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Investigation, numerical model, and monitoring for Follo line - a metro project in Oslo

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Abstract. Just south of Oslo Central Station the new high-speed Follo Line railway tunnels pass beneath the existing Ekeberg road tunnels. This paper presents the construction methods, numerical model, and monitoring program used to assess the stability of the E6 road tunnels during the excavation of the Follo Line tunnels only a few metres below. The construction of the Follo Line was approved subject to three conditions: (1) There should be no negative effect on the stability of the Ekeberg tunnels, (2) The traffic flow in the Ekeberg tunnels must be maintained at all times and (3) Any risk of instability in the existing tunnels must be detected beforehand so that necessary precautionary action could be taken in good time. In order to deal with the challenges, SINTEF has carried out different investigations (including rock stress measurements), established a comprehensive numerical model, and a thorough monitoring program for analyses. The activities were combined in a so-called "rock mechanic tool", and the tool has been used successfully in this project, operating smoothly to provide adequate information for excavation planning and decision making.

1. Introduction

BaneNOR (Norwegian National Rail Administration) has decided to construct the Follo Line Project with new railway tunnels connecting Oslo and Ski. The excavation period commenced in 2015, and it is scheduled for completion in the end of 2021. In 2015, the estimated cost of the project was 25 billion Norwegian kroner (NOK) [1]. The location and layout of the Follo Line project and the junction is shown in Fig. 1.

The project comprises a 22 km long twin-tube-tunnel to be excavated mainly with tunnel boring machines (TBM, D = 9.96 m), but also by drill & blast and drill & split (D = 9.5 m). The drill & blast and drill & split tunnel section was in the first part of the Follo Line tunnels, near Oslo Central Station, and where the Follo Line tunnels go below the Ekeberg tunnels. Vertical distance between Follo Line tunnels and Ekeberg tunnels in this junction was just less than 4 m, as shown in Figure 2. This made the construction of the intersection to be very challenging. In addition, the Ekeberg tunnels have high traffic as part of European highway No.18 and No.6. Thus, the construction of the Follo Line tunnels in this intersection is performed with the following requirements from The Norwegian Public Roads Administration (SVV):

- No negative effect on the stability of the Ekeberg tunnels.
- No stopping of traffic in the Ekeberg tunnels during the construction of the Follo Line tunnels. Thus, the stability of the existing tunnels must be ensured at all time.

- Any risk of instability in the existing tunnels must be detected beforehand to make necessary precaution actions.

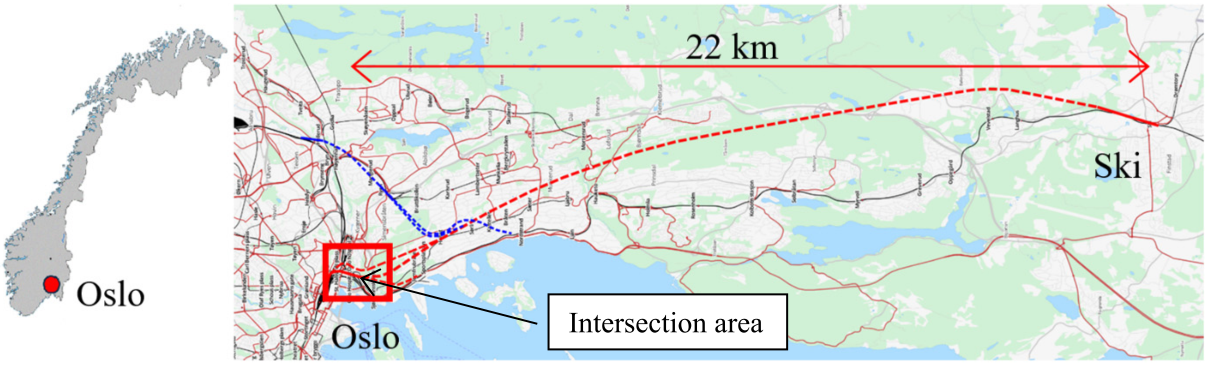

Figure 1. Location and plan view of general layout of the Follo Line project.

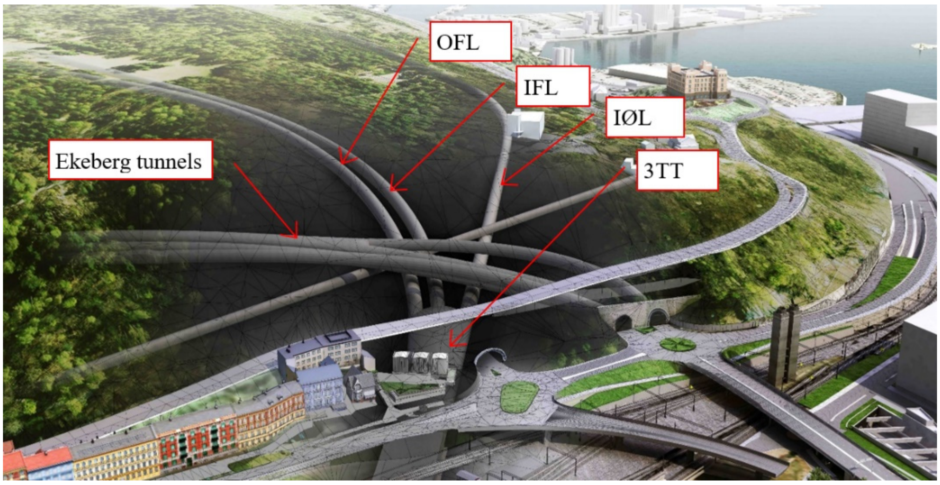

Figure 2. Junction between Ekeberg tunnels (existing) and the Follo Line tunnels with the following names: Inbound Østfold Line (IØL), Inbound Follo Line (IFL), Outbound Follo Line (OFL), 3-Tracks Tunnels (3TT) [2].

Since 2014, SINTEF has assisted Bane NOR dealing with the rock mechanics challenges and safety requirements for the construction of the mentioned intersection in this project. To meet the requirements from SVV and to study the stability of the existing Ekeberg road tunnels and the Alna river tunnels in connection with the construction of the Follo Line tunnels, SINTEF uses a comprehensive approach, which is a combination of three components: Investigation – Numerical modelling – Monitoring, forming a rock mechanic tool for the project.

The excavation of the project was safely completed in January 2018, and it is now in the final stage for opening. Throughout the project, it is proven that the rock mechanic tool from SINTEF was a useful tool for planning and construction. Thus, it is necessary to present the whole concept for possible application in future projects.

2. Investigations

Detailed description of the geological conditions and different surface and sub-surface investigations had been presented in Holmøy et al. in 2015 [3]. This paper briefly presents the in-situ rock stresses measurements and rock mass properties.

2.1. In-situ rock stress

In pre-excavation stage, SINTEF carried out stress measurements in 2011 and 2012. During excavation of the Inbound Østfold Line (IØL), in 2016 when the tunnelling face was at chainage 1890, an additional 3D stress measurement was carried out to obtain the in-situ stress condition at the site.

The measuring method was over-coring method, as described in Trinh et al. 2016 [4]. The measurements in 2011, 2012, and 2016 were 3D- and 2D-stress measurements, as shown in Figure 3. Location of the stress measurement in 2011 is not presented in this figure because it is about 1200 m south, off the site. Results from the 3D-stress measurements are given in Table 1.

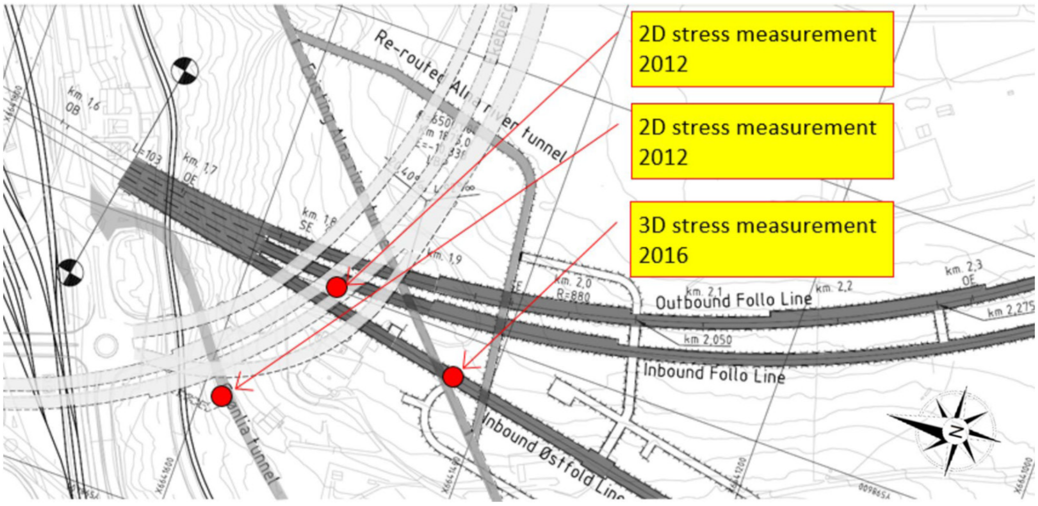

Figure 3. Locations of the stress measurements (3D-measurement in 2011 is 1200 m out of this map).

Table 1. Results from 3D-stress measurements carried out by SINTEF.

Year of measurement	Measured Stress 3D overcoring	Magnitude (MPa)	Dip direction (degrees)	Dip (degrees)
2011	Sigma 1	9.9 ± 1.9	N248.4	24° SW
	Sigma 2	7.5 ± 1.9	N145.0	27° SE
	Sigma 3	1.9 ± 2.8	N14.0	61° SE
2016	Sigma 1	21.6 ± 2.1	N338	35° SW
	Sigma 2	17.3 ± 3	N224	27° SE
	Sigma 3	10.9 ± 0.9	N104	61° SE

The in-situ stress level measured in 2016 was much higher than the measurements in 2011, sigma 1 was twice and sigma 3 was 5 times higher than the measurements in 2011. This may be explained by a local weakness zone or maybe caverns/tunnels or the existing Alna river tunnel not too far away from the location of 2016 measurements. Comprehensive calibrations the numerical model with result of stress measurements in 2011 and 2016 were done during planning and early construction stages of the Follo Line project. It was found that all the numerical model results with input from 2016 measurement gave far higher values than the results obtained from 2D stress measurements measured in the existing infrastructure, whilst with input from 2011 measurement, the numerical model results fitted quite well. Thus, it was decided that the results from the stress measurement in 2011 can be used as representative in-situ stress for input in the numerical model for this project. In-situ stress for the model was estimated based on the measurement in 2011. At elevation zero, the sigma in east-west direction was 10 MPa, north-south 6 MPa, vertical 4.5 MPa, and the stress had gravitational gradient.

2.2. Rock mass properties

During early establishment of the model and simulation, the inputs for rock mass properties has been estimated based on mapping and laboratory tests. Results of this model were verified with the registered data obtained from monitoring equipment (stress change and displacement in connection with the tunnelling progress). Through certain construction progress, a very comprehensive calibration and testing of the model with collected data from monitoring equipment were carried out. This work was done with weekly excavation reports and monitoring data. Result of this calibration was that the rock mass properties used in the initial analyses were updated. The updated inputs of the rock mass properties for the 3D numerical model are rock mass Young's modulus (E_m)= 10 GPa, poisson ration is 0.15, internal friction angle = 55 degrees, and cohesion is 2 MPa.

3. Numerical modelling

Based on the scanning of the existing tunnels and the drawings of the planned Follo Line tunnels, a 3D numerical model was established. FLAC3D [5] code was used to model this junction. Geometry of the Ekeberg and Follo Line tunnel system is presented in Figure 4.

When constructing the geometry for the simulations, the excavation method and sequence were modelled as a specific process.

The excavation method was conventional "drill and blast" in the area outside existing tunnels. Whilst near or under the existing tunnels, the excavation method "drill and split" was applied to minimise damage to the rock mass around the tunnel. In the "drill and blast" sections, a normal pull length of 5 m for each blasting round was used. In the "drill and split" section, a pull length of 2.5 m for each splitting round was used. Thus, in the model geometry, the Follo Line tunnels were divided into every 5 m and 2.5 m in the "drill and blast" and "drill and split" area, respectively. By doing this, every excavation step was simulated to obtain the whole development of stress and displacement from the starting of the construction process.

Simulation process in this project is as follow:

- Simulation 1: No excavation in the model. This simulation was to obtain the original in-situ stress condition within the site.
- Simulation 2: All existing tunnels were excavated to model the existing condition, before the construction of the Follo Line tunnels. This simulation was done to obtain the existing stress situation and deformation and verify with the observation and 2D measurements in the existing tunnels. This step was considered as an early verification of the model.
- Simulation 3: This was the most complicated simulation for the project, where all of the planned excavation steps and sequences were strictly followed: 63 simulation steps for the excavation of the Inbound Østfold Line, 58 simulation steps for the Inbound Follo Line (IFL) and Outbound Follo Line (OFL), 65 simulations steps for the "Three track" tunnel.

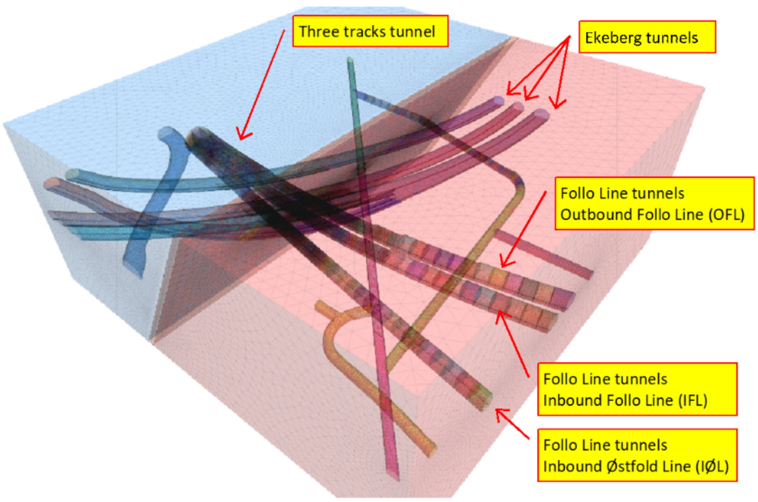

Figure 4. Geometry of the 3D numerical model for the intersection between Follo Line tunnels and Ekeberg tunnels.

Some results of the 3D-model are shown in Figures 5 to 7. According to the figures, the following comments were made:

- The maximum stress component (sigma 1) around the tunnel was estimated to increase slightly from about 12 MPa (in-situ original condition) to about 17.5 MPa. In the critical area (the horizontal rock pillar between Follo Line tunnels and Ekeberg tunnels), the model estimated the same amount of stress increase.

- The minimum stress component (sigma 3) around the tunnel decreases from about 5 MPa (in-situ original condition) to about 2.5 MPa. The reduction is approximately 2.5 MPa.
- The tunnel excavation results in a displacement of about 2 to 3 mm around the tunnel. Below the existing Alna river tunnel, the model showed that displacement in the new tunnel is from 4 mm to 6 mm. It is thus expected that the maximum displacement in the junction will be 4 to 6 mm after completion of the construction of Follo Line tunnels.
- Before excavation of the Follo Line tunnels, the model result showed yield elements in the floor of the Ekeberg tunnels; whilst after excavation of the Follo Line tunnels, the model results showed slightly more yield elements in the horizontal pillar.
- In general, the model results showed that there is a certain impact from the excavation of the Follo Line tunnels on the Ekeberg tunnels. However, the amount of change was estimated to be modest (stress change of about 5 MPa, and the displacement change of 2 to 6 mm depending on excavation stage). Model results gave an impression of overall stable condition for both tunnel systems.
- A monitoring system consists of extensometers and long-term-door-stopper monitoring (LTDM) were installed at key locations for better control of the stability situation. The monitoring system will be presented in the next chapters.

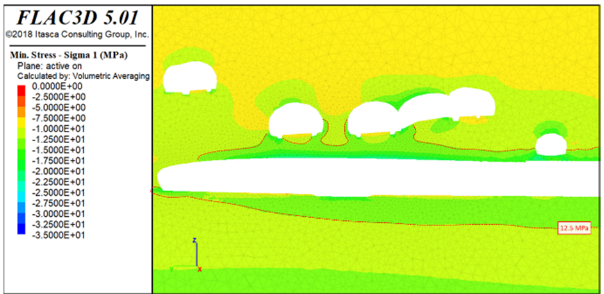

Figure 5. Distribution of sigma 1 at final excavation stage – Vertical section along IFL (negative value means compression).

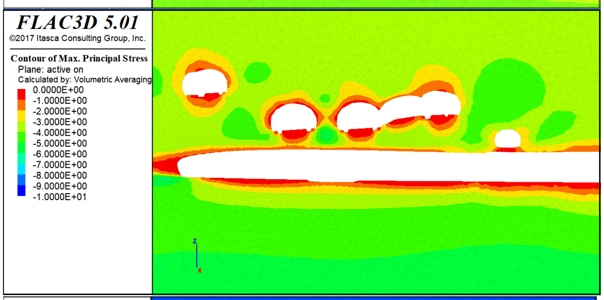

Figure 6. Distribution of sigma 3 at final excavation stage – Vertical section along IFL (negative value means compression).

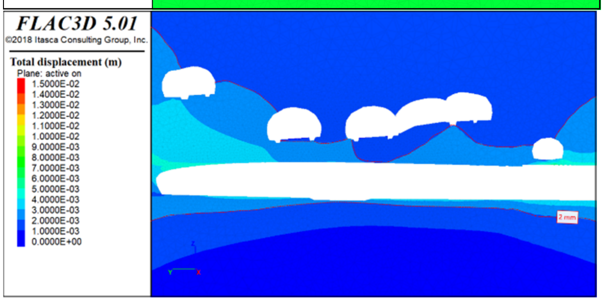

Figure 7. Distribution of displacement at final excavation stage – Vertical section along IFL.

4. Stress and displacement monitoring

In this project, it was very important to catch the stress and displacement development in very early stage, well before any instability problem may appear. The purposes to get early information were:

- Early information can be used to calibrate the numerical model, improving the model during 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 a good time for further study and actions.
- Early registered data from monitoring equipment can be used with the corresponding rock mass behaviour observed during the construction to design and test the warning system well before the construction progress to the critical area – under the Ekeberg tunnels.

Description of the monitoring program and warning system can be found in Trinh et al. [4] and [6]. The locations of the monitoring system are presented in Figure 8.

Data from monitoring equipment was used to control the quality of the numerical model, to make the model becoming a reliable forecasting tool. Results from the numerical model were compared with the stress data from the monitoring devices, the data from two critical LTDMs ("LTDM-Pillar" and "LTDM-Floor") are presented in Figures 9 and 10. These two LTDMs were installed to monitor the stress evolution in the existing Ekeberg tunnels as a result of the excavation of the Follo Line tunnels. The LTDMs were installed at the most critical locations, where the Follo Line tunnels were at their closest to the Ekeberg tunnels—less than 4 m vertical distance. Both LTDMs were installed in May 2015, when the excavation of the Follo Line tunnels was still a very long distance away (more than 150 m) and, therefore, having practically no influence on the Ekeberg tunnels. Early installation of the LTDMs provided a good possibility of obtaining, from the start, the evolution of induced stress in the Ekeberg tunnels as the excavation of the Follo Line tunnels approached. Any abnormal change or evolution of stresses during the excavation progression could be detected early enough to implement appropriate precautionary measures, if necessary. The early monitoring data were also used for model verification.

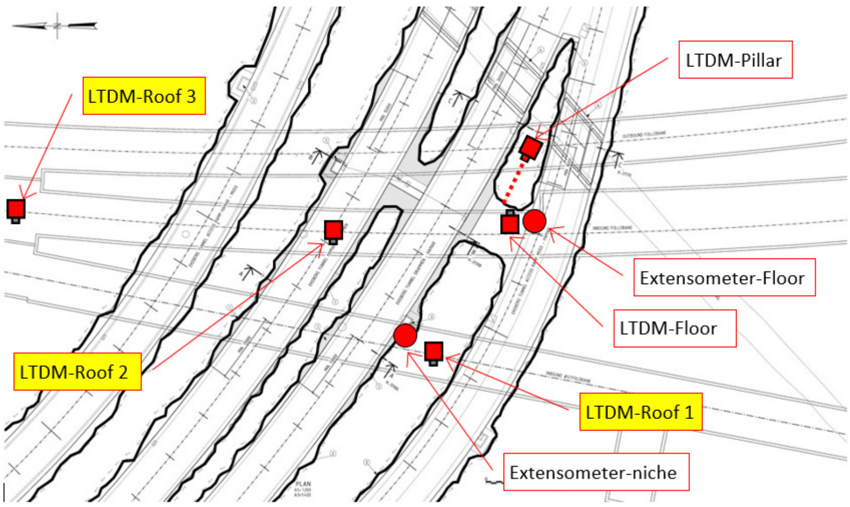

Figure 8. Locations of monitoring equipment for monitor the stress and displacement [7].

The results from the numerical model and the recorded data at the "LTDM-Pillar" shows that they fit relatively well as shown in Figure 9. The model results versus the monitoring data for the “LTDM-Floor” are presented in Figure 10. As can be seen from the figure, the model results did not fit well before September 2017. After September 2017, the stress in this location quickly increased, and the model results fitted better with the monitoring data. A possible explanation for this could be joint movement and better rock contact to increase the stress evolution. After the "no reading" period, data from the LTDMs became unreliable as pointed out in Trinh et al. 2021 [6].

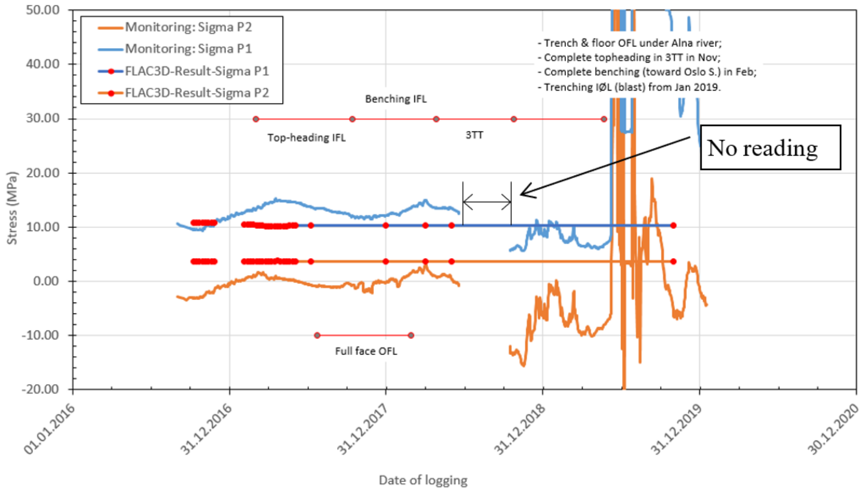

Figure 9. Comparison of stress from monitoring (LTDM-Pillar) versus numerical model.

Figure 10. Comparison of stress from monitoring (LTDM-Floor) versus numerical model.

Displacement result from the numerical model was compared with the data from "Extensometer-Floor", as shown in Figure 11. It can be seen that the model result fit well with the monitoring data. More detailed information for stress and displacement comparison can be found in Trinh et al. 2021 [6].

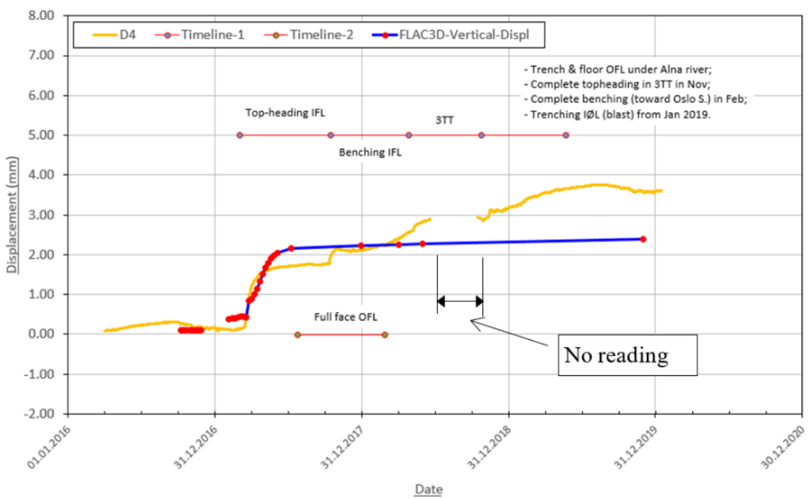

Figure 11. Comparison of displacement from monitoring versus numerical model.

5. Concluding remarks

The project was successfully excavated in 2019. Experience from the construction was that the entire rock mechanics procedure was working smoothly providing reliable information for evaluation of the safety situation for both new and existing tunnels. With help from other components, the 3D numerical model established for the Ekeberg and Follo Line junction was a reliable tool for planning and construction of this complicated junction.

The described rock mechanic approach in this project can be divided into three components, which are:

- **Investigations**: Stress measurements 2-D and 3-D, laboratory tests, and geological mapping. The investigations provide inputs for the numerical model.
- **Numerical model**: Comprehensive three-dimensional model was established for the entire junction complex, including existing and future tunnels, and the construction sequence was simulated carefully. The obtained results were used for model calibration in the existing tunnels and evaluation of the overall stability related to the construction of the new tunnels.
- **Monitoring**: A monitoring program was established to monitor the displacement and stress change at the junction during the construction of the Follo Line tunnels. The monitoring program was established for stability monitoring and the data was also used for model calibration.

With successfully application in this project, it is believed that these three components (Investigation, Numerical model, and Monitoring) are important pillars for dealing with any challenged rock engineering project.

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