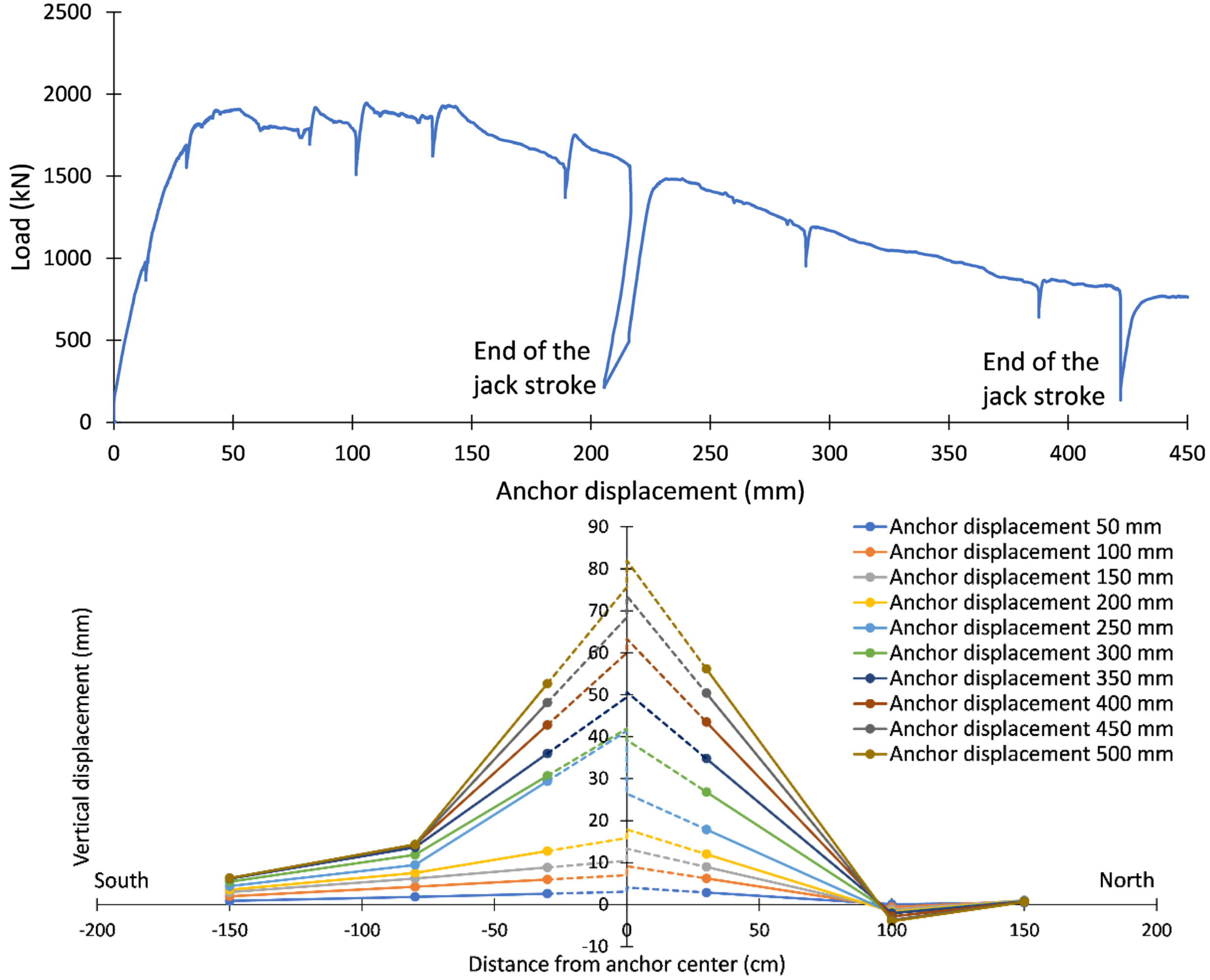
- 64 mm anchor of 2.5-3 m length at 1-1.5 m depth.
- Steel beam with 3 m span.
- 3500-kN hydraulic jack.
- Instrumentation:
  - Pressure gauge on jack.
  - LVDT on anchor.
  - Load cells in boreholes.
  - Extensometers in boreholes.
  - LVDT on aluminium truss.
  - Geophones on rock surface.
  - Optical televiewer.

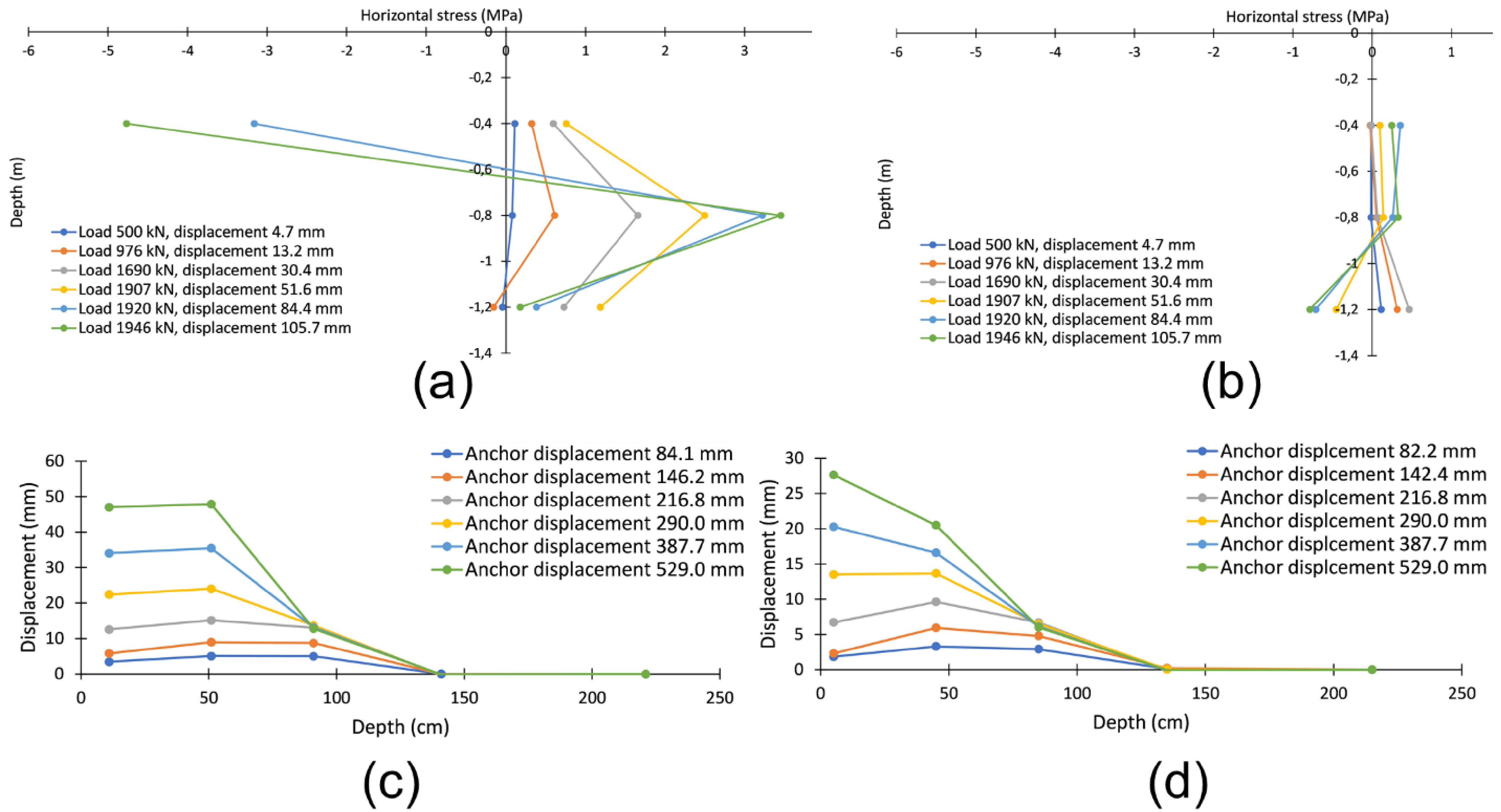


Test procedure

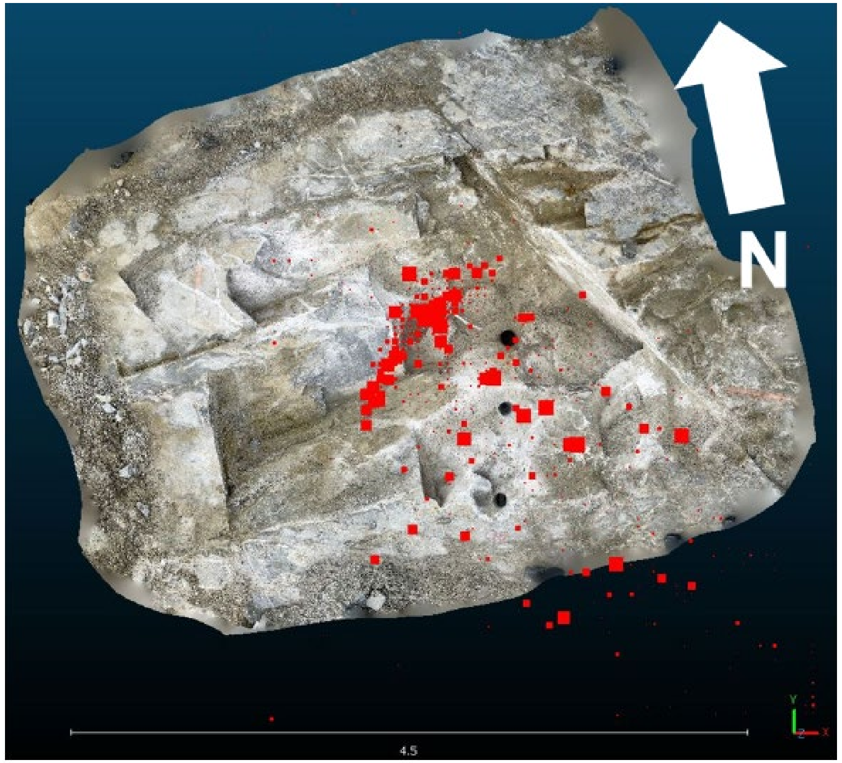
- Load was applied in ways:
  - Continuous until failure with a load rate of 5-7.5 kN/s.
    - Two shortest anchors with less instrumentation.
  - Stepwise with each load step held for 5 minutes, with a load rate of 11.5 kN/s.
    - The borehole extensometers took only one reading per 5 minutes. Therefore, all load steps were held for 5 minutes to get a reading per step.
- After the tests, the anchors and the loose rocks around the anchor location was removed. Then the failure surface was scanned with the lidar on an iPad.

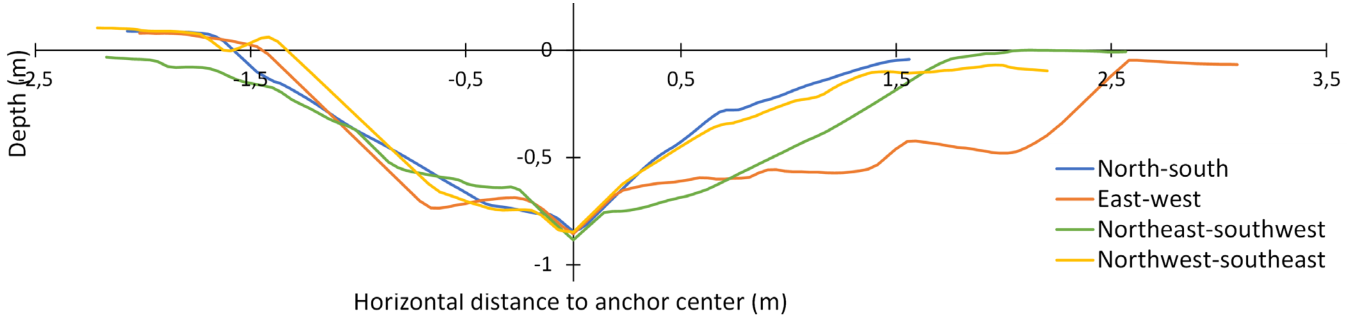
Test results and analysis



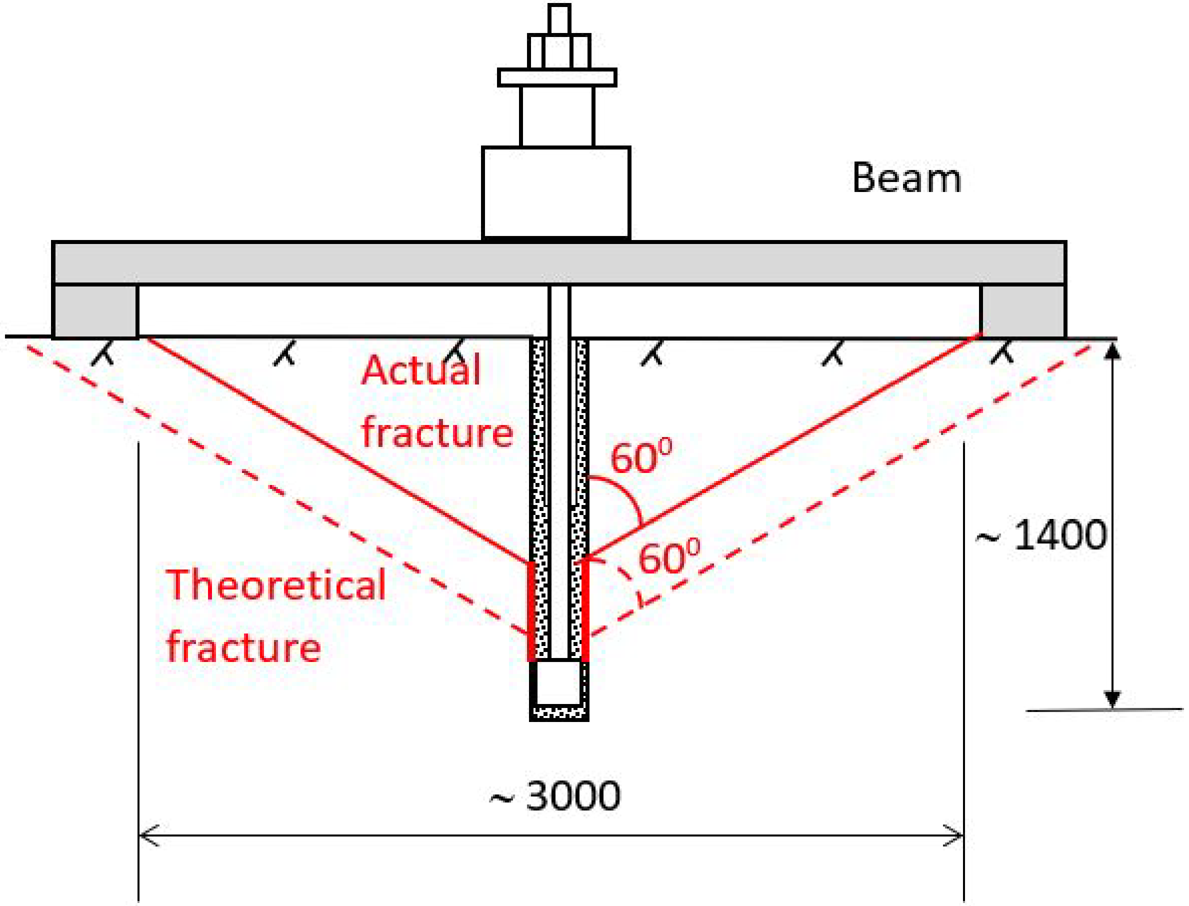

Horizontal stress (MPa)
Depth (m)
Load 500 kN, displacement 4.7 mm
Load 976 kN, displacement 13.2 mm
Load 1690 kN, displacement 30.4 mm
Load 1907 kN, displacement 51.6 mm
Load 1920 kN, displacement 84.4 mm
Load 1946 kN, displacement 105.7 mm
(a)
Horizontal stress (MPa)
Depth (m)
Load 500 kN, displacement 4.7 mm
Load 976 kN, displacement 13.2 mm
Load 1690 kN, displacement 30.4 mm
Load 1907 kN, displacement 51.6 mm
Load 1920 kN, displacement 84.4 mm
Load 1946 kN, displacement 105.7 mm
(b)
Displacement (mm)
Depth (cm)
Anchor displacement 84.1 mm
Anchor displacement 146.2 mm
Anchor displacement 216.8 mm
Anchor displacement 290.0 mm
Anchor displacement 387.7 mm
Anchor displacement 529.0 mm
(c)
Displacement (mm)
Depth (cm)
Anchor displcement 82.2 mm
Anchor displcement 142.4 mm
Anchor displcement 216.8 mm
Anchor displcement 290.0 mm
Anchor displcement 387.7 mm
Anchor displcement 529.0 mm
(d)

Failure shape





Failure mode



Load capacity of the rock mass

Anchor no.	**A1m**	**B1m**	**A1.5m**	**B1.5m**
Bonded section (m)	0.9	0.9	1.4	1.4
Maximum uplift load (kN)	2461.6	2309.5	2422.6	1946.2
Anchor displacement at max load (mm)	66.7	59.6	71.8	105.7
Cone volume (m^3)	2.28	2.27	3.55	3.66
Apex angle (degrees)				
- *from extensometers*	-	-	105-170	105-170
- *from televiewer*	-	-	-	125
- *from profiles*	127	131	142	132

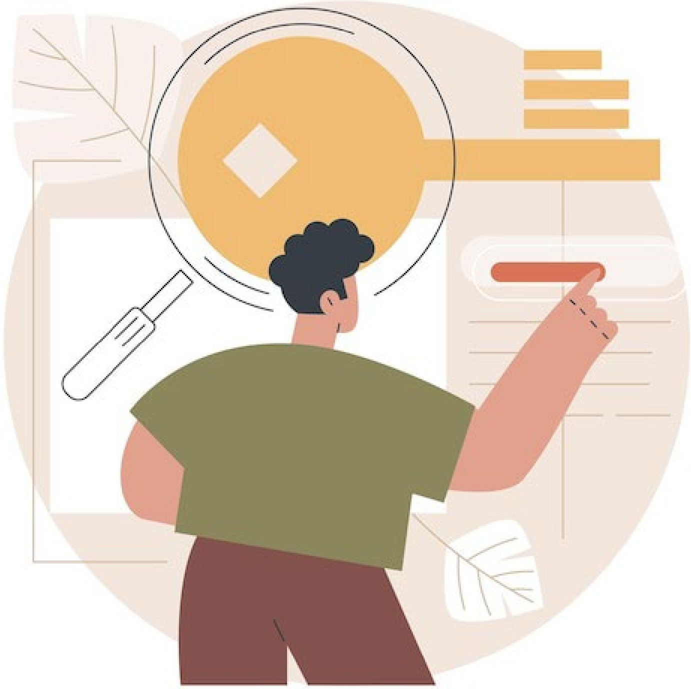
Depth (m)	**Apex angle (degrees)**	**Cohesion from back calculation (MPa)**	**Presumptive cohesion from NPRA (2018) (kPa)**	**Weight force (kN)**	**Max shear resistance from back calculation (kN)**	**Max shear resistance from NPRA (2018) design (kN)**
0.9	90	0.5	50	20.2	1029	146
1.4	90	0.5	50	76.1	2312	327

Conclusions

- The rock mass uplift capacity was higher than estimated with the current design method.
  - Current design method is very conservative for a medium hard rock mass.
- The estimation based upon back calculation of historical data was more accurate.
- The apex angle measured, 120-140^o, was higher than the recommendation in literature, 60-90^o.
- The horizontal stress increased slightly, which could indicate load arching in the rock mass around the anchor.

Further research

- It is necessary to test anchors at increasing depths to see if and how the failure shape and failure mechanism changes with depth.
  - Brown (2015) argued that the joints in the rock mass would have less effect on the failure at large depths.
  - One could also argue that the rock mass would be the strongest part of the anchor system after a certain depth.
    - Finding the critical depth would be useful, as in the current design method the rock mass uplift failure defines the anchoring depth and it often results in long anchors.
    - Bruce (1976) observed that the rock mass was the strongest part of the anchoring system when installed at depths (>2 m).



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.
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We want to thank our partners in the project for making this research possible!

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Questions?

Thank you for letting me have this presentation and please

with the next one.