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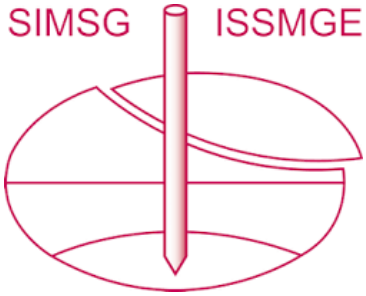

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Monitoring of permanent post-tensioned rock anchors

Surveillance d'ancrages permanents en post-tension dans la roche

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ABSTRACT: The methods used in design of anchors in strong unweathered rock types is often based on conservative assumptions. The paper presents monitoring data from post-tensioning, and the first year in service, for permanent rock anchors used to support the foundations for three design power line transmission towers in Norway. The towers consist of a steel tube, 1.8 m in diameter, which is attached to octagonal shaped concrete foundations slabs casted directly on a blasted rock surface. The total height of the towers are 32.3 m, 34.8 m and 38.8 m respectively. The foundations are anchored with 12 steel rod tendons (Ø40 mm), each of them installed and grouted 12 m into strong rock. Presented results from elasto-magnetic sensors installed at different depths in the fixed length of the anchors confirm a non-uniform bond stress mobilization, in contrast to common assumptions in design today. Load cells at the anchor heads also show a loss of post-tension force between 40 to 80 kN during the first 399 days after tensioning, corresponding to about 4-10 % of the lock-off tension force. The plan is to gather monitoring information from the anchors for at least ten years, to gain more knowledge on the long-term behavior and hopefully improve the current design methodology for anchors in strong rock types.

RÉSUMÉ: Les méthodes utilisées pour le dimensionnement des ancrages dans les types de roches dures non altérées sont souvent basées sur des hypothèses conservatrices. Le document présente des données de surveillance sur des ancrages permanents dans la roche utilisés pour soutenir les fondations de trois pylônes de lignes électriques en Norvège. Les pylônes sont constitués d'un tube en acier de 1,8 m de diamètre, d'une hauteur totale de 32,3 m, de 34,8 m et de 38,8 m, fixés respectivement à des fondations en béton de forme octogonale, directement sur une surface de roche dynamitée. Les fondations sont ancrées à l'aide de 12 tendons d'acier (Ø40 mm), chacun d'eux installé et injecté dans 12 m de roche solide. Les résultats présentés des capteurs élasto-magnétiques installés à différentes profondeurs le long des ancrages, confirment une mobilisation non uniforme des contraintes de liaison, contrairement aux hypothèses courantes dans la conception de nos jours. Les cellules de charge en têtes d'ancrage montrent également une perte de force de post-tension d'environ 40 à 80 kN pendant les 399 premiers jours suivant la mise en tension, ce qui correspond à environ 4 à 10% de la force de tension de blocage. L'objectif consiste à mesurer des données aux ancrages pendant au moins dix ans, dans le but d' acquérir davantage de connaissances sur le comportement à long terme et, si possible, à améliorer la méthode de dimensionnement pour les ancrages dans les roches dures.

Keywords: Anchor; monitoring; rock; bond resistance

1 INTRODUCTION

Post-tensioned anchors are often used to maintain the overall stability for tall structures founded on rock, e.g towers for bridges, powerlines and wind turbines. Such structures often have low self-weight, and are subjected to large lateral forces and moments. Inspection of ground anchors is practically impossible. Thus, monitoring the behaviour of anchors is important to assess and to document that they are performing as intended during the structures service life time.

The methods used for design of rock anchors in strong, unweathered rocks like the ones often encountered in Scandinavia, is based on conservative assumptions. Despite extensive research on rock anchors in the past seventy years, summarized by Littlejohn and Bruce (1975) and Littlejohn (1997) the progress has been limited. However, by testing and monitoring the behaviour at the specific site, it is possible to optimize the design and reduce the costs.

The paper presents and discuss monitoring results from permanent post-tensioned anchors used to support the foundations for three specially designed power line towers in Norway. Some concluding remarks are given in the end. The aim is to gather monitoring information from the anchors for at least ten years. With more knowledge about the long-term behaviour we hope to improve the current design methodology for anchors in strong rocks.

2 PROJECT DESCRIPTION

2.1 Objective

Statnett SF have constructed a new 420 kV power line from Lysebotn to Tjørhom in the south-western part of Norway, see map in Figure 1. The power line passes a popular viewpoint at tower No. 9. Here Statnett wanted to erect a new type of tower, with a design that suits the landscape and do not diminish the enjoyment for ten thousands of tourists visting each summer. An industrial designer proposed to support the conductors by three independent tall and slim steel tube towers, see picture in Figure 2.

Figure 1. Map of the southern part of Norway with the location of Lysebotn illustrated. (Source: Google Earth © Google, 2018)

Figure 2. Picture of the steel tube towers at tower No. 9 above Lysebotn during tensioning of powerlines in May 2018. (Source: Statnett SF)

2.2 Geology and rock mass classification

The specially designed towers are constructed in an area with a bedrock consisting of igneous granodiorite and granitic gneiss. Based on a geological mapping of the rock surface, the rock mass was classified as class 1 according to a technical specification developed for Statnett SF, described by Valstad et.al. (2016). The bedrock at the site is slightly jointed with two joint sets and a joint spacing between 0.6 m to 2.0 m. The

rock is slightly weathered along the joints. The unconfined compressive strength of intact rock is above 50 MPa.

2.3 Design of foundation slab and anchors

When the idea of three tall steel tube towers came up, it was quickly decided that post-tensioned anchors would be the best solution to maintain overall stability of the foundations.

The three steel tube towers are 1.8 m in diameter, and placed with a centre distance of about 10 m. The height of the towers from top of foundation is 32.3 m, 34.8 m and 38.8 m. Each tower is attached on an octagonal foundation slab of 2.0 m thickness. The foundation slabs are casted directly on a rock surface which is levelled by blasting and chiselling. The foundations are anchored deep into bedrock using 12 steel rod tendons, each with 12 meter total length. Figure 3 presents a plan view of the tower foundation with rock anchors, and Figure 4 a picture of the concrete foundation and anchors.

The power lines and the towers are in this area subjected to large environmental loads from wind and ice. Since the overturning moments on the towers are large compared to the stablilizing gravity loads, post tensioned anchors is an efficient solution to acchieve satisfying stability. Table 1 presents the critical load cases and foundation design loads for tower No. 9, calculated according to the Norwegian Electrotechnical standard NEK EN 50341-16 (2009) and design rules by Statnett SF (Valstad et.al., 2016).

Table 1. Design loads (actions) including load factors acting in centre top of the concrete foundation in tower No. 9.

Load combination	Vert. load [kN]	Hor. Load [kN]	Moment [kNm]
1 Full ice load	-284	266	6600
2 Wind + ice on line	-222	195	4390
3 Line failure	-256	309	8263
4 Installation	-147	217	5706

The anchors are designed according to Eurocode 7 (2016) and Eurocode 2 (2008) for a service life time up to 100 years. The selected anchor system have European technical approval (ETAG, 2012). All anchors are made with double corrosion protection according to EN 1537 (2013) by encapsulation with a corrugated sheating filled with cement grout. Design of the rock anchors and determination of necessary post-tensioning force follows the eccentricity criteria given by the German standard DIN 1054 (2015).

To achieve satisfying stability for the foundations, 12 anchors, each with a diameter of 40 mm and a post-tension force of minimum 650 kN was required. Taking into account future stress loss due to relaxation in steel, friction loss, plus creep and shrinkage of concrete, the lock-off load P_0 was set to 750 kN. Acceptance testing of each anchor was carried out as part of tensioning with the procedure shown in Table 2. The final proof load P_p was set to 945 kN, equal to 79% of the characteristic yield capacity $R_{0.1k}$. The proof load was kept constant for 10 minutes for all anchors, and no displacements were measured.

Table 2. Procedure for tensioning and acceptance testing of rock anchors.

Step	Tension force (kN)
0 – Datum load P_a	75
1 – $0.35 \times P_p$	330
2 – $0.60 \times P_p$	570
3 – $0.85 \times P_p$	800
4 – $1.00 \times P_p$	945
5 – Datum load P_a	75
6 – Lock-off P_0	750

The required fixed length of rock anchors is determined based on the bond resistance between tendon and grout ($f_{bc,d}$) as well as between grout and rock surface ($f_{br,d}$). The design was based on an assumption of a uniform bond distribution along the fixed length, with $f_{bc,d}$ = 1.8 MPa and $f_{br,d}$ = 1.0 MPa which gave a required fixed length of 5 m for a 100 mm diameter borehole.

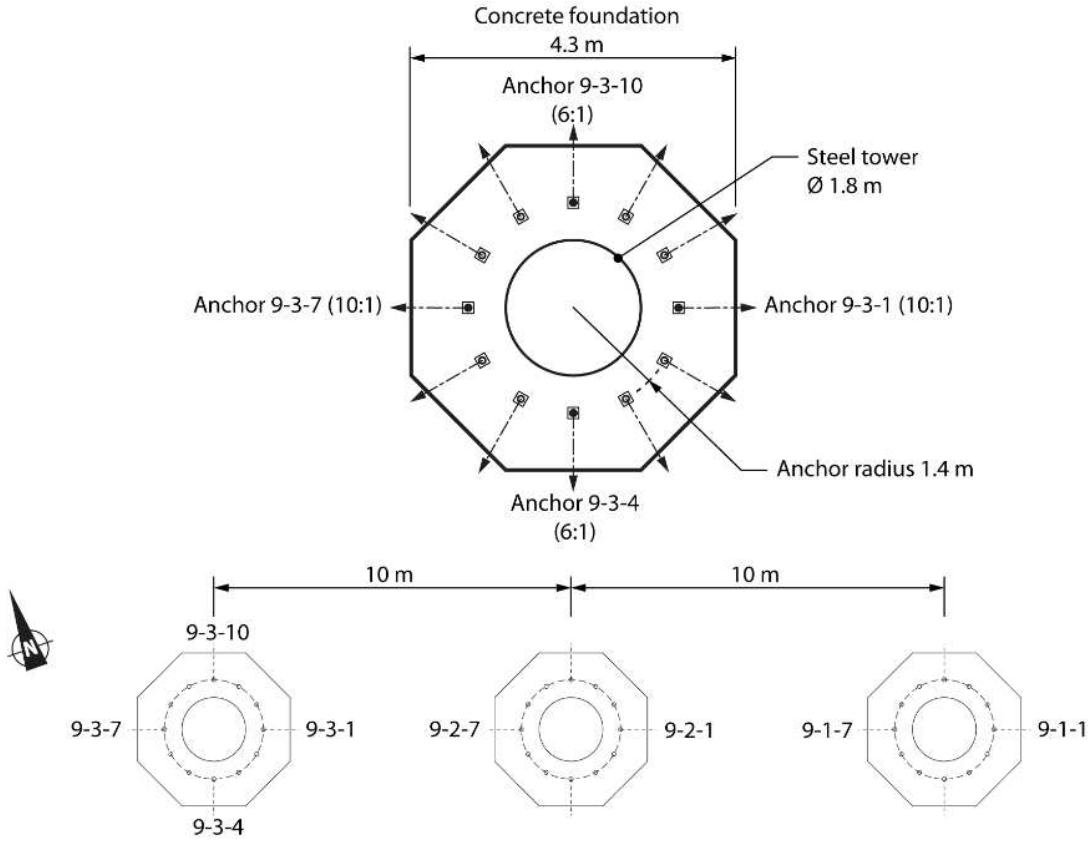

Figure 3. Plan view of octagonal shaped concrete tower foundations with rock anchors (Ø40 mm) at tower No. 9. The anchors are installed with an outward inclination, and plunging alternately 10:1 and 6:1.

Figure 4. Octagonal concrete foundation for tower No. 9-3 showing the rock anchor heads and the template with foot bolts prior to attaching the tower.

2.4 Monitoring of anchor load

As part of an R&D cooperation between NGI and Statnett SF, four of the anchors for foundation No. 9-3 have been equipped with elasto-magnetic sensors (Wang et.al., 1998) to measure the anchor load. The sensors are installed at 0.3 m, 1.5 m and 3.0 m depth measured from the transition between free (elastic) and grouted fixed length. It is the first time that these type of sensors are being used in geotechnical application in Norway. In addition to the sensors deep in the bedrock, there are also load cells underneath the anchor head, where the anchor load is transferred to the concrete foundation, see picture in Figure 5.

The objective is to monitor how the tensile force in the anchor is mobilized and distributed along the fixed length of the anchor. The aim is to monitor the anchor performance over a long period to assess the long-term behaviour of the anchors.

Figure 5. Anchor head with protective steel cap, load cell and cables from elasto-magnetic sensors coming up through steel plate.

3 MONITORING RESULTS

Figure 6 presents the tensile forces in the anchors measured by the elasto-magnetic sensors during post-tensioning 13th September 2017. All sensors showed a reference value of about 70-80 kN before tensioning started. The sensors at 0.3 m depth showed a clear response to the increasing load steps during tensioning. For the proof load, P_p = 945 kN, they showed a tensile force of 640 to 700 kN subtracting the reference force. Limited response of only 10 to 100 kN was measured in sensors at 1.5 m depth, while no response was noticed in the two sensors at 3.0 m depth during tensioning.

New readings were carried out in February 2018 after the steel tube towers were installed, and similarly during tensioning of the power lines between tower location 1 and 12 in early May 2018. The measured tensile forces in the anchors seem to be rather stable and unaffected by the installation work. However, by comparing to the results right after post-tensioning (Figure 6), there has been a slight decrease in the sensors at 0.3 m depth of 10 to 50 kN, while the sensors at 1.5 m depth show an increase in force of 30 to 70 kN.

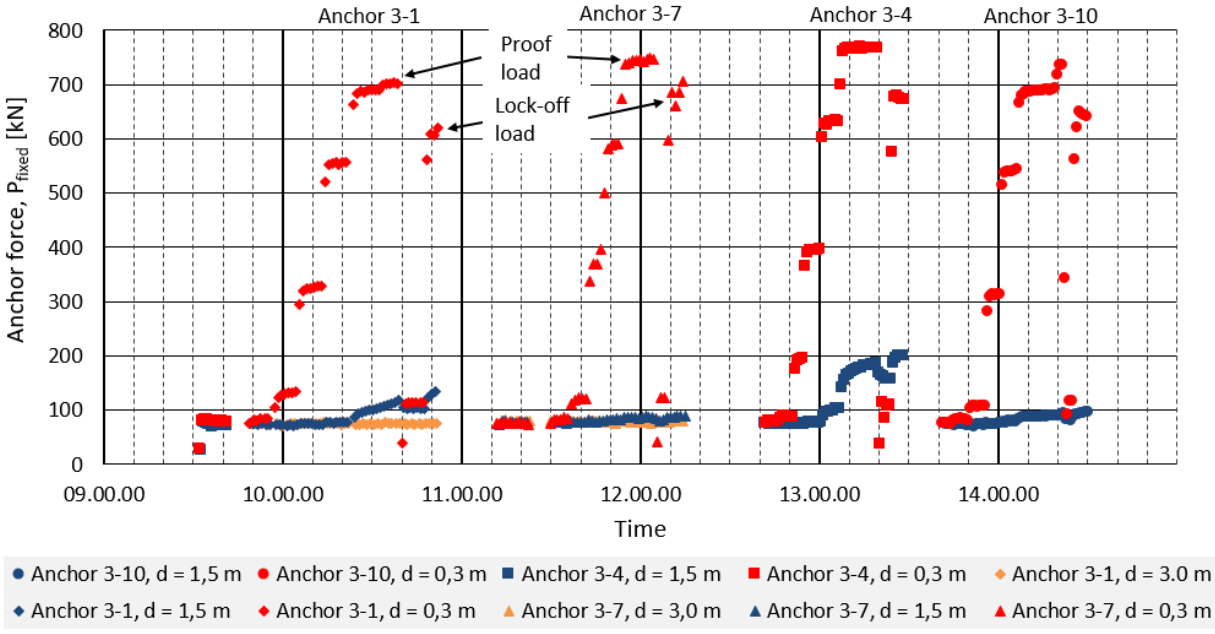

Figure 6. Measured tension force in different depths of the fixed length of rock anchors during post-tensioning 13th September 2017.

Figure 7 presents measurements from load cells at the anchor heads during the different steps of post-tensioning, and the following 399 days after lock-off of the anchors. There were some variations in the anchor load at the different tensioning steps, probably due to some imperfections in the anchor inclination and friction in the tensioning system. The load cells were used to tune in the specified lock-off load P_0 = 750 kN. The results show a general trend of tension loss in the range of 40 kN (4%) to 80 kN (10%) during the first 399 days after lock-off. Anchor 9-3-4 showed an unexpected increase in force during the first 189 days, and after 399 days it was over the maximum load range of the load cell. That means that the load cell is most likely out of function.

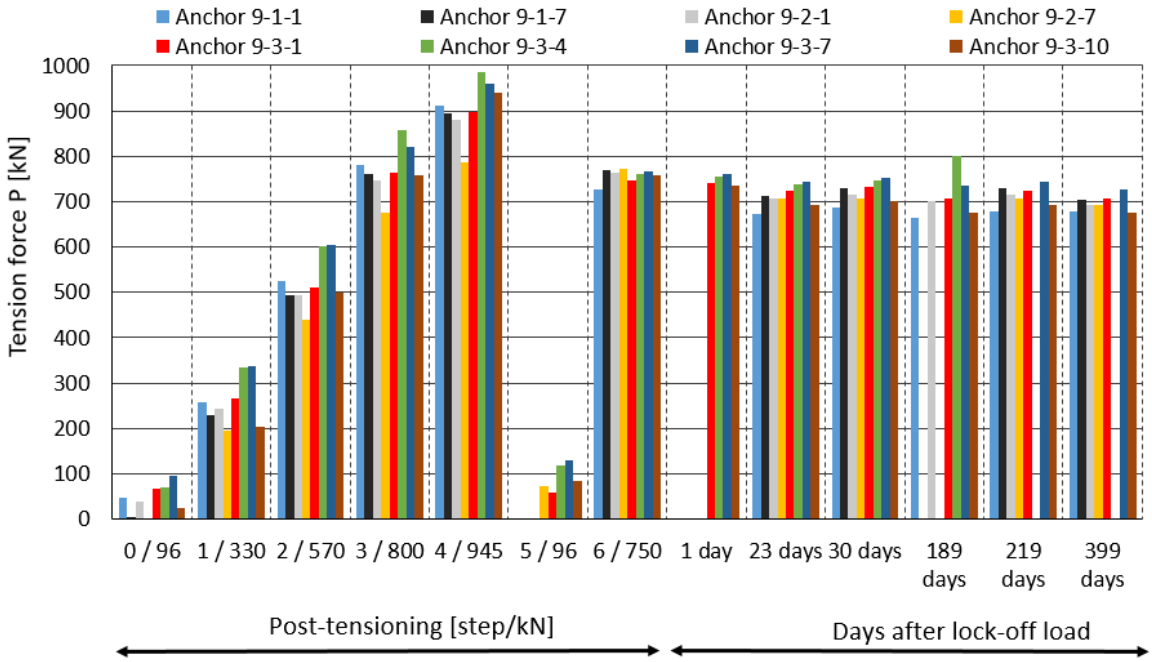

Figure 7. Tension force P in rock anchors measured with load cells on anchor head. Results from post-tensioning steps 0 to 6 (left side), and the first 399 days after lock-off load (right side).

4 DISCUSSION

The monitoring results presented in Figure 6 clearly show that most of the tensile force applied by the hydraulic jack at the anchor head is mobilized in the upper part of the fixed length, thus proving a non-uniform bond stress distribution. This is in good aggreement with previous theoretical analysis and experimental field tests described by Littlejohn and Bruce (1975). Numerical modelling by Coates and Yu (1970) showed that non-uniformity is likely to appear for most rocks where the ratio between Young modulus for grout and rock, E_{grout}/E_{rock} is less than 10. This means that the uniform distribution often used in anchor design is non-realistic for most rock types in Scandinavia, where the ratio typically is in the range between 0.5-2,0.

The results also indicate that no, or limited partial debonding, has taken place in the proximal end of the fixed length, thus confirming a low utilization ratio of the real ultimate bond strength between tendon-grout and grout-rock. This is in

accordance with previously published results (Phillips, 1970) and (Littlejohn and Bruce, 1975). For strong rocks, it seems reasonable to choose a characteristic ultimate bond strength between grout and rock of 1/10 of the uniaxial compressive strength of massive rock, up to a maximum value of 1/10 of the compressive strength of concrete (Littlejohn and Bruce, 1975).

The changes in tensile forces in the fixed length between September 2017 to May 2018 indicate some creep in the rock mass and joints, causing re-distribution of shear stress along the fixed length.

Figure 8 presents the calculated loss of tensile force in the rock anchors due to relaxation in steel, plus creep and shrinkage in the concrete foundation according to Eurocode 2 (2008). For the first year, the calculated total loss is about 25 kN, which is between 30 to 50% of the measured values in Figure 7. One reason for this difference could be the assumptions and uncertainties related to the creep and shrinkage calculations for the 2 meter thick concrete foundations. However, the effect from creep and shrinkage should be much less than relaxation in steel. Another reason could be that creep in the rock mass is neglected, taking into consideration the strong, competent bedrock at the site. Future readings will provide valuable data to assess the performance of the anchors, and decide if re-tensioning is necessary.

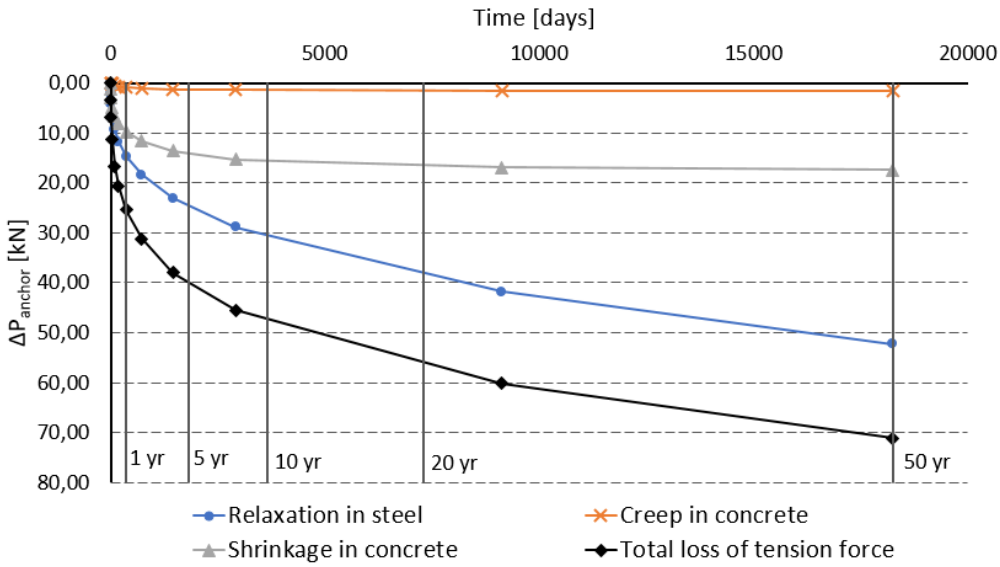

Figure 8. Calculated loss of tension force in rock anchors at tower point 9 due to relaxation in steel, plus creep and shrinkage of concrete foundations.

5 CONCLUSIONS

This paper presents monitoring data from post-tensioned anchors in strong rock. The data confirm that the common assumptions of an uniform bond stress distribution along the fixed anchor length is non-realistic for strong rocks. The design values for bond strength between cement grout and rock commonly applied in Norway underestimates the real strength. Testing of ultimate anchor capacities by pull-out tests, combined with monitoring are recommended to help improve the design.

The measured loss of tensile force in the anchors during the first 400 days after installation is higher than predicted, thus indicating that effects from creep in the concrete and the rock mass is underestimated. Future readings of load

cells and sensors will provide valuable data to help assess the long-term performance. This will also assist in the decision if re-tensioning is necessary during the service lifetime for the power line towers. The aim is to improve the current design of anchors in strong rock based on the knowledge gathered through this project.

6 ACKNOWLEDGEMENTS

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