Tunnelling for a Better Life – Yan, Celestino, Thewes & Eberhardt (Eds)

"SINTEF-TriPOD" in underground design – A demonstration for two projects in Norway

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ABSTRACT: Many rock engineering projects today may face rock mechanics challenges such as particularly complicated profile or excavation plan, located near to existing infrastructure and thus pose a high risk to such structures, and complicated geological conditions. In such situation, there may be no similar existing experience to lean on. Thus, empirical methods have limitations and uncertainties in such cases. Therefore, SINTEF has developed a rock engineering tool to deal with the challenges. The tool is a combination of Investigation, Numerical modelling, and Monitoring. We use the term "SINTEF-TriPOD" for the methodology, and through projects it has proved to be a reliable tool.

This paper presents the application of the SINTEF-TriPOD for two important infrastructure projects in Oslo, Norway, which are Follo Line metro project (4 billion USD) and a fresh water supply project (approximately 1.2 billion USD).

Keywords: Stress measurement, Numerical modelling, Monitoring, Metro railway, Water supply, Underground complex

1 INTRODUCTION

Many rock engineering projects today may face rock mechanics challenges such as particularly complicated profile or excavation plan, located near to and thus cause a high risk to existing structures, and complicated geological conditions. In such situation, there may be no similar existing experience to lean on. Thus, empirical methods have limitations and uncertainties in such cases. Therefore, SINTEF has developed a reliable rock engineering tool to deal with the challenges. The tool is a combination of Investigation, Numerical modelling, and Monitoring:

- Investigation: The investigation can be rock stress measurements before and during construction (hydraulic fracturing from rock surface, 2D and 3D over-coring), different geological surveys, drill holes, and geological engineering mappings to evaluate the rock mass quality. Obtained information is used for the second component of the "SINTEF-TriPOD" – a numerical model.
- Numerical model: Establish a comprehensive numerical model, normally 3D numerical model is preferred as the model can handle complicated geometry and construction plans and methods. Simulations are to be carried out in certain order with clear objectives for each simulation steps. This is done to follow the planning and construction closely, helping the project team in making correct decision.
- Monitoring: To improve the numerical model even further, stress and displacement are monitored continuously, and comparing them to the modelled values. The model is calibrated, verified, and improved with the observations made in the surveillance program. This gives us a reliable tool to help for decision making during implementation of the project.

We use the term "SINTEF-TriPOD" for the methodology, as shown in Figure 1.

This paper presents the application of the "SINTEF-TriPOD" for two important infrastructure projects in Oslo, Norway, which are Follo Line metro project (4 billion USD) and a fresh water supply project (approximately 1.2 billion USD).

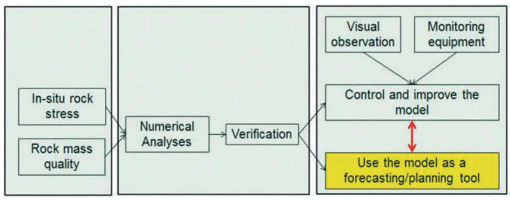

Figure 1. Three components of the "SINTEF-TriPOD" methodology.

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DOI: 10.1201/9781003495505-51

2 FOLLO LINE PROJECT

2.1 *Project information*

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 was opened for operation in early 2023. In 2015, the estimated cost of the project was 25 billion Norwegian kroner (NOK) (Kruse, 2017). The location and layout of the Follo Line project and the junction is shown in Figure 2.

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.

Since 2014, SINTEF assisted Bane NOR in 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 tunnel in connection with the construction of the Follo Line tunnels,

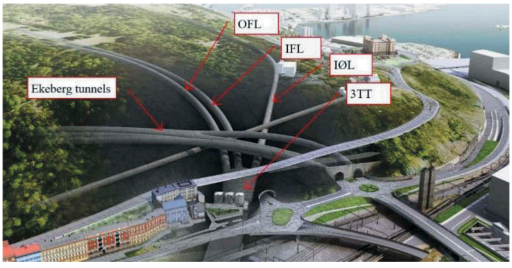

Figure 2. Junction between Ekeberg tunnels (existing) and the Follo Line tunnels with the following names: Inbound Østfold Line (IØL), Inbound Follo Line (IFL), Outbound Follo Line (OFL), 3-Tracks Tunnels (3TT) (BaneNOR, 2021).

SINTEF used a comprehensive approach, which is a combination of three components: Investigation – Numerical modelling – Monitoring, forming a rock mechanic tool for the project.

2.2 *Investigations*

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

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. The measurements in 2011, 2012, and 2016 were 3D- and 2D-stress measurements. Results from the 3D-stress measurements are given in Table 1.

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

Year	Measure stress 3D overcoring	Value (MPa)	Trend (Degrees)	Plunge (Degrees)
2011	Sigma 1	9.9±1.9	N248.4	24
	Sigma 2	7.5±1.9	N145	27
	Sigma 3	1.9±2.8	N14	61
2016	Sigma 1	21.6±2.1	N338	35
	Sigma 2	17.3±3	N224	27
	Sigma 3	10.9±0.9	N104	61

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 existing caverns/ tunnels or the existing Alna river tunnel not too far away from the location of 2016 measurements. Comprehensive calibrations of 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 the 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 a 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.

During early establishment of the model and simulation, the input for rock mass properties have 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 (Em) = 10 GPa, Poisson's ratio = 0.15, internal friction angle = 55 degrees, and cohesion = 2 MPa.

2.3 *Numerical model*

Based on the scanning of the existing tunnels and the drawings of the planned Follo Line tunnels, a 3D numerical model was established, as shown in Figure 3. FLAC3D (Itasca, 2021) code was used to model a 3D picture of the crossing of these tunnels. Geometry of the Ekeberg and Follo Line tunnel system is presented in Figure 3. When constructing the geometry for the simulations, the excavation method and sequence were modelled as per a specific process according to the contractor's plan.

The excavation method was conventional "drill and blast" in the area outside the crossing. 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 distribution 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 dedicated to obtain the original in-situ stress condition within the site boundary.
- 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 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 tracks" tunnel.

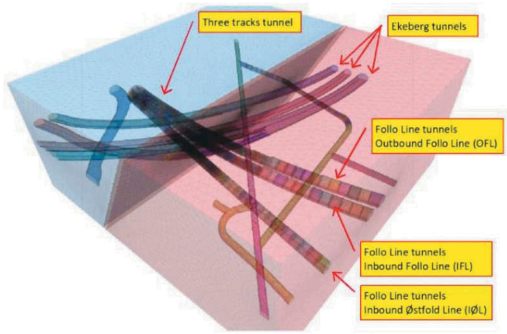

Figure 3. Geometry of the 3D numerical model for the intersection between Follo Line tunnels and Ekeberg tunnels.

Some results of the 3D-model are shown in Figures 4 to 6. According to the figures, the following comments were made:

- The maximum stress component (sigma 1, as shown in Figure 4) 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, as shown in Figure 5) 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, as shown in Figure 6. 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 consisting 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 4. Distribution of sigma 1 at final excavation stage – Vertical section along IFL (negative value means compression).

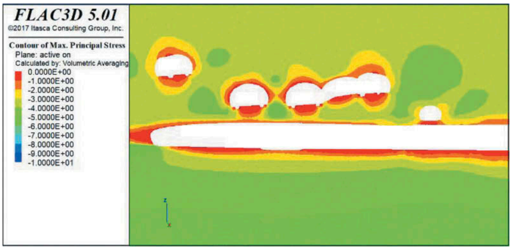

Figure 5. Distribution of sigma 3 at final excavation stage – Vertical section along IFL (negative value means compression).

Figure 6. Distribution of displacement at final excavation stage – Vertical section along IFL.

2.4 *Monitoring of stress and displacement*

In this project, it was very important to capture the stress and displacement development in a 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 redistribution 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. (2016 and 2021). The locations of the monitoring system are presented in Figure 7.

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 8 and 9. 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.

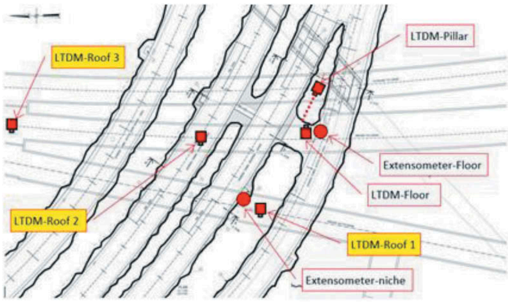

Figure 7. Locations of monitoring equipment for monitor the stress and displacement (Trinh et al. 2021).

The results from the numerical model and the recorded data at the "LTDM-Pillar" show that they fit relatively well as shown in Figure 9. The model results versus the monitoring data for the "LTDM-

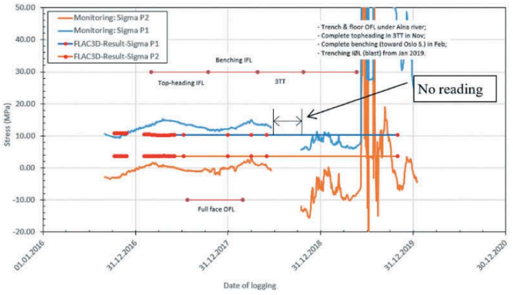

Figure 8. Comparison of stress from monitoring (LTDM-Pillar) versus numerical model.

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).

Displacement result from the numerical model was compared with the data from "Extensometer-Floor", as shown in Figure 10. The verification of the numerical model with the displacement monitoring data can be divided into three periods:

- Before September 2017: Displacement monitoring in this period is presented in Figure 9. This period includes both the non-critical excavation stages and part of the critical excavation stage which started in February 2017 with the top heading. During the non-critical excavation stages when excavation was relatively far from the junction, the displacement results from the numerical model fit well with the monitoring data. During the critical excavation stage, the numerical model displacement prediction was approximately 0.5mm greater than that from the monitoring data. This numerical model result was acceptable due to: (a) The difference being only 0.5mm, (b) The model result and monitoring data show the same evolution pattern, and (c) Full face excavation was implemented in the model whilst in reality only top heading excavation was carried out. Thus, it is reasonable that displacement in the numerical model is higher than the registered data from the "Extensometer-Floor". This concludes that for this period, the numerical model appears to be a reliable tool for planning, construction, and decision-making. The model can be used for predicting displacement and stability evaluation of the upcoming critical excavation steps.
- Between September 2017 and March 2018: Displacement monitoring in this period is as shown in Figure 10. During this period, the benching in the IFL tunnel was excavated producing full face conditions as simulated in the numerical model. The results from the numerical model and the recorded data were almost identical during this period, which demonstrates a very good match between the numerical model and the actual recorded data. With this level of accuracy, the numerical model proved to be a reliable and an important tool for evaluating the stability condition at the junction during the critical excavation stage. The monitoring data indicates that the excavation of tunnel bench can cause 0.5 mm of displacement above the tunnel.
- After March 2018: Critical excavation had already been completed in February 2018. After March 2018, the excavation activities were (a) at Three-Tracks Tunnel (3TT) with approximately 30m span, and (b) excavation of a small trench in the floor of the OFL and IFL tunnels by drill and blast. During this period, the numerical prediction gave 1.0 to 1.5mm displacement less than that from the monitoring data. It seems that the numerical model was unable to fully calculate the displacement caused by drill and blast in the Three-Tracks Tunnel (3TT), which was approximately 100m away from the extensometer. Studying the excavation progress in the 3TT and the monitoring readings during the same period, the displacement caused by the 3TT excavation was estimated to be approximately 0.5mm at the "Extensometer-Floor" location. The additional 1mm displacement recorded at "Extensometer-Floor" occurred during the excavation of the trench in the floor of the OFL and IFL tunnels. This excavation was by drill and blast, directly below the extensometer. Even though the size of the trench was only 1m x 1m, it had a greater influence on the displacement than the excavation of the 3TT with a 30m span. This is most likely due to the much shorter distance to the excavated trench compared to that from the 3TT which was 100m away. Displacement for the whole period from 2016 to 2019 is as shown in Figure 11.

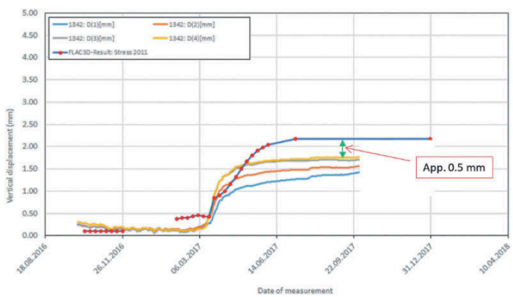

Figure 9. Displacement registered by the "Extensometer-Floor" versus predicted value from numerical model – Just before critical excavation steps.

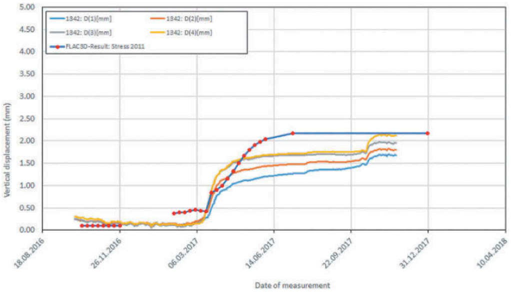

Figure 10. Displacement registered by the "Extensometer-Floor" versus predicted value from numerical model – During critical excavation steps.

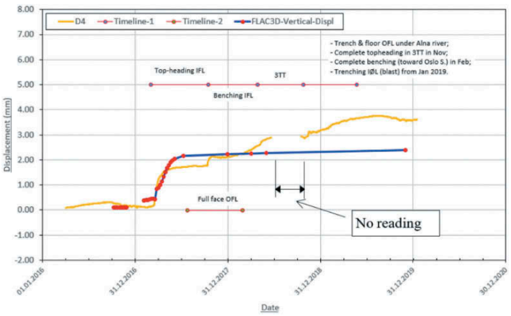

Figure 11. Comparison of displacement from monitoring versus numerical model for 4 years.

3 NEW WATER SUPPLY PROJECT

Oslo is the fastest growing city in Europe. The prognosis indicate that the population growth will continue. Today 90% of the water supply to Oslo is from a limited source named Maridalsvannet and its water treatment plant is at Oset. This makes the city very vulnerable to incidents that strike either the source or the treatment plant. The Oslo Municipality Water and Sewage Administration (VAV) is therefore in the process of building a secondary water supply. According to the plan, by 1st January 2028 the new water supply to Oslo will be ready. The new water treatment plant is located at Huseby. The treatment plant consists of six large caverns with cross sections BxH varying between 20m x 24m to 26m x 43 m. In addition, an assembly chamber for a TBM is being excavated within this underground complex. The treatment plant consists of three different levels and is a complicated system of caverns and connecting tunnels. The volume is approximately 1 million m3 which is all excavated in a relatively small area (Mørck et al., 2022).

Based on initial geological investigation and design, it was expected that the geological conditions were not very favourable in this underground treatment plant. The plan was to use heavy rock support with arches of lattice girders in combination with rock bolts and sprayed concrete. As a reference, similar but smaller and less complicated caverns nearby were built using the same rock support concept. There were also identified several weakness zones, adding the reason for the need of the designed lattice arches.

VAV found it necessary to follow-up the effect the excavation of such a large volume on such a small area could have on the stress conditions in the rock mass and the potential deformations in the caverns. In collaboration with the contractor Skanska, SINTEF was engaged to model the development of the stress redistribution and displacement before starting the actual excavation. The same "SINTEF-TriPOD" procedure was applied in this project as in the Follo Line project. The whole campaign is as follows:

- Investigation: Rock stress measurements were carried out before construction (hydraulic fracturing from rock surface and 3D over-coring in an existing cavern nearby) and during early stage of construction (2D and 3D over-coring). Different geological investigations were made, including drill holes and geological engineering mappings were made before and during early stage of construction to evaluate the rock mass quality.
- Numerical model: Comprehensive 3D numerical model was established. In this project, FLAC3D program was used. Several simulations were carried out including simulation of original condition, simulation of up-to-date excavation progress, simulation with and without rock support. This was to follow the planning and construction closely, helping the project team in making correct decision.
- Monitoring: Stress-meters, extensometers, and instrumented bolts were installed in this project. Stress and displacement were monitored continuously and comparing them to the modelled values. The model has been calibrated, verified, and improved during construction of the project.

Examples of simulation result are presented in Figures 12 and 13.

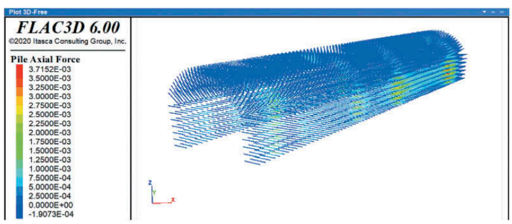

Figure 12. Axial force in the systematic bolts. The result indicated that maximum axial load in bolts is 0.37 ton, whilst the capacity of the bolts is design to be more than 30 tons.

During early stages, displacement result from the numerical model was almost identical to the monitoring data at MPBX1, as shown in Figure 14. At MPBX2, the displacement result in the numerical model (3 mm) was higher than the monitoring data (less than 1 mm), as shown in Figure 15. This is an expected result due to a conservative assumption used in the numerical model. The model results versus the monitoring data for the stress were not as good as those for the displacement, as can be seen in Figures 16 and 17. Stress results in the model were only comparable to the monitoring data in term of the order of magnitude. Due to the differences only about 5 to less than 10 MPa, stress results from the numerical model were acceptable from the practical point of view. Despite of the stress result, general impression of the model results, displacement monitoring, in-situ observations, it is concluded from the early stage that the numerical model can be used as a reliable tool for the planning and construction.

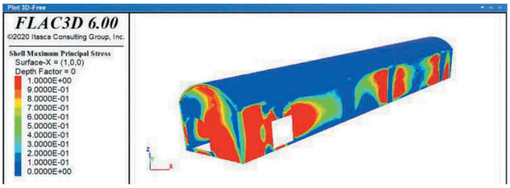

Figure 13. Minor principal stress (due to mathematical convention in FLAC3D this is named as "maximum principal stress") in sprayed concrete. Red areas indicate tensile stress is larger than tensile strength of the sprayed concrete.

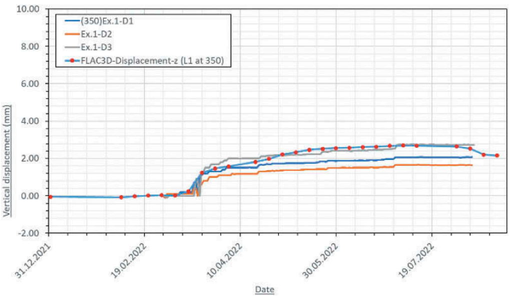

Figure 14. Deformations modelled versus recorded deformations in extensometer MPBX1.

The comprehensive simulations and the monitoring gave the project owner's site team the confidence to reduce the amount of rock support in the caverns. The caverns are now supported by 20 cm thick sprayed concrete applied in two layers and rock bolts with length between 5 m and 6 m applied between the two rounds of sprayed concrete (lattice girders were planned originally). Based on the results from the numerical model, a list of areas has been identified for frequent visual inspection throughout the excavating process. So far, fracturing of sprayed concrete has

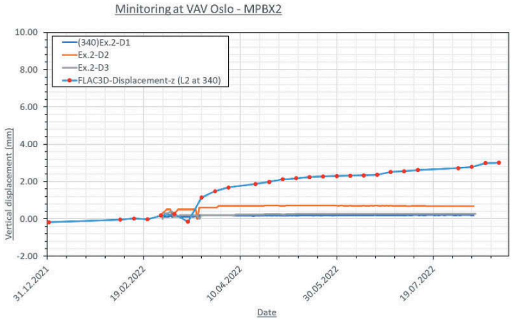

Figure 15. Deformations modelled versus recorded deformations in extensometer MPBX2.

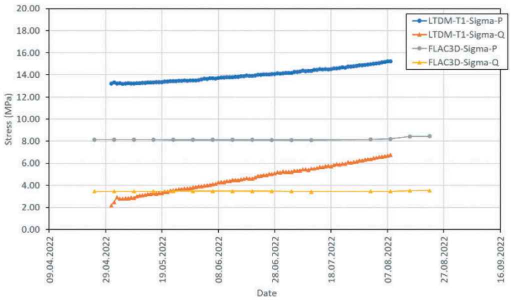

Figure 16. Stress modelled versus stress obtained in LTDM-T1.

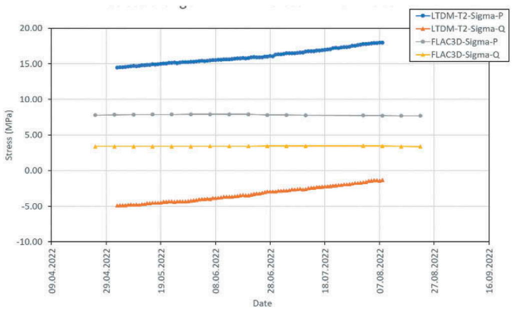

Figure 17. Stress modelled versus stress obtained in LTDM-T2.

been found, which could be due to overloading, but may also be shrinkage. No or very little spalling of sprayed concrete have been found. Actual construction is as shown in Figure 18.

4 CONCLUDING REMARKS

The Follo Line project was successfully excavated in 2019. Experience from the construction was that the entire rock mechanics procedure (the "SINTEF-TriPOD") was working smoothly providing reliable information for evaluation of the safety situation for both the new and existing tunnels. With help from

Figure 18. Photo from the end wall in one of the halls. The picture shows the rock support of the end wall in the roof and the upper part of the wall (Mørck et al., 2022).

other components, the 3D numerical model established for the Ekeberg and Follo Line junction demonstrated that it is a reliable tool for planning and construction of such complicated crossings.

The application of the "SINTEF-TriPOD" to the New Water Supply project provided vital inputs to optimise the rock support for the underground complex. Project cost saving from the optimisation process was estimated to be more than 100 million Norwegian krone. It is also expected a lot of time saving from construction work with the reduction of the rock support.

The described rock mechanic toolbox (the "SINTEF-TriPOD") in this paper can be divided into three components, which are:

- Investigations: Stress measurements 2-D and 3-D, laboratory tests, and geological mapping. The investigations provide input parameters for the numerical model.
- Numerical model: Comprehensive numerical model (two- and/or three-dimension) was established for stability analyses of the project. The numerical model should be able to include as much as possible the geometrical details such as 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 these projects, it is believed that the "SINTEF-TriPOD" toolbox, which is a combination of three components (Investigation, Numerical model, and Monitoring), is an important tool for dealing with challenged rock engineering projects.

ACKNOWLEDGMENTS

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

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