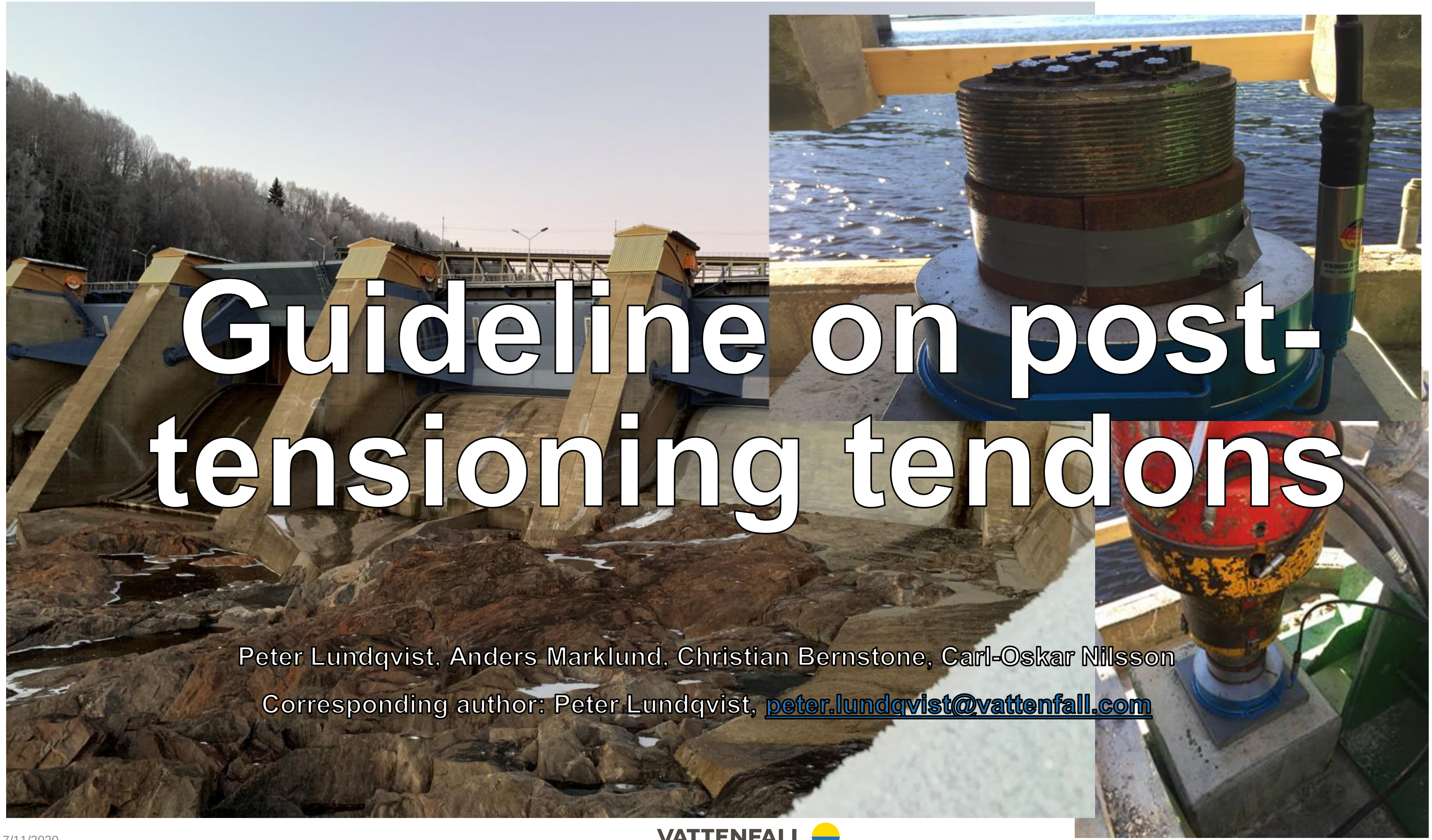


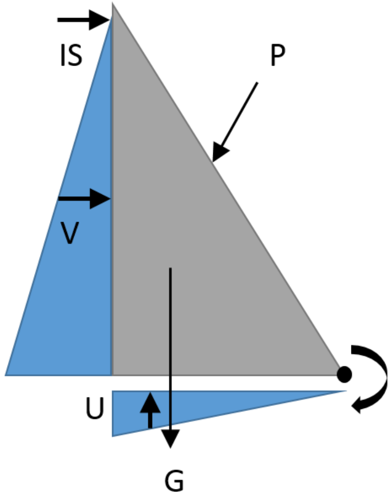
Guideline on post-tensioning tendons

Peter Lundqvist, Anders Marklund, Christian Bernstone, Carl-Oskar Nilsson

Corresponding author: Peter Lundqvist, peter.lundqvist@vattenfall.com

VATTENFALL

Tendons in hydro power

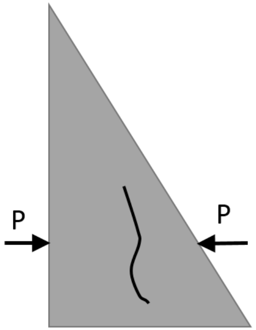


Post-tensioning tendons are used for:

1. Rock anchors (increase structural stability).
2. Reduce effects of concrete cracks.
3. Anchoring of foundations for e.g. the generator.

Tendons are installed in existing structures (1 and 2) or during construction (3).

The structural safety is directly dependent of the tendon forces → determine the tendon forces accurately is of vital importance.



Tendons in hydro power

Ageing of the hydro power structures → increased need for tendons

– Currently, no common tendon management practice exists.
– Up to each owner and/or contractor to incorporate their own strategy.

A series of projects have been initiated:

– Financed by a branch of industry R&D program (Energiforsk).
– Overall purpose: develop a guideline on management of post-tensioning tendons for dam owners in Sweden.

Foto: Uniper

Project in several phases

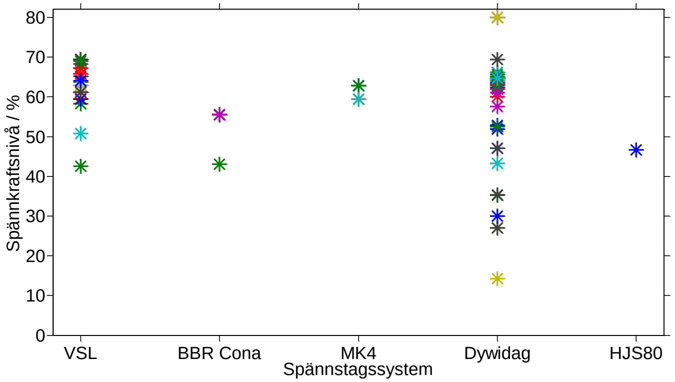
Three projects finalized so far:

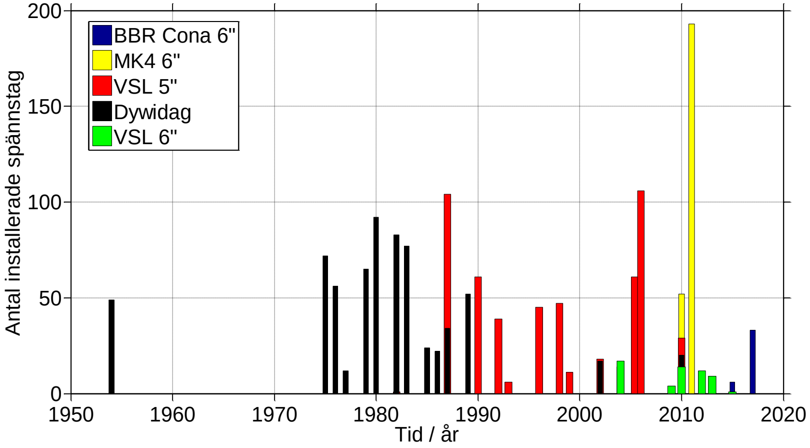
1. Compilation of information regarding installed tendons.
2. Condition assessment of tendons
   1. Recommendations for developing ageing management program.
   2. Methods for measuring tendon forces.
   3. Instrumentation with load cells.
3. Management of tendons
   1. Tendon forces – safety margins and acceptance criteria
   2. Recommendations for design and installation of tendons
   3. Factors influencing the anchorage zone

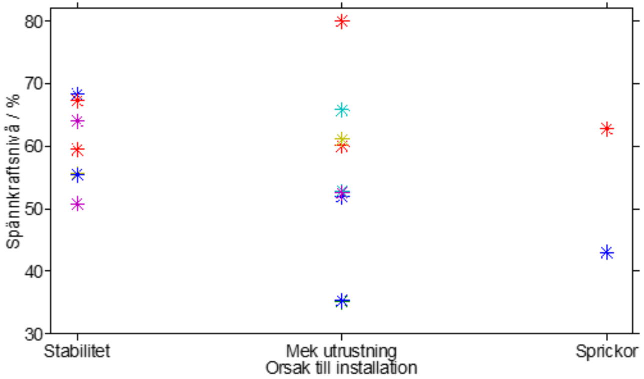
Compilation of information

Data from more than 1300 tendons in over 50 plants were compiled:

- Tendon system.
- Purpose of the tendons.
- Forces in the tendons.
- Inspection program.
- Experiences from installation and/or operation.







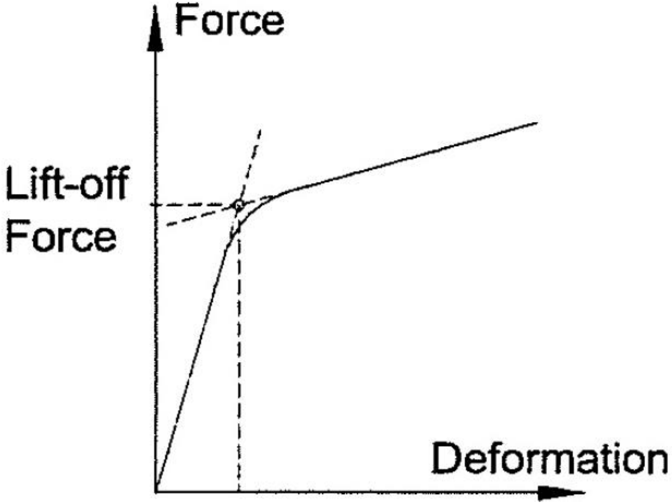
VATTENFALL

Tendon force measurements

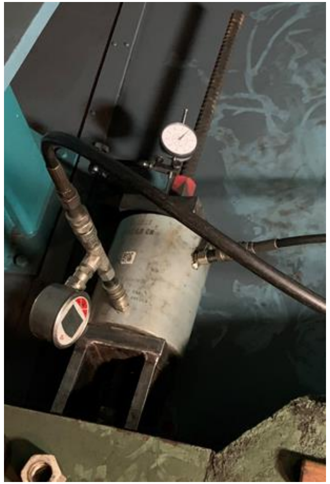
Tendon force measurements

Tendon forces are measured regularly by contracted external service companies using hydraulic jacks:

- Lift-off force = force that cause the anchor head to move.
- Intersection in displacement-force diagram = lift-off.



Tendon force measurements



Several issues identified with existing methods:

– Measurement accuracy.

– No standardized measuring method → different methods for:

  – Measuring force and elongation.
  – Determining lift-off force.
  – Performing the measurement.

↓

– Different results from different contractors.

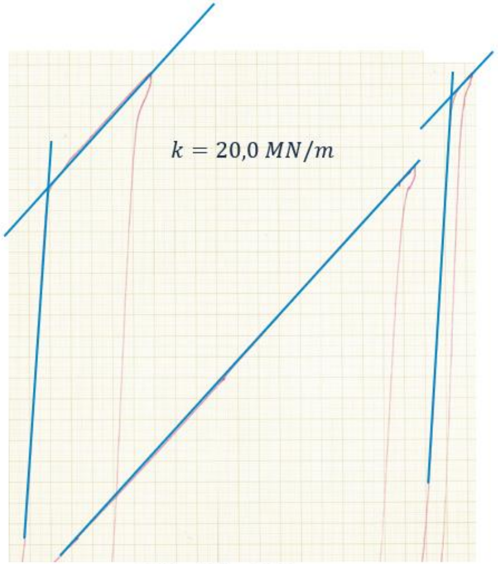
– Results from different measurements are not comparable.

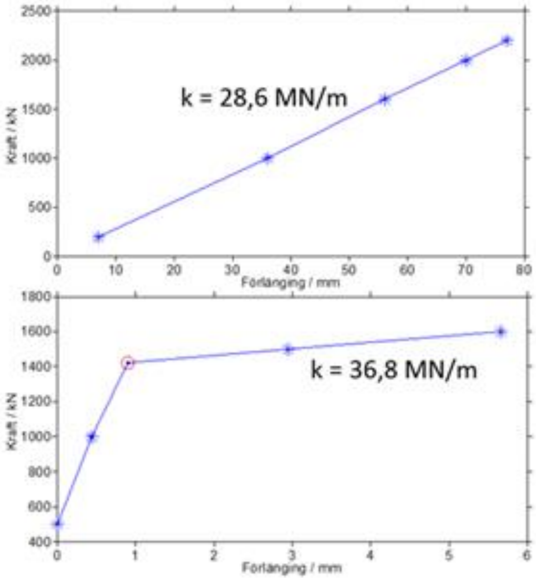
Tendon force measurements

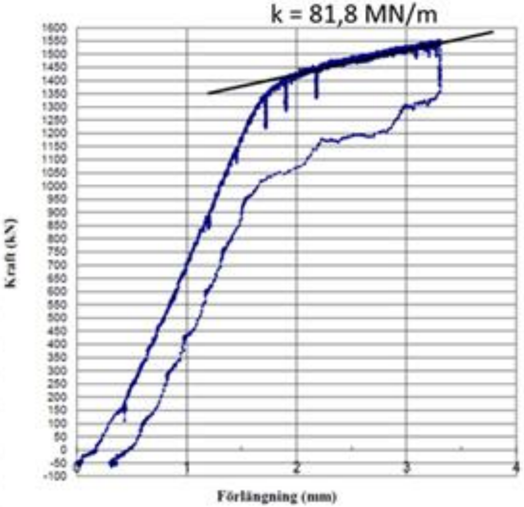
Difference between different contactors:

- Up to 20 % regarding the tendon force.
- More than 200 % regarding stiffness of the tendon.

$$k_{teor} = \frac{195 \cdot 10^3 \cdot 2850}{19.5} = 28.5 MN/m$$







$$k_{teor} = \frac{195 \cdot 10^3 \cdot 1900}{18} = 20,6\ MN/m$$

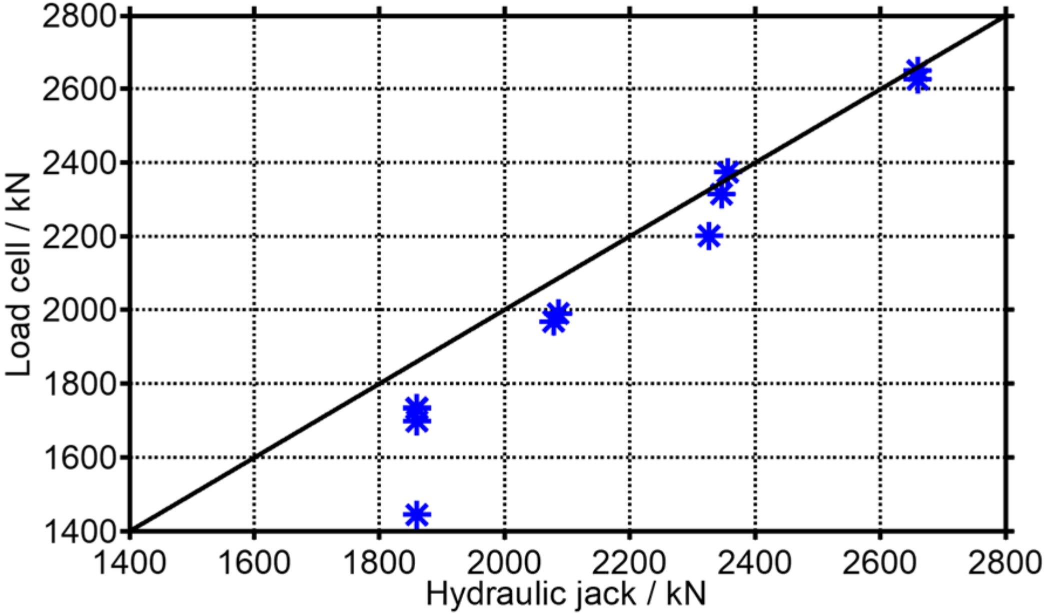
VATTENFALL

Measurement accuracy

Comparison between load cells and hydraulic jack measurements at installation:

– Lift-off tests overestimate the tendon force.

– Difference up to almost 30 %.



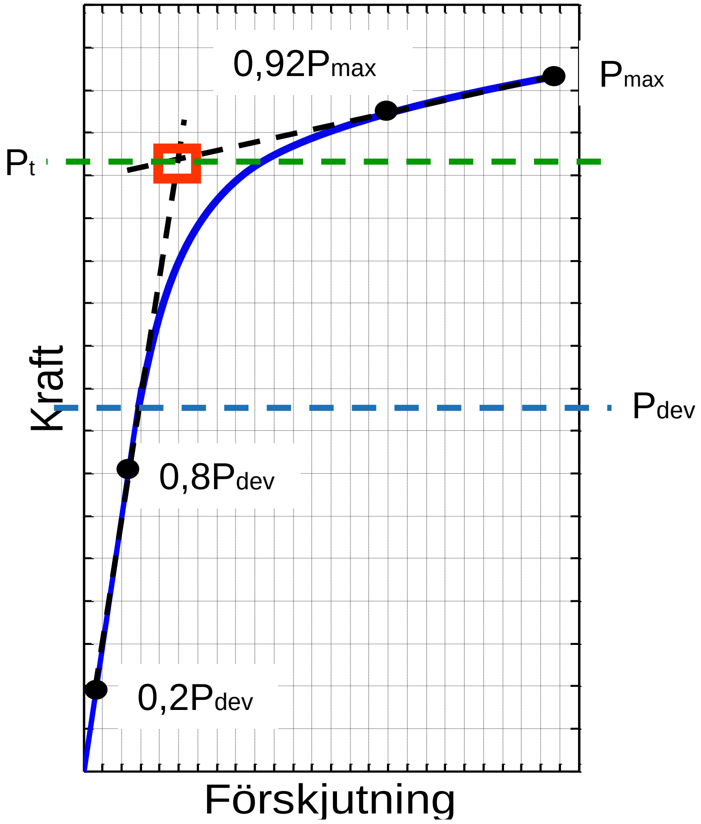
– True forces are lower than the measured forces.

– Reduces structural safety.

New measurement method

Proposition on standardized measurement method:

- Continuous recording of both force and elongation.
- Elongation is measured on either the piston on the hydraulic jack or anchor head.
- Force rate around $0{,}1P_0$/min
- Maximum force is the lowest of $1.2P_0$ or 0.1% of strain in the tendon.
- Visual confirmation that lift-off has occured.



Tendon force management

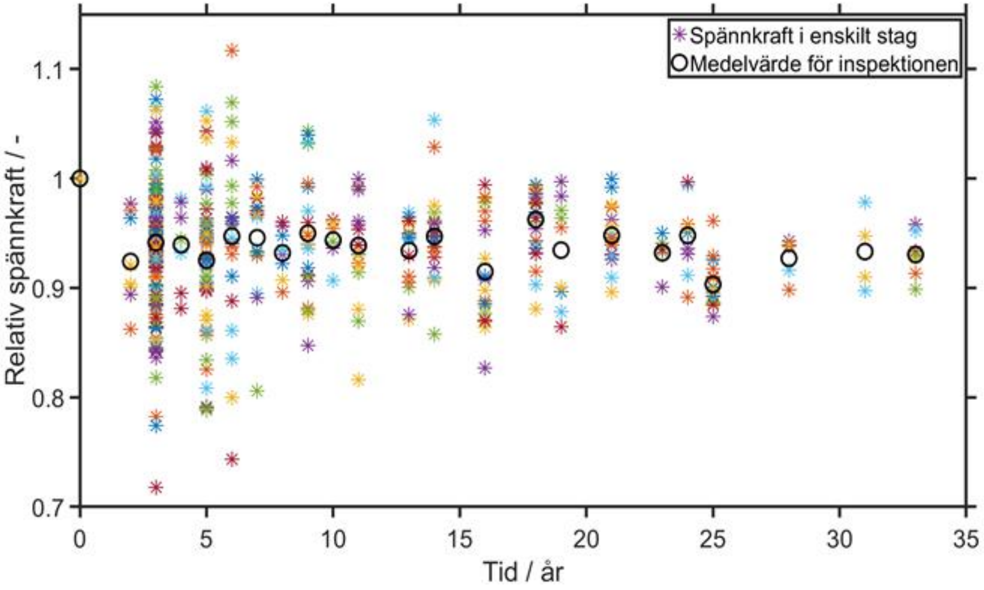
Tendon force management

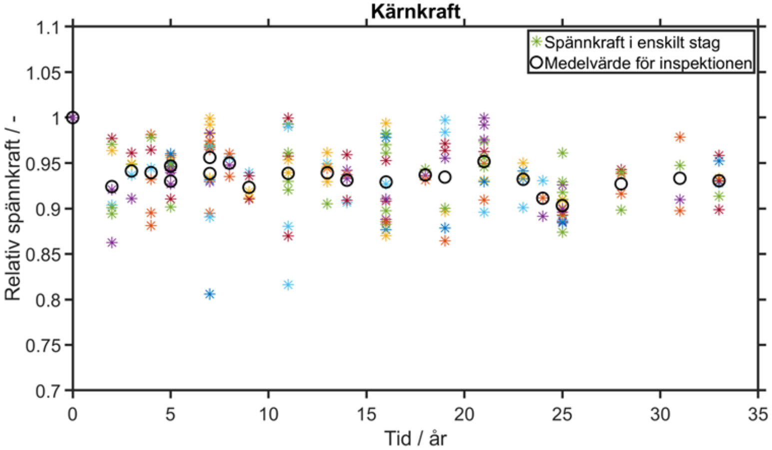
No standardized methods for tendon force management exist regarding e.g.:

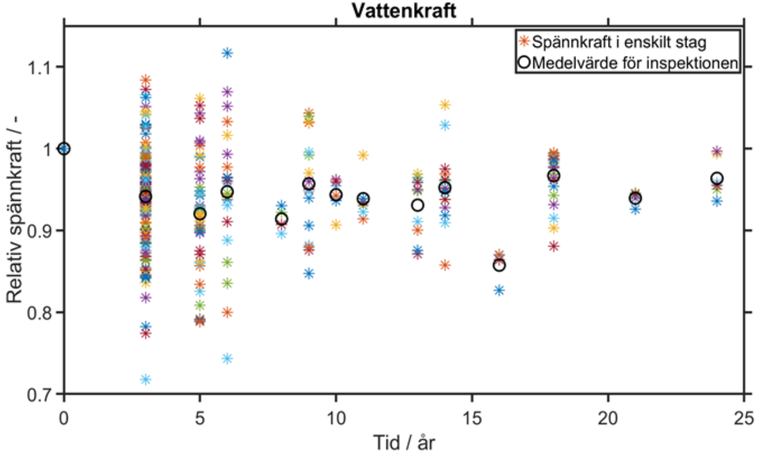
- Acceptance criteria for measured tendon forces during service:
  - Only general criteria, e.g. 10 % loss of force.
  - No relation between criteria and tendon force for balancing the design loads.
- Safety margin between lock-off tendon force and the tendon force from design:
  - No standard method for e.g. predicting prestress losses.
  - In some cases the lock-off tendon force is equal to the force needed to counterbalance the design loads, e.g. no loss of force is allowed.

Measured tendon forces

Measured tendon forces in both nuclear and hydro power structures

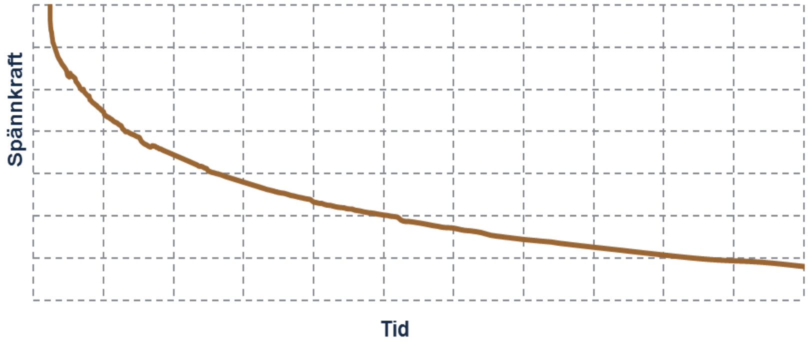


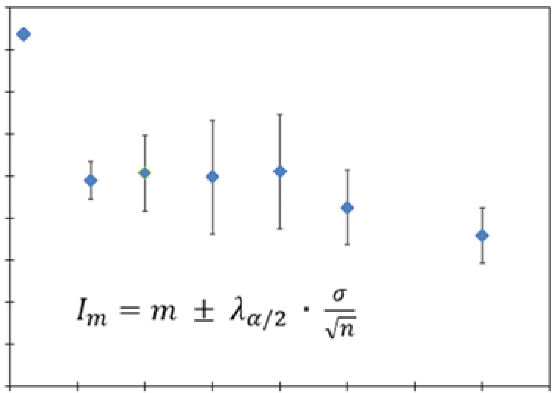




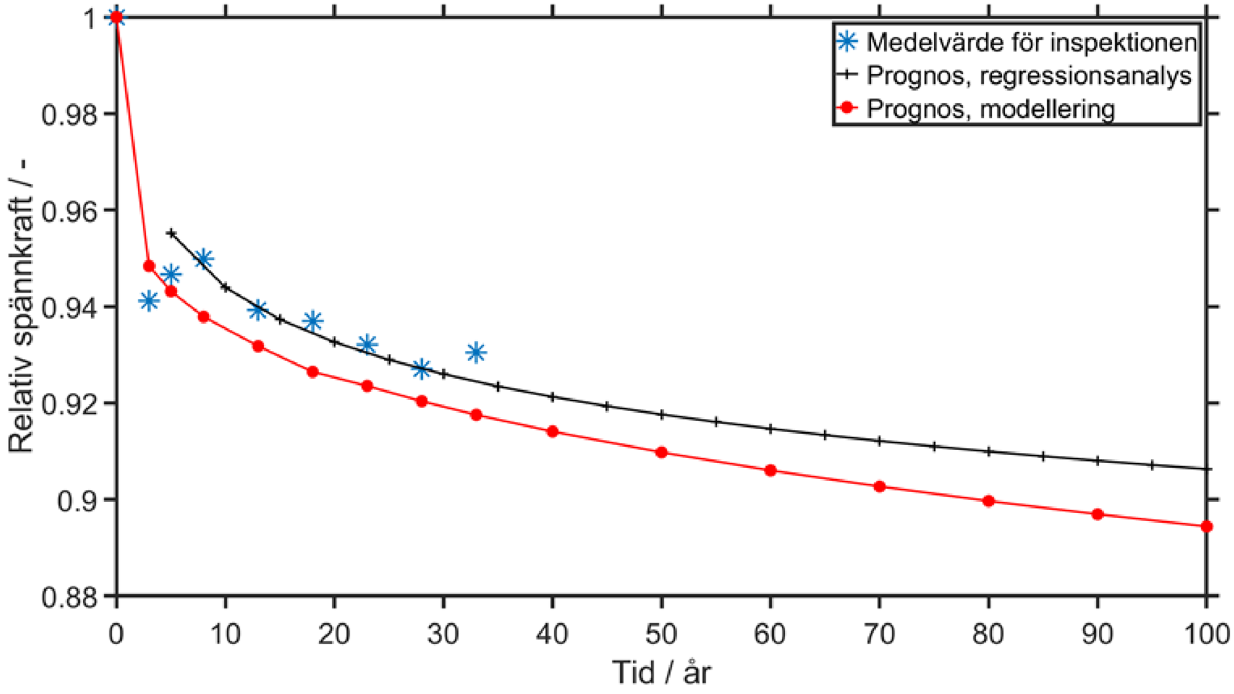
Prediction of tendon forces

- Two different methods for predicting tendon force development over the design life:
  - Regression analysis on measurement data,
  - Modelling using prediction equations i Eurocode 2 (creep, shrinkage and relaxation),
- Predictions are based on the mean value of the tendon forces in the structure,
- Confidence intervals for estimating lower boundary levels:
  - Estimate of an interval for the mean value of the tendon forces.
  - Confidence levels of 0.95 and 0.99 were chosen for the estimate.





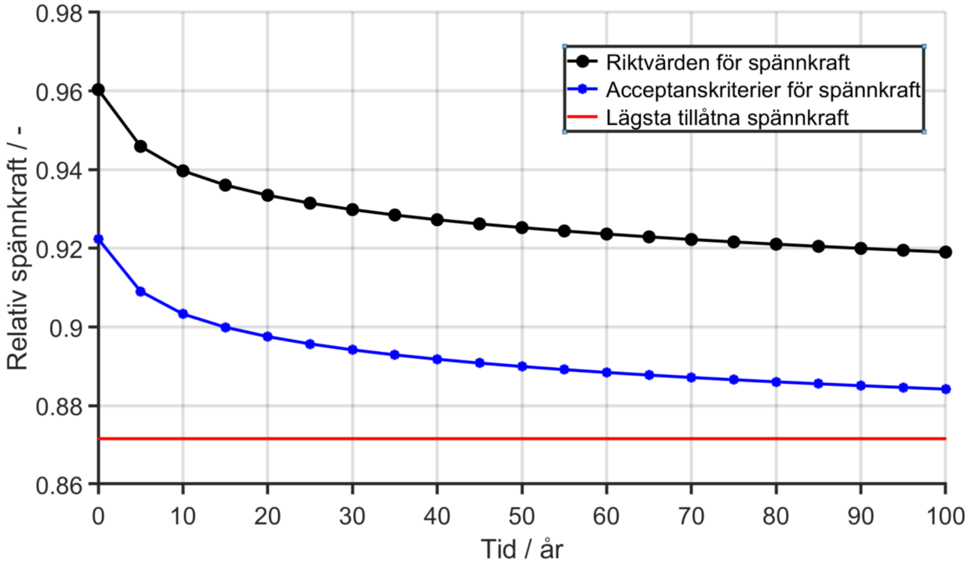
Prediction of tendon forces



Acceptance criteria

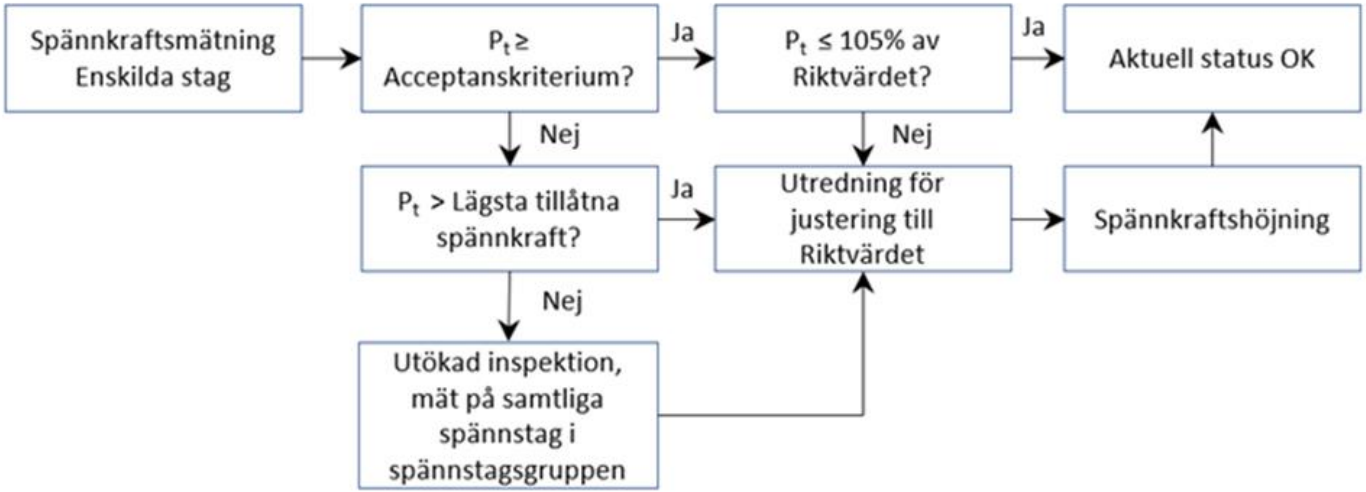
Acceptance criteria for measured tendon forces:

- Expected tendon force = estimated mean value.
- Acceptance criteria (for further investigation) = 0.95-interval for estimated mean value.
- Lowest acceptable tendon force (lock-off force at tensioning) = 0.99-interval for estimated mean value.



Evaluation of measurements

Guidance on evaluation of tendon force measurement on one tendon related to the proposed acceptance criteria.

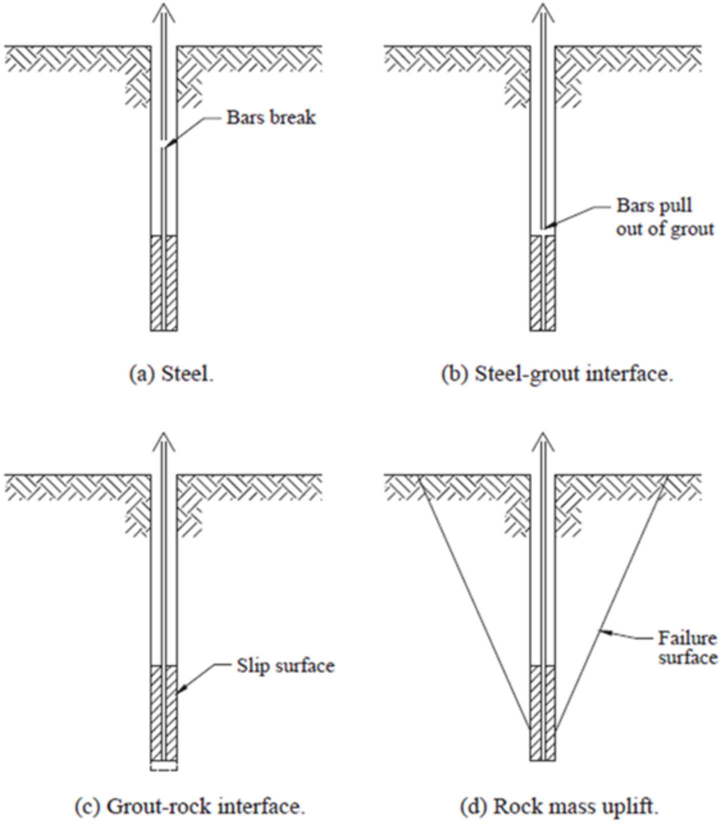


Anchor zone

Failure modes

Five failure modes are considered in design:

1. Post-tensioning steel.
2. Steel-grout interface.
3. Grout-rock interface.
4. Rock failure, i.e. rock mass uplift.
5. Grout-duct interface.



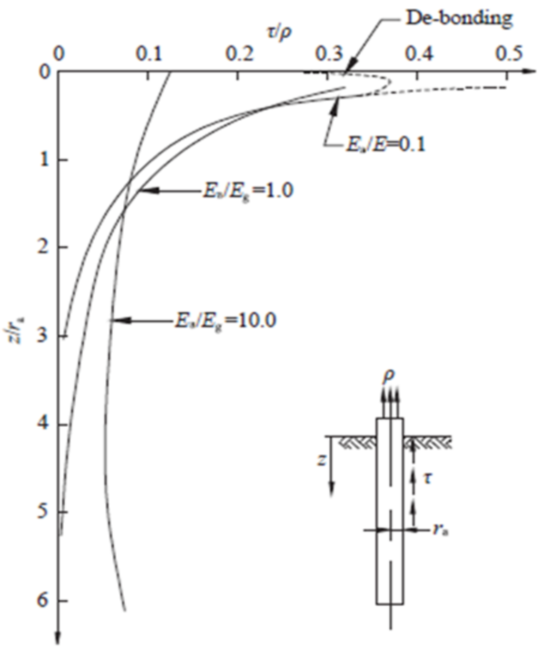
Brown, E.T: Rock engineering design of post-tensioned anchors for dams – A review, Journal of Rock Mechanics and Geotechnical Engineering 7 (2015) 1-13.

Steel-grout or grout-rock interface

Over-conservative assumptions are being made in design:

- Uniformly distributed shear resistance is assumed.
- In reality, the stress distribution depends on the modulus of elasticity of rock, grout and tendon.

- Other factors influencing the load bearing capacity:
  - In-situ stresses in the rock mass.
  - Variations in the rock mass, e.g. shear zones or faults.
  - Strength of the grout.

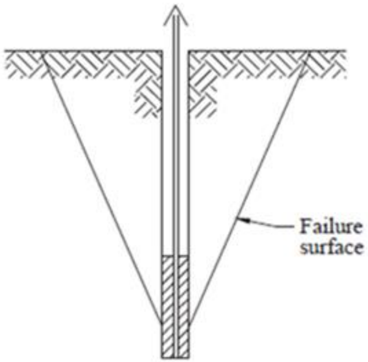


Brown, E.T: Rock engineering design of post-tensioned anchors for dams – A review, Journal of Rock Mechanics and Geotechnical Engineering 7 (2015) 1-13.

Rock mass failure

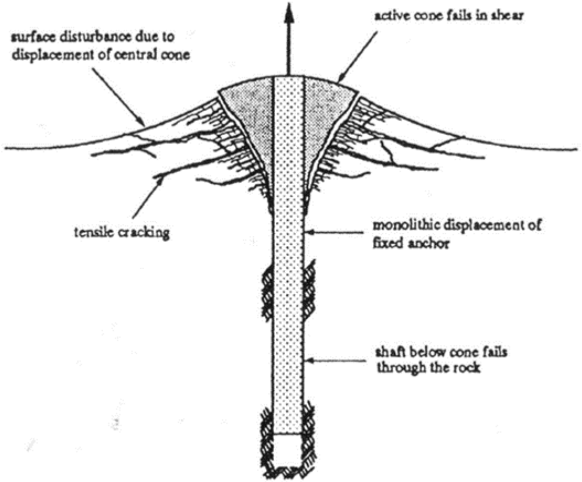
Over-conservative assumptions are being made in design:

- Resistance = weight of a rock cone.
- Tensile strength of the rock is neglected.
- In tests almost no rock failure is observed for anchorage lengths > 4.5 m.
- In most tests the failure load is 7 – 65 times the weight of the rock cone.



(d) Rock mass uplift.

Brown, E.T: Rock engineering design of post-tensioned anchors for dams – A review, Journal of Rock Mechanics and Geotechnical Engineering 7 (2015) 1-13.



Weerasinghe R.B., Littlejohn G.S., Uplift capacity of shallow anchorages in weak mudstone, Ground anchorages and anchored structures, 1997.

VATTENFALL

Failure modes

Theoretical example where:

Strand based tendon: 12 x 15,7 mm strands, tendon force: 2000 kN, diameter of duct: 100 mm, Grout bond strength = 3 MPa, Rock mass tensile strength = 3 MPa

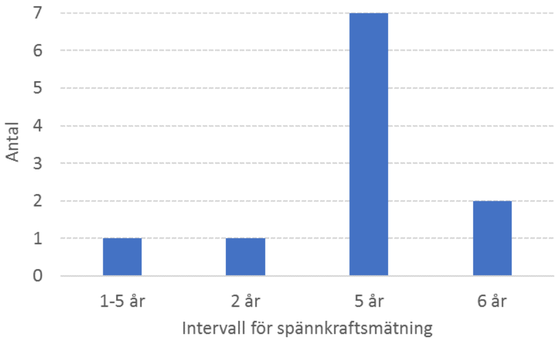
Failure mode	Bond zone length / m
Tendon/grout	1.3
Grout/rock	3.2
Rock failure, cone angle = 60°	7.1
Rock failure, cone angle = 90°	4.9
Rock failure incl. rock strength, (cone angle = 60°)	0.67
Rock failure incl. rock strength, (cone angle = 90°)	0.46

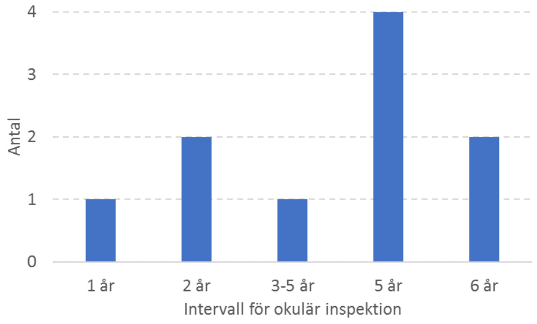
Inspection program

Inspection program

Review of standards and recommendations regarding rock anchors and tendons (e.g. hydro and nuclear power):

- Monitoring extent (number of inspected tendons):
  - 50 – 100 % (in hydro power)
  - 2 – 15 % (rock anchors, nuclear power)
- Inspection frequency
- Acceptance criteria:
  - Only general acceptance criteria are given in most standards, e.g. < 10 % prestress losses.
  - Only in regulations for tendons in the nuclear industry are the acceptance criteria related to external loads.





VATTENFALL

Design of inspection program

Recommendations regarding:

- Extent of the inspection (number of included tendons).
- Frequency.
- Acceptance criteria.
- Tendons divided into groups based on:
  - Structural parts.
  - Purpose of the tendons.
- Two types of inspections:
  - Annual visual inspection of anchorage zone.
  - Detailed inspection every 4 – 6 years (including tendon force measurements)

Dam safety class	Number of included tendons / %
A and B	50
C	33
E	20
D	33 or 20

Thank you for your attention!

Reports from the different project phases can be found on the following links:

1. Sammanställning över spännstag inom vattenkraften
2. Övervakning av status på vattenkraftens spännstag
3. Rekommendationer för hantering av vattenkraftens spännstag