Verification of the rock anchor design on the rock anchored wind turbine foundation with real-world measurements

Juha Tirkkainen1 and Matti Kangaspurokari1
1Ramboll Finland Oy and 2Structures and Construction Technology Research Group, University of Oulu

Abstract
Experimental measurements were carried out in Saarenkylä Wind Farm, Finland, to verify Peikko’s current FEM-design procedure of the rock anchors in the rock anchored wind turbine foundations. It was observed that stresses of the rock anchors in the FE-models matches measured stresses, if modelling technique of the rock anchors can take prying and bending effects into account. These and local deformations in the clamped parts and joint components causes partial joint separation in earlier stage than linear theories predict. Deformation of the adapter and characteristics of the tower bolt and rock anchor joint combination leads to a fact that behavior of the rock anchor may be highly non-linear. The stress state of the rock anchor is combination of tension, which is effected by prying, and bending stresses [1]. Depending on pre-tension force level these effects may have significant influence on the fatigue life of the rock anchors.

Objectives
This research is part of larger series of full scale measurements in Saarenkylä Wind Farm set up by Peikko Group. One rock anchored foundation of Vestas V126-3.3MW wind turbine is instrumented with extensometers, strain gauges and load cells from depth of 30 meters in the rock up to the turbine shell. The objective of the whole research is to verify Peikko’s current design procedure and form a basis for future the research and development of the wind turbine foundations. Measurements started at 8th of November 2016 and have been active since then for short electrical breakdowns.

Methods
Acting forces on the rock anchors were measured with load cells which were installed to four inner side rock anchors such that angle between each measuring point is 90 degrees. Stress state of the tower shell was measured with strain gauges at the height of one meter from six measuring points. Tower bending moment and wind direction were calculated from the measured strain data. Measuring frequency with all sensors was set to 10Hz. Measured data was split into 10 minute events and filtered with 9th order Savitsky-Golay filter. For comparison between methods, zero load point of the measured rock anchor force was shifted to match pre-tension force of 1200kN (666MPa).

Overall 50 main wind direction events were examined, including gusts, startups, shutdowns etc. In the main wind events maximum deviation from the main wind directions was allowed to be ±2 degrees. Bolt force diagrams, as presented in Figure 5, were generated from 50000 samples and were compared to analytical and numerical design calculations.

Static analysis of the rock anchors consists of analytical calculations with the theories of the preloaded bolted joints and numerical calculations with FEM. Analytical methods follow theory presented in VDI2230 [8], in which the stiffness of the joint is controlled by the free length of the rock anchor. FE-analysis was carried out with Abaqus CAE software. Three different models were generated with different bolt modelling techniques:

- In first model all tower bolts and rock anchors were modelled as connector elements.
- In second model instrumented rock anchors were modelled as solids, others as connectors.
- In third model instrumented rock anchors were modelled as beams, others as connectors.

Fatigue analysis from the measured data was carried out with Matlab using Rainflow algorithm by Adam Nieslony [3]. Wind turbine specific design regulations [5,6], e.g. correct Wöhler-curves, were implemented to the code. Fatigue classes 36° [5] and 50 [7] were used in the analysis. Comparative results were calculated with fatigue loads presented by Markov matrices. In all cases, Palmgren-Miner cumulative damage theory was used for fatigue damage accumulation.

Results
Recorded rock anchor forces during sample event at 10.1.2017 are presented in Figure 4. Maximum recorded overturning moment during the measuring period was 110624 Nm. Rock anchor forces were noticed to follow load cases presented in VDI2230 with three separate phases. In the first linear phase, without joint separation, external load is mostly transmitted via the clamped parts, 35% from the external loads was found to be transmitted via the rock anchor [4].

The second phase and partial joint separation starts around the overturning moment of 50000Nm and anchor load increases along the circular path. In the third phase anchor load continues to increase linearly with steeper slope. The anchor load curve was obtained by fitting a curve to the measured data. With all evaluated events anchor load followed the fitted curve very precisely. Correlation between measured data and FE-models was obtained to be excellent, as presented Figure 6, especially with the cases of solid and beam modelled rock anchor.

Conclusions
The scope of this research was to analyse measured data from the rock anchored wind turbine foundation and compare results with the design calculations. Measured rock anchor forces were noticed to follow presentation in VDI2230 with the circular increase of the rock anchor load in the partial joint separation phase. Correlation between measured and design data was found to be excellent and Peikko’s design procedure was verified. It was noticed that modelling technique of the rock anchors should take prying and bending effects into account. With examined foundation, mainly due to high number of rock anchors, different methods ended up with similar fatigue performance and it was noted that in this case rock anchors are not sensitive to the fatigue.

The greatest meaning of this research comes in the future, when turbine sizes are expected to grow significantly. Increased foundation loads mean that effect like bending deformations and prying will be more dominating in design procedure. Increased non-linearity on the rock anchor loads affects also to the fatigue resistance of the foundation. Thus at this point it is very important that design procedure is already benchmarked with data from real world measurements.

References
[8] VDI 2230 (2005) Turbulent calculation of high-duty bolted joints with one cylindrical belt, VERÖFFENTLICHER INGENIEUR.