2017

FJELLSPRENGNINGSDAGEN
Oslo, 23. november 2017

BERGMEKANIKKDAGEN
Oslo, 24. november 2017

GEOTEKNIKKDAGEN
Oslo, 24. november 2017

ARRANGØRER:

NFF

NORSK BERGMEKANIKKGRUPPE

NGF 1950 NORSK GEOTEKNISK FORENING

Tekna

FJELLSPRENGNINGSTEKNIKK

Oslo, 23. november 2017

BERGMEKANIKK

Oslo, 24. november 2017

GEOTEKNIKK

Oslo, 24. november 2017

Arrangører:
Norsk Forening for Fjellsprengningsteknikk, Norsk Bergmekanikkgruppe og Norsk Geoteknisk Forening

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FJELLSPRENGNINGSTEKNIKK
BERGMEKANIKK/GEOTEKNIKK 2017

VARSLINGSSYSTEM UNDER BYGGING AV FOLLOBANE TUNNELENS KRYSSINGUNDER EKEBERG TUNNELENE

Warning system during construction of Follobanen tunnels under the Ekeberg tunnels

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SAMMENDRAG

Denne artikkelen beskriver et nylig case-studie med overvåkning av stabilitet av Ekebergtunnelene I forbindelse med bygging av Follobanetunnelen. Follobanentunnelen krysser ca. 4 under Ekebergtunnelene. I dette prosjektet har SINTEF utviklet en omfattende program som kombinerer kontinuerlig overvåkning av bergspennings- og setningsmålinger med 2-D og 3-D numerisk modellering. Kontinuerlig bergspenningsmålinger og endringer er aktivt brukt sammen med numerisk modellering for å overvåke stabiliteten i Ekebergtunnelene. Dette for å sikre at enhver risiko for ustabilitet i eksisterende tunneler kan oppdages i god tid for å kunne utføre nødvendige korrigerende tiltak.

SUMMARY

This paper presents a case study of a monitoring program for the stability of Ekeberg tunnels in connection with the construction of the Follobanen tunnels, just a few meters below. In this project, SINTEF has developed a comprehensive procedure, combining continuous rock stress measurements and displacement measurements with 2-D and 3-D numerical modelling. Continued rock stress measurements and rock stress change monitoring are actively used together with numerical modelling to monitor the stability situation in the Ekeberg tunnels. This is to make sure that any risk of instability in the existing Ekeberg tunnels can be detected in a good time to make necessary precaution actions.

INTRODUCTION AND BACKGROUND

Bane NOR (Norwegian National Rail Administration) has decided to construct the Follo Line Project – new railway tunnels close to the existing Ekeberg road tunnels in Oslo area in Norway, connecting Oslo and Ski. The project comprises a 22 km long twin-tube-tunnel to be excavated mainly with tunnel boring machines (TBM), but also by drill & blast and drill & split. The drill & blast and drill & split tunnel section is in the first part of the Follobane tunnels, near Oslo Central Station, and where the Follobane tunnels goes under the Ekeberg tunnels. The main construction phase commenced in 2015, and it is scheduled for completion in the end of 2021. Geological conditions of the area can be found in Holmøy et al (2015).

In the first part of the tunnel near Oslo Central Station, there is a special rock mechanics challenge. In this part of the project, the new tunnels intersect the existing road and sewage tunnels at different levels and with short distances. The minimum theoretical distance is less than 4 m between Follobanen tunnels and Ekeberg road tunnels. This makes the intersection very complicated as shown in Figure 1. The construction of the Follobanen tunnels is performed with the following requirements:

- No negative effect on the stability of the Ekeberg tunnels;
- No stopping of traffic in the Ekeberg tunnels during the construction of the Follobanen tunnels;
- Thus, the stability of the existing tunnels must be ensured at all time. Any risk of instability in the existing tunnel must be detected beforehand to make necessary precaution actions;
- Note that the Ekeberg tunnels are about 11.5 m diameter, and the Follobanen tunnels are about 9.5 m diameter.

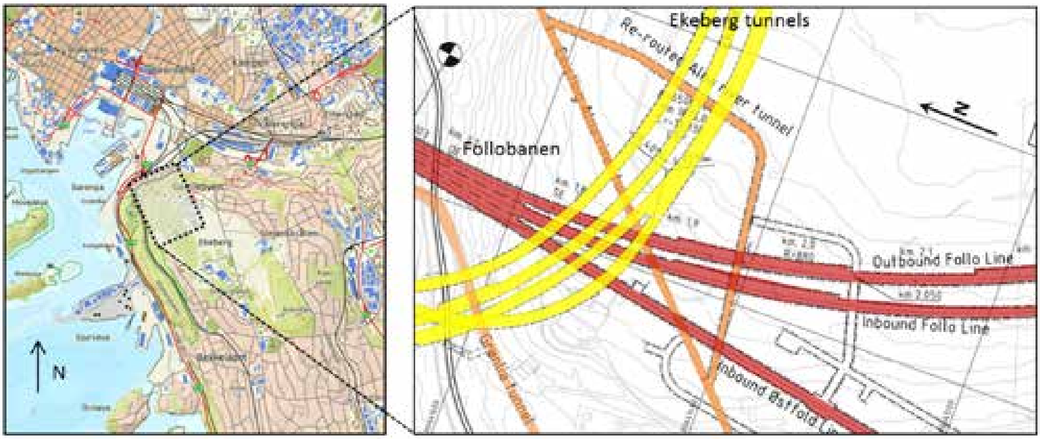

Figure 1. Location of the Follobanen project and layout of the junction area.

SINTEF was invited to assist Bane NOR in dealing with the rock mechanics challenges. To meet the requirements and to study the stability of the existing Ekeberg road tunnels and the Alna river tunnels, SINTEF uses a "tripod-approach", which is combination of Stress measurement/Laboratory – Numerical modelling – Monitoring. In-situ stress conditions obtained from the measurements together with thorough geological mapping provides reliable inputs for numerical modelling. Based on these inputs, a comprehensive numerical model can be established and simulated to provide information needed for further evaluation and decision-making. To increase the reliability of the model even further, equipment for long term monitoring of stress and displacement is installed, and the model is then followed, verified, and improved along the way by communicating with monitoring equipment. Any discrepancy between the model and in-situ observation or monitoring data must be studied carefully in order to detect the pitfalls and possible improvement, so that the model becomes useful tool for planning. This approach has been developed in SINTEF over the years and proven to be realistic, successfully applied in mining projects (Trinh et al., 2016). Based on this approach, the following activities were planned for the Follobanen project:

- Several stress measurements were carried out during pre-construction phase of the project. The measurement included both 2-D and 3-D in some underground openings closest to the concerned intersection area. Laboratory tests for obtaining intact rock mechanics properties were carried out in connection with the stress measurements;
- Geological mapping was carried out to obtain the rock mass characteristics and conditions in the existing tunnels;

- Comprehensive three-dimensional model was established for the entire junction complex, including existing and future tunnels, as shown in Figure 2. The construction of the new tunnels is modelled following the blasting steps and construction sequence as planned. The model will provide results regarding stress distribution, displacement, and yielding zones. The obtained information is used for model calibration in the existing tunnels and evaluation of the overall stability related to the construction of the new tunnels;
- A monitoring program is established. The monitoring program has two main purposes: (i) the measurements will be used to verify and calibrate the numerical model and (ii) to give early warnings if changes in stress conditions start to develop negatively or if deformations affect the stability of the Ekeberg tunnels. The monitoring program is set-up to run in parallel with the construction process. Model verification with visual observation as well as with monitoring data will be performed throughout the whole construction progress. Any discrepancy between the model and reality will be detected and studied for improvement so that the model becomes a reliable tool to predict the stability situation of the upcoming construction stage.

The stress measurement and the establishment of the 3-dimension numerical model can be found in Holmøy et al. 2015. This paper focuses on describing the monitoring and warning system implemented during the construction of the Follobanen tunnels.

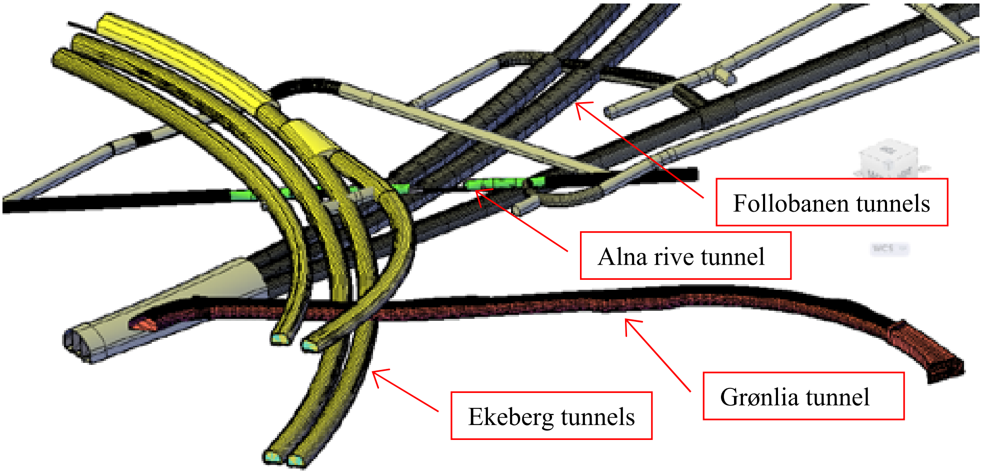

Figure 2: Layout of existing and new tunnels used for numerical model.

MONITORING PROGRAM

A comprehensive monitoring program was established to obtain the information for numerical verification, but more crucially to monitor the behaviour of the rock mass between the existing and new tunnels. During the excavation of the new tunnels, stress and displacement of the rock mass may be developed in connection with the excavation progress. It is very important to catch this development in very early stage, well before any instability problem may appear. The purpose to get early information are:

- Early information can be used to calibrate the numerical model, improving the model along the early construction so that the model becomes a reliable tool for testing the critical excavation stages – excavation close to or directly below the Ekeberg tunnels;

- The stress and displacement development in the rock mass can be followed from the beginning, so that any "unexpected development" can be detected in good time for further study and actions.

Taking into account the purpose of the monitoring, the installation of the monitoring equipment was carefully established and as soon as the suitable locations were available. Some locations were available before construction, but some locations were available only after certain progress of excavation. The monitoring equipment were installed as described below:

- Long-term-door-stopper monitoring (LTDM) in pillar – LTDM-Pillar: This stress monitoring was installed in May 2015, when the excavation of the Follobanen tunnel is relatively far from the Ekeberg tunnels. This LTDM was installed in a horizontal hole in a pillar. This LTDM is almost on top of the centre line of the Outbound Follo Line (OFL);
- LTDM-Floor: This stress monitoring was installed at the same time with the LTDM-Pillar (May 2015). This LTDM was installed in a vertical hole from the floor of the Ekeberg tunnels down toward the planned Follobanen tunnel (Inbound Follo Line - IFL). This LTDM is almost on top of the centre line of the IFL;
- Extensometer-Floor: This displacement monitoring was installed at the same time with the LTDM-Pillar (May 2015). This extensometer was installed in a vertical hole from the floor of the Ekeberg tunnels downward to the planned IFL. This extensometer is almost on top of the centre line of the IFL;
- Extensometer-niche: This displacement monitoring was installed in March 2016. This extensometer was installed in a vertical hole from the floor of the Ekeberg tunnels (in a SOS niche) down toward the planned IFL;
- LTDM-roof: This stress monitoring was installed in October 2016. At this time, the excavation of the Inbound ØstFold Line (IØL) arrived to this location, and thus the LTDM-roof was installed just a few meters behind the tunnelling face. This LTDM was installed in a vertical hole from the roof of the IØL upward. This LTDM is almost on top of the centre line of the IØL;
- Location of the LTDMs and extensometers is shown in Figure 3.

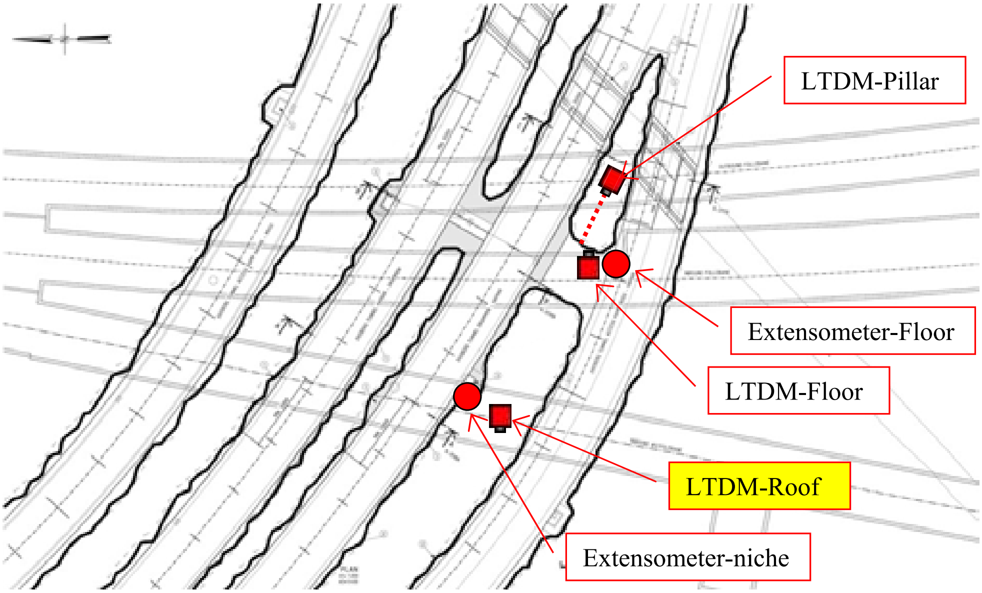

Figure 3: Monitoring equipment – Long-term-Door-Stoppers (LTDMs) and extensometers. The LTDM-roof is in "yellow box" because it is installed in the Follobanen tunnel. All other monitoring equipment were installed from the existing tunnels.

WARNING CRITERIA

Main purpose of the monitoring system was that during the construction of the Follobanen tunnels the monitoring system monitors the development of stress and displacement in the rock mass between the existing tunnels and the new tunnels. When the changes reach to certain magnitude, proper warning will be sent to all involved parties for necessary actions. A warning system similar to traffic light (Green / Yellow / Red) is applied for the construction of the junction between Follobanen and Ekeberg tunnels. The system is described as below:

- Value in "Green" areas meaning that the overall stability condition of the tunnel crossing is good and the excavation and rock support can be performed as planned.

- Value in "Yellow" areas meaning that the overall stability condition is developing toward an unfavourable situation. This situation needs to be followed-up closely. Meeting for evaluation and discussion need to be organised regularly to clarify the development and safety condition;

- Value in "Red" areas meaning that the stability condition is in an unfavourable situation, which may cause instability in the tunnel system. In this situation, all the construction activity must be stopped. Experts must be called-in immediately for inspection and evaluation of the situation and provide a clear action plan for rock support and stability control.

To meet the requirement that "*any unexpected development can be detected in good time for further study and actions*", the monitoring equipment is logged every 10 minutes, and the logged data is posted in a provided website as graphs of continuous change of stress and displacement. An information technology company was used to provided and design the website so that necessary warnings ("Yellow" or "Red") are send automatically when the monitoring values reach the correspondent thresholds.

According to the warning system described above, when the value of stress and displacement is in "Green" range, no warning is necessary. As soon as stress or displacement reaches "Yellow" range, SMS and email will be sent to all registered mobile phones and email addresses, and necessary actions as described will be implemented. Similar procedure is applied when the value of stress and displacement reach to "Red" level.

During very early stage of the construction (in 2016), when the construction was still relatively far from the junction area and limited information regarding the rock mass behaviour, conservative thresholds were selected for the "Yellow" and "Red" warnings. The threshold at that time were:

- Initial warning threshold for stress:
    - "Yellow" warning will be activated when stress changes 5 MPa (corresponding to approximately 75 micro-strain);
    - "Red" warning will be activated when stress changes 10 MPa (corresponding to approximately 150 micro-strain);

- Initial warning threshold for displacement:
    - "Yellow" warning will be activated when displacement reaches 3 mm;
    - "Red" warning will be activated when displacement reaches 6 mm;

- It was commented at that time that the threshold should be considered as temporary, and these thresholds must be updated with more information from new stress measurements and observations during construction.

With the temporary thresholds, the whole system of monitoring-warning-actions performed smoothly. When the first "Yellow" warning was reached on 24th February 2017 at LTDM-Pillar as shown in Figure 4, the "Yellow" warning SMS and email were sent and necessary actions were carried out as planned. The actions included stress calculations from the logged strain and comparing with the 3D numerical model, inspection of the new and existing tunnels, meeting to discuss the results, and following-up the situation.

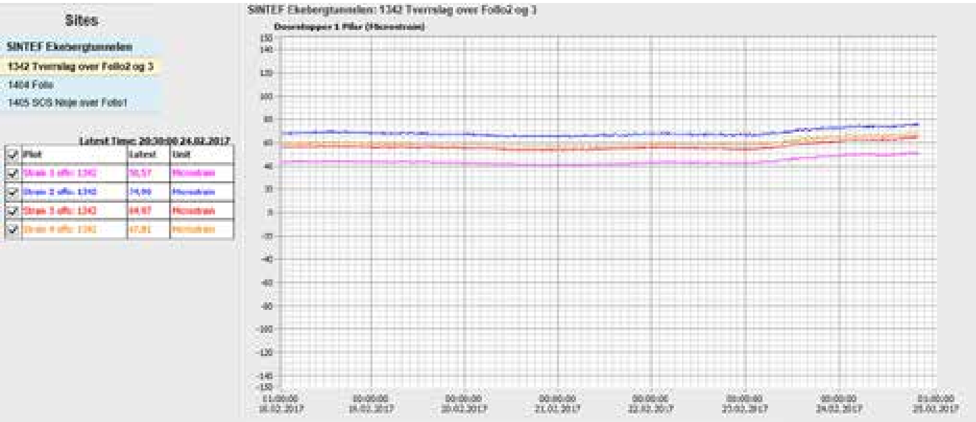

Figure 4: The first "Yellow" warning from LTDM-Pillar, sent at 19h10' 24/2/2017.

After the first "Yellow" warning, a careful discussion was made, and evaluating all of obtained information was done. It was as anticipated concluded that the temporary thresholds were too conservative and it was a need to review and set-up new theshold values. The review was based on new obtained information, including:

- The behaviour in the LTMD-Pillar: the logged strains have raised gradually with small fluctuation, and when it reaches 75 micro strain the small fluctuation triggered many "Yellow" warnings ON and OFF;
- When converting the logged strain to stress, the maximum in-plane-stress is almost vertical in the pillar and having value of about 14 MPa (thus the stress change is about 3.3 MPa from its initial stress condition);
- The registered displacement at Extensometer-Floor (nearest extensometer) was less than 2 mm;
- The monitored stress and displacement results were comparable with the 3D numerical model for the corresponding tunnelling progress;
- Inspection of new and existing tunnels by Bane NOR and found that there was no indication of instability;
- Information from additional stress measurements in connection with the installation of LTDM-Roof;
- Observation of the rock mass behaviour made during the tunnelling so far.

With all the new obtained information, the new thresholds were set as follow:

- Warning threshold for stress:
    - "Yellow" warning will be activated when stress changes 10 MPa (corresponding to approximately 150 micro-strain);
    - "Red" warning will be activated when stress changes 20 MPa (corresponding to approximately 300 micro-strain);

- Warning threshold for displacement:
    - "Yellow" warning will be activated when displacement reaches 4 mm;
    - "Red" warning will be activated when displacement reaches 8 mm;

- Even though the thresholds were raised significantly, the threshold is considered to be in a safe side. This is necessary to maintain the safety in the Ekeberg tunnels to meet the requirement that "*no stopping of traffic in the Ekeberg tunnels during the construction of the Follobanen tunnels*".

The warning system is now working with the new thresholds. The latest development of excavation and monitoring in the junction area is:

- The excavation is completed for the Inbound Østfold Line;
- The top heading is completed for the Inbound Follo Line. The benching for this tunnel is in progress;
- Full face excavation of the Outbound Follo Line is progressing from the south, and the top heading is progressing from the north. The southern tunneling face is now almost below the LTDM-Pillar;
- There is a fast development of strain in the LTDM-Floor. The logged strain is now more than 150 micro strain as shown in Figure 5, triggering new "Yellow" warnings;
- The "Yellow" warning SMS and email were sent and necessary actions were carried out as planned;
- The situation is closely monitored and new actions are under planning.

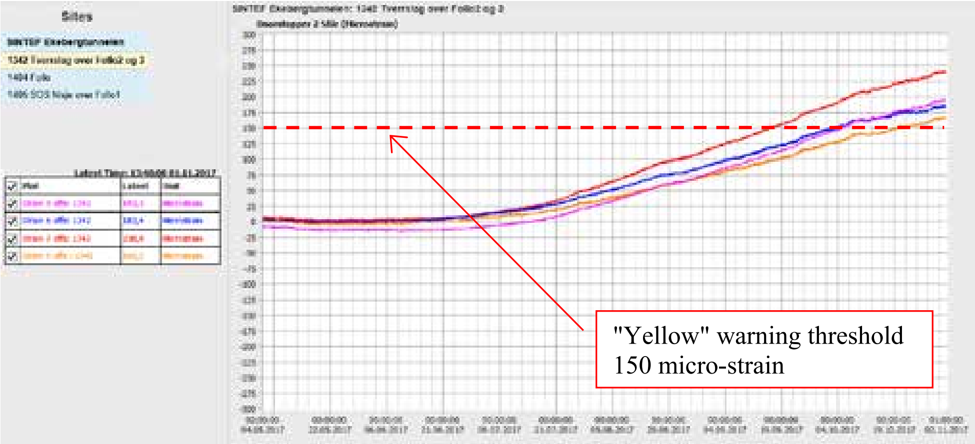

Figure 5: The "Yellow" warnings from LTDM-Floor (first sent at 18h30' 15/9/2017).

CONCLUSIONS

The new Follobanen tunnel is planned to be just about 4 m below existing Ekeberg tunnels. The short vertical-distance between new and existing tunnels create a huge rock mechanics challenging for planning and construction of the new tunnels. In addtion to the short vertical-distance, the traffic flow in the existing tunnels must be maintained at all time.

In order to deal with the challenges, a comprehensive program including stress measurement, numerical model, and stress and displacement monitoring was established and implemented for planning and following-up during the construction of the new tunnels. Experience so far from the construction is that the whole system is working smoothly and providing reliable information for evaluation of the safety situation for the new and existing tunnels. The system is also providing necessary warning as it is designed for. Practical experience from planning and construction of the new tunnels proof that the system is an usefull and reliable tool in dealing with the desribed challenges in this project.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Bane NOR for permission to prepare and publish this paper.

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