NORWEGIAN TUNNELLING SOCIETY

Publication no. 28

Digitalisation in Norwegian Tunnelling

DIGITALISATION IN NORWEGIAN TUNNELLING

Publication No. 28

NORWEGIAN TUNNELLING SOCIETY
2019

DESIGN BY KONSIS, OSLO, NORWAY

PUBLICATION NO. 28

ISBN 978-82-92641-45-3

Front page image:
Bever Control

Layout:
Konsis Grafisk AS
konsis@konsis.no
www.konsis.no

DISCLAIMER


Let the rig
do the drill
plans

Contents


AMV
ETABL. 1860
AMV
WWW.AMV-AS.NO

Preface

The Norwegian Tunnelling Society (NFF) is open to individuals, companies, institutions and government services that are engaged in or associated with the construction industry where use of the underground and the related work tasks and disciplines are central.

The Society's members, both personal and corporate, come from every single segment in the industry chain. The publication Digitalisation in Norwegian Tunnelling is part of a series of publications published by NFF.

The working group responsible for this publication was composed of the following members:

Ausra	Aalborg	*Norwegian Public Roads Administration*
Torbjørn	Andersen	*Norconsult*
Mari Lie	Arntsen	*NGU*
Håkon Walter	Bjørnsrud	*Norconsult*
Jessica Ka Yi	Chiu	*NGI*
Geir	Dehli	*Norwegian Public Roads Administration*
Leon	Eide	*Bane NOR*
Henning	Ekström	*BetonmastHæhre*
Øyvind	Engelstad	*SN Power*
Anne-Line	Ferstad	*Nye Veier*
Emil	Festin	*Bever Control*
Silje Hatlø	Hagen	*Bever Control*
Joakim Navestad	Hansen	*Bane NOR*
Tom Frode	Hansen	*Bane NOR*
Sara	Hegge	*NTNU (MSc student)*
Kjetil Andrè	Hellebust	*Skanska*
Jan Erik	Hoel	*Trimble*
Harald	Juvland	*AF Gruppen*
Marcus	Lawton	*Bane NOR*
Edvard	Lothe	*NTNU (MSc student)*
Kristin	Lysebo	*Bane NOR*
Odd-André	Rustad	*Bane NOR*
Morten	Sigvartsen	*Bane NOR*
Torstein	Standal	*Bane NOR*
Martin	Stormoen	*Bane NOR*
Christian	Svendsen	Bever Control
Fredrikke	Syversen	*Bane NOR*
Simen	Thorsen	*Veidekke*
Thorvald	Wetlesen	Bever Control

NFF and DigiTUN would like to thank everyone who has contributed to this publication. The two MSc students, Sara Hegge and Edvard Lothe deserve special attention and gratitude. The success of the working group has been dependent of their professional, thorough and patient work related to both the summer project and the compiling and editing of this publication.

Oslo, April 2019

Norwegian Tunnelling Society (NFF)
Development Committee and the International Committee

Introduction

Norway is one of the pioneer countries for model-based engineering and construction of underground space. The key behind the Norwegian success is the construction-driven processes and close cooperation between the tunnel workers, the software developers and the project management from both clients and contractors. The digital industry of Norwegian tunnelling has been a subject of accelerating research and development for several years. Thus, the Norwegian Tunnelling Society (NFF) saw a great potential in coordinating these processes.

In 2018 the Norwegian Tunnelling Society (NFF) initiated the DigiTUN working group. The main purposes of the working group are to gather experiences, map common practices and synchronise future research projects related to digitalisation of the tunnelling industry and the items related thereto.

The first initiative of the DigiTUN working group was a summer research project conducted by master students from the Norwegian University of Science and Technology (NTNU). The project scope was to provide an overview of the current digitalisation status in selected Norwegian tunnelling projects. The project report has been further developed into this publication.

The main purpose of this publication is to share the knowledge gained from the Norwegian tunnelling industry, from a practical point of view.

The publication has been structured in three sections. Section one reviews the most important disciplines for model-based engineering, referring to engineering and construction phase. The second section provides an overview of the status and future visions of the three largest tunnelling clients in Norway, whilst the third section consists of selected Norwegian underground projects and their successful application of digital processes.

This publication summarises an enormous work amount and added value for the tunnelling industry. Contributions from most levels of the supply chain are collected; from software producers, contractors, consultants and clients. Since such compilation has not yet been provided in any Norwegian underground forum; highlights from the collected information are summarised and discussed in the last chapter.

Scope of the publication

This publication describes the status of the Norwegian underground industry and emphasises the utilisation of emerging technologies and BIM (Building Information Modelling) with a practical approach. Disciplines as geology, machine operations, Measurement While Drilling (MWD) data utilisation, rock bolting, technical installations and environmental monitoring are included and discussed in the first section of the publication. The tuwnnel clients have been nominated as the main contributors to standardisation and future development of digital processes. By including a chapter for three of the main clients for tunnelling projects in Norway, the publication also provides a wider perspective with regards to future visions and development within the industry. In conclusion, successful implementations of digital processes are highlighted in terms of case-studies.

Content

To highlight the development that has been ongoing in Norway since the early 1970s, the publication starts with a timeline summarising the history of the digital processes in Norway. Further on, the concept of “Building Information Modelling” (BIM) is briefly described, as it is important to the understanding of the further information included in the publication.

The main part of the publication is structured into three sections

1) Engineering and construction phase of the project. Disciplines for digitalisation divided into the following sub-groups:
   - Ground conditions
   - Rock support
   - Production data
   - Machine operations
   - Water and frost protection
   - Technical installations
   - Environmental monitoring
2) Status and future visions from the main tunnelling clients in the Norwegian tunnelling marked:
   - Nye Veier
   - Norwegian Public Roads Administration (NPRA)
   - Bane NOR
3) Case studies, where innovative solutions have been applied, are structured into different stages of a project:
   - Design:
     i. Ringeriksbanen (FRE16)
     ii. E18 Western Corridor Lysaker – Ramstadsletta

- Construction:
  i. The Follo Line Project
  ii. E6 Arnkvern – Moelv
- Finalised
  i. Vamma 12 Hydro Power Project
  ii. E18 Kjørholt – Bamble Tunnels (E18 KBT)
  iii. The New Ulriken Tunnel (Arna – Bergen)

In conclusion, the publication provides a summary of the main findings related to the chapters included in the publication.

Timeline

The development of computer control systems and the related software solutions for mining and tunnelling has taken place in a close cooperation between research institutes and universities, clients, consultants, contractors and private companies. Key players in addition to the contractors have been the Norwegian University of Science and Technology (NTNU), the research organisation SINTEF and the private organizations NGI, AMV, Asplan Viak, Aas-Jakobsen, Bever Control, Vianova and Powel.

To illustrate the development computer assisted tunnel design and construction has seen since introduction of the first computers, the authors of this paper have established a timeline. This timeline presents milestones and other steps forward made by the industry towards a computerised process.

In 1973, a concept for computer-controlled drilling was presented at an NFF conference in Oslo. In 1979, construction started on the first Norwegian tunnelling project that employed computer-controlled drilling rigs. By 1982, the Vardø Tunnel was completed as Norway’s first subsea road tunnel. The early computer-rigs used drill plans and tunnel lines stored on cassettes.

By the end of the 1980s, a range of more advanced planning software was launched. The digital road model VIPS (‘Vegvesenets Interaktive Vegmodell’) was developed by NPRA and launched in 1989. The user input is parametric; describing the road surfaces, the layers in the road superstructure and cut/fill against the terrain model. The resulting model can be exported as lines, surfaces or solids.

Entering a new millennium, several companies gave focus to the collection and use of *Measurement While Drilling* – MWD-data. Bever Control launched their first full version of Bever Team – a database which stored data collected from the drilling jumbo. In 2010, Wi-Fi enabled instant and wireless transfer of data from the drilling jumbo to the office computer, giving the analysis of MWD a new dimension – real time monitoring.

Further digitalisation of tunnel machinery gave automatic positioning, shotcrete robots with thickness scanners and computer-controlled grouting platforms.

In a short period around 2009, a digital PDA-based software called TunnDoc was introduced by SINTEF. With this equipment, the geologist could perform a digital registration of the tunnel geology at face. This equipment was however prone to problems such as lack of battery capacity, the need of a special pen to do the registration etc.

In December 2006, part of the roof collapsed in the Hanekleiv tunnel along E18 south of Oslo. Through this incident, the lack of an systematic and thorough archive of geological registrations for Norwegian road tunnels was discovered. Due to this the NPRA launched a program to establish a regime for better registration of tunnel geology and rock support at site and a common digital archive solution for these registrations.

As a part of this initiative, Novapoint Tunnel was introduced in 2010 as the tool to be used for geology and rock support registrations at all road tunnel projects in Norway. The development of this tool was financed by the NPRA. This software soon became leading in this domain, and it was used for registration of geology and rock support in nearly all road and railway tunnels.

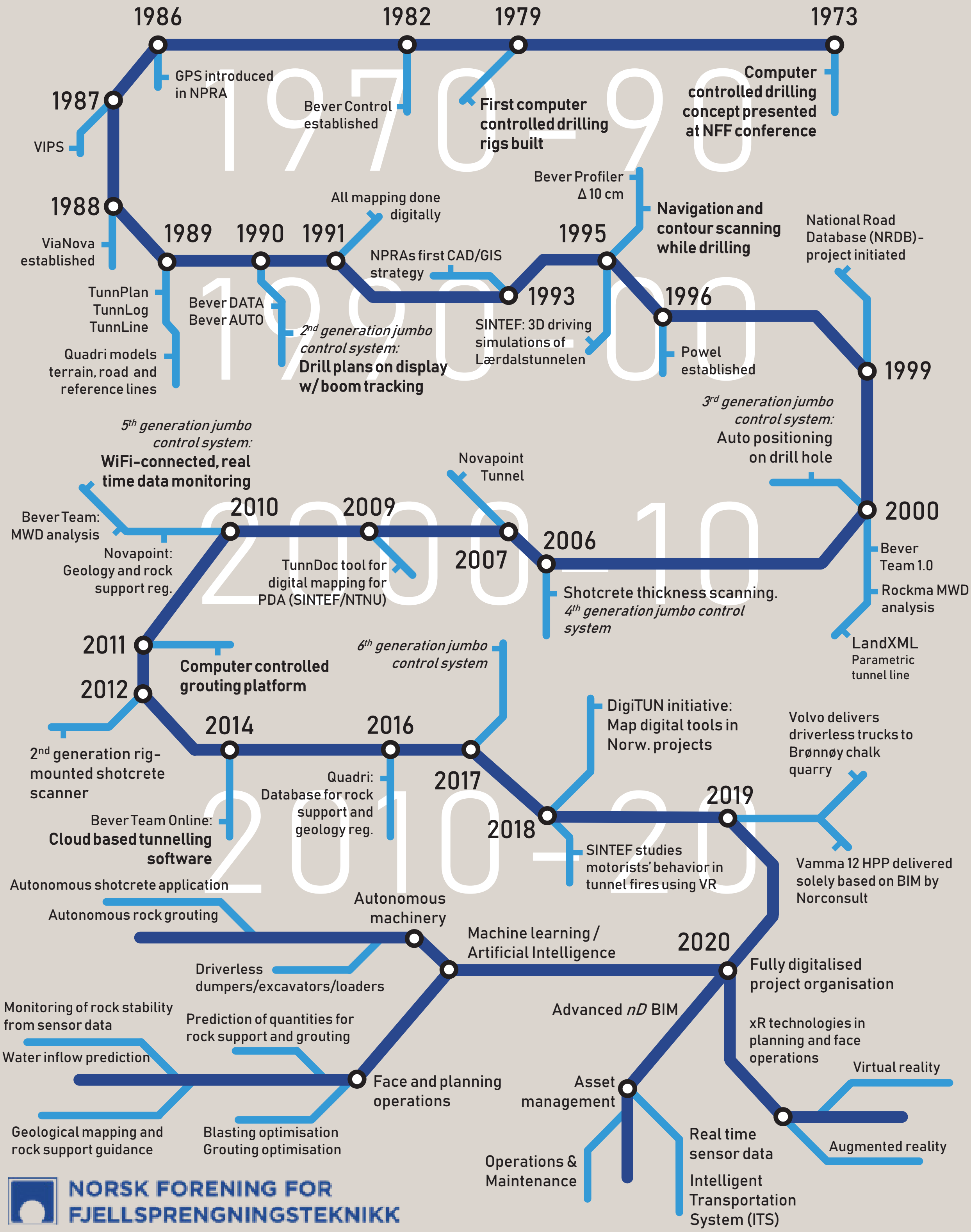
LandXML specifies an XML file format for civil engineering design and survey measurement data. The primary goals for the format are data exchange between software applications and long-term data archival. More can be found at http://landxml.org.

In 2016, Novapoint introduces a server/database storage solution for tunnel geology and rock support registrations called Quadri. The software started as a digital terrain model including support for road models in 1989. From 2016, Quadri is a flexible object-based BIM-server supporting team collaboration.

Novapoint Tunnel only supports paper-based registrations at site; the registration forms are automatically produced by Novapoint, but the geologist must manually write the registrations on the paper and then register them over again into the Novapoint Tunnel software back at the site office. To simplify this double-registration process, Bever Control launched the Bever Mapping app in 2017.

TIMELINE

Evolution of computer assisted tunnel design and construction



In 1995, SINTEF investigated the effect interior design solutions has on motorists driving through a road tunnel using a driveable 3D-model. The background for these tests were the planning of, what at that time was, the world's longest road tunnel, the Lærdal Tunnel (24.5 km). The client, NPRA, wanted to evaluate effects on safety and comfort, with special focus on monotony and anxiety among drivers.

Emerging technologies that enable models to be more appropriate for simulation purposes became more available and relevant at the turn of the decade 2010. Tools for Virtual Reality (VR) allow us to experience and test our buildings before they are built. In 2018, SINTEF launched a research project with NPRA as their client, studying motorists' behaviour during tunnel fires.

NPRA launched a project called "*The National Road Database*" (NVDB) in 1999. By 2005 the system was operative, and NPRA is currently developing a new database that better fits modern needs. The database will store information about all state, municipal and private roads in Norway. All together 206 000 km of road. NVDB will store both basic data and calculated data like traffic accidents and average annual daily traffic.

Airports and all stop points and terminals for bus, subway, railway and ferries will be included in the database. Other static data is permitted axle load, surface material, road curvature, speed limits, road width, tunnels and bridges, road furniture, rails, traffic signs, manholes, ditches, brick walls, etc. Environmental data and pollution from traffic will also be registered into the database.

The purpose with the NVDB is to establish a basis for an information system that secures an optimal management, maintenance and development of the national roads. NPRA also wants to secure an effective information system for the road-owner and the road-users about the traffic and incidents on the road network.

From 2020 and the years to come, the timeline is based on future visions. In a fully digitalized project organization, three key technology trends are described. Artificial intelligence (machine learning), with data from real time sensors, is expected to play a major role in the development of autonomous machinery, preventive maintenance, and optimized face- and planning operations. Advanced nD BIM-models will continue to add value to digital models, with examples like asset management, operations and maintenance. Finally, we expect to see an emerging use of XR technologies like AR (Augmented Reality) and VR (Virtual Reality) in construction sites and planning offices.

Definition of key terms

To ensure a common understanding of some core terms included in the publications; some definitions and terms are briefly explained in this chapter.

Building Information Modelling

When discussing the use of BIM in the perspective of underground infrastructure, it is key to hold a clear difference between terms BIM and 3D model. Whereas a 3D model is a purely geometrical representation of objects, a BIM also includes information about the objects.

As defined by The National Building Information Model Standard Project Committee:

> *Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.*
>
> *A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder [1].*

BIM can support dimensions extending the three geometrical dimensions. Time is commonly recognised as the fourth dimension, allowing the users to keep track of project progress and schedule. Additional dimensions are typically cost, lifecycle assessment, health and safety, environmental impact, facilities management and operations and maintenance. All these nth dimensions expand the BIM by adding new data that further builds understanding of the project.

With BIM follows several major potential benefits. This statement can be delivered with a high grade of certainty because of what we have seen in the building industry the last decade. However, there are factors in play that make the construction industry different from the building industry.

On a general level, some of the expected main benefits of BIM

- Less design flaws
- Less construction flaws
- Higher predictability
- Better planning

- Easier early involvement of contractors
- Early identification of project inferences or conflicts
- Better base for decision makers early in the project

BIM has after a slow start become an integrated part of planning, design and construction also in large infrastructure projects involving tunnels. BIM is helping to ensure good coordination and information exchange between all parties in the project. For tunnels and underground facilities, data from the BIM is used directly to operate the jumbos and TBMs. Further data both automatically (scanning, drilling logs, MWD etc.) and manually (surveying, photography, etc.) collected, and fed back into the BIM for ongoing assessments and adjustments, and form basis for "as built" documentation and support the asset management of the finished facility.

The process of utilizing BIM in engineering and construction has been captured by the term *Virtual Design Construction*. This emphasizes that while BIM delivers the technology, VDC joins parallel processes and ensures that the different disciplines can coordinate and share information.

BIM has in recent years become more common in connection with infrastructure projects involving large structures (bridges, culverts etc.), roads, earthworks, tunnels and underground construction. Although BIM has been utilized extensively in engineering, the interface towards the contractors have to a large extent been based on publishing 2D drawings. Changing this practice involves removing all 2D drawings and constructing solely based on the BIM directly.

The reasoning behind this approach is the desire to ensure optimal flow of information between the parties and reduce manual data handling to an absolute minimum. The aim is to ensure that all parties have a full understanding of how the various elements are interacting to create the final product, to achieve optimum flow in the process, and to ensure high productivity and correct fit in all interfaces.

Table of key terms

Term		Chapter, page
Bane NOR	Norwegian government agency responsible for the planning, development, administration, operation and maintenance of the national railway network, traffic management and administration and development of railway property.	0, p. 109
Bever Team		1.1.5, p. 29
BIM	Building Information modelling	BIM, p. 13
DWG	Data format launched by Autodesk for CAD tools in 1982.	
GIS	Geographical Information System	
IFC	Industry Foundation Classes, open and neutral data format for openBIM managed by buildingSMART.	
IREDES	International Rock Excavation Data Exchange Standard (https://iredes.org/)	1.2.2, p. 54
LandXML	Specifies an XML file format for civil engineering design and survey measurement data.	Timeline, p. 9
MWD	Measurement While Drilling	1.1.5, p. 29
NPRA	The Norwegian Public Roads Administration	2.3, 109
NRDB	*Nasjonal vegdatabank (NVDB)* National Road Database	Timeline, p. 9

Term		Chapter, page
NTNU	Norwegian University of Science and Technology	
Nye Veier	Independent road building company fully owned by the Norwegian Government.	2.2, 107
Quadri	Object-based BIM-server.	Timeline, p. 9
VDC	Virtual Design and Construction	3.5.1, p. 139
VIPS	*'Vegvesenets Interaktive Vegmodell'* Digital road model, NPRA (1989-)	Timeline, p. 9
WLAN	*Wireless Local Area Network.* Wi-Fi is the most common technology for this purpose.	1.3.2, p. 66
Big Data	*Large quantities of structured or unstructured data*	Future visions
IoT	*Internet of Things*	Future visions
AI	*Artificial Intelligence*	Future visions
xR (VR/AR)	*Virtual Reality / Augmented Reality*	Future visions

References

[1] The National Building Information Model Standard Project Committee. 2019. What is a BIM. [20.01.2019] Available at: http://www.nationalbimstandard.org/faqs#faq1


ORICA
HandiLoader™

1. Disciplines for Digitalisation

1.1. Digitalisation of ground conditions in the engineering phase

Authors:
- *Håkon Walter Bjørnsrud, Norconsult*
- *Jessica Ka Yi Chiu, NGI*
- *Marcus Lawton, Bane NOR*
- *Jan Erik Hoel, Trimble*
- *Christian Haugen Svendsen,* Bever Control
- *Mari Lie Arntsen, NGU*

1.1.1. Introduction

Background and content

Ground conditions are the basis of tunnel design. In rock tunnelling, the characteristics of the rock mass, weakness zones and areas with water ingress have influence on the choice of tunnelling method and possible tunnelling challenges. Therefore, it is important to map, interpret and report the ground conditions to other tunnel designers. To accomplish this, geology and ground conditions should be modelled and visualised in a BIM model. A complete BIM model is a model that visualises objects in 3D and contains information of all subsurface data and interpretation of the ground conditions. The BIM model will help making more accurate estimates of a projects progress, cost and success, as well as the level of uncertainty. The model is thus very useful for planners and other designers, as well as the tunnelling contractor.

According to the DigiTUN student project conducted in summer 2018 [1], many projects in Norway still commonly deliver separate engineering geological plan and profile drawings in 2D. Normally the drawings contain important engineering geological information including expected rock mass distribution, assumed weakness zones, assumed rock surface, data from ground investigations (drillings, geophysics, geological and engineering geological mapping, etc.), maximum allowed water ingress and expected rock mass conditions. The aim of establishing a digital 3D engineering geological model is to visualise every object in a typical engineering geological drawing in a 3D *dynamic model*. The term dynamic model is here used for a model where the interpretations of the ground conditions can be changed and become more detailed with time. The engineering geological models should be integrated in the project to gain better control of the ground conditions, make communication easier and help other planners consider the ground conditions.

The purpose of this chapter is to describe the current status of BIM modelling in ongoing Norwegian rock tunnelling projects and initiate the discussion for standardisation of digitalisation of ground conditions in 3D. This article will suggest how different types of engineering geological data could be visualised, as well as attributes (metadata) and limitations/uncertainties for the modelled objects. Further, how the model can be utilised in design phases and construction phase will be discussed.

Formats and software

The geological models described in this chapter are created in different software. For example, Autodesk Civil3D, Powel Gemini terrain, Novapoint and Bever control are used. The models for the design phase are made with the purpose of handling in Autodesk's software Navisworks. The model files can easily be exported to different drawing formats, such as IFC, DWG or DWF. Different GIS software can also be used.

There are many commercial softwares with the purpose of creating complete 3D geological models. Examples are among others Leapfrog Works (for transportation and road tunnels), Move, Vulcan, Hole base SI, or Prorok. These softwares offer an easy way to create and visualise 3D geological models. However, most of the commercial software have been developed for the mining industry and does not fit all the needs of the tunnelling industry. Other challenges with using separate disciplinary software is associated with the workflow involving other planning tools and making sure to always be working with updated models from other disciplines.

Models for design phase

The models for the design phase are divided into two functional types; a basic model and a discipline model. A basic model contains all the information needed to design the tunnel project and shows the existing situation and collected data from pre-investigations. A discipline model contains objects to be built and shows the engineered situation. Rock cannot be *built* but the anticipated ground conditions associated with tunnelling are presented in the discipline model.

The geological basis and discipline models will be joined together with other basis and discipline models (e.g. installations, concrete constructions) to an interdisciplinary model for the tunnel project. This is further discussed in other parts of this publication.

1.1.2. Basic models: Geological pre-investigations

Deep weathering maps for tunnelling

Based on interpretation of airborne magnetic data and the topography NGU has produced action maps for tunnelling that indicates zones with deep weathering. The maps cover Eastern Norway and are available in 2D from NGU [3] in dwg and shape formats.

The maps are projected at a digital elevation model (DEM) into a 2.5D model that shows areas with probability of deep weathering and areas with less probability of deep weathering, see Figure 1.1.1.

Filled violet areas indicate where you probably have deep weathering, contour in pink indicates less probability of deep weathering. The same method can be used to visualise other datasets. For example, with mineral resources, marine geology, radon susceptibility and gravel and crushed stone maps, available at NGU [4].

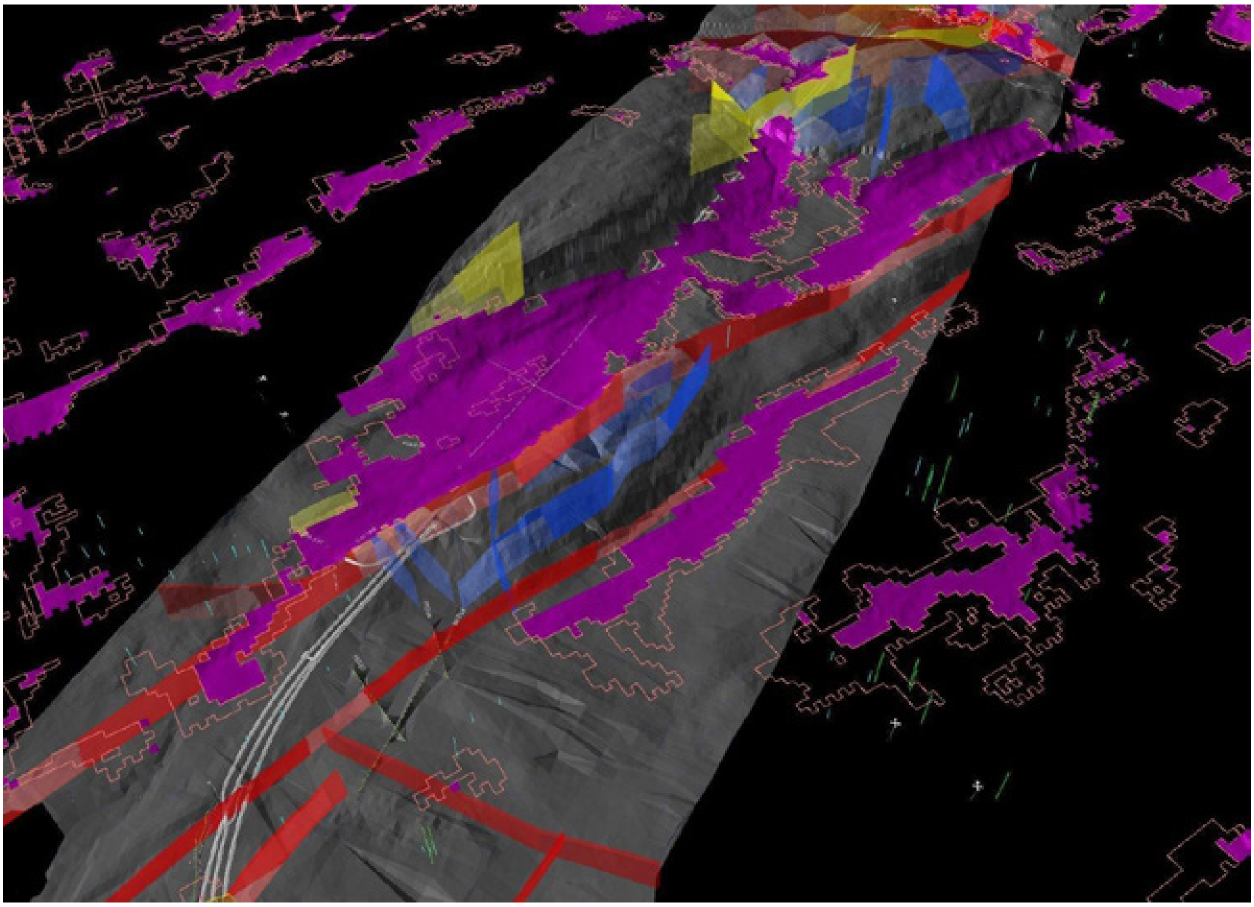


Figure 1.1.1: Deep weathering maps for tunnelling from the project FRE16.

Geological drillings and borehole geophysics

An example of how results from drillings and borehole geophysics can be visualised in a geological model is shown in Figure 1.1.2. The core holes are presented as a pipe with standard diameter of 1 m along the deviation-logged borehole. Different rock types logged along the core hole are presented according to the standard colour chart from NGU.

Planned core drilling/hammer hole drilling is shown in a similar manner, but only the colour of grey is used.

In addition to rock type distribution, crushed zones and areas with high water outflow are shown along the borehole. In this example this is shown as white and blue pipes with a diameter of 2 metres for crushed zone and water drain, respectively. The pipe encloses the borehole at the length of the crushed zone and/or water loss. Crushed zones have been defined as sections of more than 1 m with RQD <10. Based on a professional assessment, there may be deviations on which crushed zones are presented in the core drilling. High water outflow is in the FRE16 project defined by sections where Lugeon water-tests are performed and Lugeon value is greater than 10, i.e. typically classified as medium hydraulic conductivity. In other projects a Lugeon water-tests with continuous visualisation could be more appropriate. In geophysical borehole logging, a professional assessment can be performed based on the rate of change in the recorded water flow.

RQD values and water outflow can be shown, instead of the crushed zones along the borehole. This can be done by dividing the borehole in sections for a given range of RQD values and define a specific diameter for each RQD range. Commonly used RQD ranges are; 0-10, 10-20 ... 90 -100, with diameter from 0.4 m to 2.4 m, with interval of 0.2 m.

The following metadata is presented for each drilling hole (example shown in Figure 1.1.2):

- Status: planned/executed
- Date of execution
- Person responsible/to contact
- Length of borehole
- Trend and plunge of borehole
- Type of drilling/survey
- Reference to further information

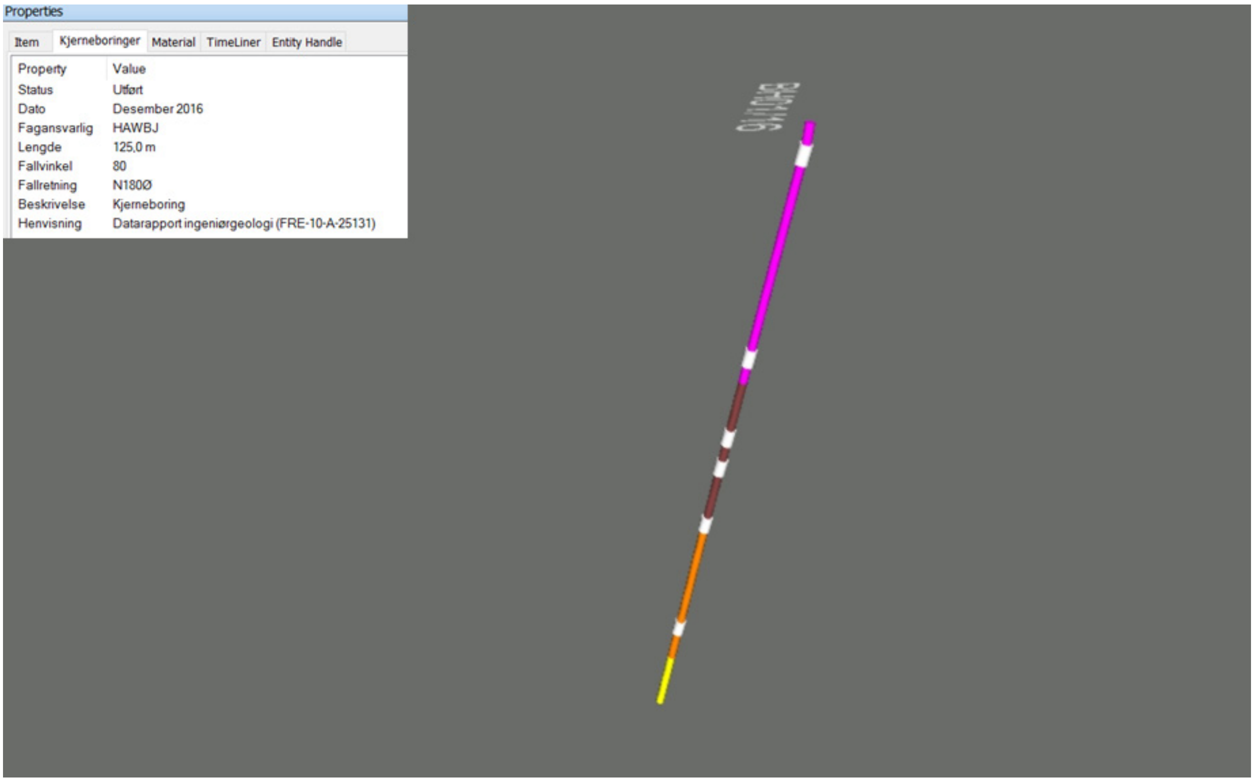


Figure 1.1.2: Core drilling from geological model FRE16

<u>Probe drillings from surface/soil – rock total sounding</u>
Probe drillings from surface can be visualised with pipes from terrain to the drilled depth. The length drilled in soil is shown with white colour, and the length drilled in rock is shown with red colour (as shown in Figure 1.1.3). The definition of the colours also appears from the layer name. The name of the probe hole is shown for each hole.

The National database for ground investigations (NADAG) shows boreholes (points) where ground surveys are already carried out. The data points in NADAG includes the depth to rock surface. Data points in Geosuite Format can be downloaded from the NADAG application [4] to the software Geosuite and then used to produce drawings, bedrock surface, 3D borehole views etc. in Novapoint and AutoCAD. After finishing a project, borehole data should be delivered to the NADAG database for possible future use.

The following metadata could be presented for each drilling hole:

- Type of survey
- Status: planned/executed
- Surface and bedrock level
- Length drilled in soil and rock
- Stop code
- Link to borehole profile
- Notes from drilling operator

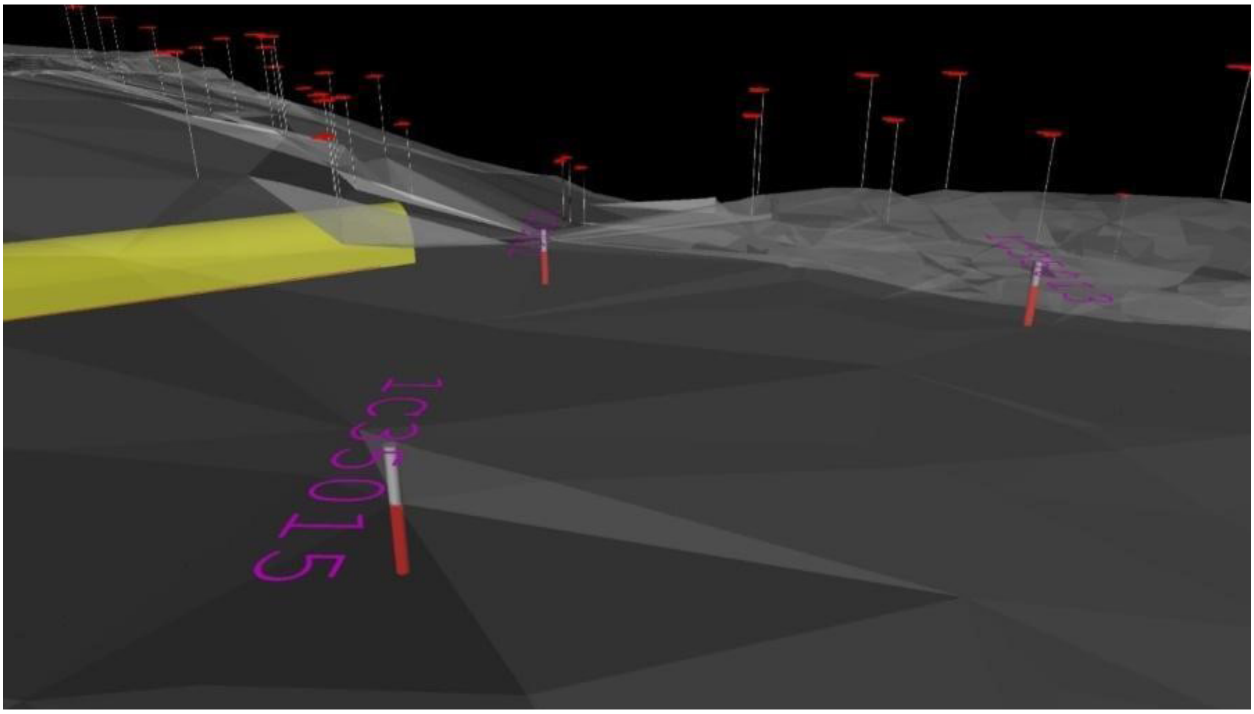


Figure 1.1.3: Probe drillings from FRE16 geology model.

Near-surface geophysics: Seismic and resistivity measurements

Example of how results from refraction seismic and 2D resistivity surveys can be presented in a 3D model is shown in Figure 1.1.4. Seismic lines are visualised as pipes with different colours and diameter. Green pipes with diameter of 1 meter indicate interpreted velocity above 4000 m/s. Red pipes with a diameter of 2 m indicate low velocity zones (interpreted velocity below 4000 m/s). Also, the velocity is shown for the low-velocity zones. The length of a low velocity zone is according to interpretation performed by the geophysicist. The centres of the seismic pipes are on the interpreted rock surface.

The results from resistivity survey and tomographic interpretation of the seismic data are visualised as volumes with different properties. The different volumes are shown in different colours to indicate different properties, most often differentiated by velocity or apparent resistivity. By selecting volumes with low velocity/low resistivity, it is possible to create a volume of predicted low rock mass quality.

Planned near-surface geophysics is shown in the model as a grey solid pipe that follows the terrain surface.

The following metadata is presented for each near-surface geophysics object:

- Type of survey
- Status: planned/executed
- Date of execution
- Person of responsible/to contact
- Reference to further information

Engineering geological mapping

Areas where engineering geological mapping is performed can be shown in a 3D model as symbols with a pole down to the bedrock surface model as shown in Figure 1.1.5. The engineering geological mapping symbol is only shown where sufficient engineering geological data of the rock outcrop have been registered. That means where type of rock, degree and characteristics of fractures and other important engineering geological information have been registered. If only a registration of a bedrock outcrop is done, this is marked with a double V (Figure 1.1.7).

In the example shown in Figure 1.1.5 following metadata is presented for engineering geological mapping points:

- Locality number
- Type of rock
- Characterising of rock mass quality
- Other registrations

Other field registrations are also included in the model; a red surface that follows the terrain with relevant metadata that indicates an area with for example risk of avalanches, strike and dip symbols, joint rosette or a link to a picture taken from field mapping.

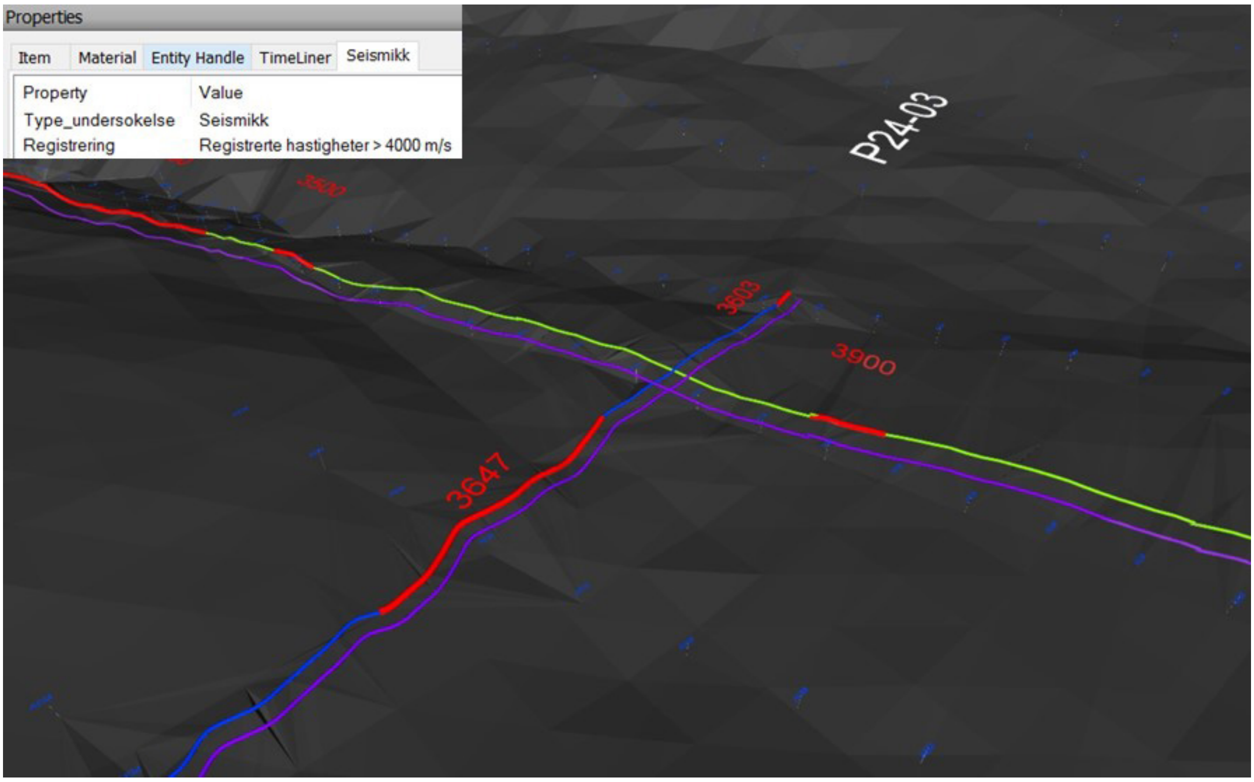


Figure 1.1.4: Seismic survey in geological model FRE16.

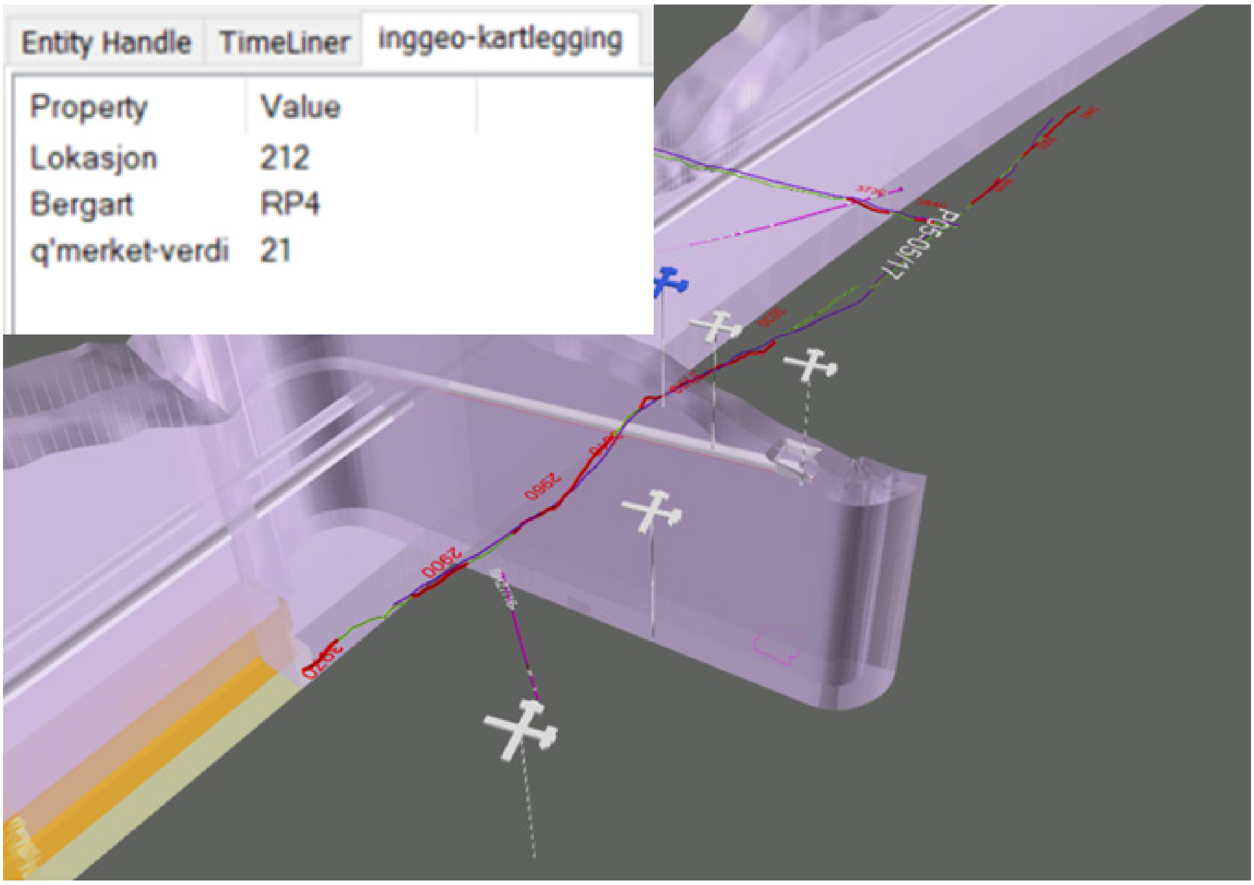


Figure 1.1.5: Example of how geological mapping is visualised. From FRE16 geological model.

Engineering geological mapping can also be carried out by extracting relevant information from a 3D surface model of high resolution. For instance, rock joint mapping using a 3D surface model has normally been done for rock slopes and rock cuts with difficult access. The principle of this mapping method is to construct a georeferenced 3D surface model from point cloud, extract planar features, calculate orientation (dip and dip direction) of the planes, and export the data to stereograms for further analyses. Point clouds can be acquired by LiDAR or photogrammetry. The same technique can be applied both above ground and underground.

Extraction of planar features is commonly achieved by specifying a maximum angular threshold between triangles in a triangulated mesh and a minimum area threshold as the definition of planes. There are academic, commercial, as well as open-source software that can perform planar feature mapping of 3D surface models of rock mass automatically and/or interactively (see examples in Table 1.1.1).

Software/function	Developer
FACETs plugin in CloudCompare	Open-source software
PlaneDetect	NGI
Coltop 3D	Terranum (spin-off from the University of Lausanne)
Geotechnical module	Maptek
ShapeMetrix3D	3GSM GmbH
Sirovision Open Pit	Datamine & CSIRO
Joint Finder	Deswik

Table 1.1.1: Examples of software with planar features mapping function.

A 3D surface model showing identified discontinuities or discontinuity sets differentiated by colours can be obtained (Figure 1.1.6). The model can be integrated into the geological model.

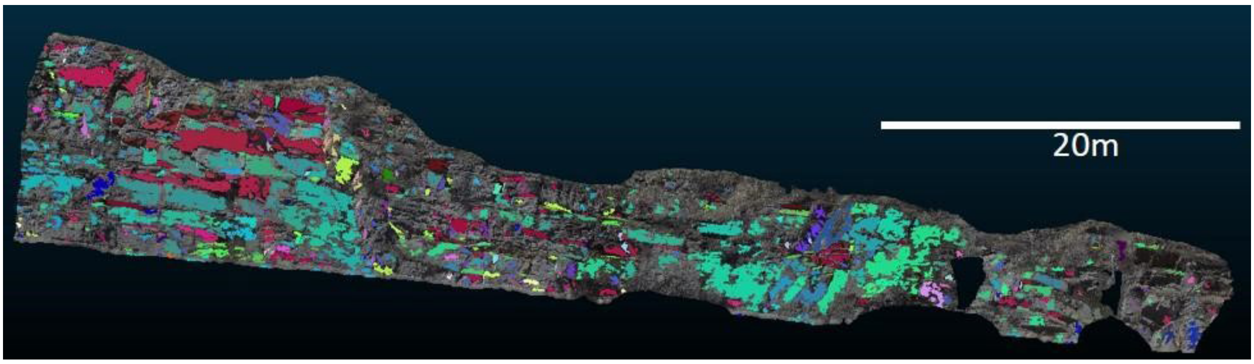


Figure 1.1.6: 3D photogrammetry model with automated joint mapping results (similar colours representing planes with similar orientations). E6 Oslo East project.

The following data of individual planar features can also be enquired:
- XYZ coordinates
- Area
- Dip and dip direction
- Joint spacing
- Waviness/curvature of discontinuities

The quality of mapping results, which can be assessed by whether planar features can be identified, and the orientation of the planes be calculated accurately, are influenced by several factors:
- For LiDAR scanner; range accuracy of the scanner and scanning conditions.
- For photogrammetry; photo quality.

- Resolution of the point cloud.
- Accuracy in orientation and georeferencing of the point cloud.

1.1.3. Basic model: Geological information

Bedrock surface

The bedrock surface (assumed boundary between soil and rock) is important in order to assess areas with low overburden and to design the tunnel entrance and other objects that must consider the bedrock level. The investigation methods for mapping the bedrock surface include drillings, seismic surveys, resistivity measurements, airborne electromagnetic measurements (AEM) and outcrop registration.

The bedrock surface model can be shown as a solid transparent surface in Figure 1.1.7. This is a triangulation of the data from various investigations, with adjustment based on professional estimates, typically where the interpolated bedrock surface by triangulation does not match the estimated depth. Each triangulation point corresponds to a specific investigation that is illustrated with a symbol or text. For example, outcrop is indicated with a double V, see Figure 1.1.7. Adjustment points are added as own "investigation"/ triangulation points categorised under "interpreted". Each investigation point has metadata attached to it, stating type of investigation, date, model owner and if available, reference to a data report.

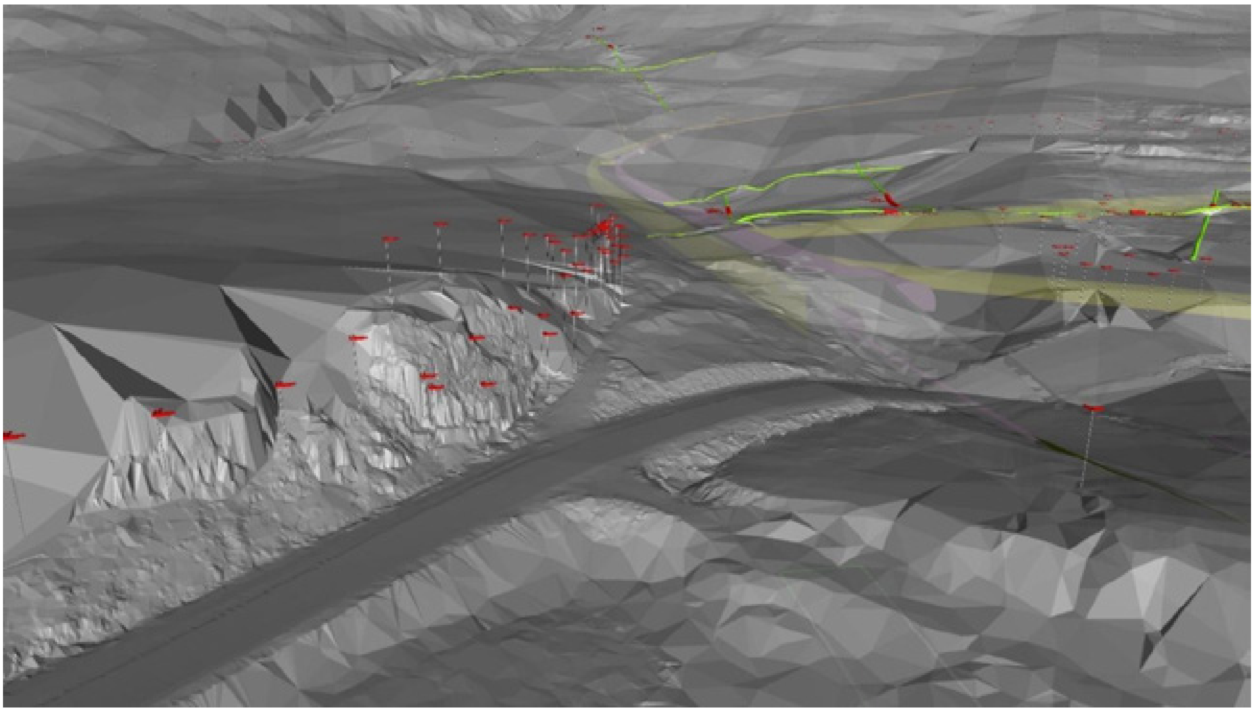


Figure 1.1.7: Bedrock surface model from project FRE16. The model is based on registration of outcrop, geotechnical drillings and refraction seismic.

The bedrock surface model is limited to areas with investigations, but the model is still encumbered with uncertainties. Large uncertainties occur in areas with few investigations, i.e. long distance between triangulation points, and areas where the model is based solely on low resolution data, particularly AEM data. When using the bedrock model, it is necessary to consider the model's inputs and limitations. As presented here, there are no visualisation of uncertainty in the model. Uncertainty associated with the bedrock surface is the same as in standard geological drawings. One solution could be to divide the model into different areas based on the level of uncertainty and present this in metadata and/or visually for each area/surface.

Bedrock geology

The Geological Survey of Norway (NGU) carries out mapping, map compilation and research on Norway's bedrock geology. This has resulted in 2D geological surface maps in scale 1:50.000 and 1:250.000, openly accessible through their website as a WMS service or downloadable format (ESRI Shape, SOSI, ESRI File Geodatabase or PDF) [4].

The bedrock geological map from NGU - adjusted based on own observations, are projected onto a digital elevation model (DEM) to create a 2.5D model showing the distribution of different rock units at the surface, see Figure 1.1.8. In this case a DEM with resolution of 25 x 25 m is used to generate the model. The different rock types are specified with standard colour from NGU [4] and are sorted in different layers that make it possible to click in the map and observe rock units from the selected layer. The accuracy of the model depends on the accuracy of the NGU map, information from earlier studies and the extent of geological mapping and investigations done.

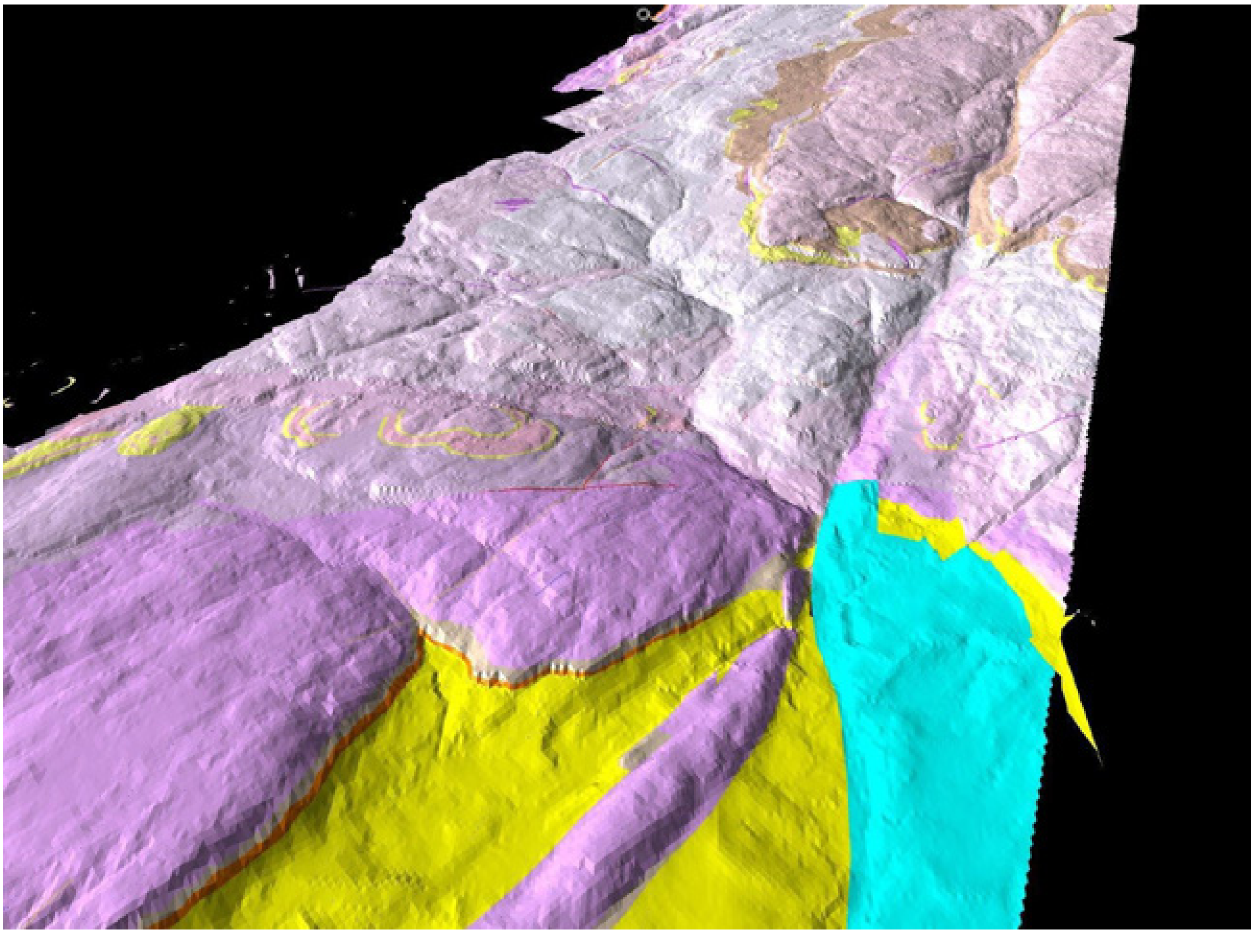


Figure 1.1.8: Bedrock geological model from project FRE16. The model shows rock units draped at the terrain surface in 2.5D.

Assumed rock type distribution against depth

The assumed rock type distribution against depth along the tunnel alignment can be included in a 3D model as volumes of different colours, shown in Figure 1.1.9. The colour is set according to the geological maps from NGU [4], and the rock type is stated in the layer name and as metadata for each volume.

The rock type distribution is based on an overall interpretation of the structural geology, existing maps and geological cross-sections, geological and engineering geological field mapping, core drilling and geophysics. Uncertainty has not yet been incorporated into the model. Uncertainty is greatest in areas far from points of investigations and generally increases with depth.

For the FRE16 project (shown in Figure 1.1.9), rock type distribution is modelled in a corridor of 40 metres to each side of the tunnel alignment. A total of 80 m wide corridor is chosen in this stage because the tunnel profile is basically defined within this corridor, and rock type distribution is assumed to be similar within this width in this case. A wider corridor requires a more comprehensive interpretation of the geology. The extent of the rock interpretations against depth should be based on the detailed level of the planning phase.

The rock type distribution is defined in top by the bedrock surface model. Rock types are separated by planar boundaries. This is a simplification of reality, and the rock type boundaries are rarely as sharp as they appear in the model.

Metadata included for each rock type volume are in the FRE16 project:

- Type of rock
- Assumed rock mass quality

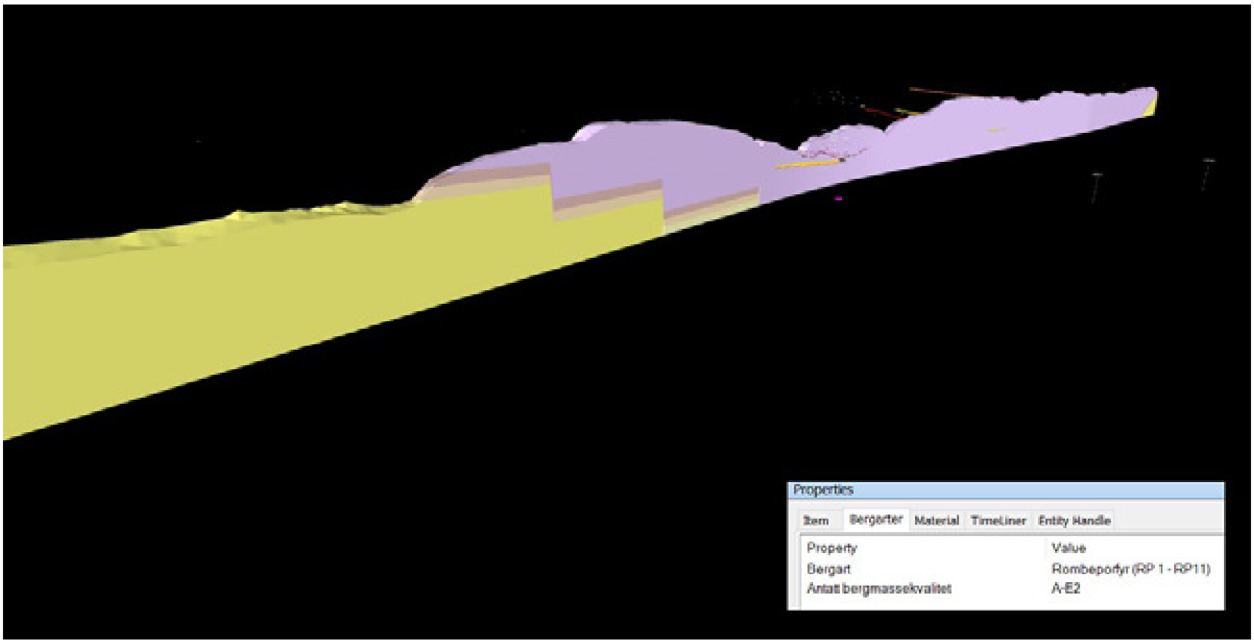


Figure 1.1.9: Assumed rock distribution against depth along the tunnel profile. From geological model FRE 16.

Assumed weakness zones

Weakness zones defines areas where the tunnel excavation is expected to be more challenging because of low rock mass quality and is thereby important to visualise in a model. The zones can be integrated into a 3D model as volumes with a specified width, dip and strike that is based on interpretation of topography, pre-investigations and geological mapping, see Figure 1.1.10. The weakness zones are delimited by planar surfaces, stretched from assumed rock surface to below the tunnel level, unless other information is available. In this example the widths of the zones are constant towards depth.

By using strike/dip recordings of the zones or information from depth is available, for example from an existing tunnel or core drilling, a more detailed shape can be made.

In Figure 1.1.10 the zones are given three different colours based on their assumed weakness zone class, indicating how much the zone are expected to adversely affect the tunnel excavation. The weakness zones are classified from class I to IV, as shown in Table 1.1.2. Zones of higher classes are expected to present greater challenges to tunnel excavation than those in the lower classes.

Weakness zone class	Colour	Classification / Assumed stability / Water ingress
I	Blue	Challenging ground conditions / fair excavation conditions / block fall / possible water ingress
II	Yellow	Challenging ground conditions / poor excavation conditions / block fall / possible water ingress
III	Red	Very challenging ground conditions / very poor excavation conditions / possible total failure / possible water ingress
IV	Red	Extremely challenging ground conditions / extremely poor excavation conditions / possible total failure / possible water ingress

Table 1.1.2: Division and description of weakness zones.

For each weakness zone, the following metadata/attributes are included:

- Weakness zone class; see Table 1.1.2
- Weakness zone number; to identify the zone
- Interpreted from; field observation, seismic, orthophoto etc.
- Assumed width

By including the attribute "interpreted from" the uncertainty connected to the zone is somewhat accounted for by the fact that different methods are encumbered with different levels of uncertainties, e.g. zones based on seismic tomography and drilling often are less uncertain than zones interpreting from topographical maps. However, it is important to remember that there can be big variations in quality and accuracy also within one method. Adding an own attribute to account for this could be an option to better deal with the level of uncertainty.

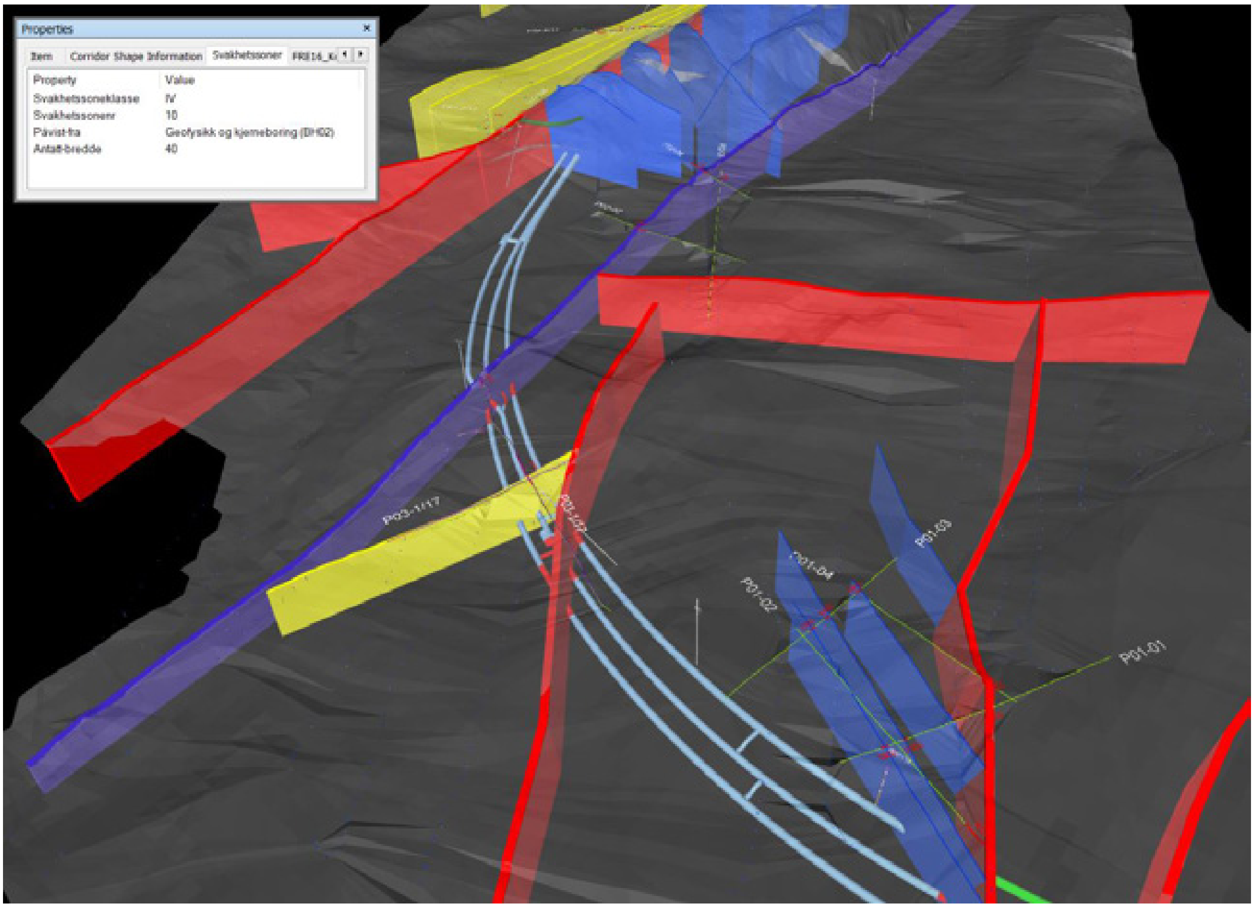


Figure 1.1.10: Assumed weakness zones in the geological model from FRE16.

<u>Groundwater and hydrogeology</u>

Existing wells, typically geothermal or water wells, can be included in a 3D model as simple lines from surface location and down to theoretical depth according to the drilling information. The wells are marked with borehole information at the surface. Existing wells give important information of water levels and can be used during the construction phase to monitor the excavation's influence on the groundwater table. It's therefore important to know the position of existing wells. The National groundwater borehole database (GRANADA) provides information about groundwater and groundwater wells all over Norway. The dataset can be downloaded as shape, SOSI and ESRI File Geodatabase from [4].

The interpreted groundwater table is modelled as a solid blue surface based on the groundwater information from drillings, maps, surface registrations and existing wells. Between the various registration points the groundwater surface is triangulated with the condition that the water table basically follows parallel to the terrain surface between the various registration points. The groundwater model is limited to areas with investigations, but the model is still encumbered with uncertainties.

1.1.4. Discipline model: (Engineering) geological tunnelling information

Assumed rock mass quality and rock support class

Based on an assessment of the ground conditions and pre-investigations, an interpretation of the rock mass quality along the tunnel alignment is included in the geological model. The rock mass quality is visualised by dividing the tunnel profile in different colours depending on expected rock mass quality, as shown in Figure 1.1.11. Classification of rock mass quality can for example be done by the Q-method [5], where a specific range of Q-values corresponds to a given colour. The layer name also states the given rock mass quality for each colour.

Where relevant, the same method could be used for other rock mass parameters, such as usability of tunnel spoil for construction purposes.

Water ingress limits and pre-grouting estimates

In tunnelling projects, a maximum allowed water ingress is set, in order to prevent undesirable lowering of the water table. The water ingress limits can be visualised in the geological model as a square object around the tunnel alignment. In Figure 1.1.12, different colours represent different allowed water ingress limit. By selecting one object (colour) the maximum water ingress will display from the layer name. Together with the hydrogeological model this can be used for creating a model of the estimated need for pre-grouting during excavation.

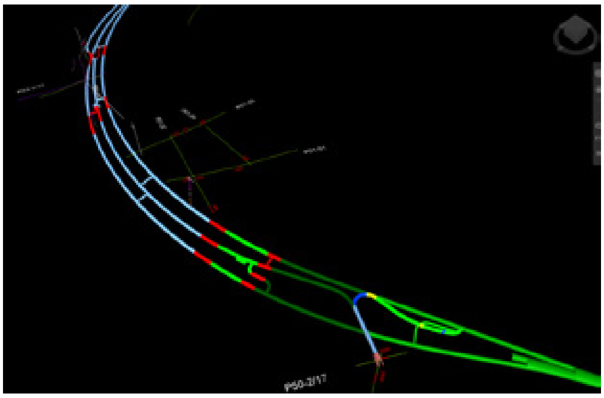


Figure 1.1.11: Rock mass classification along the tunnel alignment. From FRE16 geological model.

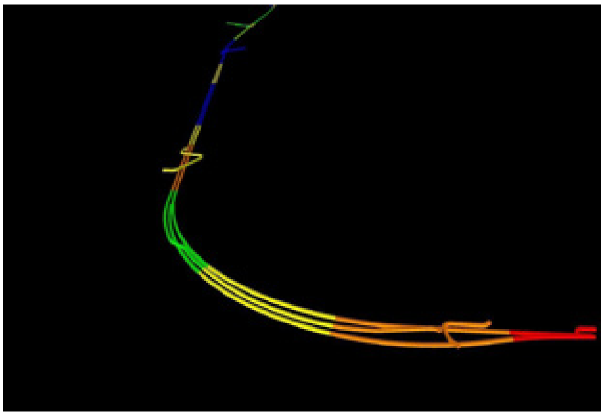


Figure 1.1.12: Water ingress limits along the tunnel alignment. From FRE16 geological model.

1.1.5. Geological models for the construction phase

A model-based project will ideally have a geological model which includes all data from pre-investigations and interpretations from earlier phases. During construction this model would serve several important purposes:

- To contribute to a better understanding of the ground conditions among involved parties.
- A database for all pre-investigations, making investigation data more accessible when relevant during construction.
- A baseline to compare actual ground conditions with the predicted.

During the construction phase, several sources contribute with geological information. Most tunnel projects will use geological registrations at the tunnel face as the main input. The tunnel profile and/or face is usually mapped along with tunnelling progress to make a continuous geological record for the whole tunnel. Nevertheless, geological mapping is to a certain degree a subjective source of information, where the quality of data depends fully on the experience and opinions of the person performing the mapping. One should therefore strive to include as much production data as possible into the model, to reduce the level of uncertainty.

The registered data can be summarised as "as-built geological documentation". This documentation is contractual in most projects, and a mandatory delivery at the end of the project.

Registration of geology at the construction site

The manual registration of geology at the construction site is mainly done at the tunnel face during the tunnel construction. For drill and blast tunnels the contractors are normally obliged to allow for engineering geological mapping. In most projects, the tunnel owner performs the registrations, but at some sites the contractor carries out the registrations.

In addition to the manual registrations, data logs from production machinery may be useful for interpretation of the geology. Measure While Drilling (MWD) data is an example of such production data logs.

Digital manual mapping at the tunnel face
In a short period around 2009, a digital PDA-based software called TunnDoc was introduced by SINTEF. With this equipment, the geologist could perform a digital registration of the tunnel geology at face. This equipment was however prone to problems such as lack of battery capacity, the need of a special pen to do the registration etc., so the solution was soon discarded.

In December 2006, part of the roof collapsed in the Hanekleiv tunnel along E18 south of Oslo. Through this incident, the lack of a systematic and thorough archive of geological registrations for Norwegian road tunnels was discovered. Due to this the NPRA launched a program to establish a regime for better registrations of tunnel geology and rock support at site and a common digital archive solution for these registrations.

As a part of this initiative, Novapoint Tunnel was introduced in 2010 as the tool to be used for geology and rock support registrations at all road tunnel sites in Norway. The development of this tool was financed by the NPRA. Soon, about all the railway tunnel sites used this software as well.

Novapoint Tunnel only supports paper-based registrations at site; the registration schemas are automatically produced by Novapoint, but the geologist must manually write the registrations on the paper and then register them over again into the Novapoint Tunnel software back at the site office (Figure 1.1.13). To simplify this double-registration process, Bever Control launched the Bever Mapping app in 2017.

Digital registration can avoid any misunderstandings due to hasty work, wet paper and sometimes sloppy handwriting in paper-based mapping. Figure 1.1.14 shows the basic mapping interface of the Bever Mapping app. The main functionalities of the app are drawing joints and weakness zones of different sizes, placing strike and dip symbols, registering water ingress and Q values. There is a predefined list of rock types that can be expanded if needed (Figure 1.1.14 and Figure 1.1.15). The program is fully functional like this and can be printed as is and exported to several formats including *.fbx or as a file to be imported to Novapoint Tunnel and synched to a Quadri database.

The software also has various functions that can improve the quality of tunnel mapping. For example, the app supports drawing and viewing in both 2D and 3D. Drawing in 3D can be automatically projected to 2D, and vice versa. Users can also toggle between the 2D and 3D view easily. Learning to project 3D structures on a piece of paper as often

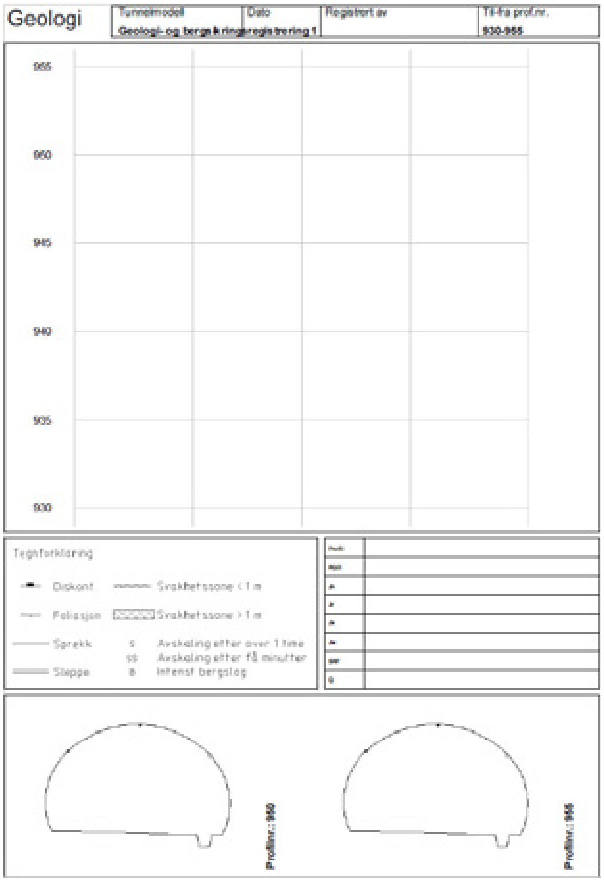


Figure 1.1.13: Registration template for geology automatically produced by Novapoint Tunnel.

performed in paper-based mapping requires some training and skills, the app is thus very helpful in this way. The app can display all the tunnel mapping data in a project. As mapping is often carried out by different geologists on shift, it is useful to be able to see the previous registrations in order to maintain a consistent mapping quality.

The software can be used on any smart device and does not require internet connection during the mapping itself. The software synchronizes with a server when the geologist is back at the office.

In the app, MWD data can be displayed in the background of the mapping interface (see Figure 1.1.15). The MWD data can assist the geologist to register structures such as weakness zones more accurately (± 10 cm, associated with the accuracy of the navigation). In addition, it is possible to import the actual holes drilled and use them as a guide (Figure 1.1.16).

There is also an option to import point cloud from scanning into the app, to show any overbreak and underbreak (Figure 1.1.17). This is a function that can be utilised with bolts and MWD data for an accurate visualisation of a blasted tunnel.

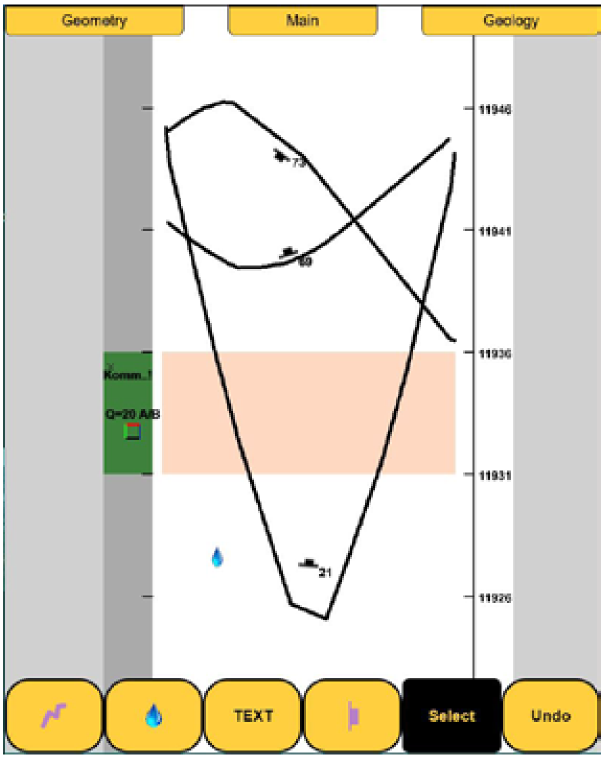


Figure 1.1.14: Bever Mapping interface without MWD interpretation. Several fractures are registered and marked with strike and dip symbols. Chainage on the right side. Q value on the left. The pink area shows how a complete rock mass classification can be registered (Bever Mapping).

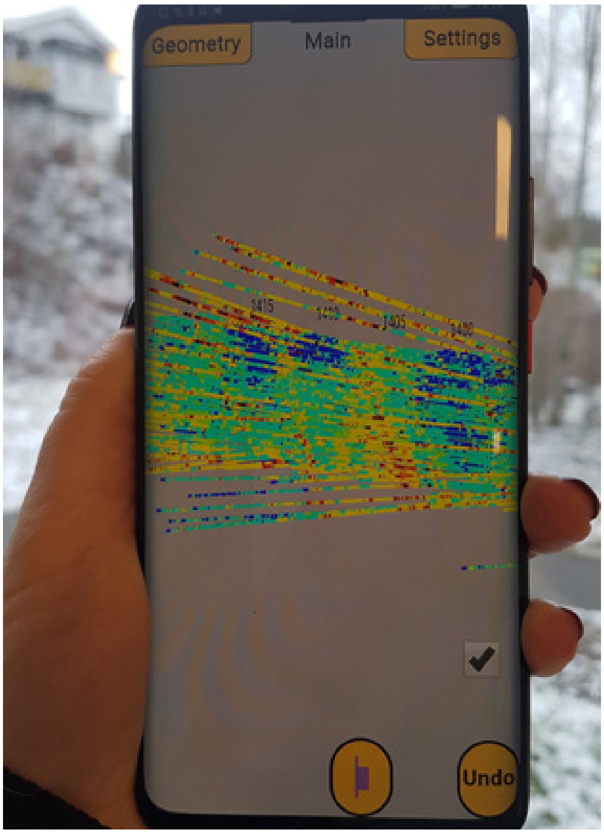


Figure 1.1.16: MWD data with calculated hardness can reveal weakness zones displayed as red and yellow. This is done in the 3D option in Bever Mapping.

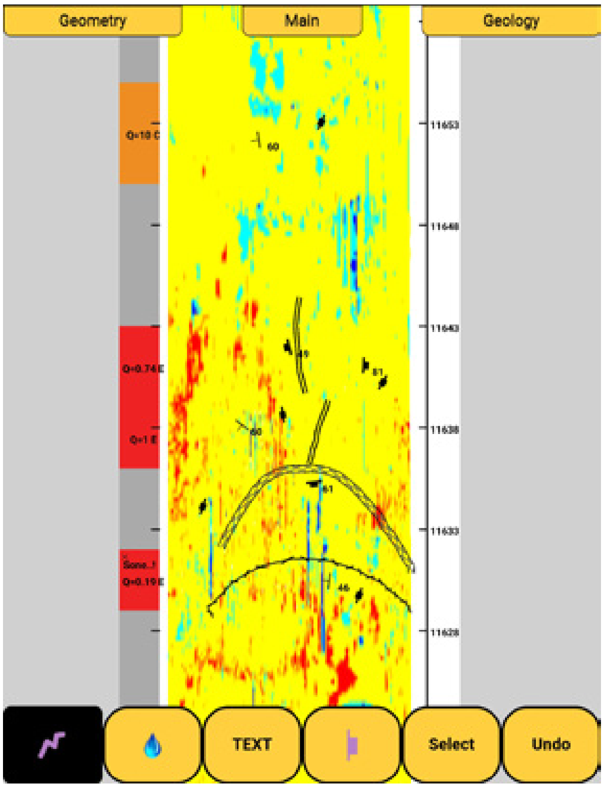


Figure 1.1.15: 2D fold-out of interpreted MWD data as background for geological registrations (Bever Mapping).

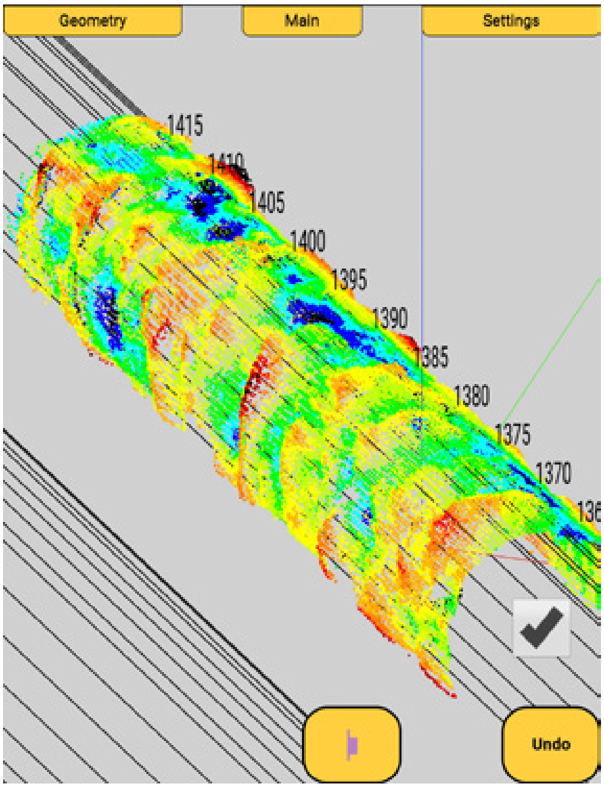


Figure 1.1.17: Point cloud from scanning of the tunnel shows overbreak and underbreak as red and dark blue, respectively (Bever Mapping).

Digital manual mapping in the site office

When the registration of geology and rock support is done at the tunnel face, the geologist must bring the paper-based registration schema or the Bever Mapping tablet back to the site office. In the site office the registrations are imported or punched into Novapoint Tunnel.

From Bever Mapping, the data can easily be imported into Novapoint Tunnel without any need for extra manual work. If the geologist has registered the data on paper, extra work is needed to re-register all the data into Novapoint Tunnel.

The geology and rock support data are registered and shown in Novapoint Tunnel in an unfolded perspective. The following geology items are supported by Novapoint Tunnel: Foliation, fractureset, single fracture, foliation, weakness zone, rock type, burst rock, Q-values and water ingress. In addition, the following rock support items can be registered: Rock bolts, spiling bolts, sprayed concrete, reinforced ribs of sprayed concrete (RRS), cast concrete inner lining, steel straps, wire mesh and grouting.

Not only does Novapoint Tunnel support manual registrations of geology- and rock support but also display of MWD colour maps and photos of the tunnel profile as background images in the registration schema. Photos and documents can also be attached to the unfolded geometry or to registered blast rounds. In addition, there is functionality for registration of water and frost protection.

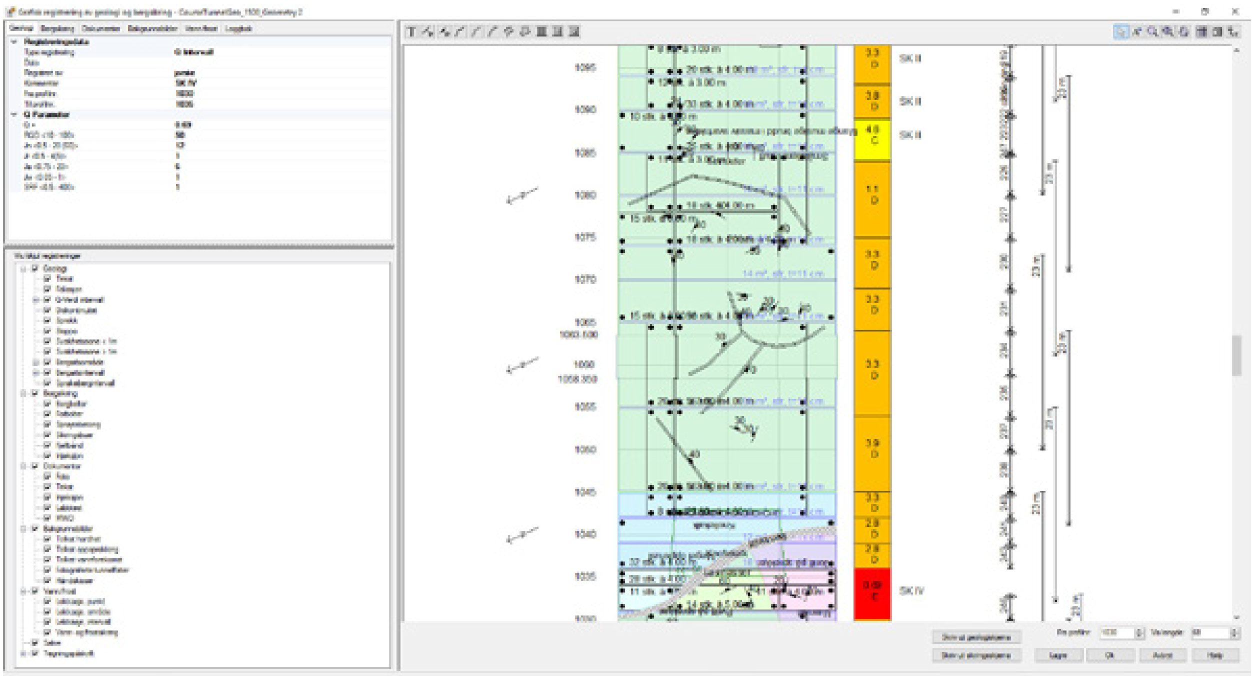


Figure 1.1.18: Geology- and rock support registrations in Novapoint Tunnel

At some sites, the built-in tunnel diary functionality in Novapoint Tunnel is used as well. This ensures that all relevant production information is preserved and can be looked up whenever needed in the future.

The registered data in Novapoint Tunnel can be shared to a central repository called Quadri. At most construction sites this is done on daily basis.

Interpreted digital logs from production machinery for drilling and blasting

Since 2013, it has been common to specify the logging and use of Measurement While Drilling (MWD) data during the tunnel excavation phase in Norwegian infrastructure projects. Before drilling of each blasting round, the drill rig is navigated. During drilling, mechanical data at the drill crown is collected by sensors on the booms of the drilling jumbo. Drilling parameters are logged every 0.02-0.10 m throughout the holes. All types of holes are usually logged, as they can give useful ground information in the tunnel and its surroundings.

Typically, the following parameters are logged (from left to right in Table 1.1.3): Penetration rate (m/min), rotation pressure (bar), feeder pressure (bar), hammer pressure (bar), rotation speed (rpm), water pressure (bar), and water flow (l/min).

Depth (m)	Penetration (m/min)	Rotation pressure (bar)	Feeder pressure (bar)	Hammer pressure (bar)	Rotation speed (rpm)	Water pressure (bar)	Water flow (l/min)
0,351	1,9	89	53	111	268	25	120
0,401	1,8	95	54	111	271	25	119
0,454	2,0	94	58	121	271	25	120
0,505	2,5	89	64	149	272	25	120
0,556	2,9	90	68	168	272	25	118
0,609	3,6	90	71	176	272	25	116
0,66	3,5	99	77	180	272	25	116
0,71	3,4	108	79	182	268	25	117
0,761	3,4	109	79	180	266	25	116
0,813	3,5	111	78	184	266	25	116
0,866	3,4	108	78	182	266	25	116
0,918	3,3	107	78	183	267	25	116

Table 1.1.3: Example of raw MWD data in table format, logged every 0.05 m (Bever Team Online).

The data in Table 1.1.3 indicates what it takes in terms of effort to drill through that intact rock. All the drilled data can be displayed individually, but without filtering and normalising the data, it is hard to see any distinct patterns. Figure 1.1.19 shows raw MWD data from only one drill rig. When there are two different, alternating drill rigs, the logs could alternate in the colour scheme. This is due to different ages or brands of drill rigs, different degrees of wear and tear, or even different operators. Without analysis and filtration, the images are quite unclear.

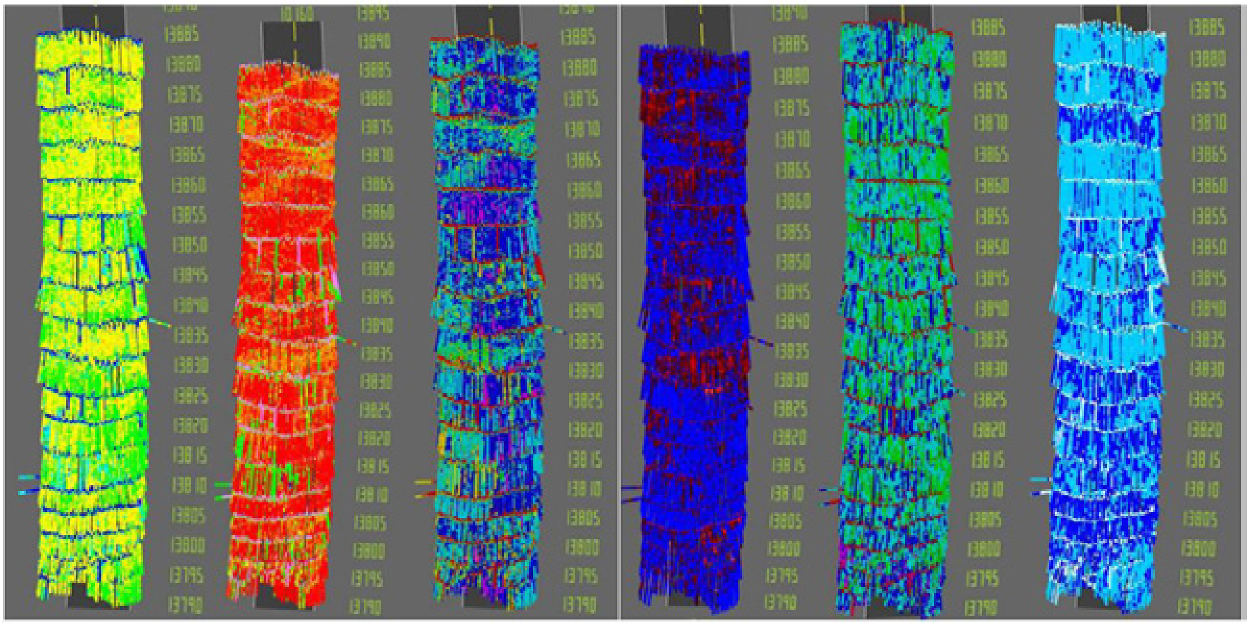


Figure 1.1.19: MWD parameters shown for a 100 m tunnel. Same order as Table 1.1.3 but without rotation speed (Bever Team Online).

The interpretation of the MWD data is usually displayed as “Hardness”, “Fracturing”, and “Water disturbance” (See Figure 1.1.20). A new calibration should be done each time the host rock changes in the tunnel, each time a new drill rig is added or replaced, or if the calibration no longer shows the points of interest clearly, like weakness zones.

The three most commonly used interpretation models are all based on all the parameters of the raw data but filtered and normalized in different ways to display the desired properties.

The most important purpose of the MWD interpretation is to utilise it as a visual aid to detect potential problem areas before reaching them. This has become more utilisable after the introduction of Wi-Fi networks all the way down to the tunnel face. Without Wi-Fi, the MWD data used to serve only for documentation purposes or studied to confirm or justify the treatment of difficult zones in a tunnel, or not even regarded at all. Now, the drill rigs can upload MWD logs after the completion of each individual hole. The logs are uploaded to a cloud-based service where they can be analysed and viewed within 5-10 minutes after the hole is completed. With a cloud-based software it can be accessed anywhere if there is an internet connection. The files can be downloaded to any device, in formats like 3D-PDF (see Figure 1.1.21), or even *.dwg.

An important contribution of MWD interpretation is now applied in probe drilling. Traditionally, the sole purpose of probe holes was to detect water. As MWD interpretation has become readily available via Wi-Fi, it can also be effectively used to detect potential weakness zones that require further investigations or extra stability mitigations.

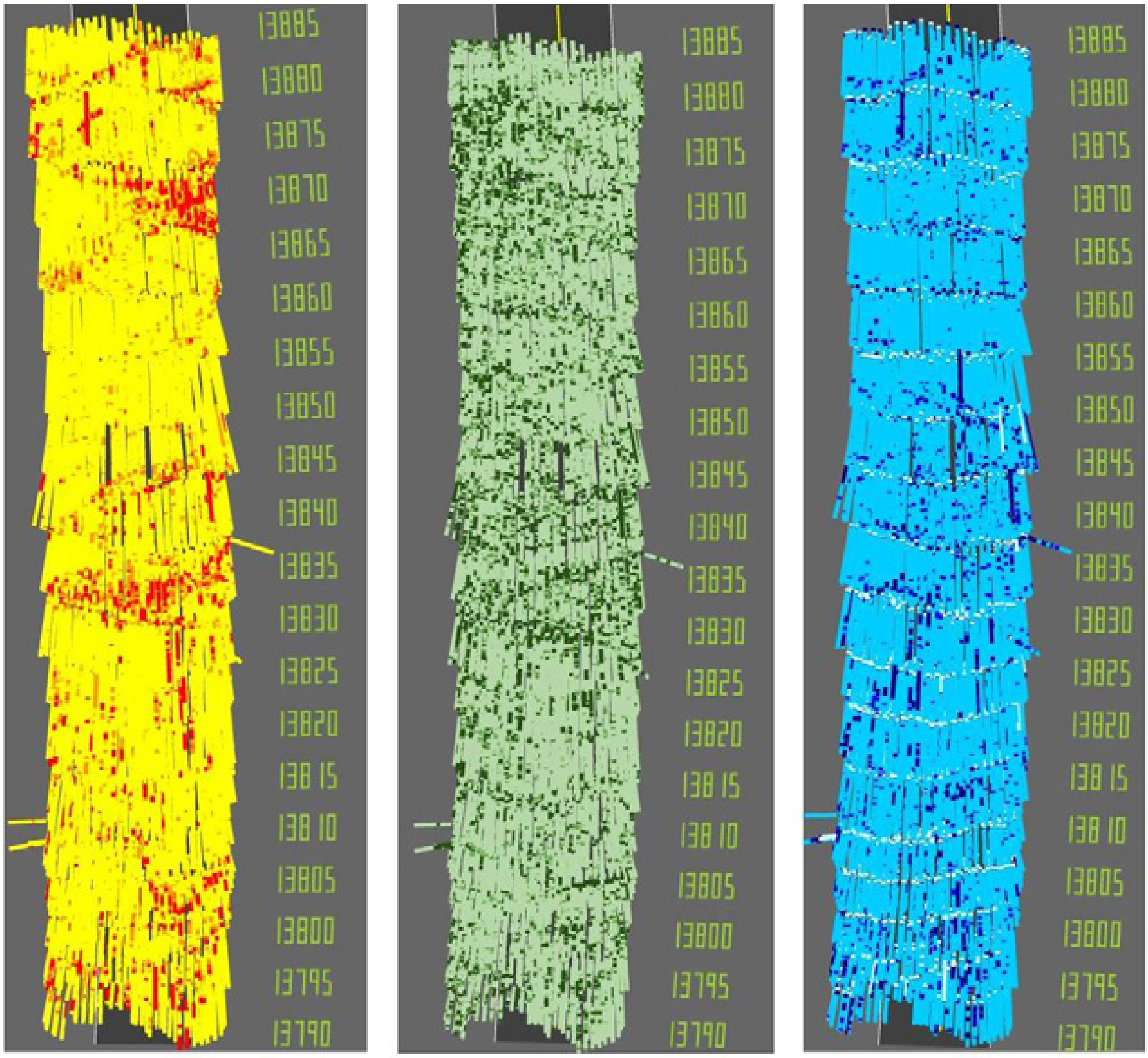
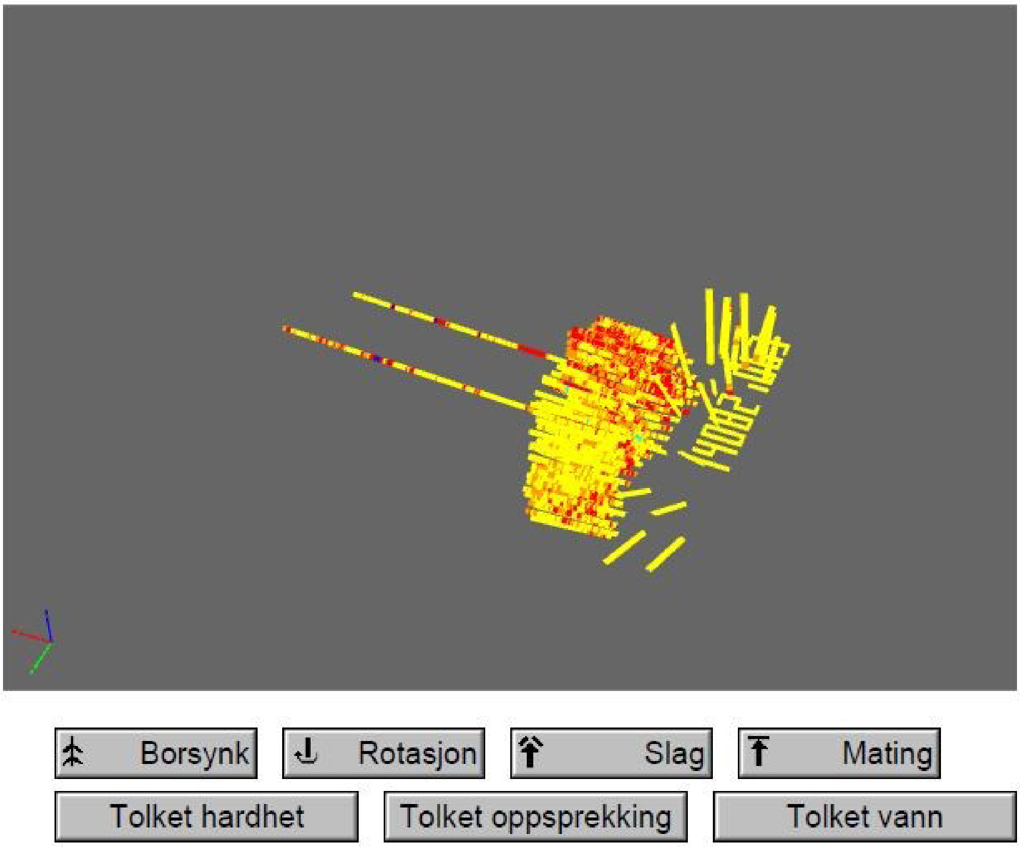


Figure 1.1.20: Calculated “Hardness”, “Fracturing”, and “Water disturbance”, where deviations from the average is show as red, dark green, and dark blue, respectively (Bever Team Online).



Tolket hardhet		
Beksrivelse	Verdi	Farge
Mindre enn 1 m/min	-100.000	
1 - 1.4 m/min	-30.000	
1.4 - 3 m/min	50.000	
3 - 3.4 m/min	70.000	
Mer enn 3.4 m/min	200.000	

Figure 1.1.21: 3D-PDF showing the interpreted "Hardness" of a single round of drilling, with bolts and two probe holes. Weak areas are displayed as red. The slight bit of blue on the left probe hole can signify a harder rock type with weaker or crushed rock surrounding

The visual aid, and therefore the visual representation of the data, is crucial for getting tunnel workers to use the information. It is possible to show single rounds, multiple rounds, and even multiple tunnels (Figure 1.1.22). When the drill and blast is a bit ahead in one of two neighbouring tunnels, information from the first can be used to interpret the second.

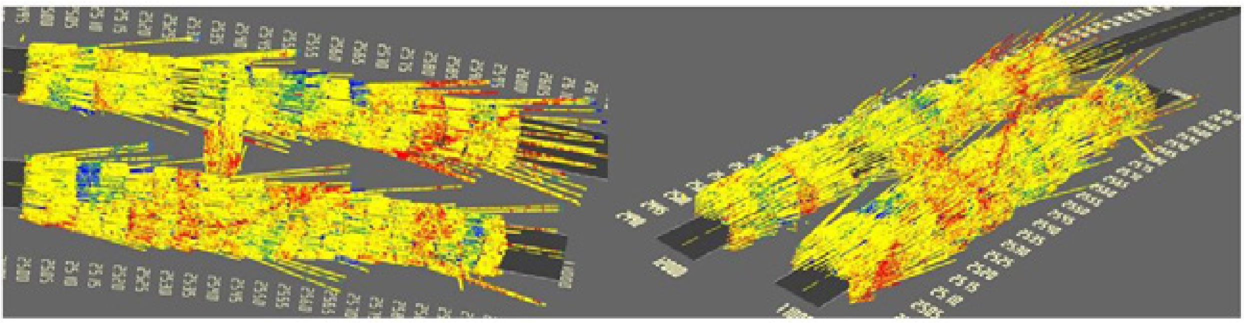


Figure 1.1.22: Two parallel tunnels with grouting umbrellas showing parallel weakness zones in red (Bever Team Online).

As mentioned, pre-Wi-Fi days, the main purpose of the MWD interpretation was documentation, and it is still used for this today. The 3D views can be flattened out to a 2D interpretation, and be applied on top of pre-investigation maps (Figure 1.1.23 and Figure 1.1.24) or imported to Novapoint Tunnel. Then it is possible to confirm or decline the relationship between the assumptions of the pre-investigations and the reality of the drill and blast. However, if a 3D model from design phase exists the same assessments can be done in 3D.

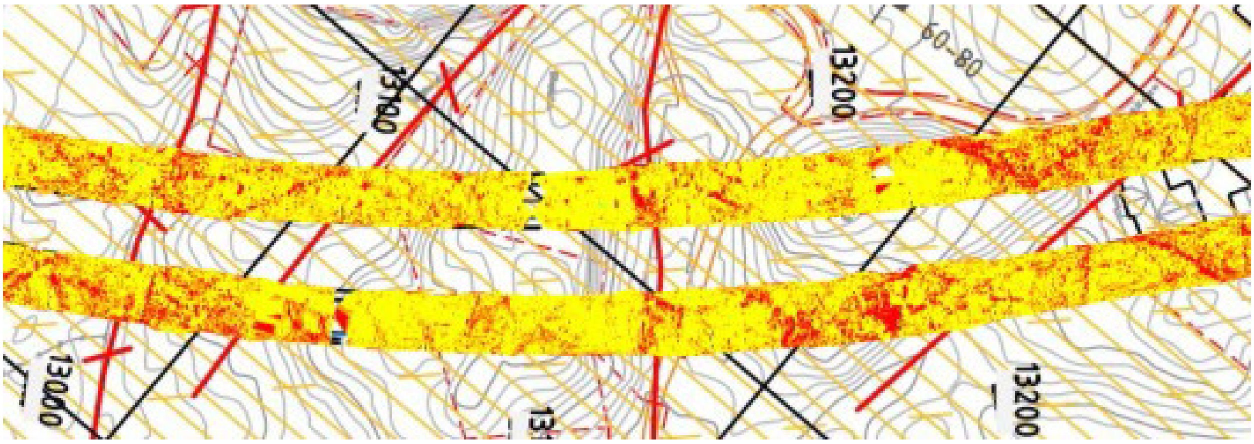


Figure 1.1.23: Two tunnels in 2D view, MWD interpretation on top of a pre-investigation geological map (Bever Team Online).

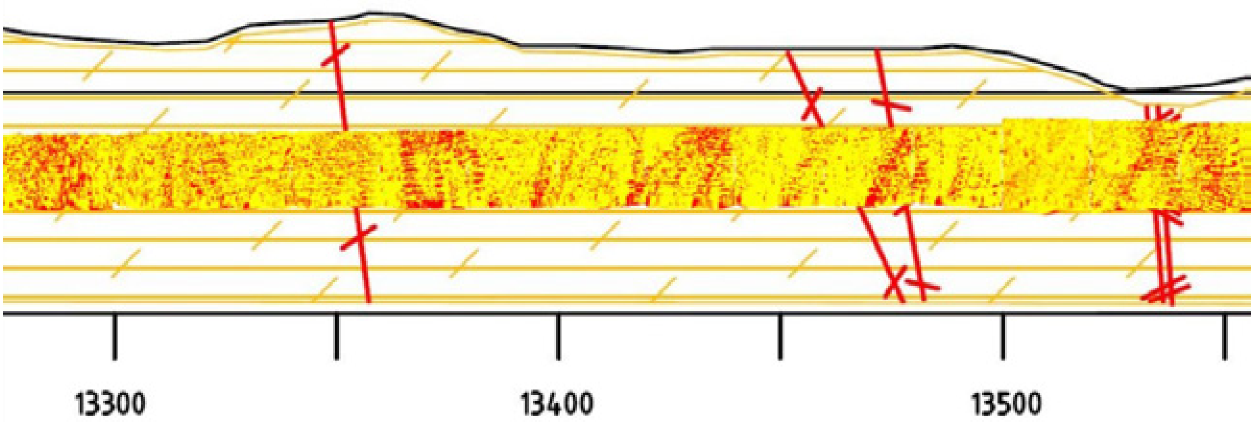


Figure 1.1.24: View from the side (tunnel MWD 2x enlarged), where the angles of the pre-investigation weakness zones don't match what was found inside the tunnel (Bever Team Online).

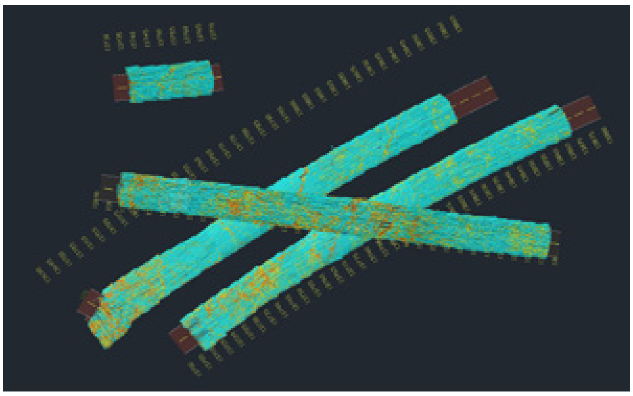


Figure 1.1.25: A 3D model in CAD format of four tunnel with Interpreted "Hardness". Weakness zones in yellow/orange can be followed from one tunnel to another (Bever Team Online).

After the documentation phase of the tunnelling, the most obvious use for MWD data in a 3D model (Figure 1.1.25) is in the maintenance perspective. Knowing the position of bolts and weakness zones may allow for better analysis of changes in the tunnel, without having to remove water and frost protection for physical access and inspection.

If a neighbouring tunnel is to be built later, the interpreted MWD data from the existing tunnel can be studied. This can likely save the cost in the pre-investigation phase of the new tunnel.

Production data from TBM

Most modern TBMs will automatically log production parameters like penetration rate, thrust force, rotation speed etc. With proper Wi-Fi coverage in the tunnel, production data can be directly uploaded to a server, allowing staff to follow production from the office. Production data from TBMs will to a certain degree be comparable to typical MWD data form a drilling jumbo. By normalizing these data and modelling them against a tunnel alignment, visualisations of rock mass boreability can be created. Figure 1.1.26 shows a visualisation the TBM penetration, normalised against thrust force. This model shows variations in boreability. Typically, weakness zones will have a much better boreability than the surrounding rock, making them stand out. In a geological model, this can be used to verify predictions as well as further interpretations of geological conditions along a tunnel. Figure 1.1.27 also illustrates how areas stands with a blue/pink colour, where they intersect the predicted weakness zones. Further, other smaller zones running parallel to the main zones can be observed, giving input to a more complete as-build model.

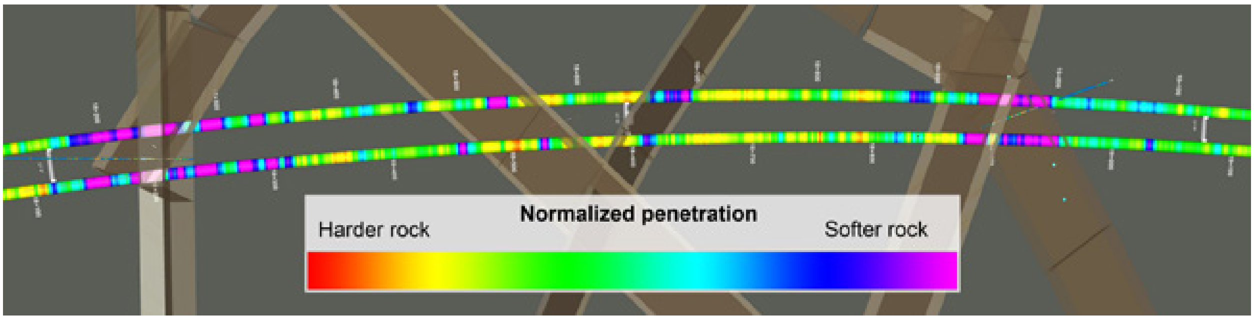


Figure 1.1.26: Normalised TBM penetration, modelled with pre-interpreted weakness zones. Weakness zones shown in brown. From The Follo Line geological model.

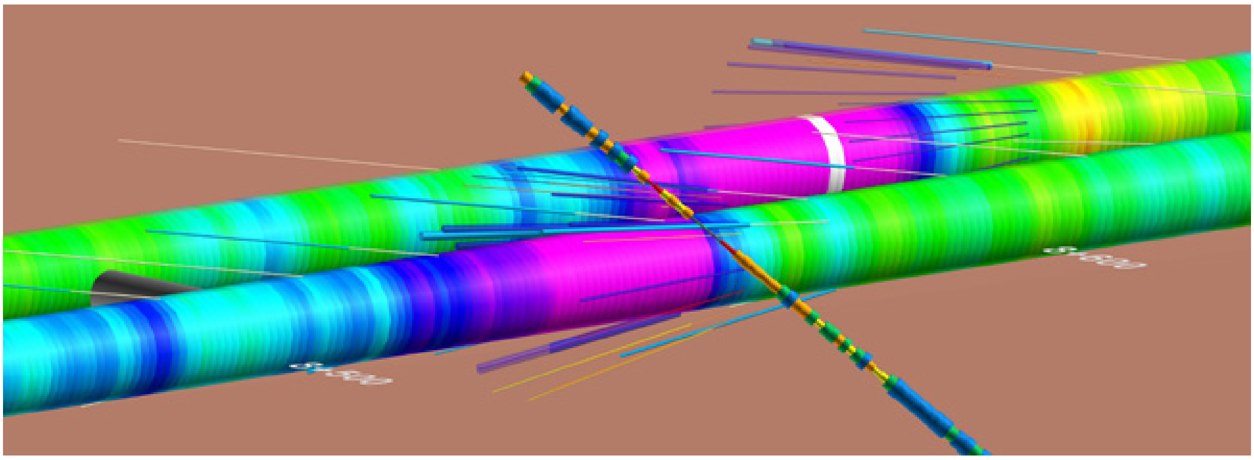


Figure 1.1.27: Normalised TBM penetration, combined with a core drilling and pre-grouting umbrellas. From The Follo Line geological model.

Optical televiewer data from probe drillings

In addition to MWD from probe drilling, some projects choose to also log the probe holes by an optical televiewer (OTV). This gives a more detailed image of the probe hole, where fractures and lithologies can be mapped. Another benefit of using a televiewer is that you can log borehole deviation at the same time. Traditionally, interpreted OTV logs have been delivered as PDF reports. However, data logs will usually contain enough data to create detailed models of the logged hole, making information both more accessible and easier to interpret in correlation to other data. Figure 1.1.28 and Figure 1.1.29 show how this have been used on the Follo Line project to illustrate both rock types and fractures along probe drillings. Fractures are illustrated by planes and the coloured cylinders represent different rock types.

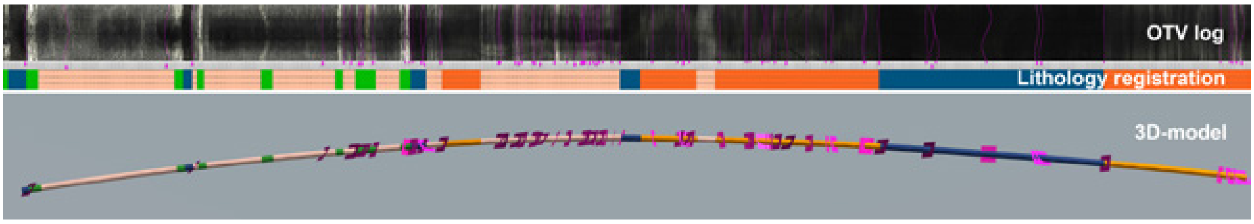


Figure 1.1.28: Example of how OTV data combined with borehole deviation measurement can be used to create a detailed model of a probe drilling. From The Follo Line geological model.

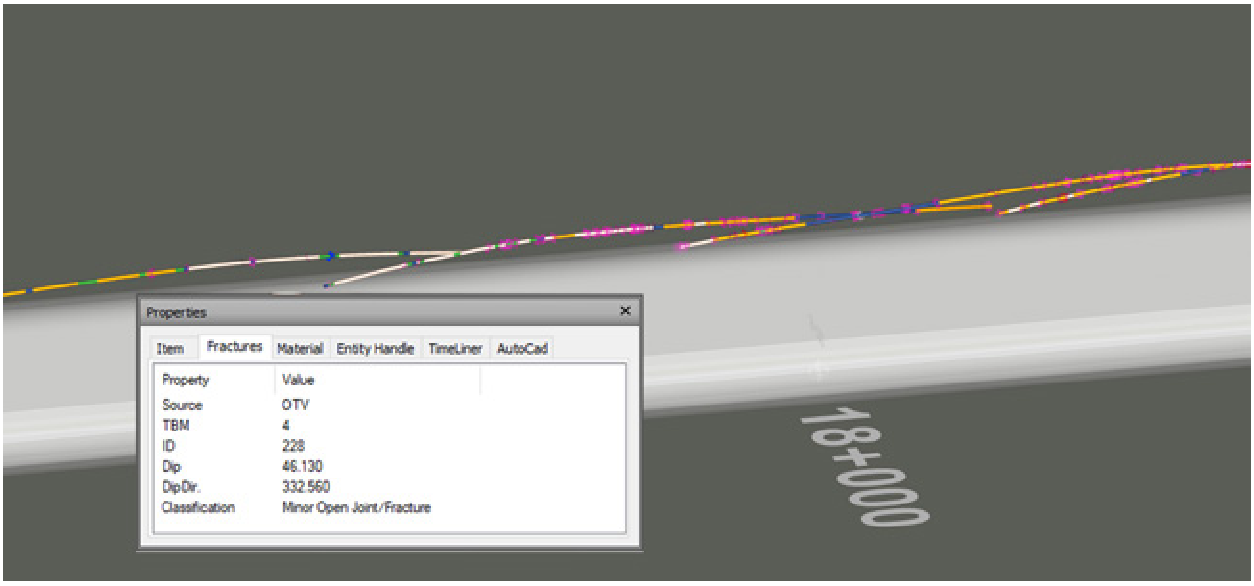


Figure 1.1.29: Several probe drillings combined in same model. An amphibolite body (blue) can be traced as it intersects different boreholes.

All data is recommended to be modelled with attributes. By doing this, data in the model becomes searchable and can be exported to other software for further analysis. This can be useful when making pole plots for sections of the tunnel or for highlighting fractures matching a certain criterion.

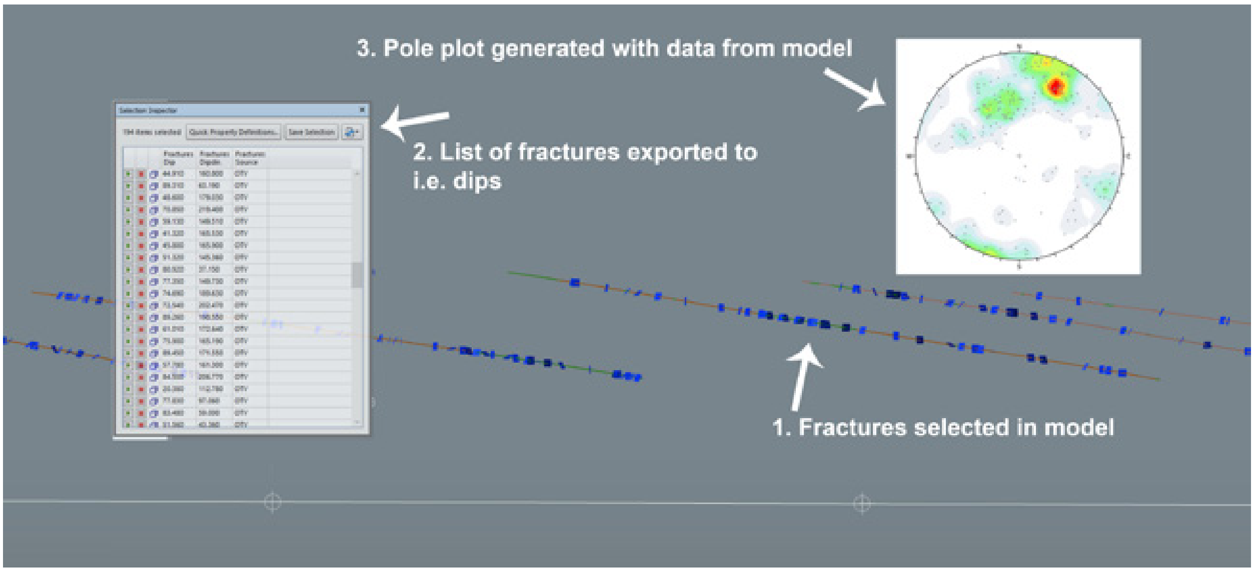


Figure 1.1.30: Example of how a model can be used as a "fracture database".

<u>Scanner data during production</u>
Control of the tunnel contour is important for the client not only to know that the tunnel is properly excavated, but also to make sure that the concrete elements and all the technical installation will fit in the pre-requested tunnel. It is crucial that the tunnel contour is within the specific limits and of the quality required by the contract. There are several computed systems that can make accurate measurements of the contour to make sure that the contour meets the specific requirements.

A tunnel profiler is a quick and accurate tool for control of the tunnel contour and can easily give an overview of the tunnel contour (see Figure 1.1.31 and Figure 1.1.32). The profiler scans the tunnel surface, then the data is processed with a software and returns the actual blasted contour and can quickly visualise underbreak and overbreak. This can be done by any scanning device, but to be able to use the data, the scanner must be navigated. By mounting a profiler on a navigated drilling jumbo, the scan be completed by the drilling operator, without the need for extra personnel in the tunnel.

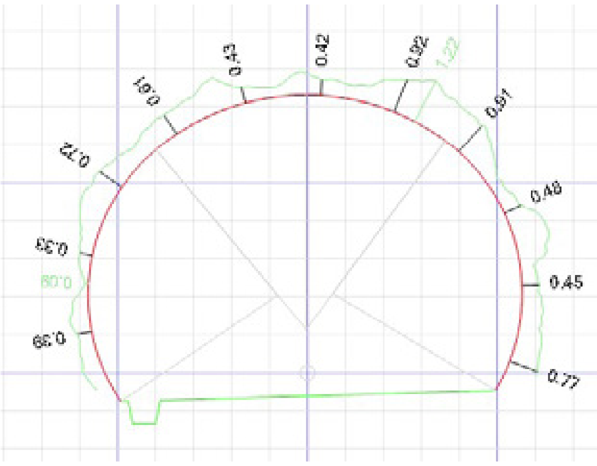


Figure 1.1.31: Cross-section of the dashed line in Figure 1.1.32. Here the maximum and minimum deviation from the theoretical profile is shown. Minimum being 0.09 metres + and maximum 1.22 (Bever Team Online).

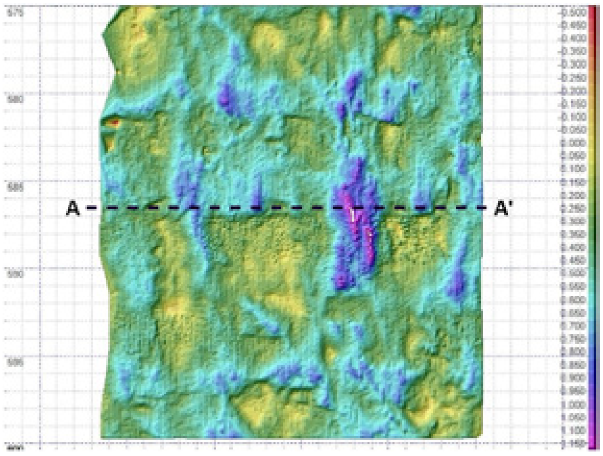


Figure 1.1.32: The profiler scans the surface of the tunnel and collects data of the tunnel contour. The data is processed, and a topographic map is produced. The colour scale is explained in the far right of the figure, where orange-red is below theoretical profile and green-violet is above theoretical profile (Bever Team Online).

A successful blasting is considered as producing a contour that is close to, but not under the theoretical profile and is no more than 0.50 m over the theoretical profile. It should be possible to achieve deviation within 0.30 m with all the analysis tools mentioned above.

In Novapoint Tunnel, Bever Team Online, Naviswork and Gemini, point clouds can be imported and triangulated to 3D-models and included in a collaboration BIM-models together with geology data, terrain data, road models, structure models etc. Figure 1.1.33 and Figure 1.1.34).

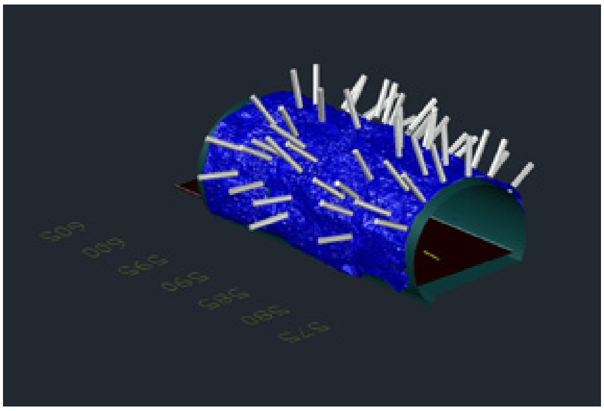


Figure 1.1.33: 3D-model of a designed tunnel and triangulated scanner data shown in Bever Team Online and Navisworks.

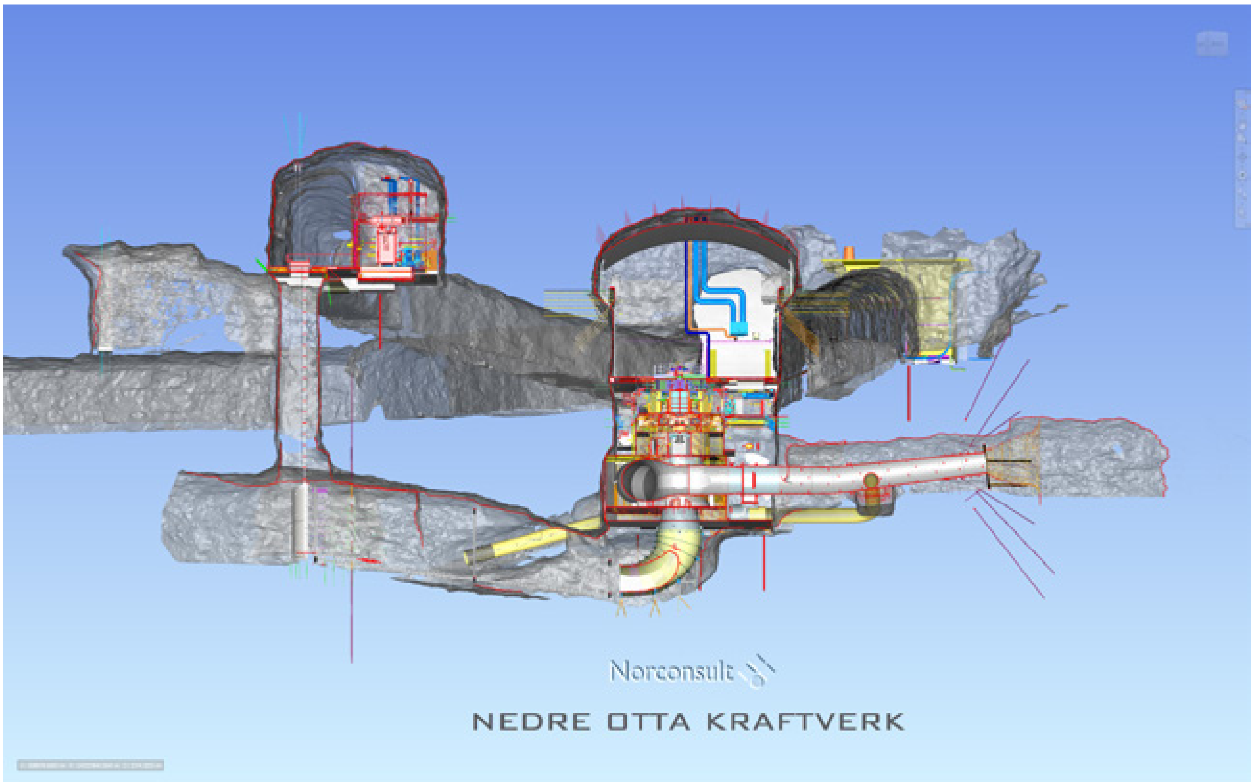


Figure 1.1.34: 3D-model of a designed tunnel and triangulated scanner data shown in Navisworks.

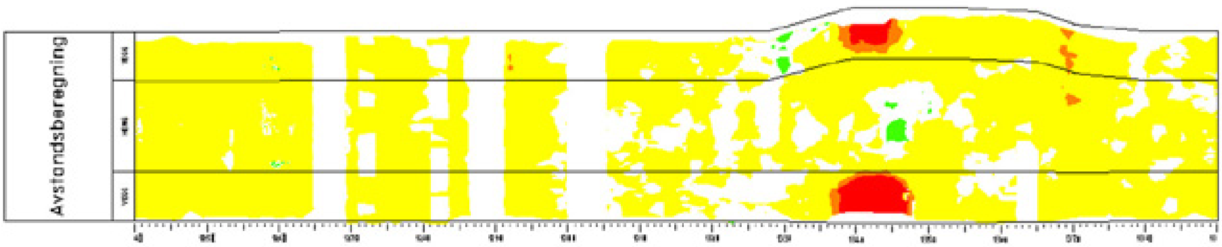


Figure 1.1.35: Novapoint Tunnel - Heatmap of triangulated scanner data compared against designed perimeter.

In addition, triangulated data can be compared against designed tunnel surfaces. This can be the contour against other triangulated surfaces, such as before and after applying shotcrete. These comparisons can be presented as heat maps.

The triangulated data can be shared to the Quadri repository and used in the future for rehabilitation purposes e.g.

The same technique of using point clouds for mapping planar features, as described in section Engineering geological mapping, can be applied underground (Figure 1.1.36). The often dark and wet conditions underground can be challenging for acquiring a good point cloud. Also, the area of the joint planes exposed in a blasted surface in tunnels is often small, making it sometimes difficult to extract planar features from a surface model. Nonetheless, geology registration based on scanning is regarded as an emerging possibility.

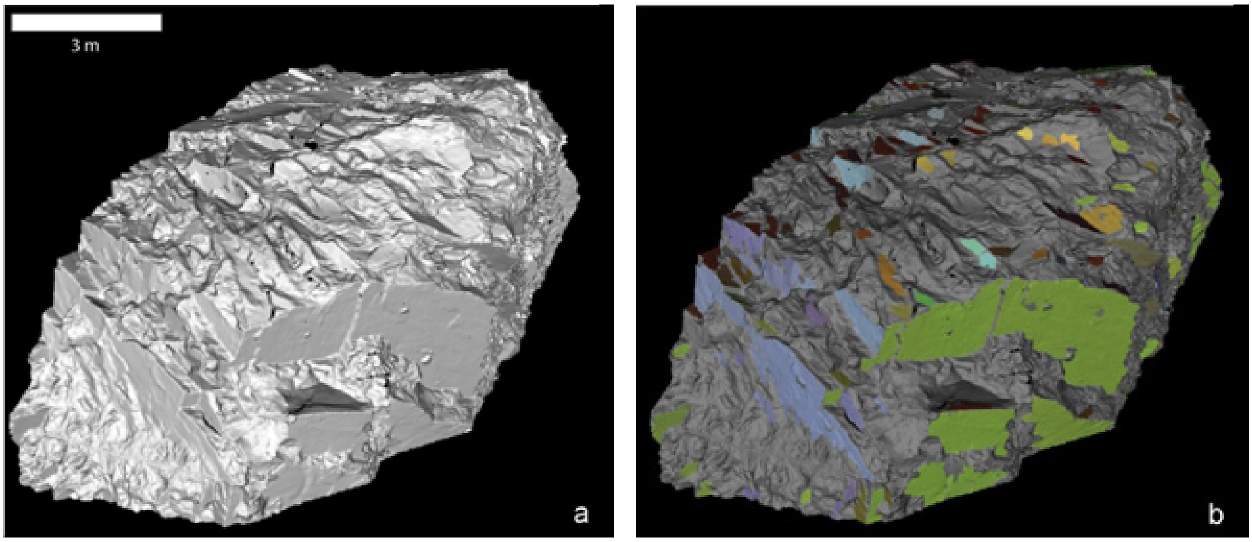


Figure 1.1.36: (a) 3D surface model derived by LiDAR scanning in tunnel and (b) automatically identified fractures by PlaneDetect at the Løren Tunnel. Image source: [6].

Pre-grouting model

In pre-grouting rounds MWD data as well as a grouting report documenting stop pressure, volume cement pumped etc. are often obtained. Combining drilling location data from the MWD dataset with data from the grouting reports can give a good visualization of where pre-grouting has been performed, as well as a basis for further interpretations of water flow in the rock mass. Figure 1.1.37 shows an example of how this can be done. In this example, pre-grouting holes have been modelled as cylinders and coloured according to volume cement pumped into the holes (darker red indicates large volumes, whereas lighter yellow indicates low volumes). Water flow through pre-grout holes before grouting have been indicated as blue cylinders, and the cylinder radius indicates the amount of water. All pre-grout holes are modelled, and attribute data is attached.

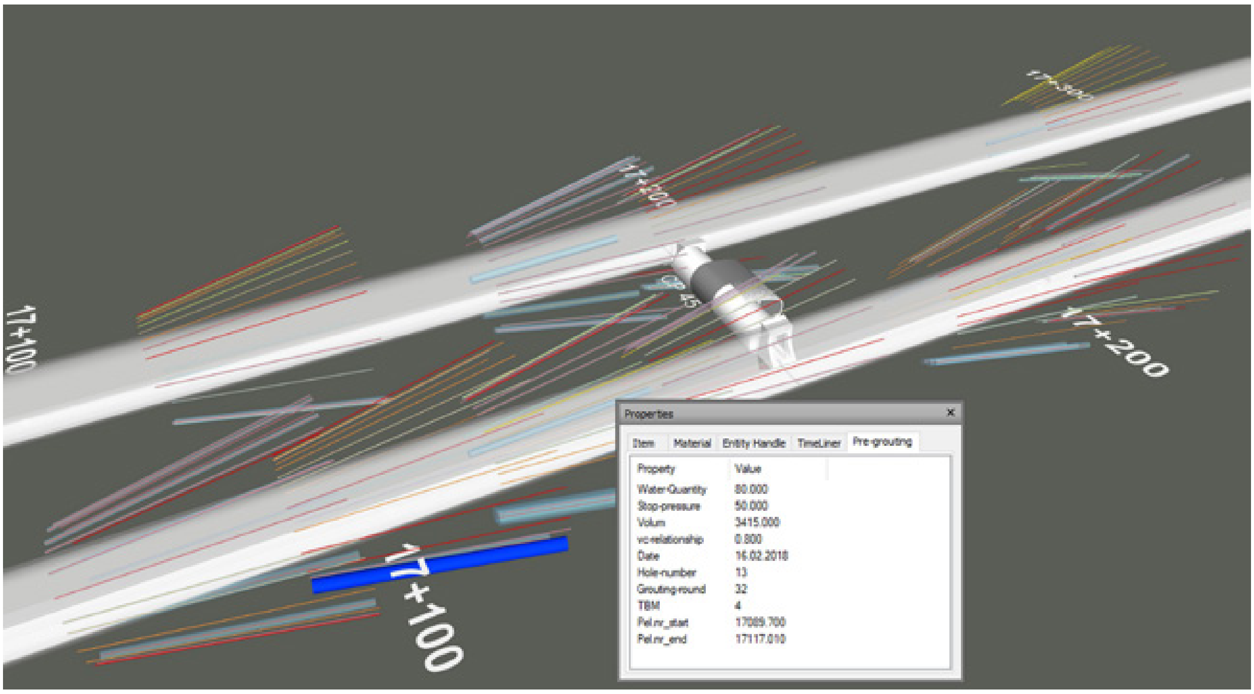


Figure 1.1.37: Modelling of pre-grouting umbrellas. From The Follo Line geological model.

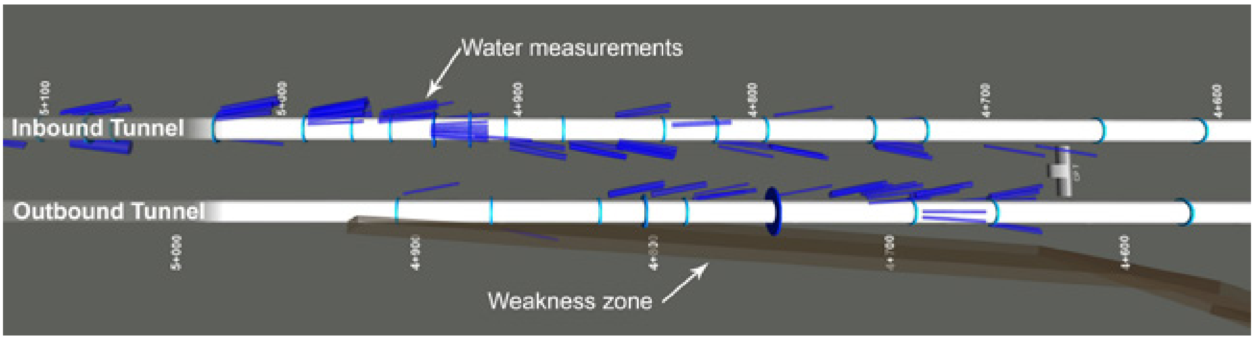


Figure 1.1.38: Water measurements from pre-grouting holes, together with modelled weakness zone. From The Follo Line geological model.

Figure 1.1.37 and Figure 1.1.38 illustrates how modelling data can give us a better understanding of water flow through fracture systems intersecting a tunnel. In this model, only large water quantities are shown. In the left half of the figure, water is predominantly registered in the inbound tunnel. Towards the right there is a change, with high water measurements being more dominant in the outbound tunnel. The water measurements can be interpreted as an alignment from upper left towards the lower right, which corresponds well with the direction of the pre-mapped weakness zone that is intersecting the tunnel.

1.1.6. As-Built geological documentation

Each project owner has their own requirements when it comes to as-built documentation from tunnelling projects. For the National Public Roads Administration (NPRA), the requirements are given in the Road Tunnels Handbook [7]. For ground conditions this includes an engineering geological map of the whole tunnel, with standardised registrations of geology and installed rock support. As of today, all tunnels should be documented using Novapoint Tunnel, and the models are stored in a common Quadri server for the whole NPRA. This central tunnel repository now contains registrations for more than 100 road tunnels built since 2010 and is a valuable asset in the case of future incidents, rehabilitation tasks or expansion of existing tunnel systems, e.g. excavating a new tunnel adjacent to the existing.

In addition to the model, a written geological report is required. Novapoint Tunnel can produce drawings and statistics to be used in the as-built geological documentation. Excel reports for blast data, fracture sets/foliations, Q-values and rock support data can be exported from Novapoint Tunnel. These Excel reports can then be used for plotting relevant graphs (e.g. Figure 1.1.39) to be included in the report.

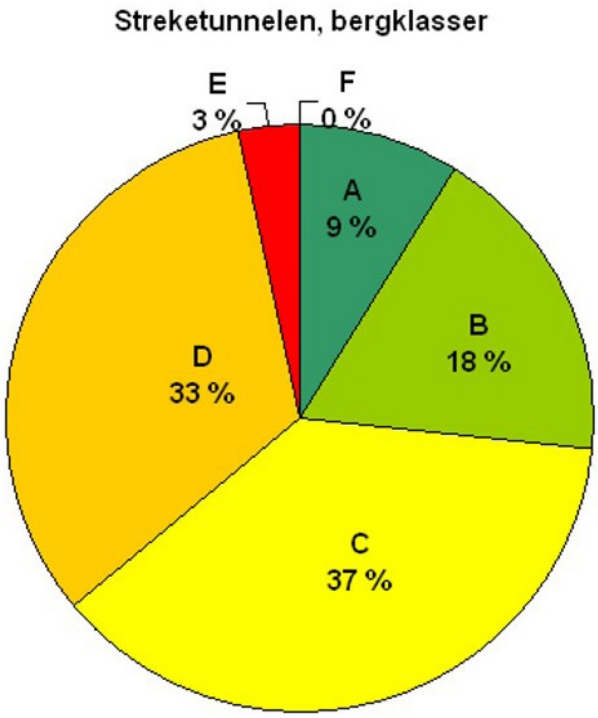


Figure 1.1.39: Rock classification from an Excel sheet exported from Novapoint Tunnel, from the Streke Tunnel.

The characteristic drawings showing geology and rock support in unfolded perspective can easily be produced by Novapoint Tunnel, see Figure 1.1.40. It is also possible to export digital mapping from programs such as Bever Mapping to a 3D format (Figure 1.1.41). This 3D mapping can be merged with the BIM/3D model used in the project and give a realistic representation of the geology in the tunnel. These drawings are an important part of the as-built geological report.

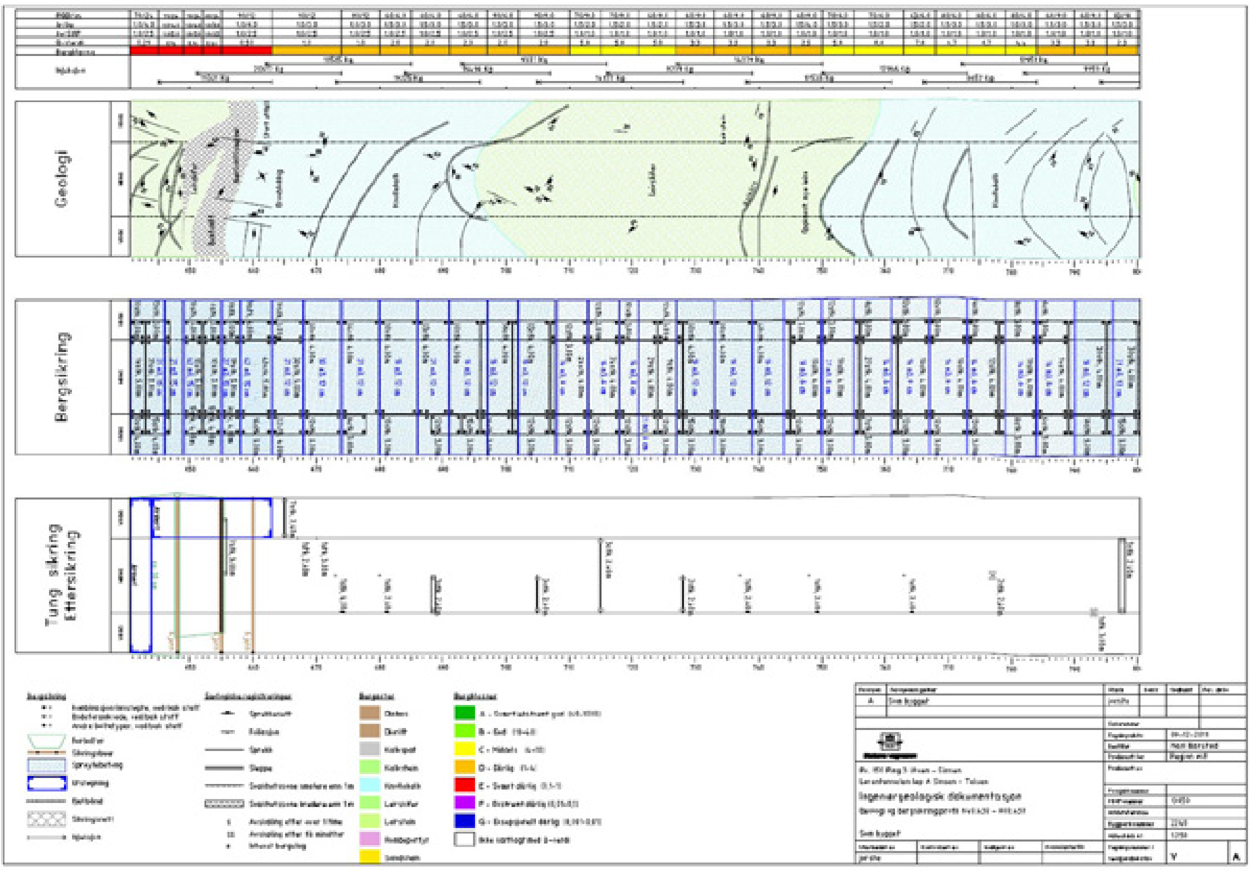


Figure 1.1.40: Geology and rock support drawing produced in Novapoint Tunnel.

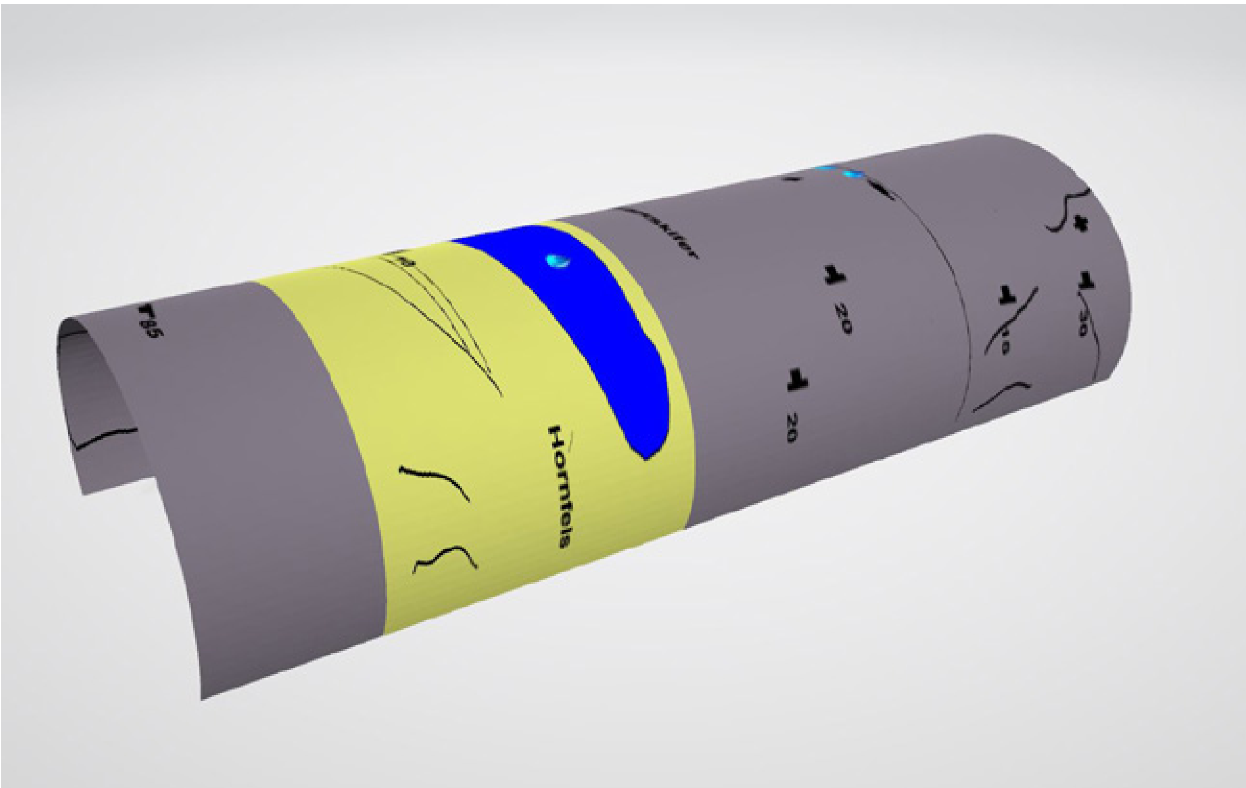


Figure 1.1.41: Digital mapping of geological registration draped over tunnel contour. Produced in Bever Mapping in .fbx format.

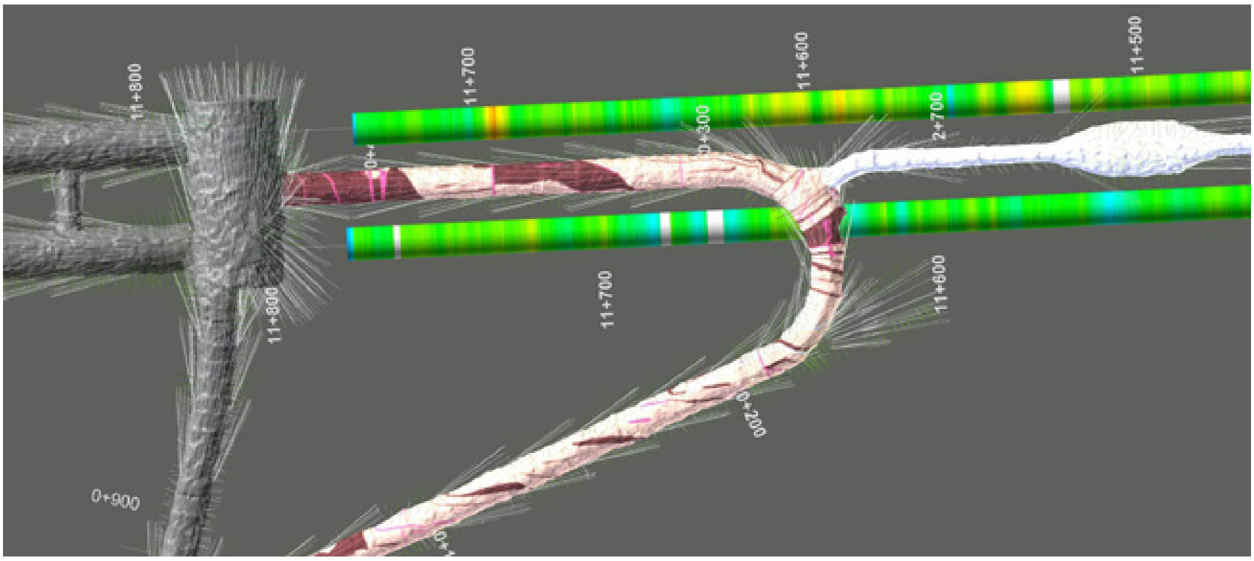


Figure 1.1.42: Geological registration draped over tunnel contour scanning, the Follo Line Project.

1.1.7. Concluding remarks

Many of the upcoming civil engineering projects in Norway are large and complex. An important success factor in the engineering phase is to share information and communicate with other tunnel designers. In order to accomplish this ground conditions should be visualized in an interdisciplinary BIM model already in the early planning stages. Understanding and predicting ground conditions is the key to robust decision making and to have successful projects regarding time and cost.

In this chapter it has been presented how different geological objects can be digitalized in a BIM model, with focus on geometry, uncertainties, limitations and associated metadata i.e. information about each object. The aim has been to initiate a discussion about standardization of modelling of ground conditions and set guidelines for future works in order to deliver uniform models that are easily recognizable from one project to another.

It has been shown that ground conditions normally presented in 2D drawings can be implemented in a digital 3D model with all the relevant information on the objects. There are always uncertainties related to actual geometry and characteristics in geology, but the uncertainties in a geological BIM model are at the same level as 2D geological drawings. It is possible to present the uncertainty of different objects using metadata, and to some degree of visualization.

A complete and dynamic geological BIM model helps set focus on the ground conditions and reduce risks in the project. As a geologist at Bane NOR working on a new railway tunnel project with a fully integrated 3D geological model put it: *"I have never worked on a project where weakness zones have been more discussed in the project meetings."*

It is important to register and store geology and rock support data during the construction phase. This documentation is necessary for rehabilitation work as well as forensic investigation of any future incidents. More than 100 road tunnels are now stored in a central server owned by the Norwegian Public Roads Administration (NPRA). Nye Veier should also make sure that their tunnels are stored in this server or an equivalent. The railway authorities should also establish a routine for collecting and storing tunnel models from their projects. The ultimate goal must be ending a tunnel construction project with an interdisciplinary as-built BIM model, which can live on in the operating phase of a tunnel, through maintenance and all the way into rehabilitation.

1.1.8. Further work

There is a lot of unrealised potential in geological modelling. Suggestion for future work is to use parameterisation of different objects to make the models more dynamic. Further suggested rock support and cost estimates based on geology and tunnel geometry with instant changes by drag-and-drop function. That means fast assessment of the best cost alignment.

By using the methods presented in this article, every project will stand free to choose how to present their geological data in the 3D model. However, to harvest the full potential of having an interdisciplinary 3D model, efforts should be put into deciding how to visually present objects and which attributes to be connected. Ideally this should be somewhat standardised so that a new model is easily readable and recognisable for all users.

The geology and rock support registrations done during the construction phase should be transformed from the traditional 2D unfolded perspective to 3D BIM-models and stored in the 3D As-Built model daily during the construction phase.

References

[1] Hegge, S & Lothe, E. (2018) Report from students in DigiTUN summer internship 2018.

[2] Geological survey of Norway (2018), map applications. Available at: https://www.ngu.no/en/topic/applications

[3] Geological survey of Norway (2018) Susceptibility maps for tunnelling. Available at: http://www.ngu.no/upload/Utbygging%20og%20arealbruk/Fjellanlegg/Tuneller/Veileder_aktsomhetskart_for_tunnelplanlegging.pdf

[4] Geological survey of Norway (2018) Datasets from NGU. Available at: https://www.ngu.no/en/topic/datasets

[5] Norwegian Geotechnical institute (2015) Handbook; Using the Q-system – Rock mass classification and support design.

[6] Lato, MJ & Vöge, M. (2012) Automated mapping of rock discontinuities in 3D lidar and photogrammetry models. International Journal of Rock Mechanics and Mining Sciences, Vol. 54 (September 2012), pp. 150-158, doi:10.1016/j.ijrmms.2012.06.003

[7] Statens vegvesen (2016) Håndbok N500 Vegtunneler. Available (in Norwegian) at: https://www.vegvesen.no/fag/publikasjoner/handboker


On safe ground

1.2. Production Data and Planning

Authors:
- *Emil Sandell Festin, Bever Control*
- *Silje Hatlø Hagen, Bever Control*

1.2.1. Background

In Norway the base for making tunnel models, drill plans and checking the tunnel e.g. under-/over break is derived either from a 3D-model or drawings. For road tunnels the cross section is selected based the annual average daily traffic (AADT). The AADT is used to choose a cross section from a standardised set. The main attributes of the cross section are (Figure 1.2.1):

- blasting contour, including floor and ditches, that indicates how large the tunnel must be made to have room for all internal components,
- normal profile, indicating the placement of the tunnel lining,
- driving box, assigned space for traffic, road surface, the level of the road itself, and any side-walks or emergency stop areas.

Digital 3D models have been used in tunnelling for many years. It started in the mid-2000s, when it was made possible to use data from the planning software used by designers directly in the drilling jumbo. Software like Trimble Novapoint (hereafter called Novapoint) and Powel Gemini (hereafter called Gemini) made this possible for Norwegian contractors.

Gemini is commonly used by surveyors from the contractor and is being used even more by the designers. The benefit from this is that a project can be created and modelled in Gemini by the designer and then handed over to the contractor. This allows for better information flow within the project. There are several types of programs for creating drill plans, tunnel models and retrieving data back from the drilling jumbo. Table 1.2.1 presents a selection of common suppliers in the Nordic countries.

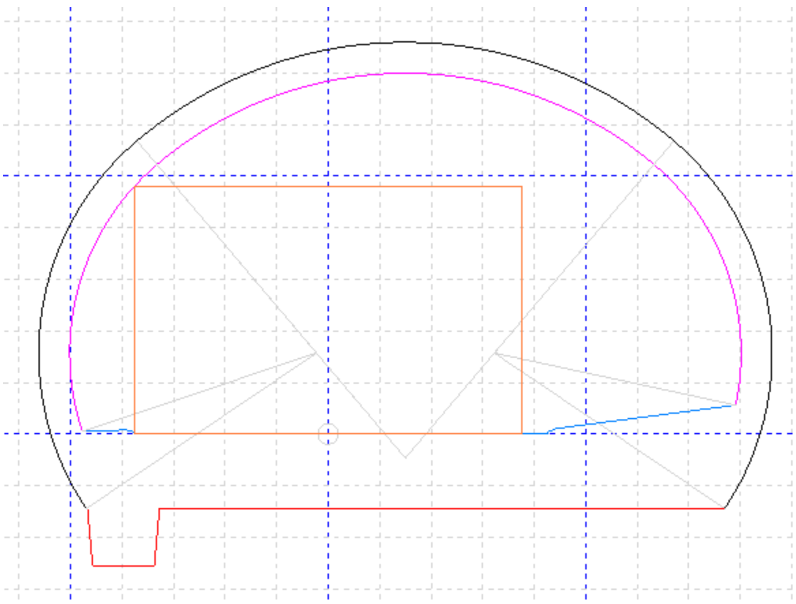


Figure 1.2.1: Cross section with multiple layers. Black and red lines indicate blasting contour. Purple and blue indicate normal profile (where the surface of tunnel lining will be) and road surface. A so called "driving box" (area designated for vehicles) marked by orange lines indicate the space where no elements are allowed to intrude. (Bever Team Online).

Manufacturer	Bever Control	Epiroc	Sandvik
Program	Bever Team 3/Online	Underground Manager	iSURE
Import cross sections	YES (multiple layers)	YES	YES
Ignitor/	YES	YES	YES
Drill plan	YES	YES	YES

Table 1.2.1: Programs for creating drill plans in the Nordic countries, with different features.

There are several benefits with having a cloud-based software, the main one being that both the client and contractor have a joint portal for data from the tunnel production. Software updates are on the server and all users instantly have access to the latest software.

When moving to cloud computing it is easy to collect and process large quantities of data. This information can ease tracking of a project with automatic generated reports. Finished projects can be stored as the company's knowledge database and be used as a basis for making offers on later projects.

1.2.2. Mutual file-/data format

Good cooperation between clients, consultants, manufactures and software suppliers resulted in the establishment of a new data format LandXML. The format makes it possible to easily send data between programs. The file contains the horizontal-, vertical alignment, camber and the contours. Bever Team products can read this format directly.

With use of either Bever Team products or Gemini it is possible send data in the IREDES (International Rock Excavation Data Exchange Standard) format to either Underground Manager or iSURE. Both programs also have some possibility to read the LandXML-format.

It is important to use open data formats for exchanging data in order to build a 3D-model from start to finish, with the desired level of detail. This involves all phases of a project, from design, through construction and in to operations and maintenance. The benefits are also thought to exceed the boundaries of the specific project and extend into the development of new projects.

1.2.3. Production data

In Norway, Bever Team 3 is a commonly used software for creating production data that can be exchanged directly with the jumbo. The drilling jumbo returns data logs and scanning of the contour. Scanning is done with either a profiler (see chapter 1.2), a total station or a point cloud scanner. Bever Team also supports multiple layers in the contour e.g. blasting- and normal profile.

The programs in the family also supports a parametrical tunnel line for higher accuracy, easier for the user and less data. If describing a curve with parametrical line you only need starting point, ending point and a radius or clotoids. If describing the same curve with points and connecting lines, the intervals between the points impact the accuracy. More points will also increase the data amount. 5 metre intervals are common.

Bever Team products supports sending and receiving data from different jumbos and is not restricted to one manufacturer, which makes it possible to have different jumbos from different manufacturers.

Drill plan (Manual and automatic)

Drill plans are either made manually at or automatic by parameters set at the office or at the tunnel face. This also uses face and bottom contour to adjust lookout when the cross-section changes. Figure 1.2.2 and Figure 1.2.3, shows automatic drill plans from

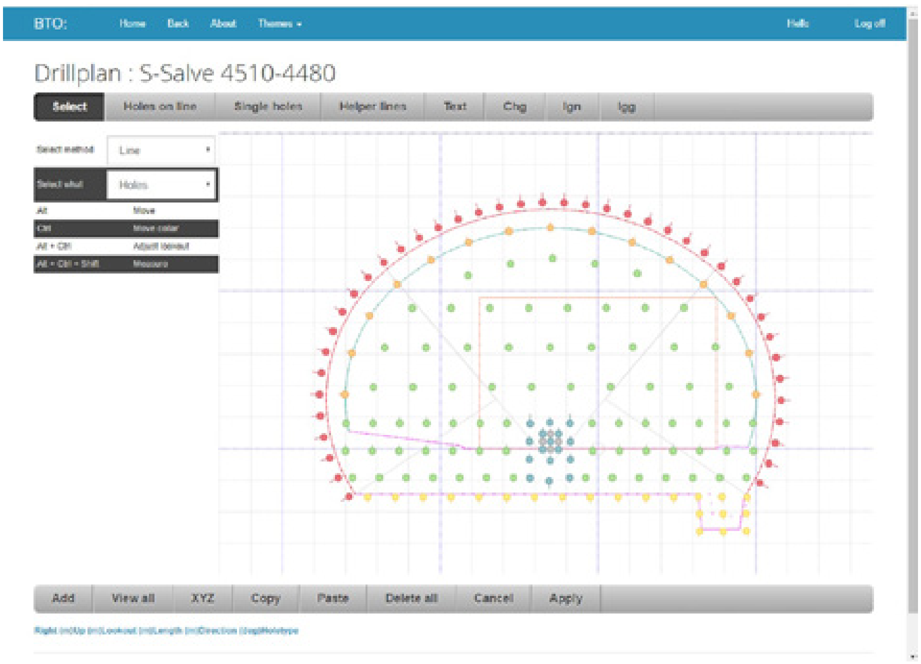


Figure 1.2.2: View of drill plan (Bever Team Online)

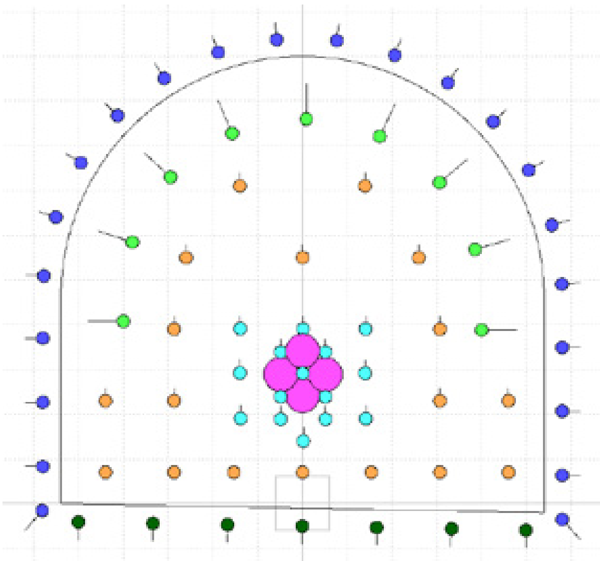


Figure 1.2.3: View of drill plan (Underground Manager).

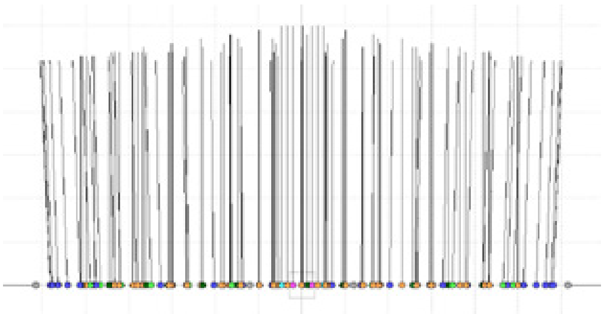


Figure 1.2.4: Drill plan with tapered shape (Underground Manager).

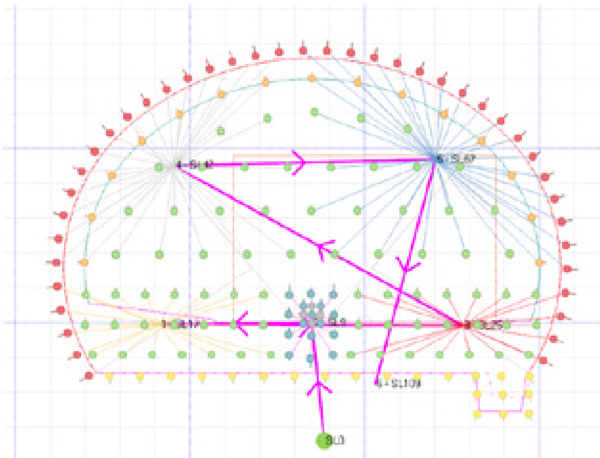


Figure 1.2.5: Bunch delays, used when problem with vibrations. Can be replaced with electronic detonators (Bever Team Online).

two software providers. Automatic drill plans have a significant advantage and can save time when the tunnel often changes cross section.

The benefit of a plan that is generated on the drill rig by the operator, is that the drill pattern will be adjusted to the actual position of the face. Unfortunately, it is not used often, because of vibration regulations. The drill- and ignitor plans for use under populated areas must be approved by the client roughly 5 days ahead of blasting. A solution for this could be to have an approved parameter set for the drill plan. However, it will not solve the problem with ignitor plan. Commonly, when not in densely populated areas a basic drill- and ignitor plan can be approved. In these cases, the geometries are usually not that challenging and the advantage of an on-face generated plan is not significant.

<u>Depth in drill plan</u>
When discussing the drill plan, there is a difference between the length of the drill holes and the depth of the hole. By using "depth" in the drill plan the desired shape in the bottom of the round can be achieved. Desired bottom shape can be seen in Figure 1.2.4. This can be done either in normal round blasting, or when connecting to another tunnel, for example a cross passage. The point of controlling the bottom shape, and thereby the next face shape, is to reduce vibrations, increase the advance for each blast, and to have less scaling. The face topography can be displayed, as the collar point for each hole is known (Figure 1.2.6). The results of adjusted depth of the bottom of holes can be seen in Figure 1.2.6 and Figure 1.2.7.

<u>Explosives plan</u>
The plan for explosives is divided in to two or three parts. Booster and pipe charge as one, ignitor, and if needed, bunch delays. When you set the booster charge you also set the pipe charge. By using software instead of traditional pen and paper, it is easy to see which holes will be set off at the same time, the order of the holes, and the amount of explosives (kg) going off simultaneously. Figure 1.2.5 shows a bunch delay. The detonation order is set by the purple arrow, starting with the cut and finishing with the floor contour.

<u>As-built</u>
Drill logs
Drill logs, and data from the jumbo, can be displayed in many ways. Either in a program, online, or in various reports in different formats. The main uses of the reports are to check that the drill logs resemble the drill plan, and if not, find ways to improve the results.

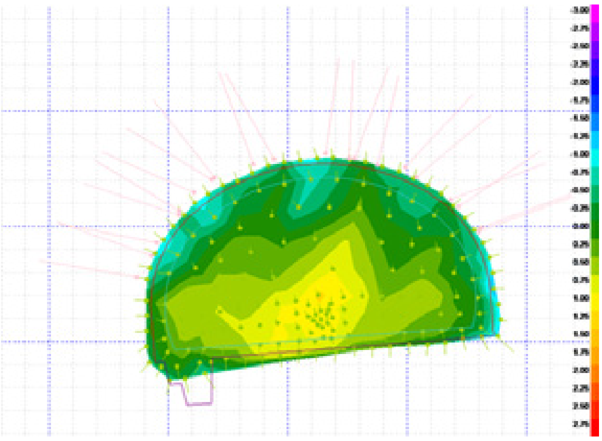


Figure 1.2.6: Topographical face map of collaring point. Colours shows deviation from reference plan, green is on the reference plan. (Bever Team Online)

A reoccurring problem is getting the drainage ditch deep enough. Doing this correctly during the drilling and blasting saves a lot of time compared to going back to re-drill. A deep ditch will of course also help with water drainage during construction. The holes in the drill plan are often seen as a point, where the drill bit has struck the face (collar point), with a line extending from it, indicating angle and sometimes also length of the hole.

As seen in Figure 1.2.8, the round holes (blue) are collared at the blasting contour and angled slightly outward. Especially in the bottom corners, the lines are longer, indicating a longer hole drilled at a quite higher angle compared to the others. The same can be seen in the ditch. The effect of this style of drilling on the profile can be discussed, as the explosives load and tension for this hole will be high without having many places to break.

The same drill log is displayed below in top view and side view (Figure 1.2.9). The top view shows a slightly rounded bottom that will result in a rounded face in the next round. But, in the side view it is clear that it's only the area around the cut that has been rounded, and so the probable end result could be like previously shown in Figure 1.2.7. The side view also shows the angle of the holes, and it is possible to recognise the floor contour and ditch holes specifically near the bottom. The ditch holes are drilled with a deviation of about 0.5 metres in the bottom compared to the collar, over 5 metres of hole length, which is not bad. Other projects have seen ditch holes or even floor holes drilled at higher angles, resulting in a very uneven, saw-toothed floor, and subsequent increased concrete use to rectify the results.

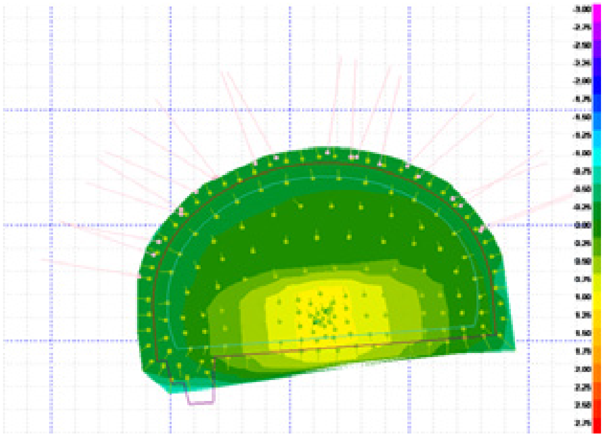


Figure 1.2.7: Topographical face map of bottom of drilled round. The contractor has chosen to make bottom of the round tapered, not flat. To make the advance greater, less scaling and reducing problems with vibrations. The cut is drilled approximately 1 meter longer than the collar for one blast. Then the cut will continue be 1 meter deeper in the round but all the round holes will have the same length. Show by the yellow colour and green colour, se scale in picture. (Bever Team Online).

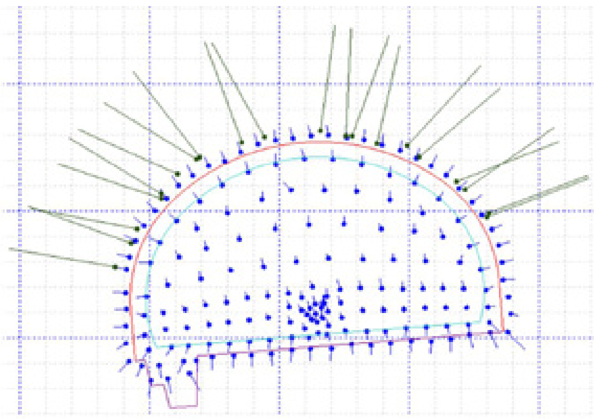


Figure 1.2.8: Front view of drill log, with rock bolts. (Blasting and normal contour). (Bever Team Online)

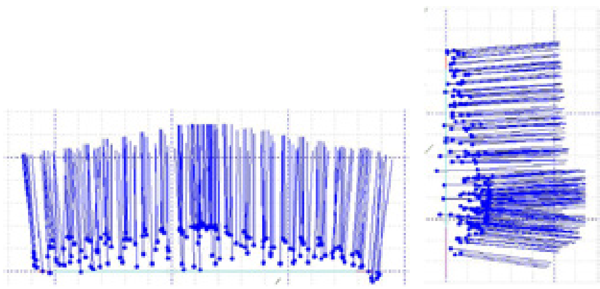


Figure 1.2.9: Top and side view of drill log. The desired shape of the bottom of the round shows clearly. It also illustrates the difference between depth and length of the drill holes. The length of the holes can be almost the same, but the depth is set to get at desired shape. (Bever Team Online).

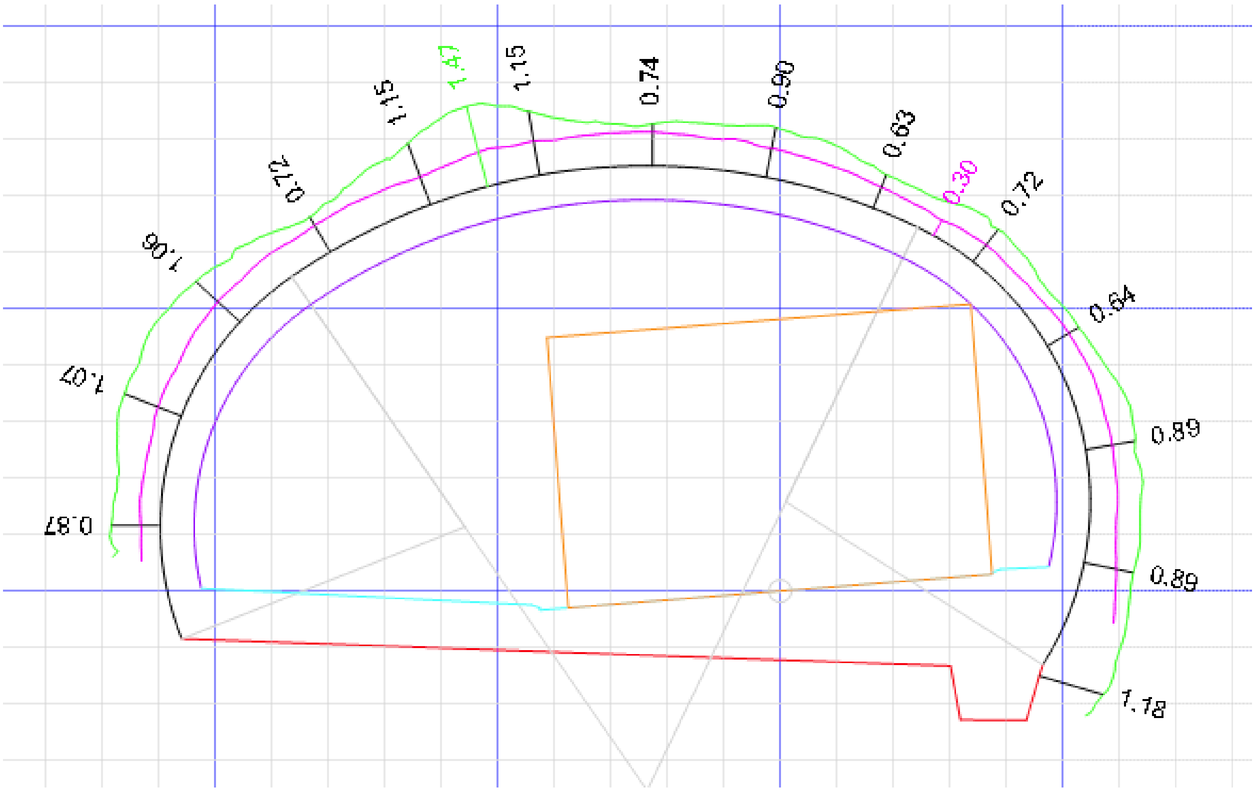


Figure 1.2.10: Cross section with multiple scanning's, from profiler, total station or point cloud scanner. Green by profiler during excavation of the tunnel. Pink with Leica MS50 (fast scanning total station), heavy rock reinforcement with shotcrete arches (Bever Team 3).

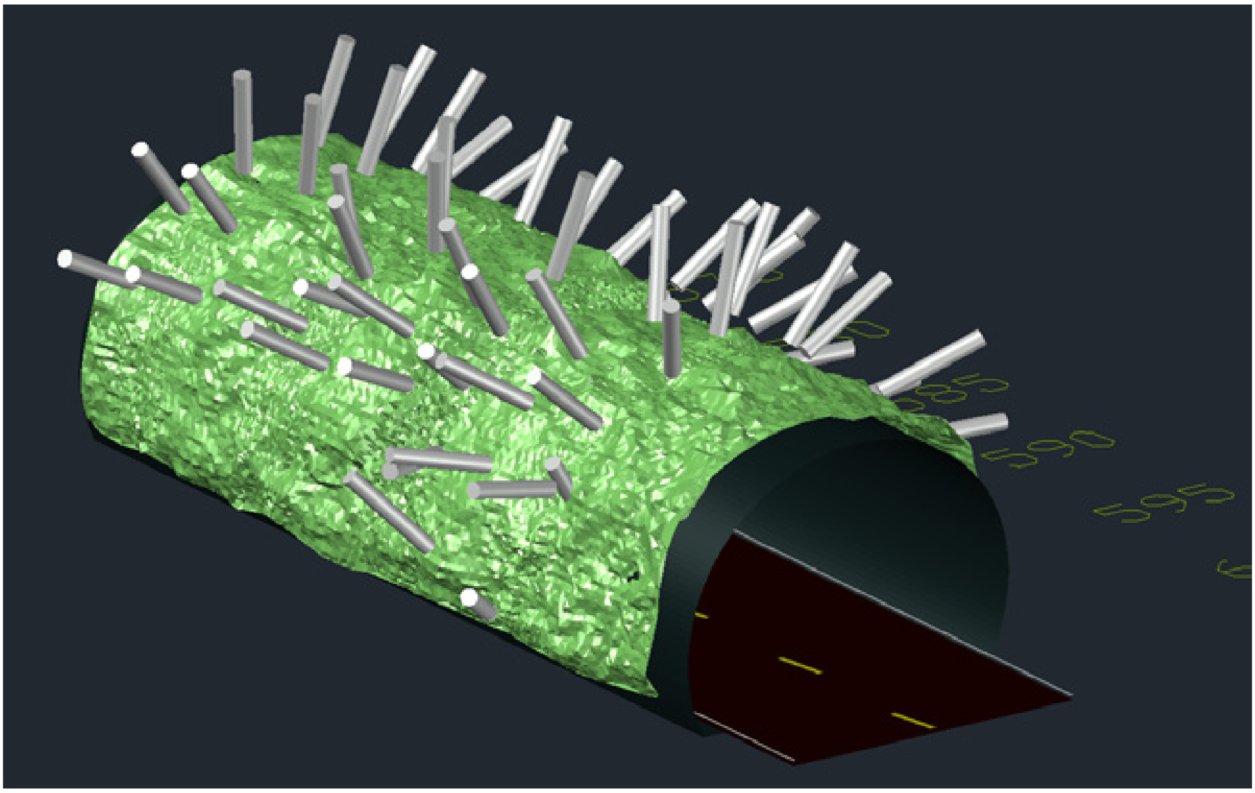


Figure 1.2.11: Scanning with bolts (dwg or 3D pdf) (Bever Team Online).

1.2.4. Scanning

As-built scanning is usually done on the face by the jumbo with the profiler. The scanning will be of either bare rock or shotcrete. In Figure 1.2.10 the bare rock is shown as a green line, and the pink line is after shotcrete and reinforcements. The image (without the pink line) will also be displayed on the drill rig. This way it is easy to see and remove unwanted underbreak in the profile directly, instead of having to go back several rounds later. In the Figure 1.2.10, the blast result is quite a lot larger than what is required, this is due to weak rock in the area, requiring additional space to have room for shotcrete arches and other heavy reinforcement.

The as-built scans can be displayed and reported in many ways, depending on what the points of interest are. A 3D model of the scans (Figure 1.2.11), complete with bolt holes to detect potential fallouts due to geological structures in the tunnel, or systematic high-angle drilling resulting in a saw-tooth-looking tunnel. Adding the bolts can be useful to see how they are drilled compared to any weaknesses, or also to check that they have been placed at the right angle compared to the tunnel surface, especially where a more intelligent bolting strategy is needed.

Some find 3D difficult to view, and prefer a flattened-out, colour coded map to show problem areas. The colour code in Figure 1.2.12 shows a contour close to the planned blasting contour as yellow, no underbreaks that would be depicted as red, but some blue and purple areas that show overbreaks larger than 0.5 metres.

Some places, around chainage 581, 587, 592 and 597 show repetition, with around one round length between them. This could indicate that the blast result at the bottom of the holes systematically is a bit too efficient, or that they are drilled at too high of an angle, creating too much overbreak. Too much overbreak will lead to increased transport costs for depositing the extra rock, as well as increased shotcrete cost, as the total area increases more shotcrete needs to be added. The one purple blob stretching along the right side of the tunnel roof from chainage 579 to 591, however, could indicate a weak rock that breaks more than intended.

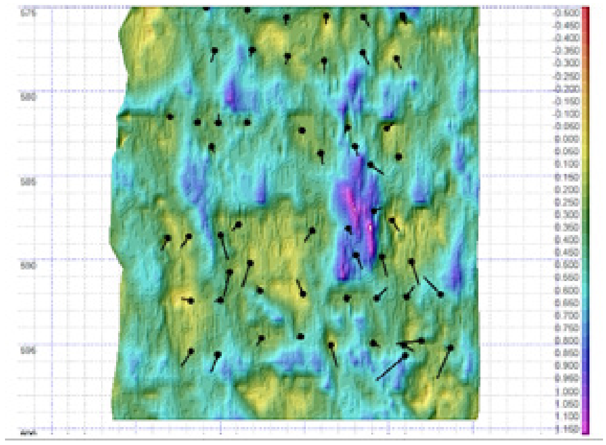


Figure 1.2.12: Scanning in a flattened out topographical map, with bolts (Bever Team Online).

1.2.5. Future development

The main focus should be to use the drill data along with geology information to optimize the blasting process. One could think that a skilled operator with permission to generate their own drill plans on the face could take into account the geology of the tunnel, to place holes in a more intelligent way. Some ideas could be:

- Placing more holes in a hard vein that has given underbreak in the tunnel, to reduce scaling and avoid re-blast.
- To place less holes in an area that shows an uncommon amount of overbreak, as the rock probably is weak and needs less explosives to break.
- To experiment with the best bottom shape for the tunnel along with vibrations measurements, especially under inhabited areas. Also experiment with bottom shape to get the maximum advance out of the same drilled length. A rounded face breaks easier than a flat one, as sharp corners require the use of more explosives and/or a denser drill pattern.

The first step towards these improvements should be changing the regulations to allow on-face, or at least online, quick adjustments to the drill plans without them having to be pre-approved days ahead.

1.3. Machine Operation

Authors:
- *Christian Haugen Svendsen, Bever Control*
- *Silje Hatlø Hagen, Bever Control*
- *Harald Juvland, AF Gruppen*

1.3.1. Drilling and navigation

Drill and blast is the most common method for excavating tunnels in Norway. It is a complicated procedure and must be well planned to make it efficient and at lowest cost possible. The first computerized drill system was developed and available on the market in 1979 and since then new drill rigs with advanced computer systems have been developed.

Computerized drill systems

Bever Control/AMV, Epiroc (former Atlas Copco) and Sandvik are the main manufacturers of highly advanced computerized drill systems in the Scandinavian market. These companies have made several series of these systems and is a standard equipment on rigs used in large infrastructure projects. Bever Control delivers their products to any jumbo manufacturer. Data acquisition records data from scanning of excavated contour, drilling parameters and drifter performance. Other notable features are Anti-jamming and auto positioning. These systems follow the same general setup, for drilling purposes they have three different modes, manual, guided (semi-automatic) and automatic. The rigs are also installed with sensors that can obtain secondary data, like Measurement While Drilling (MWD).

Common practice for drilling and blasting in Norway is using a computer controlled three boom jumbo Figure 1.3.1.

Figure 1.3.1: Bever controls computerized drill system mounted on a drill rig. The screen to the left displays the drill plan, the screen shows which holes are currently being drilled (highlighted in blue). The screen to the right is the instrumental panel and shows a detailed view of all the parameters for each boom.

The system logs all the drill holes including the bolt holes, round holes and probe holes. The drill jumbo computer has all the project data available like tunnel line contours and drill patterns and it is possible to choose drill plans for round, bolt, probe or grouting and if the rig is going to drill automatic, semi-automatic or manual. Semi-automatic is mostly used today, it is a guided drilling where the operator chooses a hole from the drill plan that is desirable and gets help by the computerized system to aim and angle the boom correctly. After the hole has been drilled the initial cm (approximately 50 cm), the boom can be put on auto and then drill the remaining length of the hole. The operator is then able to repeat this process with the two other booms and repeats this process until all holes are drilled. An example of a drill plan used in the drilling jumbo can be seen in Figure 1.3.2.

The computerized system is also equipped with an automatic adjust of lookout function. The system alerts the operator of an upcoming bend and makes the necessary calculation and adjustments on the drill plan. Figure 1.3.3 shows the drill plan and that the blasting contour of the tunnel is to expand.

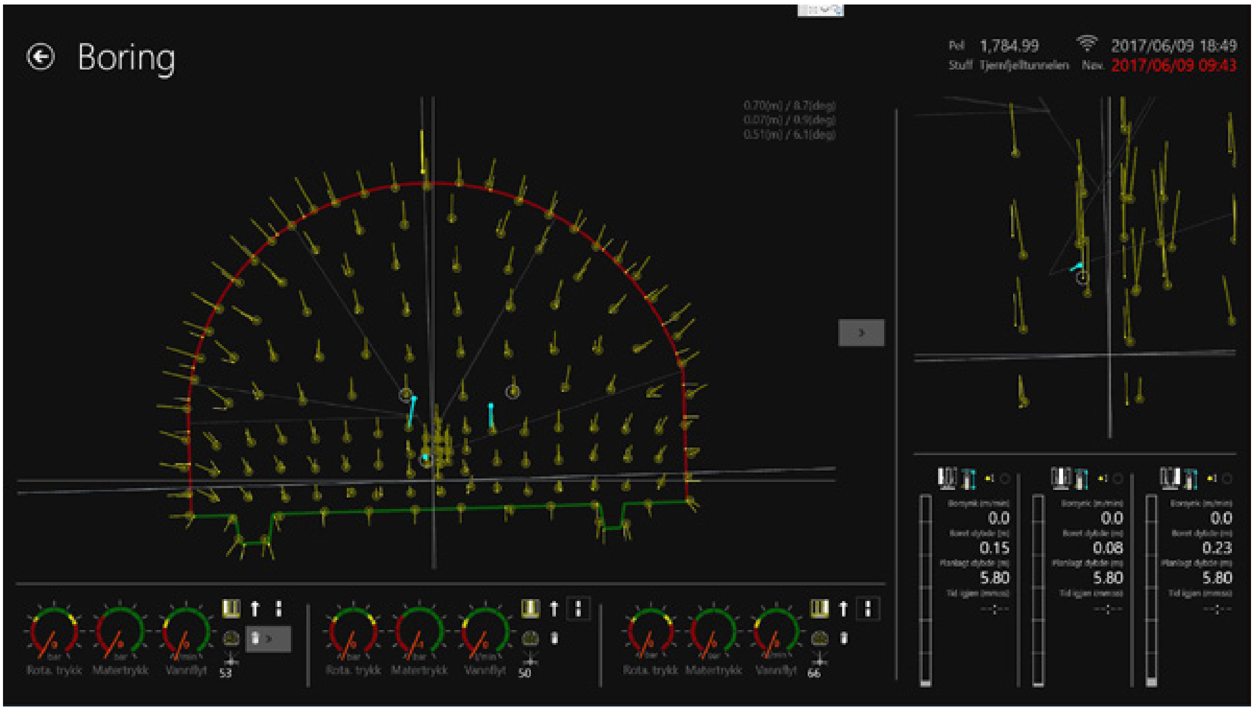


Figure 1.3.2: Drill plan, the holes currently being drilled is highlighted in blue. Under the drill plan, the rotational pressure, feeder pressure and water flow are displayed for each of the booms. To the right it is possible to see the progress of the drilling and how far it has drilled.

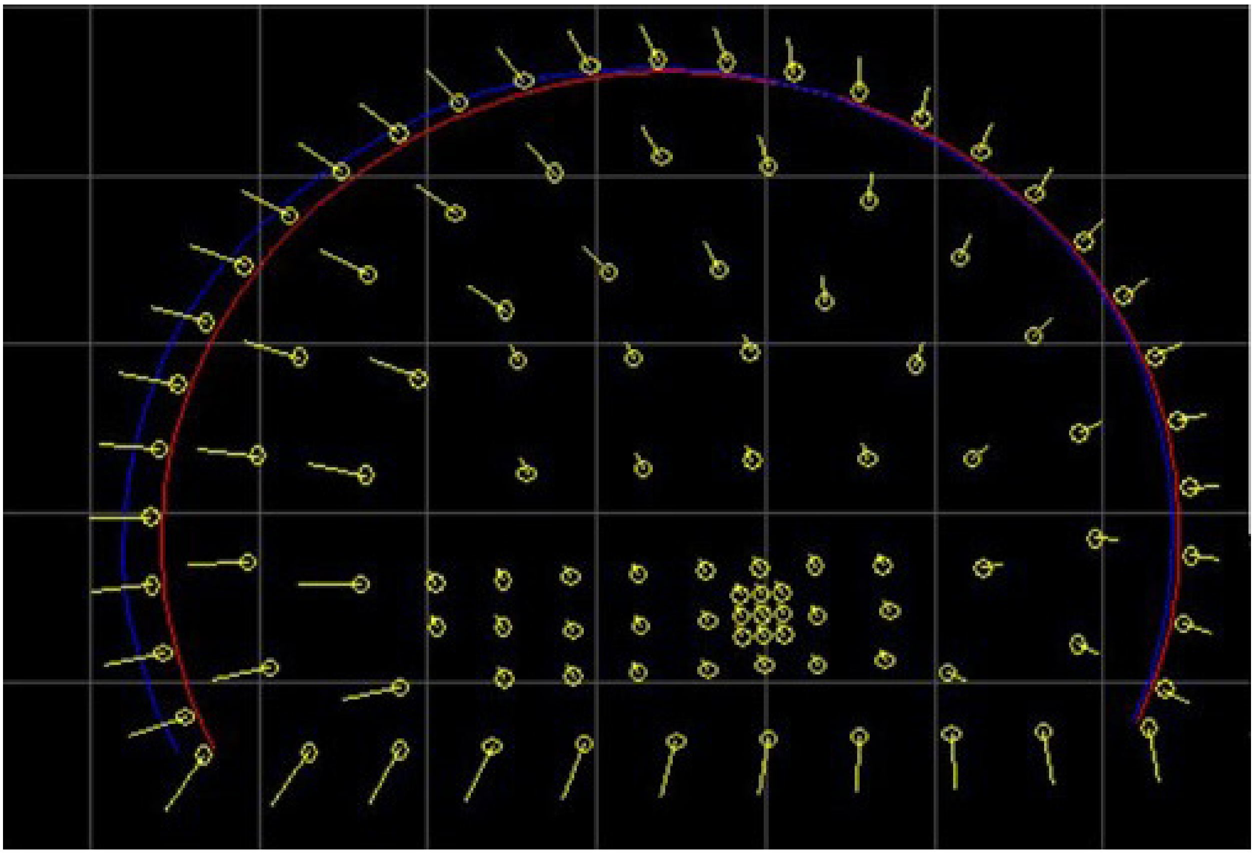


Figure 1.3.3: Automatic correction of lookout in bend. The red line is the active tunnel face where the drilling is executed. The blue line is the next profile in the following round. The drill plan show that the left side needs to widen, so the lookout is increased to add space.

Navigation

Navigation is crucial to be able to orientate the jumbo in the tunnel. Navigation tools are used to establish a geo-referenced production system to make use of the data collected by the jumbo. The drilling accuracy should be between 5 and 10 cm, which means that the navigation of the chassis needs to have an accuracy of < 5 cm [1].

The position of the drilling jumbo at the face must be measured accurate and quick and should take less than 5 minutes.

There are three methods to navigate a rig and its booms. Tunnel lasers was the most common navigation system before the profiler and later the total station came on the market. The laser is aligned with the feed on the left or right boom, the laser is less accurate than the two others and it is easier to navigate wrong, no chainage is produced, but it is small and easy to transport, rugged and waterproof, low power consumption and long lifetime Figure 1.3.4. Total station (Trimble or Leica, mostly used) is commonly used in tunnels to collect coordinates for placed bolts, obtain chainage and to navigate rigs. The total station can be of robotic type (automatic) or manual operated. The total station aims at least two, preferably three different prisms which is situated at known locations and makes it possible to navigate the rig Figure 1.3.4. The total station achieves the highest navigation accuracy.

The profiler (Bever 3D profiler) was originally constructed to be able to use as a scanner with the ability to navigate, Figure 1.3.4. The profiler aims at two or three target plates which are situated at known locations and uses them to triangulate its position by scanning them see Figure 1.3.5. The profiler is similar to the total station, but it is mounted on the jumbo and do not need extra personnel to operate it, since the drill operator can control it from the control cabin.

Figure 1.3.4: Upper right image shows a tunnel laser [2], lower left image shows a total station with a prism, lower right image shows a profiler with a target plate.

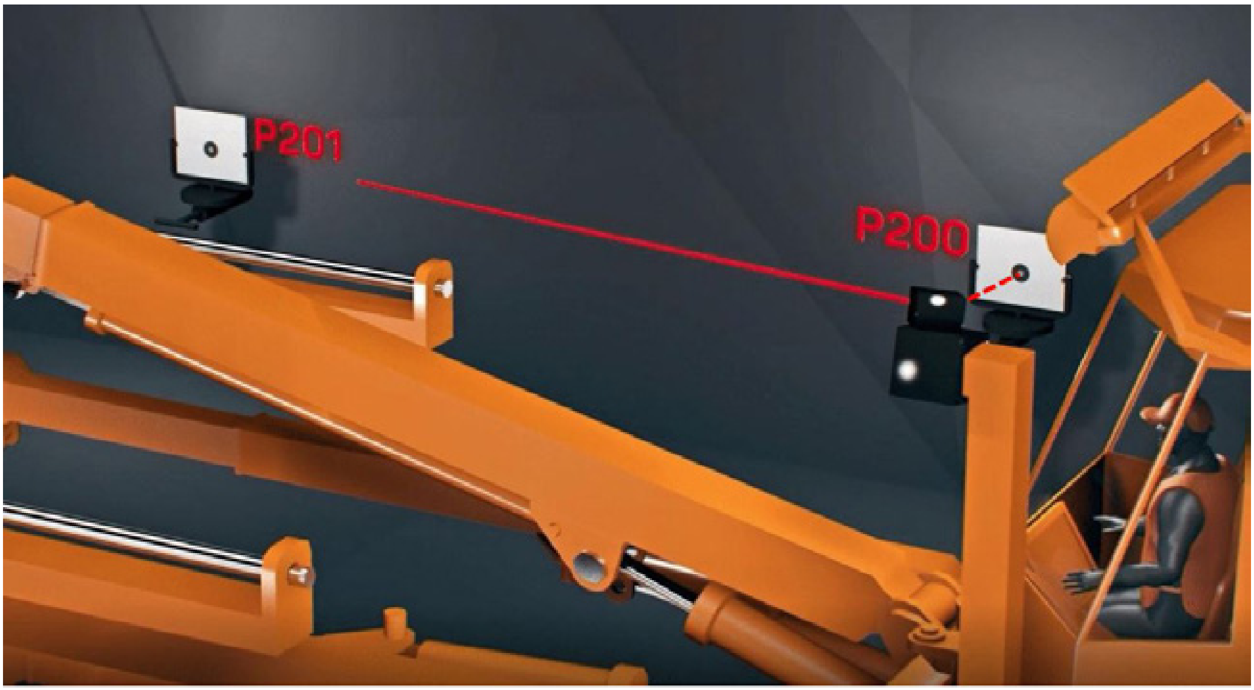


Figure 1.3.5: A principal sketch of how the drill rig is navigated with the profiler. The profiler registers the point 200, then 201 and the recorder in the profiler can tell where the chassis is relative to the known points.

1.3.2. Technical infrastructure, Wi-Fi

In today's tunnel projects in Norway most of the tunnels are "connected". This is due to two main factors. Norwegian regulations require that contractor maintain digital list of people onsite in case of emergency. Delivering MWD data "live" is a requirement in many of the contracts.

The tunnel needs connectivity outside of the tunnel. (Fiber or 4G). This signal is then connected to Wi-Fi antennas in the tunnel. Wi-Fi access points has a maximum distance for 500 m between them.

Effera is a supplier of Wi-Fi hotspots infrastructure. Drill jumbos and other tunnel equipment can connect to their cloud solutions through the Wi-Fi network. This enable live update of drilled holes (MWD data) to the cloud for live analysis.

1.3.3. Pre - grouting

Water related problems are common in tunnel engineering. Changes in groundwater levels can have a serious impact on the surrounding environment. Water erodes nearby rocks and may impact the stability and strength of the rock, thus shortens the lifetime of the tunnel. Another critical issue with tampering with the groundwater is that the groundwater reservoirs are important societal resources and the loss of groundwater in an area can have serious consequences for the nearby community and facilities [3].

The Rock grouting technology is under continuous development, this includes equipment, execution and grouting materials. The Norwegian practice for grouting is listed in Figure 1.3.6. where it can be seen how the grouting is processed in the different steps in the planning of the tunnel excavation, starting with the design and investigation phase to the execution and the result Figure 1.3.6.

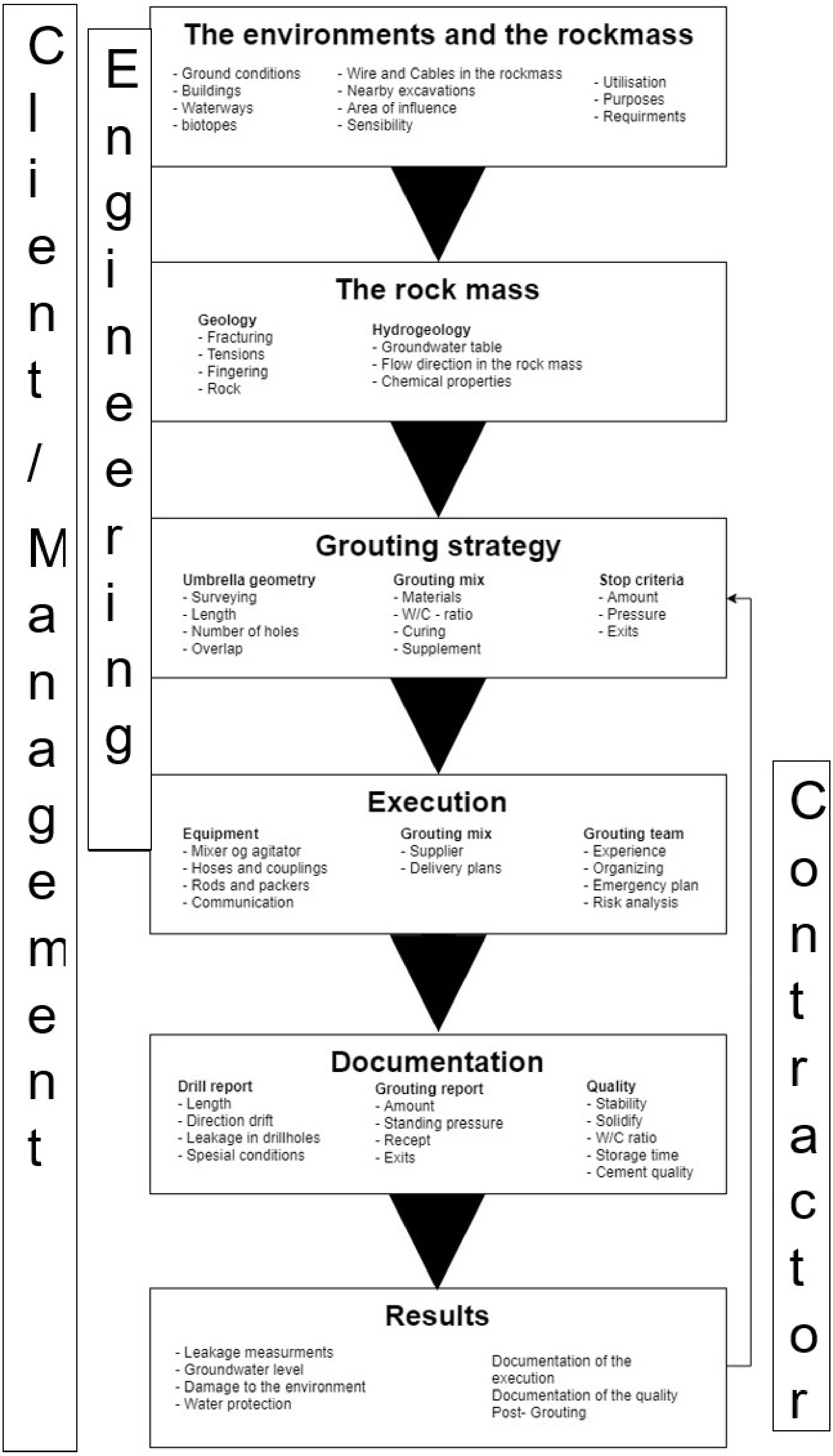


Figure 1.3.6 shows the grouting process from planning and investigation, grouting strategy, execution and end results (Modified from [4])

A common technique to reduce the groundwater flow is to seal the water-bearing fractures of the rock mass by means of grouting. Holes are drilled and grout injected under high pressure to fill fractures of the rock mass.

The common grouting practice today for the drill pattern, grouting pressure, suitable grout recipes and the stop criterion and completion criterion are all based on experience. It is only in the latest decade that extensive research has been done on this subject [3], [5], [6]. This gives a scientific perspective and will hopefully be used to complement the empirical practice that is done today.

Grouting is seen as an element that delays tunnel excavation and is time critical work for must tunnels. The cost is often 20- 30 % of the total cost of the construction phase [5]. It is of great importance that the grouting is well planned and follows a good routine to make it as efficient as possible.

Before the grouting can begin the jumbo drills holes in the rock mass at the face of the tunnel, they form a grouting umbrella, the holes are normally between 21-27 metres long Figure 1.3.7. This geometry is often complex, so it is important to follow the drill plan Figure 1.3.8. After the drilling is done, the grouting rig is brought in with the necessary equipment Figure 1.3.9. Packers are installed in the drilled holes and connected to the grouting equipment and the grouting can start.

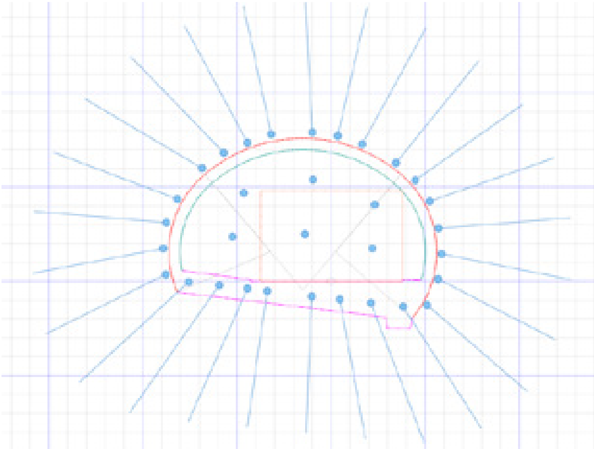


Figure 1.3.8: Drill plan for grouting and blasting. The grouting holes placement are adapted to the blasting holes (Bever Team 3).

Figure 1.3.7: Pre-grouting. Holes are normally drilled with a length of approximately 24 metres from the tunnel face [7].

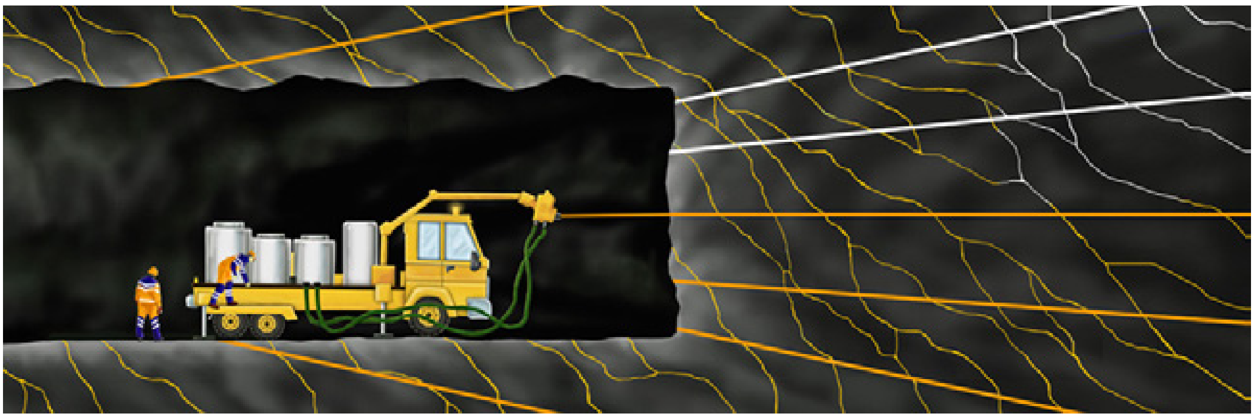


Figure 1.3.9: Pre-grouting. The grouting rig pumps cement with high pressure in the drilled holes. By doing this all waterborne fractures becomes sealed [7].

The leakage requirement for a tunnel is based on many different factors, like the purpose and location of the construction site, economic and environmental consequence of leakage and safety reasons Table 1.3.1. The maximum allowed leakage is normally given in litre per minute per 100 metres of tunnel (l/min/100m).

	Strict requirements	Moderate requirement	Site depended requirement
Allowed leakage	5l/min/100m	10l/min/100m	20l/min/100m
Performance requirements	Sensitive surroundings	Moderate sensitive	Site depended

Table 1.3.1: The three different leakage requirements [4].

Systematic grouting is necessary in medium to poor rock mass quality if the leakage requirements are strict. In tunnels where the requirements are less strict it is best to use grouting when necessary for safety reasons [4]. The test-based grouting is done by drilling a hole at the face of the tunnel and do a water loss measurement from the hole. If the value is over 15-30 l/min/100m it is recommended to grout. The overlap of the grouting umbrella is controlled by the requirements. Normally, when systematic grouting is used, an overlap of 5-6 metres is desirable, but with strict requirements it is common to have an 8-meter overlap. A good rule of thumb is that the overlap always should be minimum a round length (5 metres) [4].

Execution

The grout mix is injected under high pressure into the drill holes. The grouting pressure must exceed the groundwater pressure for the grout to spread. Grouting stops when the stop criteria are reached, and the tunnel excavation can commence. There are two main stop criteria in the Norwegian grouting process. Reached maximum pressure (stable over a given time) or reached the maximum amount of grout (amount is set by using empirical data). There are hardware and software that can log, track and control the grouting process. Software help to keep track of the time, amount, maximum pressure and maximum loss of pressure and more. The drill plan needs to be planned well

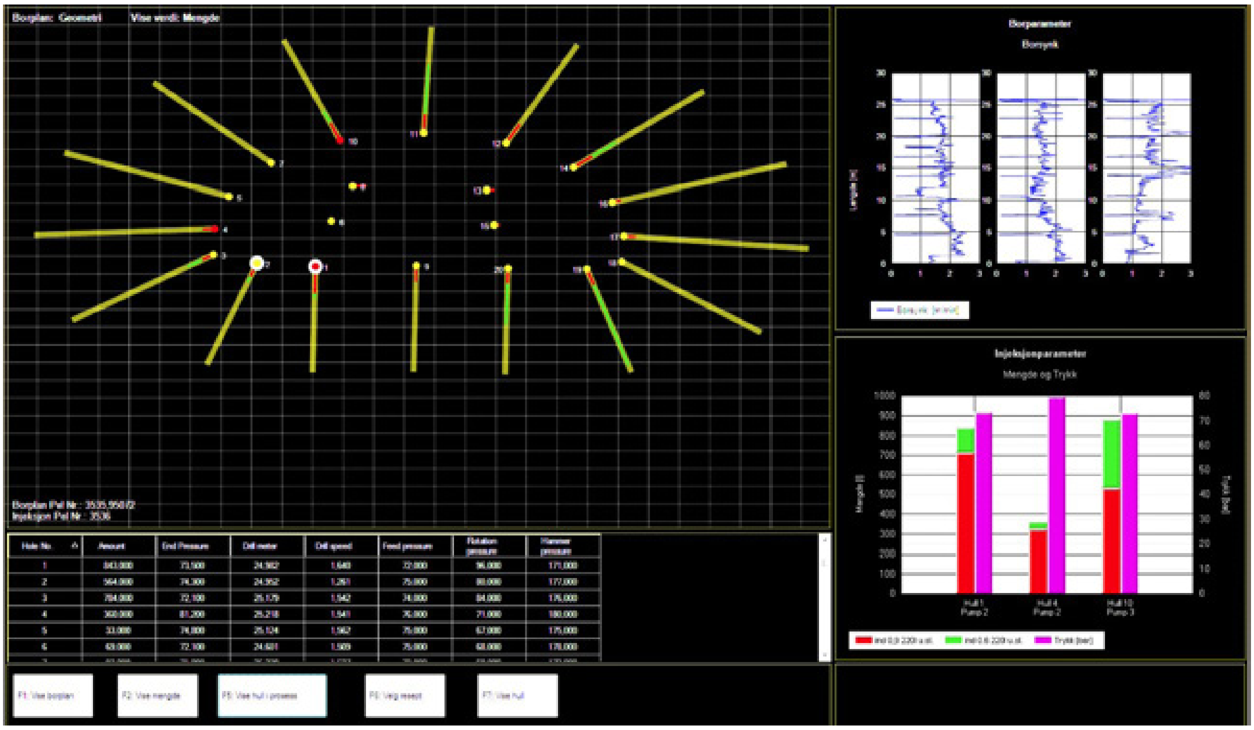


Figure 1.3.10: Left is the drill plan with the different grouting recipes displayed as different colours. Lower left is the amount of grouting mix in the individual holes and the end pressure. The same is displayed to the right as graphs (Bevercontrol)

and it is common to start with the grouting process in the bottom holes to “lift” the water away from the tunnel. Figure 1.3.10 shows the amount of grouting, which recipes that have been used in the different holes and the end pressure. This software is installed on the computer stationed on the grouting rig, see Figure 1.3.11. This gives the operator full control of the grouting process.

After the grouting process is complete in the designated area, all data is collected and gathered in one single total volumetric report, which shows the total amount of cement and additional materials that have been injected into the rock mass Figure 1.3.12 .

Figure 1.3.11: AMV Grouting rig is equipped with silos, mixers, agitator and pumps. These are standard for modern grouating rigs.

Bever Control **Injection report - Computerized grouting** 17-Dec-18

Project: **Holm** Tunnel: Default

Injection

Peg number:	80,343	Industry Cement [kg]:	29 508
Umbrella:	1	Micro Cement [kg]:	0
Number of holes:	54	Slurry [kg]:	2 465
Start pump time:	14-May-13 9:10:26AM	Additive 1 [kg]:	422
Stop pump time:	15-May-13 5:12:08PM	Additive 2 [kg]:	0
		Accelerator [kg]:	2 464
		Mauring [kg]:	0

Drilling

Drill plan	Holm_Inj_KL1_6m	Drill log	J001_0-80343-0513-1233
Peg number:	80,343.18		
Drill plan number holes:	46	Drill meter [m]:	1,221.93
Drill log number of holes:	59	Day-time [t]:	0:00:00
Start time:	30-Dec-99 12:00:00AM	Night-time [t]:	0:00:00
End time:	30-Dec-99 12:00:00AM	Cure-time [t]:	0:00:00
Drill length [m]:	2.26 - 24.00	Package [unit]:	0
Hole diameter [mm]:	0,00	Extra package [unit]:	0
Cross section [m2]:	0.00		
Comment:			

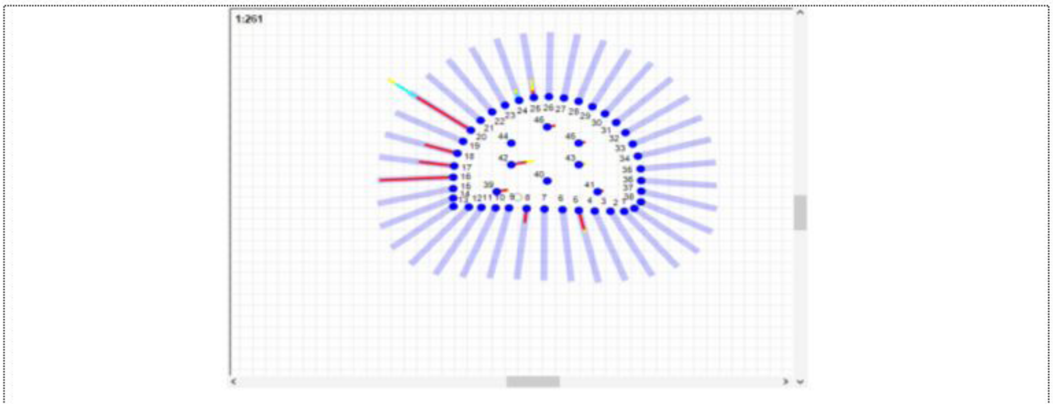


Figure 1.3.12: Volumetric report of the total materials injected into the holes of the grouting umbrella. The drill plan is also displayed and is like that of Figure 1.3.8 (Bever Team 3, Grouting Module).

Jacking
The maximum grouting pressure is of particular interest since jacking of the rock often can result in damage to the structures above and can have a negative impact on the sealing effect of the rock mass [3]. Compared to other countries like Sweden and the US, Norway uses an extremely high pressure to get a satisfying result [8] (see Figure 1.3.13).

When using high pressure, the risk of jacking the rock is increased significantly, which can make the fractures longer and larger. Jacking is a serious issue for grouting and it is not always easy to understand when it happens and what caused it to jack. The pressure alone cannot jack a rock mass [3]. Software can show present pressure and can give an alert when there is a noticeable drop in pressure and raising of flow. However successful grouting with Norwegian practice is based on good knowledge about the geology, the water-bearing fracturing of the rock mass, the material properties of cement-based mixtures and the experience of the operator.

There is an ongoing grouting project called TIGHT that is trying to shed light on the jacking problems, give scientific explanations of why it is occurring and how this can be avoided [5]. The project tried to create a warning system that could tell the operator when a potential jacking could occur, and the injection of cement should stop (see Figure 1.3.14).

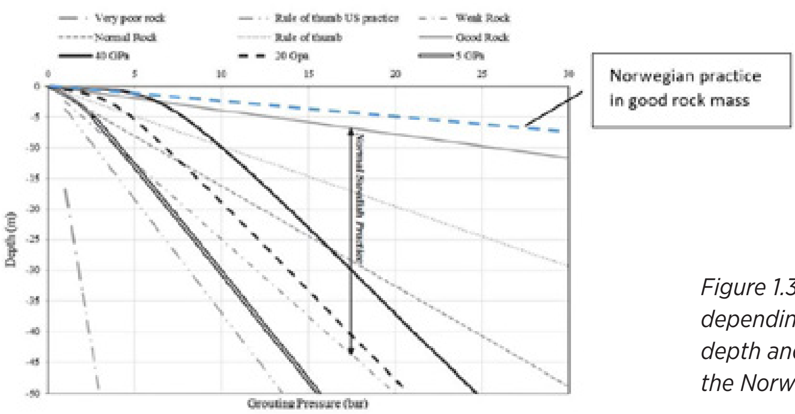


Figure 1.3.13: The graph shows the different practice depending on/ with relation to grouting pressure, depth and rock quality [9]. The blue line indicates the Norwegian practice in good rock mass [8].

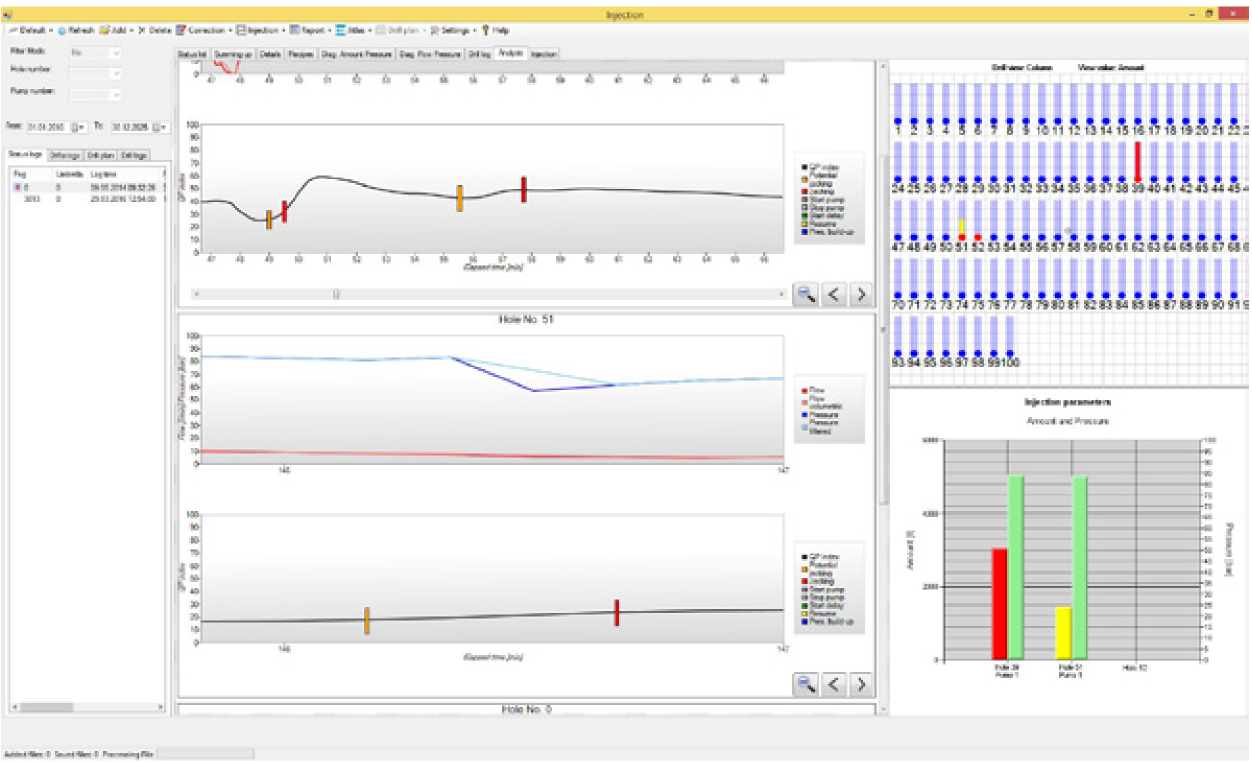


Figure 1.3.14: TIGHT project: Real-time analysis of jacking. The upper graph display pressure over time, the orange marker indicates potential jacking and the red marker indicates jacking [5].

A computerized grouting system keeps track of the amount of grouting materials and the actual grouting pressure. The MWD analysis from the drilling process give indications of weakness zones and holes that may be critical. The TIGHT project investigated how MWD data can be used to help predict upcoming water problems. The MWD data is an excellent supplementary asset that can be used to understand and map the rock mass "live" at the tunnel face. This will help to determine if grouting is needed for the next 5 – 24 m, and will help to save time and budget (see Figure 1.3.15).

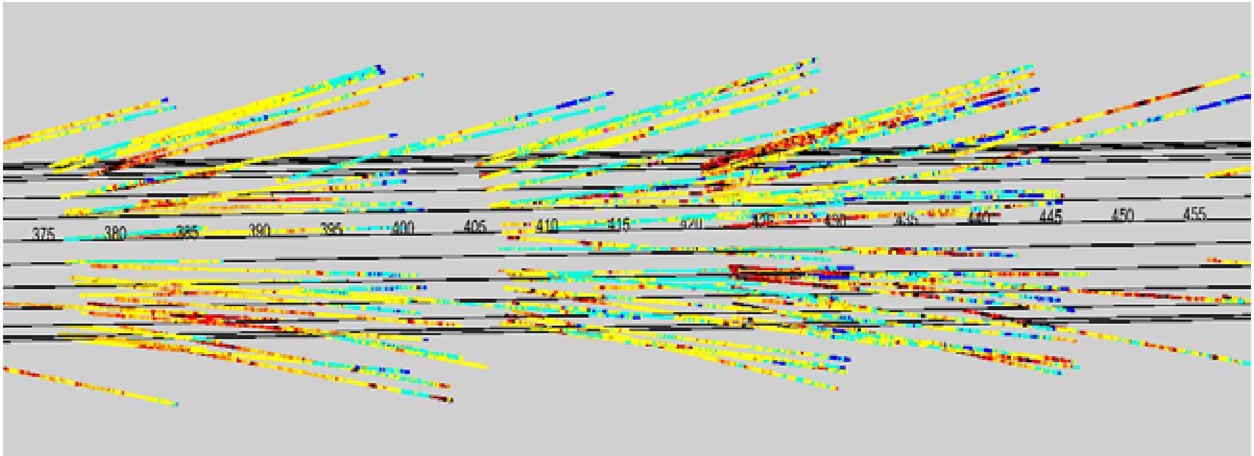


Figure 1.3.15: Grouting umbrella with overlap, visualized with MWD data (Bever Mapping).

Future features
Grouting is a subject that is getting more attention and contractors are looking to get a better understanding of the rock mass and how it reacts to the grouting process. There are huge economic and environmental benefits to optimize the grouting process. To be able to improve in these areas it is important to understand the rock mass, the grouting mix and the grouting process. The sampling intervals for the logging must increase to achieve better resolution. The data collected also need to be processed faster, so that it will be possible to see the grouting "live" and be able to stop in time to avoid jacking of the rock mass.

1.3.4. Shotcrete

Rock support in Scandinavian hard rock tunnels consists mainly of bolts and shotcrete. The types and amounts are generally specified per rock class as determined by the Q system for rock support [10], and for the individual contracts.

Usually the shotcrete is applied first, to act like a safety net for smaller rocks, and together with the bolts it also holds larger rocks in place. Successful grouting also contributes to this, by not washing out joint material, thus keeping the adherence between the rocks.

Key points for successful shotcrete application:

- Thorough cleaning of the tunnel contour with hydraulic hammer or manually – to remove already loose rocks.
- Tunnel surface is washed to minimise dust, clay or other grains that can interfere with the shotcrete adherence to the rock itself.
- If possible, the shotcrete is not applied too close to the next blast, as loose rocks that otherwise would have followed the next blast can be held in place by the shotcrete. This puts unnecessary strain on the shotcrete. If this happens, the loose rocks and affected shotcrete should be removed by hydraulic hammer or maunally before the next shotcrete application.
- Operator has an application pattern that distributes the shotcrete evenly on all surfaces.

The shotcrete is applied with a shotcrete robot (see Figure 1.3.16). It is usually mounted onto a truck, and consists of a hopper and concrete pump (see Figure 1.3.17) connected via a hose to a spray nozzle that can be controlled either from an operator cabin or from a portable operator pad (see Figure 1.3.18). Standard tunnel safety equipment, including gloves and safety glasses, is worn in addition to a dust mask.

Figure 1.3.16: Shotcrete operator cabin with extended arm and nozzle [11].

Figure 1.3.17: Shotcrete rig with shotcrete pump and concrete receiving hopper.

Figure 1.3.18: Shotcrete rig the tunnel, ready for applying shotcrete on the rock surface.

The shotcrete robot's nozzle is rotating to access all the angles of the tunnel surface, but the general direction of the shotcrete itself is determined by the operator (see Figure 1.3.19). To get an even result, the shotcrete robot operator needs training to determine a pattern that will distribute the shotcrete evenly, above the minimum criteria for thickness but also not wastefully thick.

The documentation of the amounts and thicknesses has usually been copies of the order forms from the shotcrete factory, with type and amount in m^3, and drill hole tests to determine shotcrete thickness. The drill hole test has usually been carried out every third round by measuring the thickness of the shotcrete with a folding ruler in the holes drilled for bolting, given in cm. The minimum criteria have been set as half of the thickness ordered. Areas where the shotcrete is too thin usually needs a second coat of shotcrete. Areas where the shotcrete is too thick will remain as they are, unless the shotcrete exceeds the limits of the normal tunnel contour. It will then

Figure 1.3.19: Shotcrete rig in action, E134 Gvammen-Århus, NPRA [12].

be removed either by hydraulic hammer or blasting, whichever is more useful, to secure enough room for future tunnel installations.

The newer standard used for documentation includes shotcrete scanning. A rugged scanner device is installed on the shotcrete robot (see Figure 1.3.20), where it makes a scan of the tunnel rock itself, and a second scan after the shotcrete has been applied. The scan resolution can be 16 points per m^2, and a tablet calculates and shows the thickness immediately after the second scan, as average thickness per m^2. Thus, the operator can instantly see the strength and weaknesses of the pattern used and can modify accordingly for the next application. The average thickness can also be used to calculate how much shotcrete to order next time for the same tunnel shape and size and help to reduce the shotcrete consumption (see Figure 1.3.21).

Figure 1.3.20: Profiler mounted on the shotcrete rig for scanning of the tunnel walls for accurate thickness measurement of shotcrete.

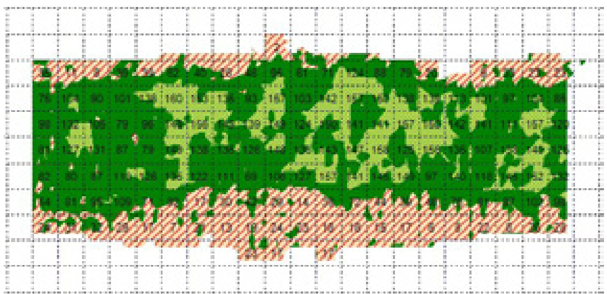


Figure 1.3.21: Result after shotcrete scan, thickness in mm as average per m^2. Red stripes – insufficient or sprayed previous round, green - sufficient, light green - more than required [13].

1.3.5. Rock bolting

Rock bolting takes care of securing any potential larger blocks and wedges along the tunnel excavation. There are several different types of bolts that all have different designs and properties. The bolts are specialized to secure a specific rock characteristic. Bolts can be end-anchored by expansion shell or resin cartridge, or they can be fully grouted to become a part of the reinforcement of the rock mass (see Figure 1.3.22). Point anchor bolts are developed by Norwegian suppliers and are unique since they can carry the load and work instantly. Combination bolts that are end-anchored and full length grouted (pre-treated by hot dip galvanizing and epoxy powder coating), may be used for immediate support and be included in the permanent support.

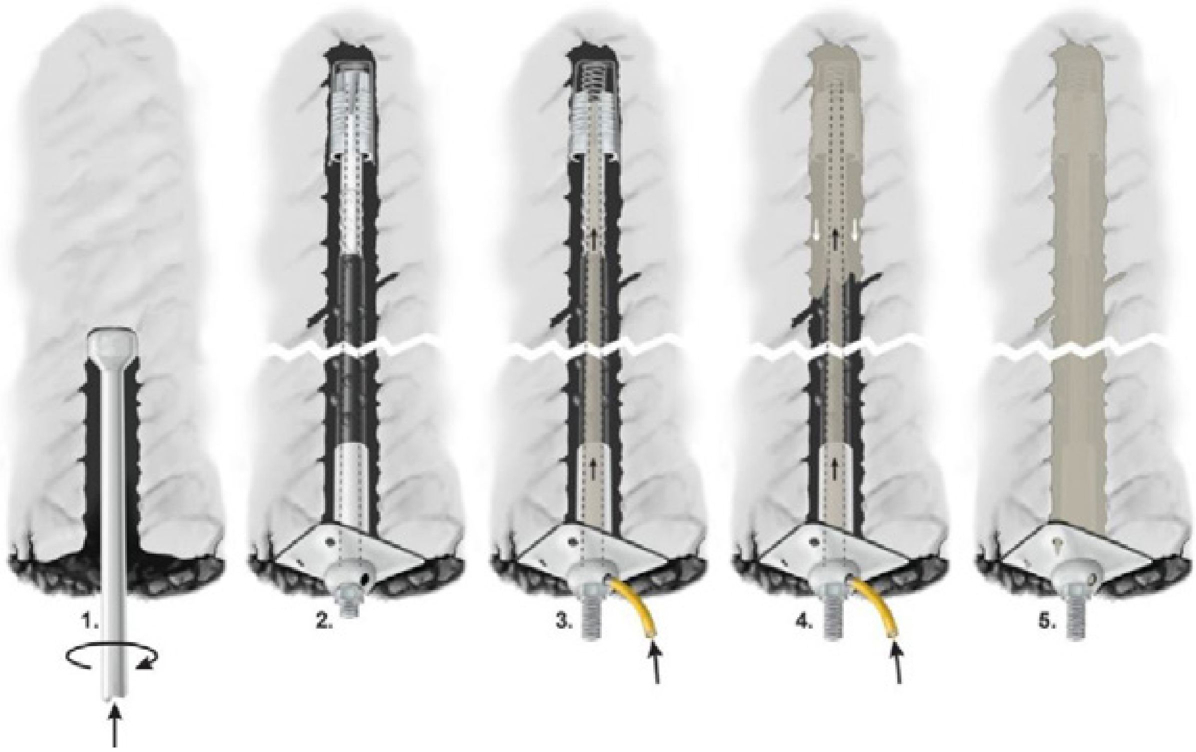


Figure 1.3.22: 1. The hole is drilled as long as the length of the bolt. 2. The bolt is installed with an expansion shell and are point anchored to ca. 50 kN. It is considered a temporarily anchored bolt until it can be fully grouted. 3 and 4. The casting is done by plugging a tube in to the sphere in the bolt and it can now begin to pump in cement. 5. Fully grouted bolt [14].

Bolts can be used in combination with other rock support equipment like steel straps, welded wire fabric and shotcrete. Bolts are relatively easy to install and can hold a considerably load. Bolts are meant to be an additional support measure as the tunnel surrounding rock is typically globally self-supporting.

The Norwegian bolting practice today uses the Q-system to determine the length and number of bolts needed to secure the tunnel [10]. The Q-value can be divided into seven categories were A is very good to exceptionally good and G is exceptionally poor rock mass [10].

The drill holes where the bolt is to be placed are drilled by the jumbo (see Figure 1.3.23), then the bolts are manually placed by an operator, tightened and later grouted with cement by a special made tube and foot (see figure 1.3.22).

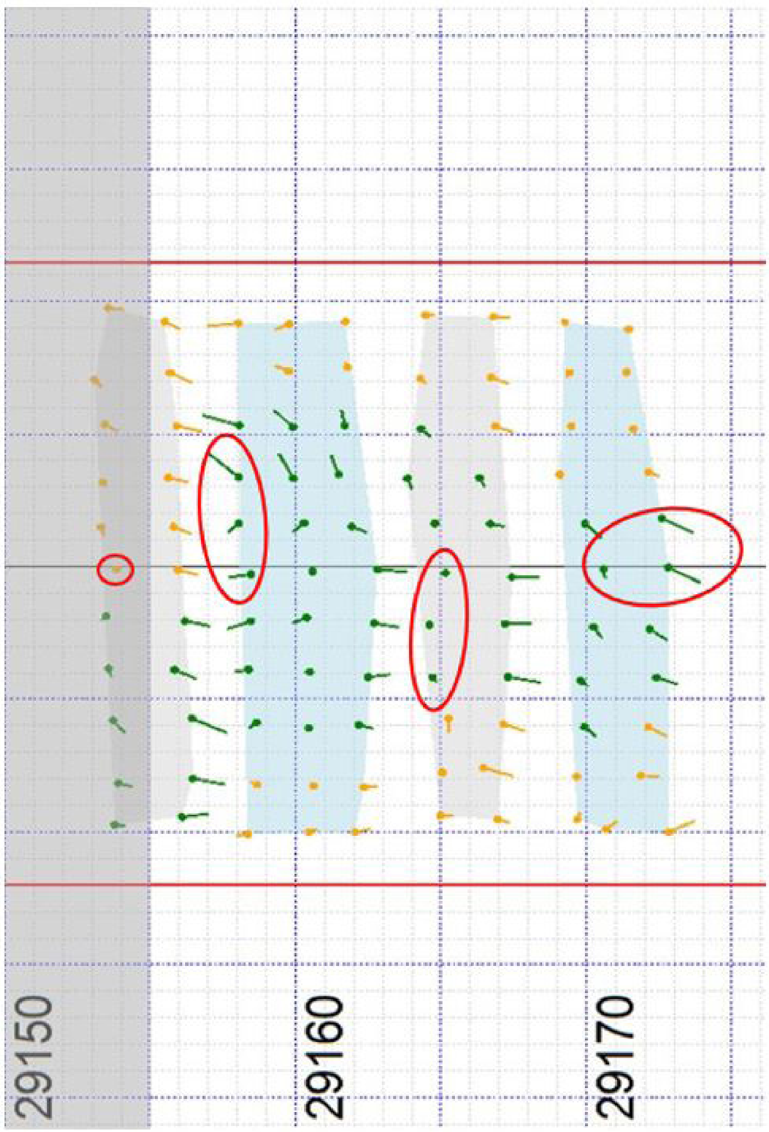
Figure 1.3.23: Jumbo drilling bolt holes.

Documentation and control of bolting

It is a requirement that the clients control engineers check the bolts placed in the tunnel. This is done either by random checks (good rock mass) or systematic when entered in poor rock mass. They check that the correct number of bolts are placed, if there is need for any extra bolts and if the bolts are placed correctly.

The control engineers use a variety of methods for controlling the bolts. One that has become more used is the drill data for bolt holes projected in a 2D format (see Figure 1.3.24) where it is possible to see the orientation of holes and its angle to the theoretical profile.

The bolt holes can also be presented in 3D format which makes it easier to understand the position of the bolts in the tunnel. Figure 1.3.25 shows the same bolts as in Figure 1.3.24.



10	Antall bolter			
11	Lengde (m)	Antall	Farge	
12	2.5 - 3.5	42		
13	3.5 - 4.5	46		

Figure 1.3.24: 2D drill log with bolt holes. The holes are displayed with colour codes based on their length. The grey and blue zones are different blast rounds. The red circles are there to highlight the bolts that are displayed in 3D in figure 1.3.25 (Bever Team Online).

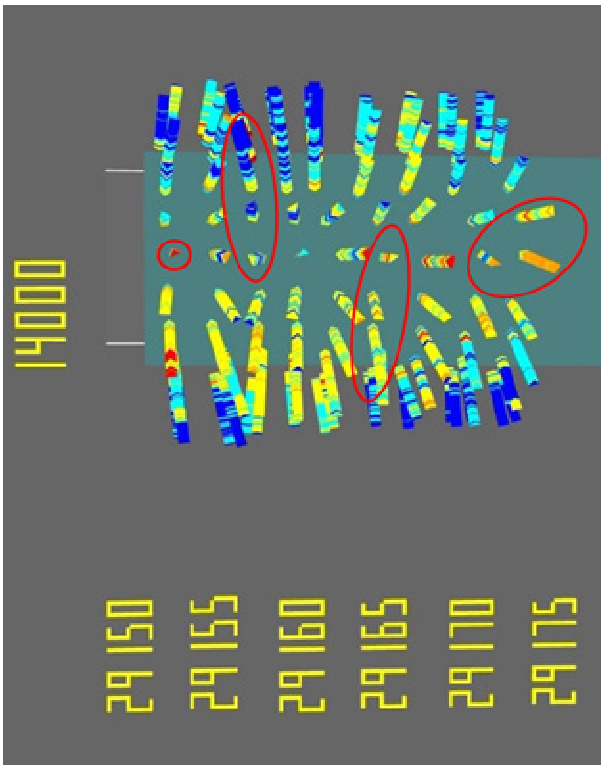


Figure 1.3.25: 3D visualizing of bolt holes. The red circles indicate the same bolts seen in figure 1.3.24 (Bever Team Online).

It is crucial that the bolts are placed correctly to achieve a secure tunnel. All bolts are supposed to be placed perpendicular to the tunnel surface and not exceed an angle of 25° to the theoretical profile. If the bolt exceeds 25° the bolt loses its effect and is more vulnerable to shear stress and cannot hold the load it is manufactured to do.

The 2D bolt hole log contains that type of information and can reveal if the bolt is exceeding this threshold. (see Figure 1.3.26)

However, it can be multiple reasons for the bolt holes to display values that exceed 25° from the theoretical profile. The actual blasted profile can have some irregularities after the blast, and it can affect the positioning and angle of the bolt. The bolt hole logs give the holes for the bolts but cannot guarantee that a bolt is placed there. Luckily there are ways to control the placement of the bolts. It is possible to check this when the control engineers are in the tunnel and take photos for documentation purposes. These photos can be taken by a handheld camera (phone or tablet) or it can be a camera fixed on the rig. The pictures are taken before and after the bolts have been placed and it is easy to see if some bolts are missing (see Figure 1.3.27).

Figure 1.3.26: Bolt log displayed with angle bias from the theoretical profile (Bever Team Online).

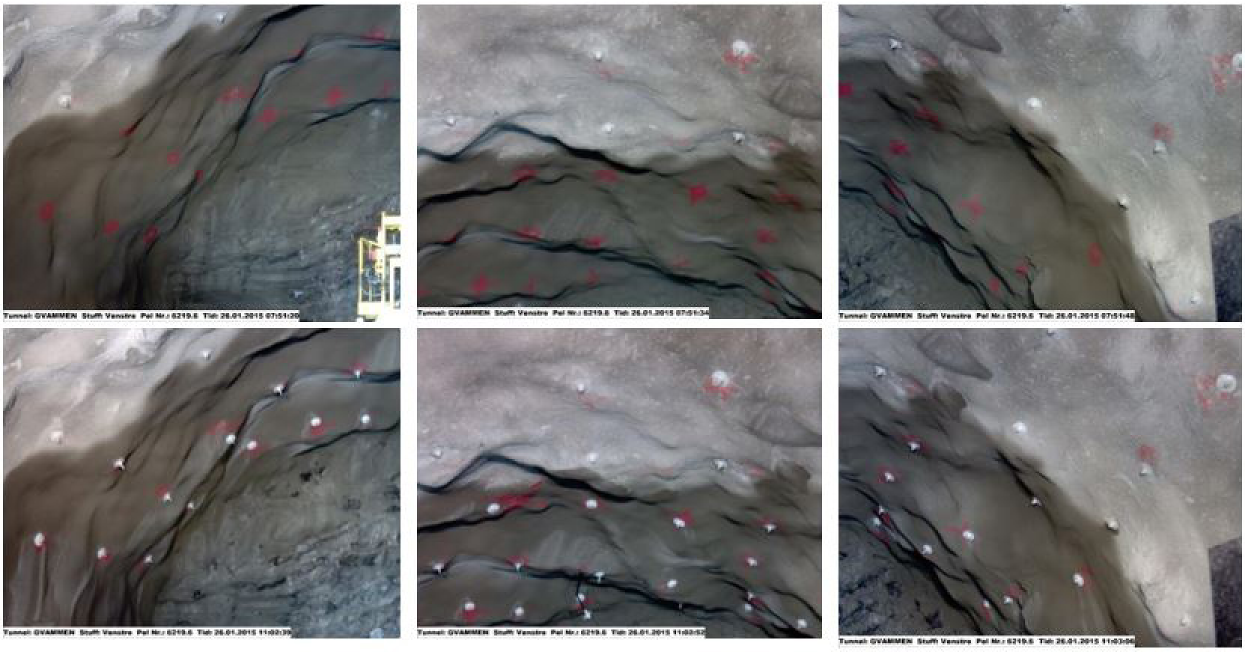


Figure 1.3.27: The upper row displays red paint on shotcrete, these are marks for the bolt operator and is used when placing the bolts. The lower row is the same area and are after the bolts have been placed (Bever Team Online).

The advantage of having a camera fixed on the rig is that it will always be the same light conditions and distance to the bolts. The photos taken are sent directly to the cloud-based server and catalogued. The photos get the chainage automatically and can be easily be merged with the bolt hole log. This removes the margin of error and helps to maintain a well-structured database.

MWD is being used in almost all large infrastructure projects in Norwegian tunnelling. MWD of bolts shows great potential and can give crucial data that is useful, both for the contractor and client. It is possible to see if the bolts are anchored in hard rocks or a weakness zone, which can affect the attributes of the bolts. The information can give a pre-warning, so that the appropriate measures are taken to secure the tunnelling even further if necessary. The 3D bolt log with MWD-interpretation shown in Figure 1.3.28, displays a clear blue intrusion rock going alongside the tunnel. The blue represents hard rock and could cause anchor trouble for the bolts in this zone and should be taken into consideration.

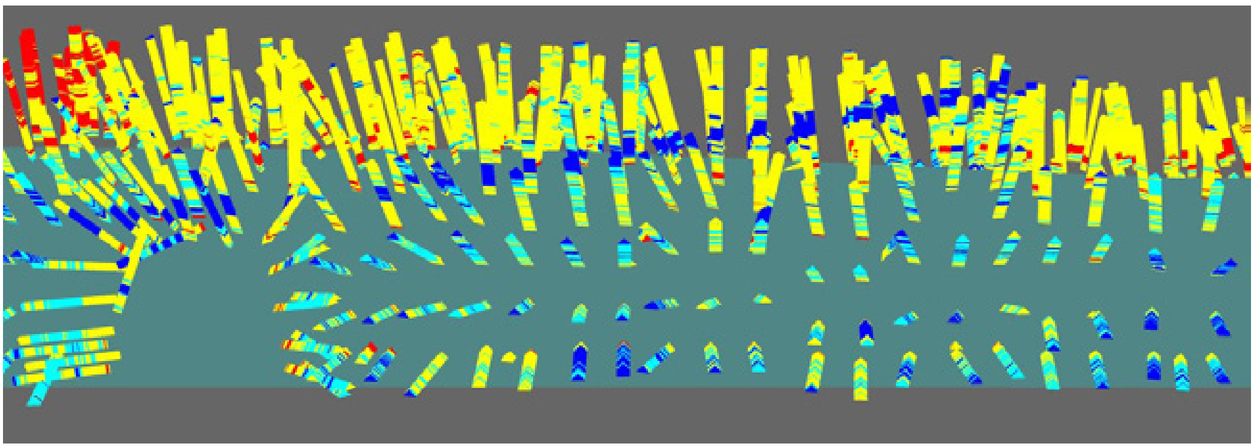


Figure 1.3.28: MWD interpretation, red is poor/fractured, yellow is the host rock and blue is good/hard rock. It is possible to see the variation of the anchorage in the bolts (Bever Team Online).

Future features
The documentation and registration of the bolts is undergoing a digitalisation. There are multiple softwares and mapping systems that are under development which aim to present bolts in a realistic manner and give the actual positioning. Figure 1.3.29 shows one possible way of displaying geo-referenced bolts with the tunnel contour. This software will ideally be able to retrieve all the information from the placement of the bolt and its attributes.

Automation of the bolt placement will improve the working conditions for the workers that are doing this manually, make the process more economical and save time.

Control system for bolting rigs (technical bolts)
Concrete elements and PE foam are part of the water and frost protection. They need specialized technical bolts and a bolt rig to place them, (see Figure 1.3.30) and software to be able to achieve the accuracy needed to correctly install these elements.

The precision required to install the technical bolts is only a few centimetres, so the accuracy needs to be extremely precise or else the bolt will not fit the predrilled holes [15]. A total station is used to navigate the rig and for tracking the prisms mounted on the feeder fixture. The tracking system uses two prisms on the rig itself, this will give the rig system the position of the drill bit. Continuous tracking of prism position gives input directly to on-board positioning software. There are installed sensors in the chassis and every joint on the boom. They also help to determine the position of the drill bit versus the drill hole where the bolt is supposed to be placed. The accuracy of the positioning is approximately 15 mm.

All this data is sent to a software in the operator cabin of the rig and with the imported drill plan and tunnel line, the operator uses this information to install the bolts (see Figure 1.3.31). The installation of the technical bolt can be done manually or automatic by the rig.

An achievement many operators have been waiting for is that the drill plans become fully fixed to a coordinate system and that every drill plan is made before the drilling jumbo starts drilling. This will also make it possible to filter the drill plans such that only the relevant drill plan is displayed according to the coordinate system, when drilling bolt holes. This will decrease the error margin and the operator will be able to work more efficient.

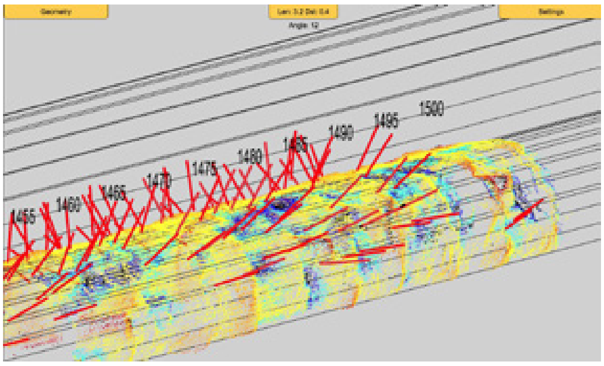


Figure 1.3.29: Newly developed digital tunnel mapping app with contour scan with profiler and bolt logs. The scan data displays the actual excavated tunnel, dark blue represents underbreak and red displays overbreak. All bolt holes are displayed as red, the red colour is the length property of the bolt, here it indicates that the bolts are 3 metres. The property of the highlighted bolt (black circle) is displayed in the upper centre of the figure. (Bever Mapping).

Figure 1.3.30: AMV Bolt rigs for technical installations.

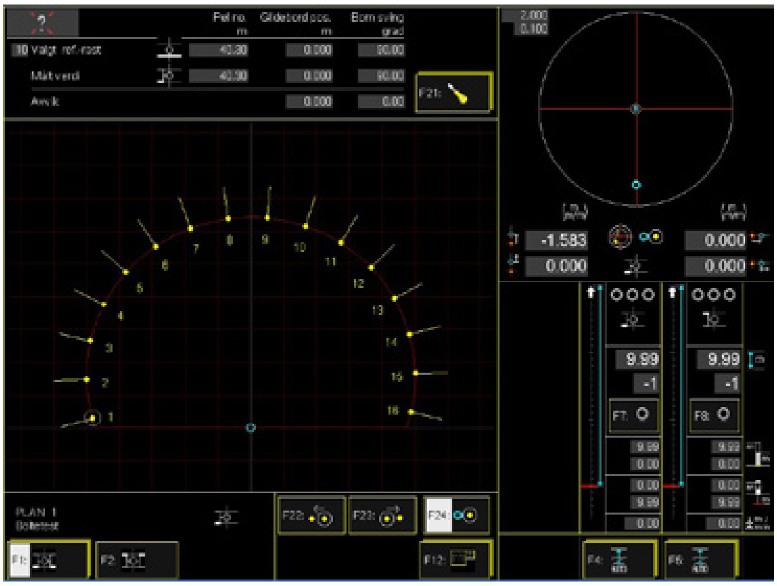


Figure 1.3.31: Interface of the tracking system for technical bolts. The blue dot in the crosshair in the upper right corner shows the position of the drill bit versus the placement of the drill hole (Bever Drill).

References

[1] Wetlesen, T., Andersen., P., Berg., H. (2014). Computer aided and construction with integrated heavy equipment. Norwegian Tunnelling Society, Norway, Publication 23, pp. 99-106.

[2] AGL. AGL SLB100 Tunnel Laser [image on internet]. 2019 [cited 2019 Jan 14]. Available from: https://www.tigersupplies.com/Products/AGL-SLB110-Tunnel-Laser__AGA6009200.aspx

[3] Stille, H. K. (2015). Rock grouting – Theories and Applications. BeFO, Stockholm, Sweden, first edition.

[4] Hognestad, H. O., Fagermo, J. I., Kveen, A., Backer, L., Grøv, E., Frogner, E., Aarset, A. (2010). Praktisk Berginjeksjon for underjordsanlegg. Norsk forening for Fjellsprengningsteknikk – NFF, Oslo, Norge, first Edition.

[5] Strømsvik, H., Grøv, E., 2017. In: Interpretation of Pressure and Flow During Pre-Grouting in Hard Rock Tunnelling, Grouting 2017: Case Histories. ASCE, Honolulu, USA, pp. 285–294.

[6] Strømsvik, H., Morud, J. C., Grøv, E., 2018. Development of an algorithm to detect hydraulic jacking in high pressure rock mass grouting and introduction of the PF index. Tunnelling and Underground space technology 81 (2018), pp. 16-25. https://doi.org/10.1016/j.tust.2018.06.027

[7] Arild W. Solerød. Forinjeksjon. 2011 [cited 2019 Jan 14]. Available from: https://www.vegvesen.no/vegprosjekter/ringvegvest/Fakta/Tunnelbygging

[8] Grøv, E., Funehag, J., Janson, T. (2014). Rock mass grouting in Sweden and Norway – A matter of cultural difference or factual causes? Geotechnical News, 32(1), pp. 41-51.

[9] Rafi, J. Y., Stille, H. (2014) Control of rock jacking considering spread of grout and grouting pressure. Tunnelling and Underground Space Technology, 40, pp. 1-15.

[10] Norwegian Geotechnical institute (2015) Handbook; Using the Q-system – Rock mass classification and support design.

[11] Mikkel Vold, AMV. AMV 6400. 2019 [cited Jan 14 2019]. available from: http://www.amv.as/en/produkter/tunnell-og-anlegg/betongsproyteroboter/amv6400

[12] Tor Andersen, AMV. AMV 7450. 2019 [cited Jan 14 2019]. available from: http://www.amv.as/en/produkter/tunnell-og-anlegg/betongsproyteroboter/amv7450

[13] Wetlesen, T., Krutrök, B. (2014). Measurement of shotcrete thickness in tunnel with bever 3D laser scanner operated from the robot. International symposium on sprayed concrete, Sandefjord, Norway.

[14] Norsk Forening for Fjellsprengning. (2017). Bergbolting. Norsk Forening for Fjellsprengning, NFF first Edition.

[15] Bever Control AS. Rock Bolting rigs. 2012 [cited Jan 14 2019]. Available from: https://bevercontrol.com/english/products/rock_bolting_rigs/

1.4. Water and Frost Protection

Authors:
- *Jan Erik Hoel, Trimble*
- *Harald Juvland, AF Gruppen*

1.4.1. Water and frost protection types used in Norwegian tunnels

The following main categories of water and frost protection measures have been used in Norwegian tunnels (not all of them are allowed to use anymore):

- Casted inner lining
- Concrete elements, walls and ceiling
- Lightweight panels/boxes (steel, aluminium, composite)
- Mesh-reinforced sprayed concrete on PE-foam
- Sprayed concrete on rock face mounted PE-foam
- Exposed PE-foam
- Sprayed concrete on rock face
- Membrane mounted on rock face

The digital workflow for the most used water and frost protection types that involves the use of some digital equipment are described in the following sections.

1.4.2. Water and frost protection supported by digital tools

Casted inner lining

At most sites a wagon with formwork is used to cast the inner lining. The formwork on the wagon is set out with regular survey equipment based on the tunnel reference line and the normal profile of the tunnel. Minor niches for SOS-equipment e.g. are handled by setting in wooden cassettes in the formwork.

The data for the normal profile and the reference line are exported from the design tool (Novapoint, AutoCAD or other systems) to the site survey software. Bever Team or Gemini can be used to transform the data from the design software to the survey software.

Figure 1.4.1: Formwork wagon from Alsaker.

Inner lining concrete elements

The shape and size of the concrete elements are modelled with BIM and CAD systems like Novapoint, Tekla Structures and AutoCAD products.

The setting out data for the foundations and mounting bolts is calculated by the same systems.

The shape of concrete wall elements and setting out data are calculated based on the road/railway edge lines. Widenings and cross fall changes of the road/railway are considered when calculating the setting out data and the skew cutting of the elements.

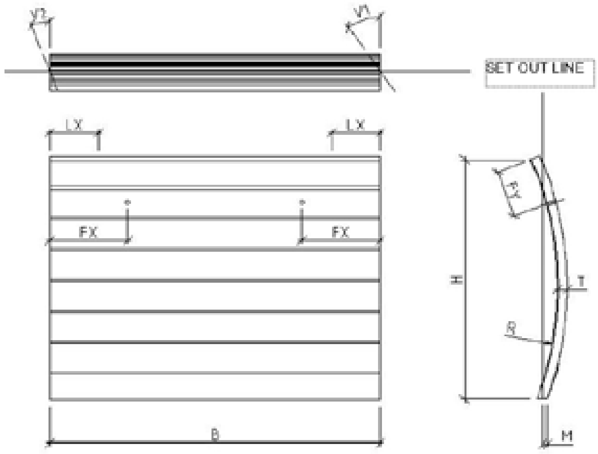


Figure 1.4.2: From Novapoint User Manual for Concrete Wall elements.

Joints are calculated and checked against design requirements for max/min joint gaps and shift in joint gaps between the top and bottoma of the elements.

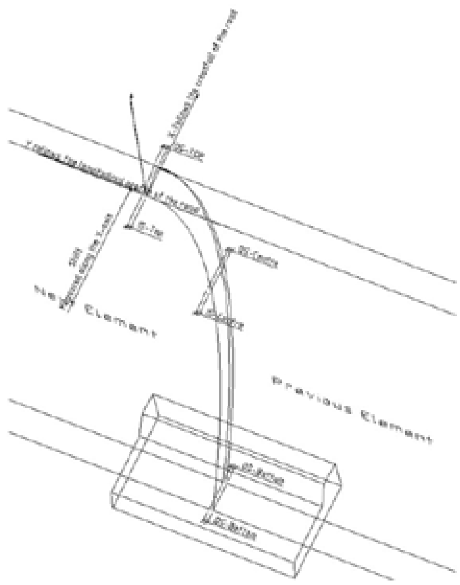


Figure 1.4.3: From Novapoint User Manual for Concrete Wall elements.

Cut outs for doors, SOS-equipment boxes etc are calculated based on the road/railway geometry and the requirements for access to the openings; height from the pavement, door width etc. These cut out shape values are used when making the formwork in the element factories.

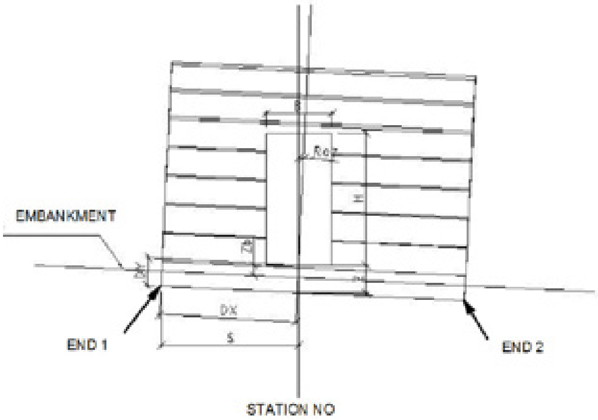


Figure 1.4.4: From Novapoint User Manual for Concrete Wall elements.

The ceiling elements are then calculated based on the top line of the wall elements and the shape of the tunnel vault. Tekla Structures, Novapoint and AutoCAD are the most used software for these calculations.

The values for element shapes and setting out data for mounting bolts and elements are calculated. Especially the areas close to niches require complex design/calculations.

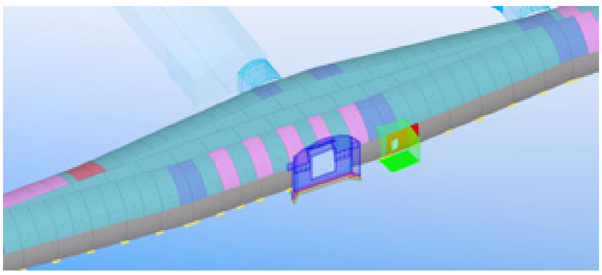


Figure 1.4.5: Concrete tunnel elements modelled in Tekla Structures based on calculations in Novapoint. Spenncon AS and Nordland-Teknikk AS.

Shotcrete on PE-foam

The reinforced shotcrete and PE-foam is mounted to the rock surface with bolts. The location and length of every bolt is modelled in the on-site tunnel software, usually Bever Team, and then transferred to the machine controlling software on the bolting machine.

The traffic side location of the bolt end is set out based on the normal profile. At the highest part of the tunnel vault, the bolt ends are placed somewhat closer to the rock surface than the normal profile. Further down against the abutments, the bolt ends are placed closer and closer to the normal profile. This is done to allow for the free flow of water down along the outside of the water and frost protection, preventing the water from being trapped in dams on top of the protection.

The length of the bolts, the width that the length of the bore hole, is decided by standard bolt lengths.

The location of the bolt end in the interpolated areas between two normal profiles is sometimes decided by using cords and let the machine operator bore the holes manually.

The reinforcement and foam are placed based on the bolts without performing any additional digital survey measurements. The shotcrete is applied with the specified thickness based on experience and manual measurement of the thickness.

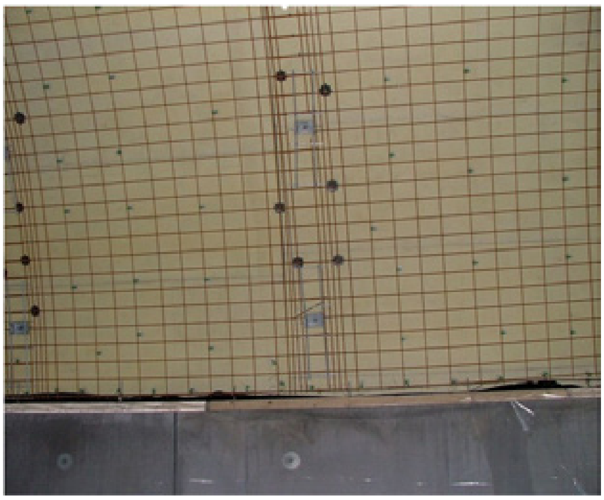


Figure 1.4.6: PE-foam, mesh-reinforcement and bolts before shotcrete is applied. Photo: NPRA

1.5. Technical Installations

Author:
- *Torbjørn Andersen, Norconsult*

1.5.1. Introduction

In modern tunnels and other underground infrastructure several technical installations are needed to make the desired quality of the infrastructure and handling safety issues related to structures underground. The technical installations make up a complex and vast system that must be placed correctly in the tunnel structure to work together and have the required effect.

This chapter will describe current practices regarding technical installations and structures in tunnel projects in Norway today. The technical furnishing of a tunnel consists of a variety of objects depending on project type. A road project will for instance have different installations than a rail project. Technical installations and structures in different types of tunnel projects will be presented below.

1.5.2. Technical installations

Tunnel projects are built in a collaboration between the client, designers and contractors. To get the best results, information must be shared between the involving parties in a good way. With the digitalisation several new ways and possibilities have made it easier to share information faster and better. Technical installations are as mentioned a complex system that must work together. Thus, the information about these components must be shared between the involving parties in a way that secures accurate execution and quality.

Digitalisation of tunnel projects is desired in the tunnel industry in Norway. With the 3D-modelling software used today, information about the tunnel project can be presented in a way that is easy to understand for all the involving parties. For technical installations the different components can be presented with numerous parameters describing material quality, level of detail (LOD) of the model, revisions, instructions, codes for the cross-discipline marking system (TFM), etc.

Level of detail (LOD) is a marking system introduced in 3D-models to label the model status of different components. This allows the involving parties of a project to always be updated on the status of an object. The level of detail ranges from concept design to as-built, and the different components are given different numbers as to which detail phase they are in. This makes it clear which components are ready to be built and which are still in the design phase.

The highest level of detail is as-built and the goal is that the model of a project and what has been built should be similar. This give a 3D-model that is a copy of what the finished infrastructure looks like. This can be further used in the MOM-phase of a project. Management, operations and maintenance will be better executed when all the information about the tunnel project is gathered in a unified model. With a model working as a digital twin of a project the status of the different objects and installations during the lifespan of the infrastructure can be tracked.

Up until recent years 2D-drawings have been the most common way of delivering construction data for technical installations to the contractor. As 3D-models became more common to deliver for surveying on the construction site, CAD-softwares such as AutoCAD was used to create the models while the files were often delivered in dwg-format. With the dwg-format it is possible to deliver points and lines in objects which the surveyor can utilize in its equipment. But these dwg-models only have as much information in each object as can be fitted in the layer name. Which means that the 2D-drawings are still very much required to give enough information to both the contractor and the project owner. With the use of BIM-models 2D-drawings become redundant as the information required for construction can be given in the model instead. But a challenge with delivering BIM-models in formats such as IFC is that there is still lack of support for these types of formats in surveying equipment. Today this is often solved by delivering dwg-files for surveying and either IFC or other BIM-formats for the coordination model. For technical installations this can be a challenge as the positioning of the objects is often defined by points.

Technical installations vary in the way they are placed in the tunnel structure. In the following text, technical installations will be divided into two categories; line-based and point-based installations.

<u>Line-based installations</u>

Line-based installations covers objects which to a certain degree follows the tunnel alignment, such as electrical conduits, water and drainage systems, concrete shoulder, cable trays, concrete railing, etc. These types of objects usually have a survey line defining their route and a constant geometry along the route.

Line-based objects which to a large degree follows the tunnel alignment have through the years been modelled in CAD-based software. Usually, 2D-drawings was the only information provided

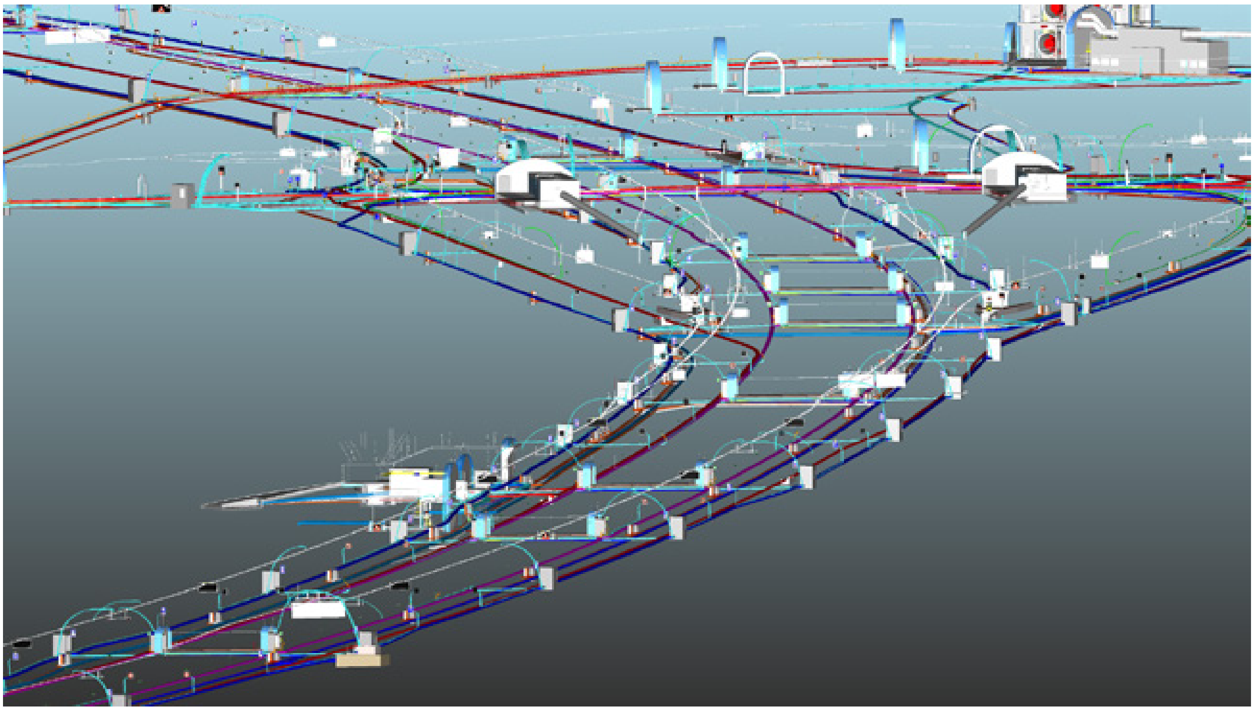


Figure 1.5.1: Illustration of a 3D-model of technical installations from E39 Rogfast.

for the line-based installations. With a lot of components in a tunnel structure it gave less control regarding conflicts between the components. This led to several conflicts between the involving parties of a project. In Norway today, these installations are usually modelled in 3D using software such as Gemini, Novapoint or AutoCAD Civil 3D. NavisWorks clash detection is used to discover clashes between the installations. These software solutions are usually preferred because they have functions for handling both road alignments and objects modelled along an alignment. Revit is for instance more challenging to use in these cases.

There are several types of challenges when it comes to modelling these types of objects. Especially, when the elements don't follow the alignment of the tunnel with a fixed offset, either due to crossings with other components or when routing in and out of draw pits, manholes, etc. The modelling then becomes quite time-consuming. If the element follows the alignment of a road it is possible to automate a lot of the modelling, but as soon as it needs to move cross-wise it can require quite a lot of manual adjustments. In areas where there are a lot of these types of elements there can be quite a few possible collisions and there is no software which can automate the modelling while avoiding collisions. An example of this is shown in Figure 1.5.2, where crossings of electrical conduits and pipes are shown by a standard technical room.

While the electrical conduits are often designed and built using 3D-models, it is not yet common to include the electrical cables to be placed inside. From a MOM point of view, including cables in the conduits with information about connection points could be useful. By including the cables inside it would for instance be possible for a maintenance worker to get a better overview of all the cables inside a single draw pit. It would also be easier to identify the routes of each cable in a tunnel. But because including such things in the 3D- or BIM-model would be quite time-consuming using software available today, it is not commonly done.

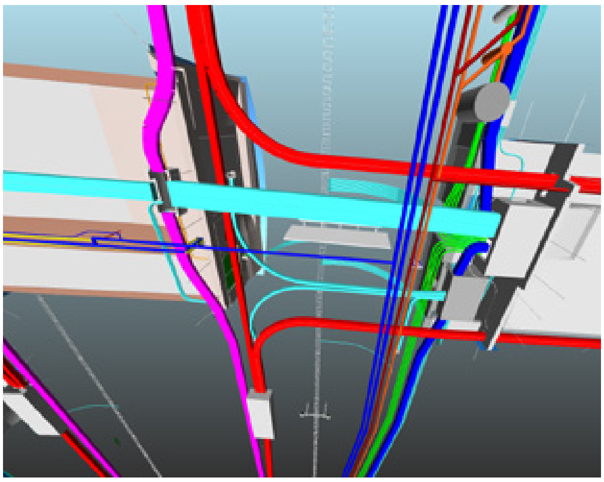


Figure 1.5.2: Example of a standard crossing with conduits and pipes at a technical building.

Point-based installations

Point based installations covers objects positioned at a point along the tunnel. This can be objects such as signs, fans, draw pits, cable trays, emergency equipment, doors, hatches, etc. These are usually placed at regular intervals and are mounted inside the water and frost protection with bolts or other suspension systems. The objects are either modelled as a 3D-solid or surface, depending on the type, and have one or more points or lines in the object to represent the positioning.

As for the line-based installations, CAD-based software was most commonly used for the point-based installations. 2D-drawing made the base for information about the components, together with the quantity statement. To get the full overview over the installations several drawings had to be studied simultaneously. Today, using 3D- and BIM-models all the information can be gathered in one model showing the complete situation of a tunnel project. The installations can then be presented with numerous parameters describing material quality, level of detail (LOD) of the model, revisions, instructions, codes for the cross-discipline marking system (TFM), etc. These parameters often vary between projects today because an industry wide standard is lacking.

The models of technical installations at E39 Rogfast, as illustrated in Figure 1.5.3, have been modelled with Revit and Dynamo. All the installations are presented as either 3D-solids or surfaces and have a set of properties connected to each object. The properties of each object for instance give information about the position in the tunnel (stationing), object type and other parameters which were previously given in the layer name in CAD-based 3D-models. The different installations are modelled as parametric Revit-objects, which makes it easy to deal with changing geometry on similar objects. The placement of all the elements in a model is handled with Microsoft Excel and Dynamo. In simple tables in Excel the information about each object with regards to stationing, relative position inside the tunnel profile, type parameters and other properties are used by Dynamo to place the objects and generate a complete model. Because all single elements in a Revit model have a unique ID it is also possible to run large changes, for instance positioning or properties, can easily be changed in Excel and transferred to the Revit-model using Dynamo.

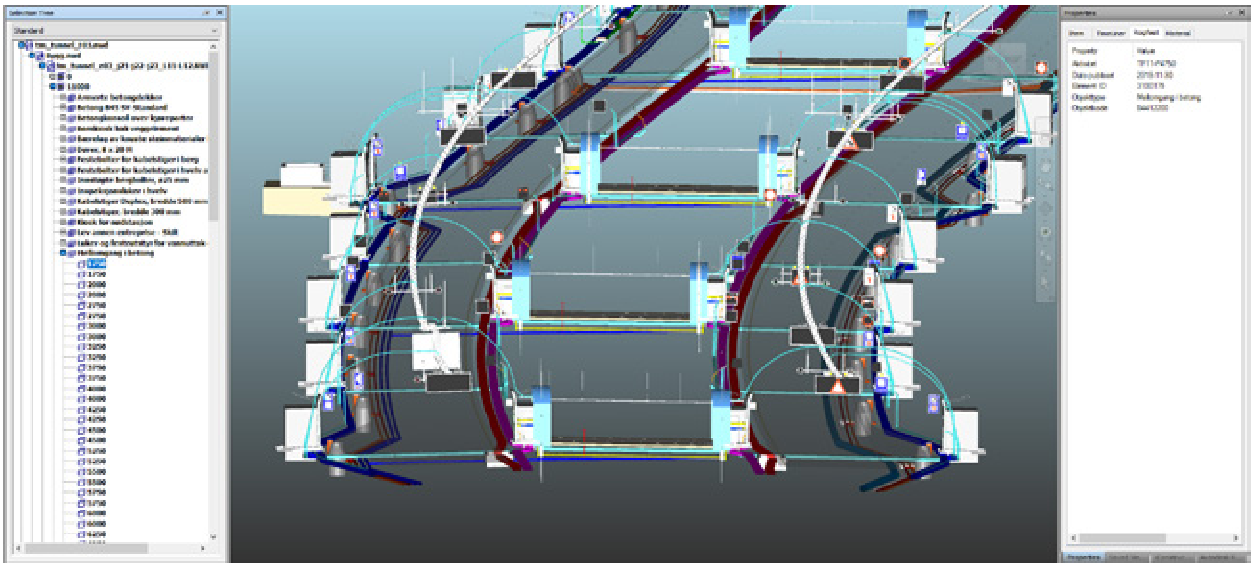


Figure 1.5.3: Example of tree structure and properties in a single technical installation at E39 Rogfast.

1.5.3. Structures

Tunnel projects consist of several structures to handle the given project conditions and to create a safe and high-quality tunnel construction. The structures inside a tunnel works as a hub for the line-based installations, which again connects with the point-based installations. Some structures commonly found in different tunnel projects are:

- Technical rooms
- Pumping stations and retention pools
- Cross passages
- Portals

In this chapter the structures will be separated in two different categories; structures along the alignment of the tunnel and technical structures crosswise to the tunnel alignment.

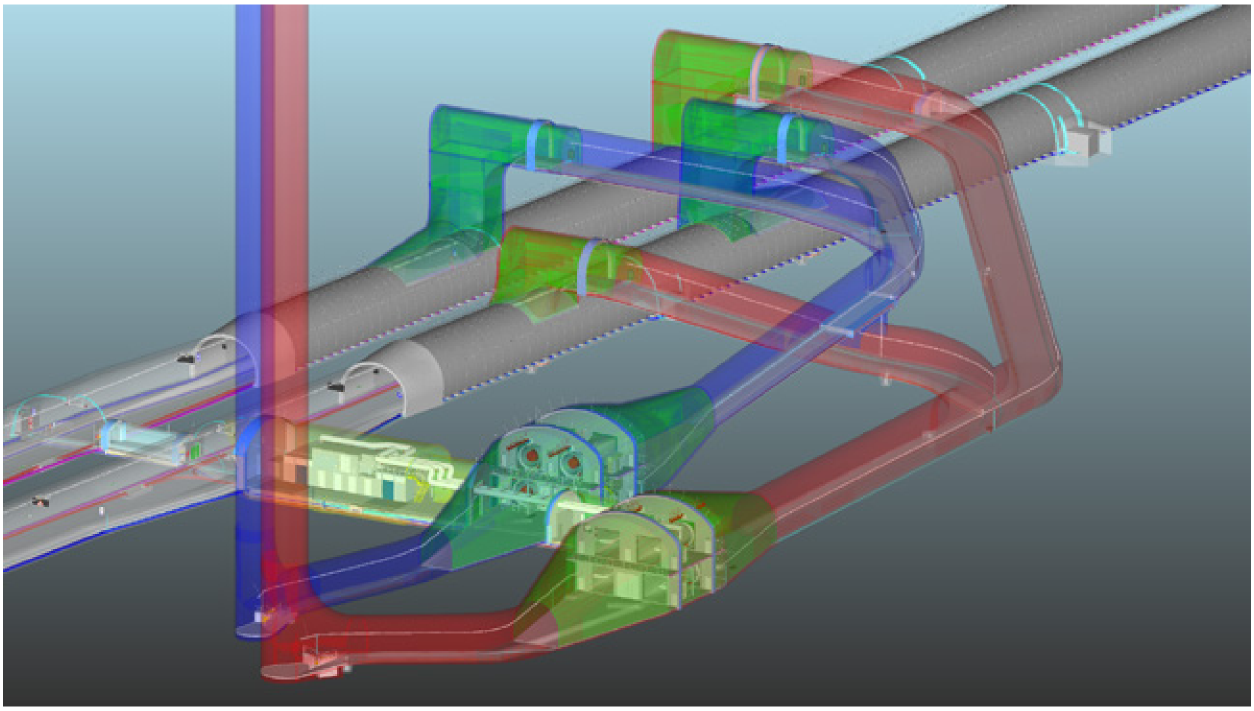


Figure 1.5.4: Example of different types of structures in a tunnel project.

Structures along the tunnel profile
Concrete structures built around the tunnel profile along the tunnel alignment can for instance be portals, cast-in-place concrete lining, etc. Due to the complicated geometry of these types of structures they have largely been modelled manually with CAD-based software, either in 2D or 3D. But during the last few years, and with the growing popularity of tools for visual programming such as Dynamo and Grasshopper for Revit and Rhino, more structures are being designed in 3D and BIM-software.

In the project E18 Tvedestrand-Arendal all the bridges and tunnel portals were modelled parametrically with Revit and Dynamo. Both the structures and the rebar were delivered to the contractor as BIM-models and model-based approval was used with the NPRA. This was the first project in Norway where a tunnel portal went through the approval process with the NPRA using model-based approval. To achieve a drawing-free approval process a great deal of work was done on preparing the information in the model to get it up to the same level as a 2D drawing.

Technical structures
Technical structures are mostly built crosswise to the tunnel alignment and can for instance be technical rooms, pumping stations, retention pools, cross passages, etc. These types of structures have in common that they are usually built outside the water and frost-protection of the main tubes and is to a certain degree built like structures on the surface. These types of structures are common to model in Revit since the software is well designed for the level-based modelling required.

The purpose of technical buildings is usually to supply the technical furnishing and structures of a tunnel with electricity. They are often built with concrete and consist of several rooms with different purposes. For the tunnel works they are usually modelled with everything apart from the electrical furnishing of the rooms, such as transformers, batteries, etc. An example of detail level for a technical building is shown in Figure 1.5.5.

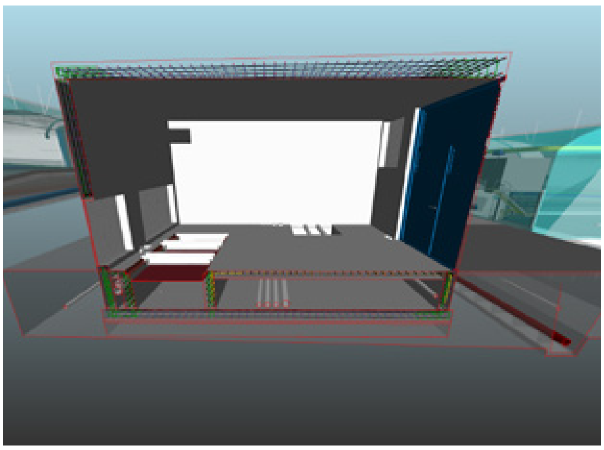


Figure 1.5.5: Example of typical components in a model of a technical room.

In the project E39 Rogfast, all the technical structures along the tunnel are modelled in Revit and are delivered as 3D-models. Both the concrete and the rebar are modelled and delivered with a set of properties replacing the information previously given in layer-names in CAD-files. An example of a structure and rebar model of a technical building is shown in Figure 1.5.6. In this project the rebar in each structure is color-coded according to shape and type. In the selection tree in Navisworks the different types of rebar are grouped according to which part of the construction they belong to. The properties of each group of rebar gives information about pos. number, structural part, diameter, quantity, shape code, length material quality, revision, etc. All the information commonly found on drawings and in the reinforcement specifications in most projects.

The positioning of each instance of a type of structure is done parametrically using Dynamo. The structures are modelled up using a local origin and then placed into a model with correct coordinates based on the stationing of the entrance door to the adit. The positioning of the door is used as a reference point as it controls the positioning of the structure inside the adit.

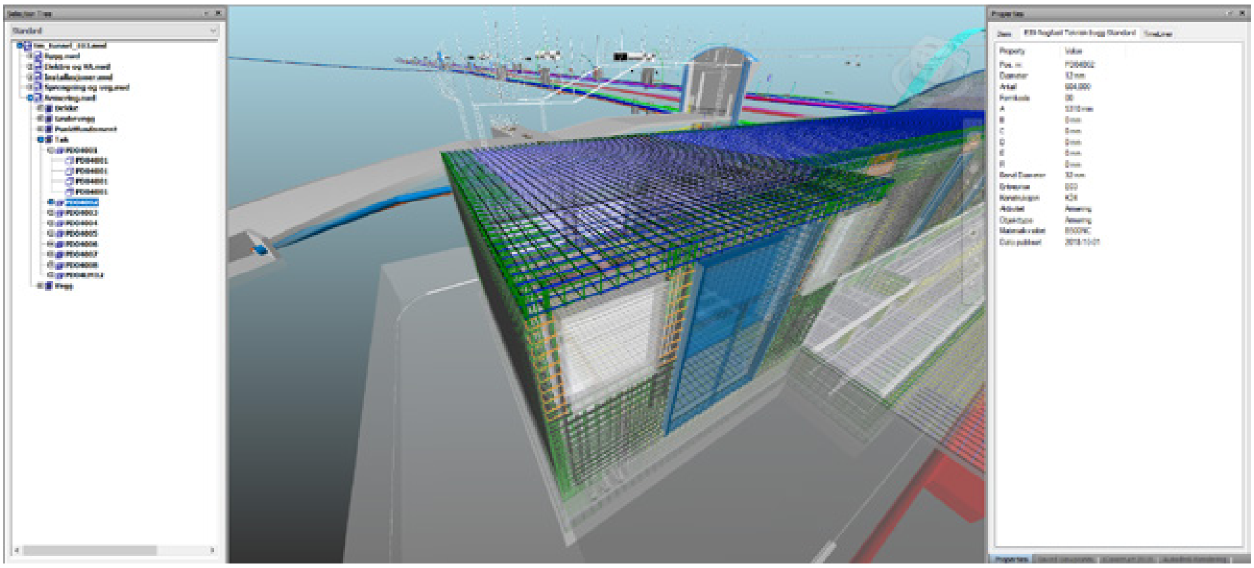


Figure 1.5.6: Example of a rebar model of a technical building from E39 Rogfast.

Cross passages are structures often found in longer tunnels. They are built as repeating structures through the entire tunnel to maintain safety in case of emergency, but also ensure streamline maintenance between the tunnels, inspection of the water and frost-protection and crossing of conduits and pipes between the main tunnels. Typically, these passages are located every 250 metres and exists in different forms such as walkable and drivable. The drivable passages are big enough to ensure the accessibility for emergency vehicle anywhere in the tunnel.

Due to complicated tunnel geometry, such as height offset between the main tunnels and the tunnel alignment, the construction inside the passages are tricky and time-consuming to model manually. In tunnels with large amounts of structures like this, quite a lot of time can be saved by automating the structural modelling. This was for instance done in E39 Rogfast, where every instance of the cross passages are modelled parametrically with Revit and Dynamo, as illustrated in Figure 1.5.7. Based on the stationing of the structure, the road geometry and a dynamic calculation of the concrete side area in each tube, the position of the structure is calculated and automatically modelled with Dynamo. By integrating these parametric calculations of the positioning of the structures between two tubes, the modelling of all the building elements within the structures can automated. This includes line-based geometry such as concrete floors, conduits and cable trays and single instances such as attach-bolts and draw pits inside the passages. Concrete walls with doors and hatches to enter the passages are also placed in the model as instances.

1.5.4. Conclusive remarks

In recent years there has been rapid development of 3D-modelling software. The need for digitalisation in the different industries has been the driving force for this transformation. Today, the possibilities for delivering tunnel projects in BIM are fully present. By substituting 2D-drawings with BIM-models

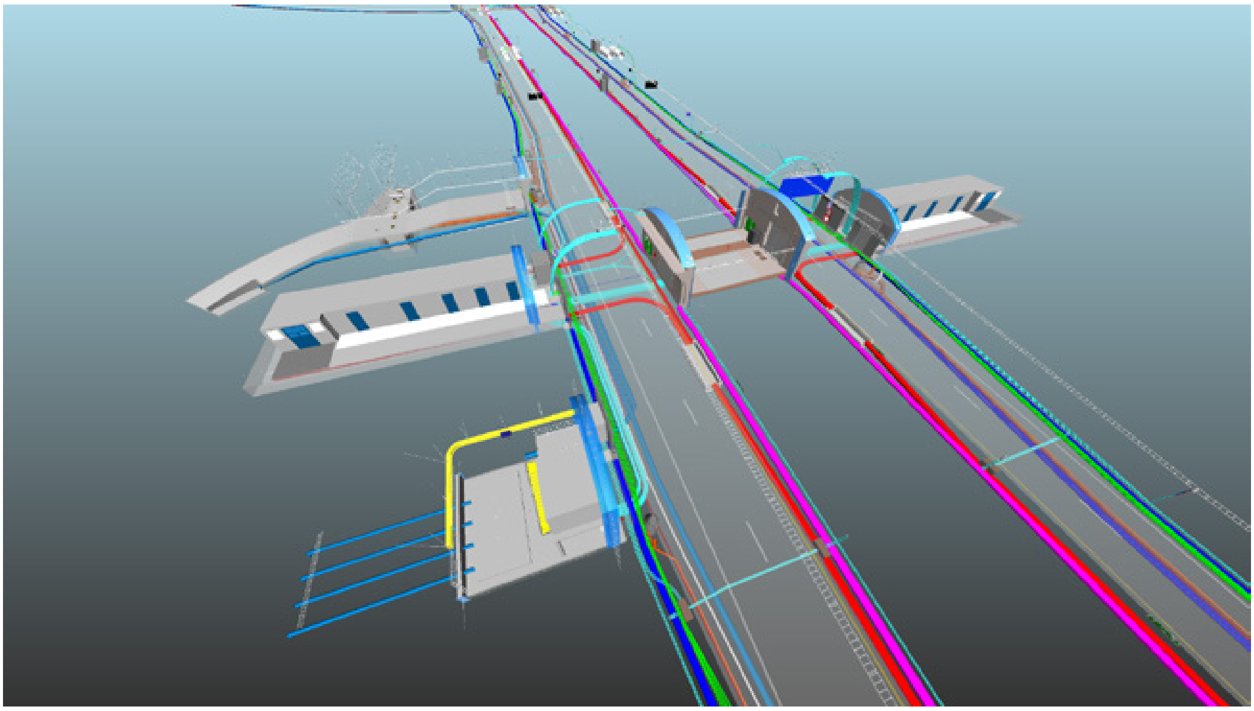


Figure 1.5.7: Model of an area with cross-passage, technical building and pumping station.

a lot of conflicts and bad design can be avoided. The structure can be better evaluated in the design phase to create a high quality and lasting infrastructure. During construction the BIM-model work as a suggestion to how the finished structure should look like, improving the understanding and execution for the contractors. Lastly, the model will work as digital twin of a finished constructed project, gathering all the information about a project in a unified model.

The digitalisation of the tunnel industry is still at an early phase. Projects are starting to implement BIM-models, but there are varying ambitions of how this should be used from project to project. The industry in Norway is lacking a common practice for how the BIM-models should be implemented and used.

The modelling of technical installations and structures have had a rapid development during the past few years. Still, there are several issues which need to be solved for the different stakeholders in a tunnel project. The software should have better solutions for automating more of the modelling. The more of a project which can be modelled in the design phase, the more possible collisions and faults can be picked up before construction. For instance, line-based objects such as conduits, ducts and pipes can today be quite time-consuming to create and maintain through all phases of a project. But these components can also be a large source of collisions in a tunnel project. As BIM become a common delivery in all tunnel projects there should also be possibilities for implementing BIM-formats such as IFC for surveying operations. This could contribute to creating a more optimal flow of information between all stakeholders. The BIM-model should be a single source of truth for information in a project.

1.6. Environmental Monitoring

Authors:

- *Fredrikke Syversen, Bane NOR*
- *Joakim Navestad Hansen, Bane NOR*

Geodetic data acquisition in urban areas and along linear infrastructure are major cost drivers in big infrastructure projects. Modern remote sensing and digital online presentation methods help us to manage data acquisitions with high effectiveness.

1.6.1. Early establishment

Early establishment of an online digital monitoring system for environmental parameters is crucial for urban tunnelling projects. Such early establishment enables the project to distinguish between annual variations and variations caused by tunnel excavation. For Norwegian tunnelling projects in urban areas, such as the Follo Line Project, the digital online monitoring system has been actively utilised during the construction phase. When data is automatically uploaded to the registration system with intervals down to 10 minutes, it also allows the projects to utilise the digital system for fine tuning their methods for e.g. pre-grouting and infiltration wells. The digital automatic online monitoring systems does not only allow an early set-up, but also an increased number of sensors. Both without increased costs related to personnel and equipment for manual readings.

1.6.2. Items for online monitoring
Demanding requirements from the Norwegian governments has resulted in an increased number of environmental parameters that are subject to online digital monitoring. The following chapters will provide a brief description of the main parameters under digital monitoring as per today. The urban double shield TBM project in Oslo, the Follo Line Project, will be the base case fo the following chapters.

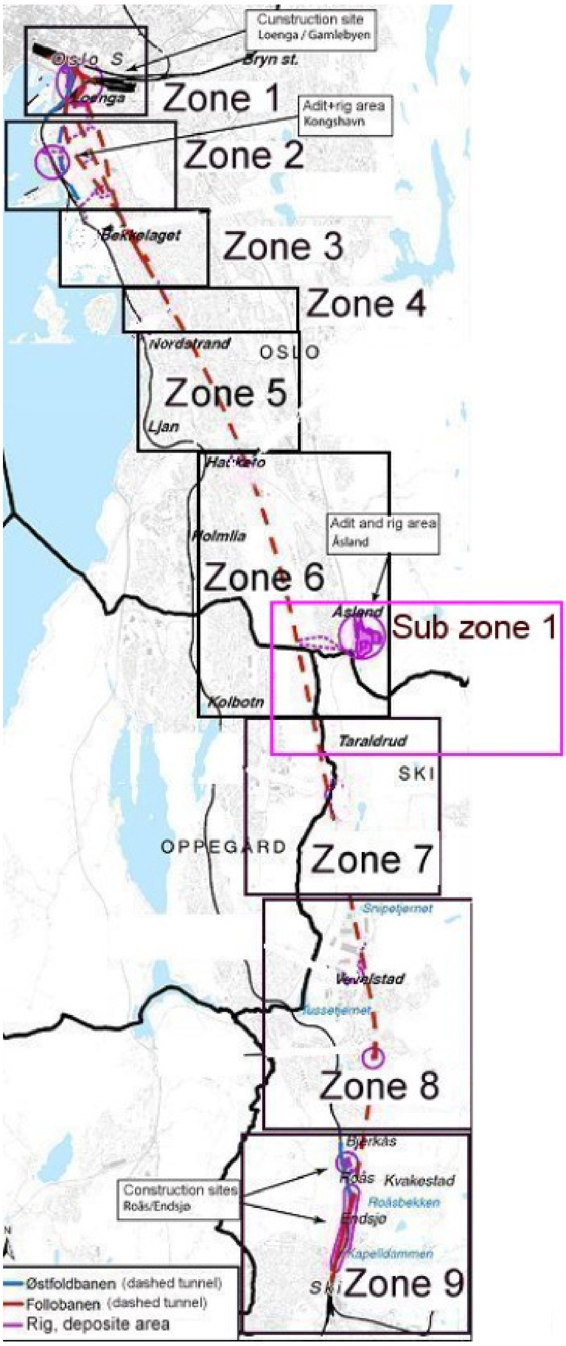


Figure 1.6.1 An example of such pore pressure monitoring from sensor 7020.

1.6.3. Pore pressure monitoring program
Tunnel projects in Norway run the risk of high water ingress during construction phase, resulting in pore pressure reduction in both rock and soil above the tunnel. This is due to risk of settlement in sensitive clay sediments and draining wetlands. Thus, it is crucial to identify areas sensitive to pore pressure reduction above the tunnel alignment during the design phase and concentrate the installation of pore pressure sensors accordingly.

Because of the isostatic uplift since the last ice age, settlement sensitive marine clays are often located in rock surface depressions. Infrastructure and buildings constructed on top of these sediments are therefore exposed to pore pressure reduction during tunnel excavation. In addition, avoiding drought damage to vulnerable vegetation above the tunnel alignment is important. To avoid dropping pore pressures and to enable a customised concept for probe drilling and on demand pre-grouting whilst tunnel excavation, it is therefore crucial to monitor the pore pressure measurements in detail.

For the 20 km long tunnel at the Follo Line Project an extensive monitoring program consisting of more than 170 pore pressure sensors in both soil and rock wells were established due time before tunnel construction. Most of the sensors were established during 2013 and 2014, whilst the TBM excavation started late 2016. The purpose of this early establishment was to register the natural seasonal variations in pore pressures. The various zones are illustrated in figure 1.6.1.

However, development of the monitoring program at the Follo Line project turned out to be a continuous and ongoing process throughout the project. After TBM excavation started the number of sensors and the packer locations were updated based on experiences gained through close monitoring of the online registration system.

All sensors are logged automatically, and the readings are uploaded to a web-based GIS portal with a frequency of every 10th minute. The webpage shows continuous, quality-assured measurement results from the sensors at their location. It includes an overview map, and by clicking on a subarea or

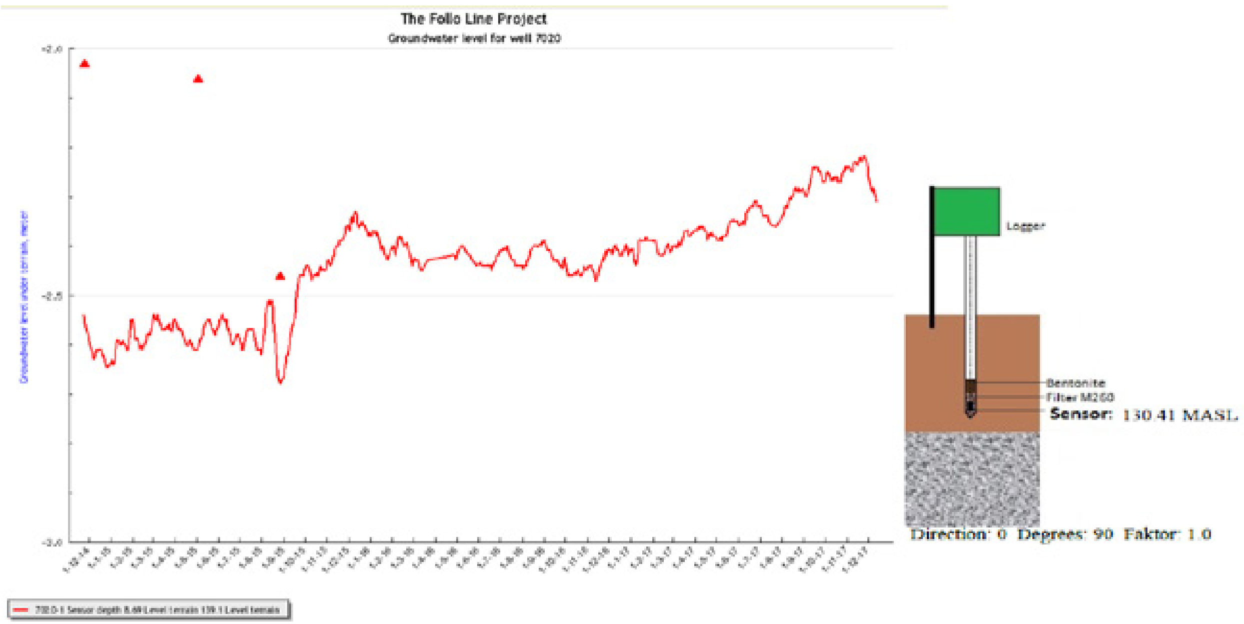


Figure 1.6.2: Pore pressure measured from 2014 and until both TBMs have passed.

metric point, one gets a map view and a list of measurement stations in the respective area. All data from each sensor can be visualised as graphs and / or downloaded as excel-files. Several sensors can be included in one graph and the data can be presented as a time function of elevation or level below terrain. The webpage includes registrations of precipitation data and air pressure as well.

The web page is accessible with a username and password, and the data is typically shared between both the client and the contractor.

<u>Data from settlement nail at dwellings and buildings</u>
For tunnelling projects in urban areas, an extensive monitoring program is required to register the settlements (if any) prior to, during and after tunnelling excavation. To collect and present the data registered from this monitoring program a web-based GIS-map solution is necessary. Such solution has been established for several Norwegian projects and the Follo Line Project is amongst them. For the 20 km long Follo Line Tunnel more than 3000 buildings are monitored and the data from settlement nails mounted at the foundations are manually collected by surveyors.

An extensive surveying program is required, which in turn also requires continuous updates of the web-based map. To ensure a more nuanced picture of the settlement developments, the map contains layers that can be switched on and off as needed. E.g. pore pressure sensor locations (as points) and polygons of bedrock, weakness zones, and soil-thickness. Settlement data collected by the surveyors can be downloaded as excel-files and presented as graphs.

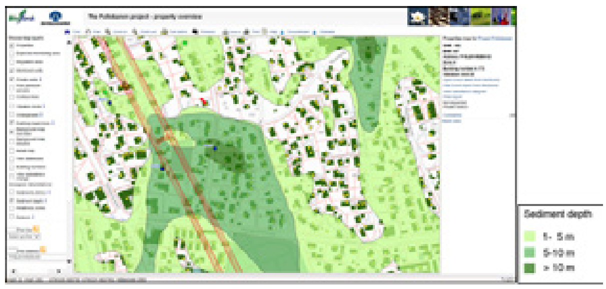


Figure 1.6.3: Example from WEB-application B, showing soil-thicknesses and house locations.

1.6.4. InSAR

Radar interferometry (InSAR) is a technique which uses two or more radar images, acquired at different times, to generate surface deformation maps with millimetre per year accuracy. Man-made infrastructure is usually a perfect target for this type of deformation monitoring, since buildings and other infrastructure (such as crash barriers, lamp posts, railway tracks) have a high reflectivity and a good coherence and thus provide good data quality. Radar interferometry enables contact-less measurement and online monitoring of parameters that are crucial in both the planning and development stage of large infrastructure tunnelling projects. It does so with a measurement density of several thousand points per square kilometre. Thereby, it is possible to considerably reduce costs by targeting the traditional in-situ measurements to areas of special interest.

Prime applications as well as limitations are determined whether terrestrial or satellite-based plat-

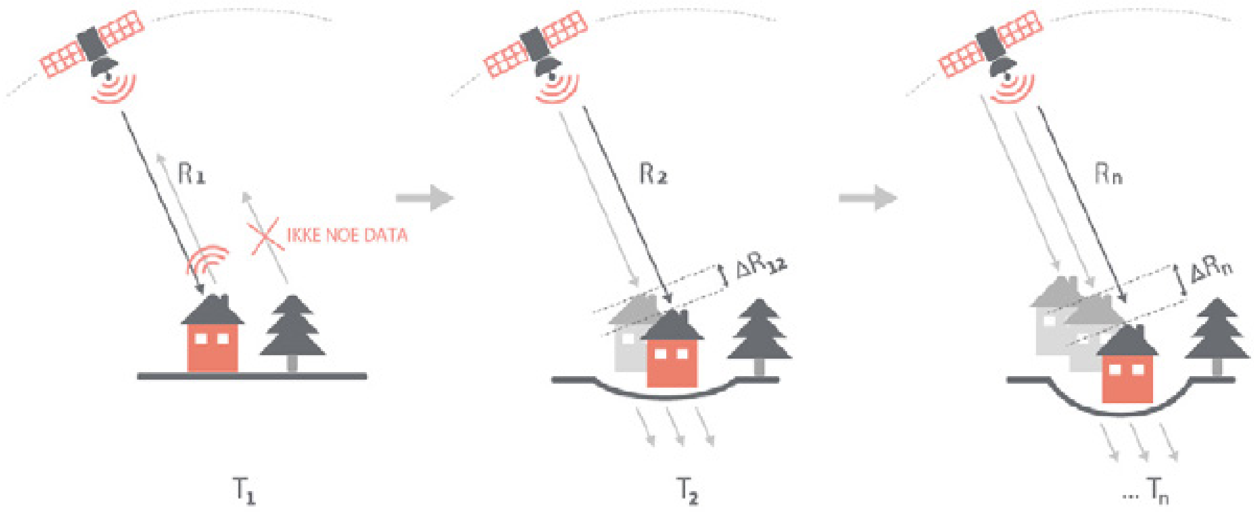


Figure 1.6.4 The principles of InSAR. Delta, in terms of distance from ground surface to satellite, is measured at the same satellite position with different time intervals.

forms are used. Satellite systems, usually applying synthetic aperture concepts, can cover large areas and are mainly sensitive to sub-vertical movements. Terrestrial radars can be used for discrete sites and are capable of sensing horizontal movements. Both solutions offer millimetre deformation accuracy with varying degrees of spatial resolution from 10s of centimetres to 10s of metres.

The Follo Line Project is being built with least possible damage to the environment. To monitor possible movements in the ground during the advancement of the four tunnel boring machines (TBMs), data from bolts in more than 3000 buildings along and across the track have been registered. The current system using bolt levelling provides a good level of reliability for the builder and residents. The exact measurements are taken at selected points, but in some cases, it can be challenging to identify the best measuring points. Therefore, radar interferometry results are delivered as a supplement to the traditional methods of monitoring ground movements. Radar interferometry results improve the factual basis for monitoring any changes that might occur during the construction period. Satellite-based radar interferometry monitoring provides a sustained overview of the entire site.

On average, 3 057 measurement points (with coherence values 0.65 or better) were measured per square kilometre, and 6 733 measurement points per square kilometre in built-up areas. The results are updated four times a year and could be updated on-demand any time, if need would arise during the advancement of the TBMs.

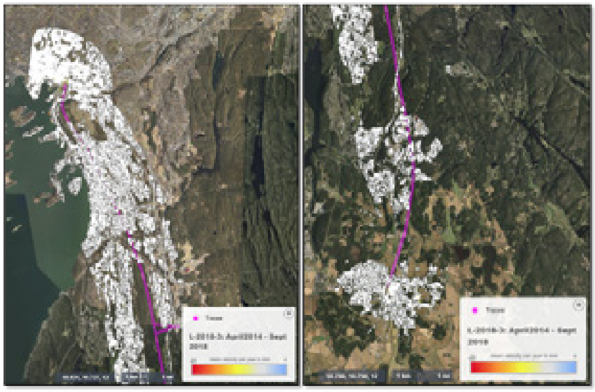


Figure 1.6.5 Illustration of the subsidence history from 06.04.2014 to 31.08.2018. The results contain 211 888 measurement points in the contracted area of interest, which comprises 104 km^2.

Figure 1.6.6 shows a zoom-in of one region along Follo Line. The blue structure examples an area where settlements can be observed. The time series show that the settlements started before the onset of the Follo Line construction. It also indicates a recent acceleration of the settlement velocity.

Interferometric radar is today successfully applied in big infrastructure projects on a worldwide basis. The method can also be applied for historical assessments. This in order to measure what has moved when and by how much. Preferably, however, and as shown in the example presented here, the method should be applied for risk mitigation and asset management during construction. Depending on the spatial resolution of the satellite data used, the interferometry results can be used to gain an overview over settlement/subsidence hotspot areas, as is the case for data with resolution in the metres to ten-metres range. In addition, the results can be directly tied to pre-existing in-situ measurement records.

1.6.5. GIS-model for structural borne noise

This sub-chapter is written in corporation with the Norwegian Geotechnical Institute (NGI, 2019).

Due to limited experience with large diameter TBMs in Norway, and the fact that the Follo Line Project had more than 14,500 inhabitants located within 200m from the tunnel alignment, the question of how the structural borne noise would affect the indoor noise level was raised during the pre-design phase. The limited excavation period required a 24/6-schedule of TBM operation, thus the risk of exceeding the indoor noise limits set out by the Norwegian government had to be managed as this potentially could delay the project. To enable such risk management, the project established an advanced GIS-model and utilised the model as a decision-making tool for relocation of the neighbours within the zone where the noise level was expected to exceed the limits during night time. This solution was accepted by the Norwegian government, and the project was allowed to excavate during night shift.

The Geographical Information Systems (GIS) model was based on geographical data that had been processed in GIS software. The input data has been gathered from project plans and documents in addition to official databases, including the following datasets:

- Digital spatial maps and tunnel alignments (in sub-meter accuracy)
- Public cadaster data
- Buildings
- Geological maps
- TBM progress
- Noise propagation

The basis for the model consisted of static data such as the terrain model and tunnel alignments, and adjustable data like buildings and their registered inhabitants, which were updated every third month to keep up with changes and spatial development. This data was also used to calculate the exact 3D distances between the TBM locations and buildings at any time. In addition, other relevant data was added to explain possible noise variations, including geological weakness zones, soil cover and construction materials for some of the buildings.

An extensive noise measurement program was established at start-up of the four TBMs to form the basis of a fixed (but adjustable) distance for the propagation of noise from the TBM excavation in the model. Other factors likely to affect noise propagation were set to geological weakness zones, soil thickness, building foundations, number of floors and construction materials. In addition to dwellings, the building database in the model also contained workplaces and businesses in proximity to the tunnel lines. The latter for notification and communication purposes. All this information had to be included in the GIS model to be accounted for. The model was also updated with the actual noise measurement results to fine tune the prediction of the noise propagation. Furthermore, feedbacks from neighbours were also mapped to keep track of possible irregularities.

The weekly average advance rate for each TBM constituted an uncertainty to the modelling of noise propagation. The expected advance rate of 90 m per week was used as a basis, but the TBMs started boring with one-month intervals and unforeseen events had to be encountered for. This emphasised the importance of utilising a GIS-model in the management of relocation of neighbours within the zones where the noise levels were expected to exceed the limits. By monitoring the actual advances of the TBMs and gaining experience from the TBM excavation, a good prognosis of the expected advance rates and the related noise propagation was successfully conducted. Thus, the project could continue the excavation during night time and the required schedule was met.

References

[1] Berardino, P., Fornaro, G., Lanari, R., Sansosti, E. (2002). A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. IEEE Transactions on Geoscience and Remote Sensing, 40(11), 2375–2383. doi:10.1109/TGRS.2002.803792

[2] Cespa, S., Del Conte, S., Giannico, C., Ferretti, A., Iannicella, I. (2016). 15 years of satellite interferometry: state of the art and new trends. Gallerie e grandi opera sotteranee, no. 118/June 2016. (in Italian).

[3] Ferretti, A., Prati, C., Rocca, F. (2001). Permanent Scatterers in SAR Interferometry. IEEE Transactions on Geosciences and Remote Sensing, 39(1), 8–20. doi:10.1109/36.898661.

2. Norwegian clients: status and future visions

2.1. Cooperation in our industry

Nye Veier AS (Literal translation: *New Roads*), Norwegian Public Roads Administration (NPRA) and Bane NOR (Norwegian national railway infrastructure) acknowledge that model-based working methods in planning, engineering and construction is a fast developing and core process in the field of transport and communications. These three clients are central stakeholders in this development process and carry special responsibility for leading and facilitating this development in order to ensure the best possible solutions.

Nye Veier AS, Norwegian Public Roads Administration and Bane NOR are involved in several important coordination forums. On a national level they participate in the Transport and Communication Council - Coordination of Regulations and Standards together with the largest consulting and contracting companies. Together the participants work for common standards and requirements, handbooks, terminology and international open standards. The goal is to create a common handbook for model-based working methods for road and rail infrastructure and share the responsibility and work effort for open standards.

On a Nordic level the same stakeholders are part of a Nordic BIM Collaboration, a shared interest group for Nordic road and railway authorities. All participants have signed a Memorandum of Understanding to share experience and knowledge regarding BIM. Meetings are held approximately three times a year and hosted in turn in the different Nordic capitals. In addition, there are Skype meetings covering different topics. Bane NOR chairs this group in 2019.

2.2. Nye Veier

Author:

- *Jan Erik Hoel, Trimble*

2.2.1. Purpose and history

Nye Veier is an independent company, but fully owned by the Norwegian Government. The company has been operative since 1st of December 2016. Today the company has 150 employees and a portfolio of 540 km highway to build to the expected cost of 150 billion NOK (approx. €15.3 billion).

The mission of the company is to build safe roads smart, fast and as cheap as possible without reducing the quality and safety requirements. In addition, Nye Veier is responsible for facility management of the roads after the completion of the construction projects.

To achieve their mission, they follow several strategies: Build larger stretches per tender, change the technical requirements where feasible, introduce new contract types based on trust and change the construction and maintenance processes to be fully digitalized.

2.2.2. Tender strategy

Nye Veier wants to test out different contract regimes based on trust. They want all parties in the construction and maintenance processes to set up common goals, common bonus-systems, sit together and develop common work processes and methods. This will lead to an open and trust-based project culture.

A new tender process called Best Value Procurement (BVP) is introduced by Nye Veier. BVP is characterized by very short descriptions from the bidders (3 documents of 2-3 pages each), interview with key personnel, agreed maximum project cost and a tender phase where Nye Veier and the bidding contractors work out a common best solution.

Design and build contracts with early involvement by the contractor is the standard contract practice used by Nye Veier. A new contract type has been introduced by Nye Veier lately. It is called Integrated Project Deliverance (IPD). IDP is characterized by a mutual dependent relationship between Nye Veier, the contractor and the design companies, full use of the competence of all the involved parties in all phases of the project, open book (all costs and profits are transparent for all parties), no company secrets and the project team sit together in a common office space.

2.2.3. BIM and digitalisation

Nye Veier's goal is to be fully digitalized within 2020. Nye Veier is a major player in the Norwegian construction industry and want to use this influence to push the industry further into a fully digitalized working process. Nye Veier aims to be the most advanced digitalised governmental infrastructure owner in Norway.

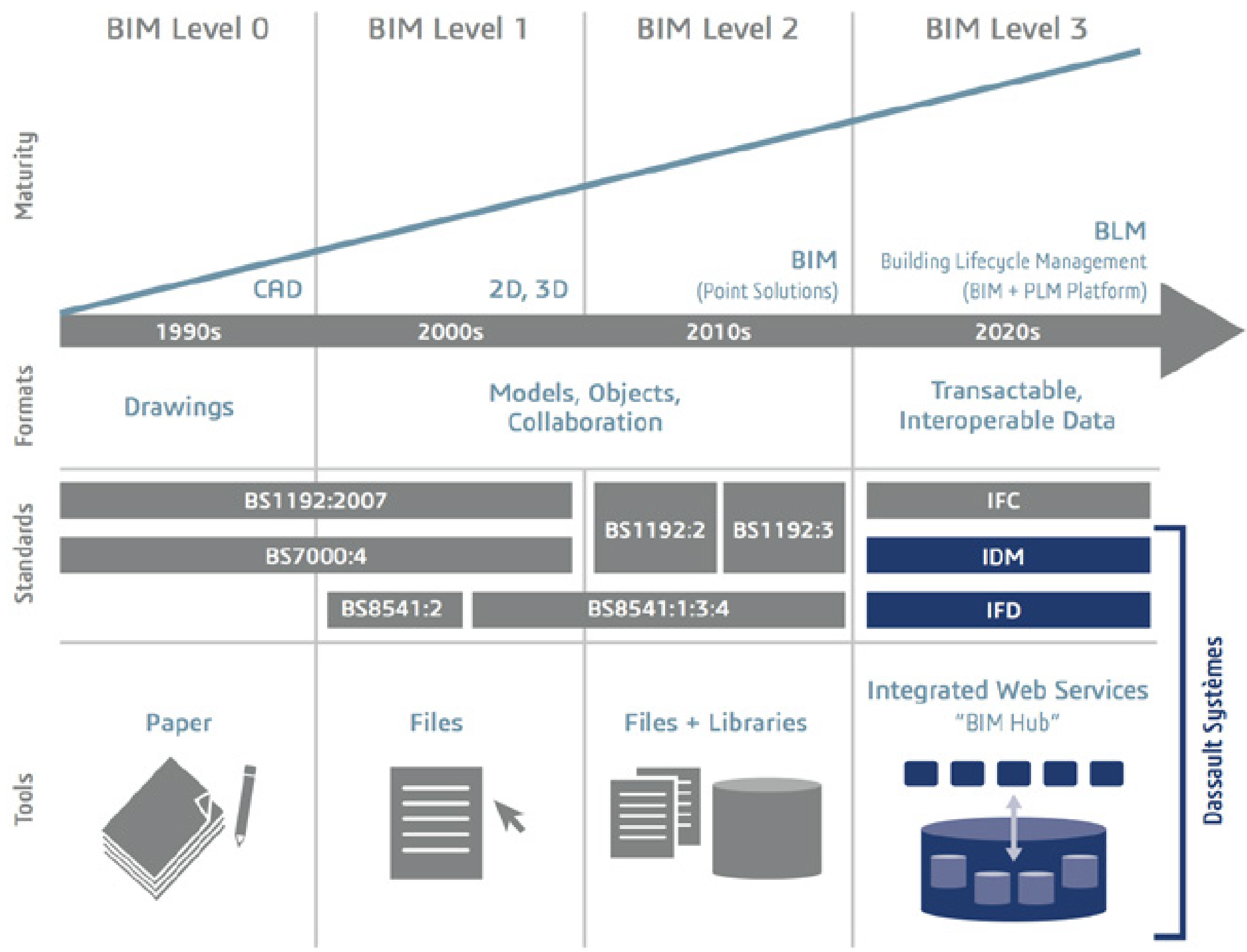
The digitalisation process will pick up speed by introducing new work processes and new trust-based contract types. By achieving a fully digitalized work process, Nye Veier can continue as a lean organization with full control of their increasing portfolio of ongoing projects and built roads.

Digitalisation is achieved through tender requirements and bonuses in close cooperation with the industry. BIM models based on open standards, is the main element in the digitalisation processes. By actively using BIM as the core element in their process, Nye Veier hope to achieve better and faster design processes, more standardized and industrialized building processes and more efficient facility management of the built roads. Nye Veier will use the BIM models for managing deviation- and approval processes, monitoring the construction processes, handling of product specifications and following up environmental parameters, HR aspects etc.

In the tenders from Nye Veier there are requirements to apply the Virtual Design and Construction (VDC) process. A main aspect of this process is the use of big rooms with good facilities for visualization of the BIM-model. In these rooms the whole design team with decision makers can sit together and do their design work at high speed.

The BIM model must fulfil the requirements for BIM level 3. There must be one common BIM-platform based on open standards. This BIM-platform must be available for all stake holders of the actual road projects.

By organizing the projects based on one common BIM-platform, Nye Veier believe they will reduce the amount of errors due to deviating versions of drawings and misunderstandings between the different parties in the design and construction processes.



The BIM Maturity Model by Mark Bew and Mervyn Richards adapted to reflect BLM's relationship to Level 3.

Figure 2.2.1: The levels of BIM. Source: Dassault Systems

2.3. Norwegian Public Roads Administration

Authors:
- *Ausra Aalborg, NPRA*
- *Geir Dehli, NPRA*

2.3.1. Purpose and history

The Norwegian Public Roads Administration (NPRA) is a Norwegian government agency responsible for national and county public roads in Norway. This includes planning, construction and operation of the national and county road networks, driver training and licensing, vehicle inspection, and subsidies to car ferries.

Before the 1846, the Ministry of Justice had the responsibility for public roads until Prime Minister Frederik Stang created the position of Roads Assistant in the Ministry of the Interior. The Roads Assistant headed a department for roads engineering. Captain (Engineer) H. K. Finne became the first Roads Assistant. The Directorate of Public Roads was established in 1864, and C. W. Berg became the first Director of Public Roads. From 1885 to 1944, the Directorate was subordinate to the Ministry of Labour, and has since been subordinate to the Ministry of Transport and Communications.

Currently the agency is led by the Directorate of Public Roads (Vegdirektoratet), and is subordinate

Statens vegvesen
Norwegian Public Roads Administration

Our vision: *On the road to a better society*
Our values: *Professional - forward-looking – inclusive*
Our mission in society: *The Norwegian Public Roads Administration strives to ensure that you get to your destination safely, whether you walk, cycle, travel by car or use public transport.*

Figure 2.3.1 NPRA's Vision, Values and Mission

to the Ministry of Transport and Communications. The NPRA is divided into five regions and thirty districts, which are subordinate to the directorate. From 2020 the NPRA will enter new era as a new organization probably with only six divisions and the Directorate of Public Roads. A new economic reality, new technological solutions and requirements for user orientation, affects the NPRA roles, responsibilities and the way the organisation solves its tasks - and thus the way its organized.

Currently the NPRA strives to ensure that the road transport system in Norway is safe, sustainable, efficient and available to all. The NPRA manages national roads on behalf of the national government, and on behalf of the county administrations. This involves planning, developing, operating and maintaining the roads. The agency is also responsible for the Norwegian Scenic Routes.

Figure 2.3.2 Pictures from some of NPRA's projects

Topographic conditions in Norway are a major challenge for infrastructure development. In Norway we have more than 1,000 tunnels on the national and county roads. At any time, 30-40 tunnels are under construction. Some of these are replacing older tunnels. The national and county roads have almost 20,000 bridges, ferry quays and other load-bearing structures (e.g. retaining walls). It is the Government and the Norwegian Parliament (Stortinget) that set the national goals for transport policy in Norway.

The National Transport Plan (NTP) describes the goals and principles on which the government is based and tells which priority areas the transport policy will concentrate on in the coming years. The national goal is to provide an efficient, accessible, secure, and environmentally friendly transport system that meets the community's transport needs and promotes regional development.

The NTP prioritizes which focus areas transport policy in Norway will concentrate on in the coming twelve years. The plan is revised every four years.

The national goal breaks down into three main goals:

- **Accessibility:** better accessibility for people and goods throughout the country.
- **Traffic safety:** reduce transport accidents in line with the zero vision; A central goal for the NPRA is to work towards a vision of "zero people killed or severely injured in traffic".
- **Climate and environment:** reduce greenhouse gas emissions in line with a transition to a low-emission society and reduce negative environmental consequences.

Figure 2.3.3 Illustrations from NPRA

2.3.2. Tender strategy

The choice of contract strategy is linked to several goals in the Road Administration's planning and building strategy. Examples of these are:

- Acting professionally, uniformly and predictably,
- Facilitating effective project implementation,
- Contributing to the development of expertise,
- Contributing to a well-functioning market of advisers and entrepreneurs,
- Contribute to good reputation and professional collaboration with everyone parties,
- Facilitate good resource utilization and sharing of experience across the industry,
- Develop appropriate and targeted templates and contract mechanisms within the different contract forms.

Until today, the unit-pricing contract, where the client designs in detail, has been the most common type of contract with a share of approximately 95% of revenue per year. Design-build (DB) contract, where the contractor is detailing the project, has thus had a very limited scope within our project and task portfolio. The current client strategy states that the share of DB contracts should be increased significantly and constitute 15–20% of annual turnover by 2020.

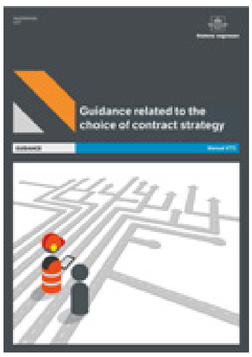


Figure 2.3.4

In order to further develop the knowledge of the effects of various procurement procedures, contract mechanisms and contract forms, it is important that practical experiments be carried out in specific projects. It is also important that systematic evaluation is carried out to see if the expected effect has been reached or whether it is necessary to make changes and adjustments. Report from evaluations must be sent to the section for Construction of the Road Directorate. This will help ensure that the contract strategy is actively used to develop the industry and manage our projects.

In order to facilitate an appropriate and targeted project implementation, it is important that the contract strategy is clarified at an early stage in the project development. Such a clarification in an early planning phase allows for an optimal planning process and level of detail adapted to an appropriate contract strategy for the implementation and operation phase.

2.3.3. BIM and digitalisation

Traditionally, road plans have been communicated with drawings and text documents. Today all the subjects included in a road project can be designed as 3D models.

In 2006 the Construction Directorate of the Roads Administration initiated a project that would facilitate more efficient design and construction of roads. The project resulted in, among other things, the guide "138 Model basis". The manual defined basic data, models and other types of documentation, and described methods for designing and constructing roads based on 3D models. In 2015, the handbook received a new number: V770 Model basis.

The methodology in manual V770 is used in many of the Norwegian Public Roads Administration's projects. Since manual V770 Model basis is a guide, it has been voluntary to work model-based. Training in new forms of work has not been prioritized, and templates for competition documents have not been very much adapted to ordering model-based documentation. It has resulted in suboptimal practices in some of the model-based projects. The methods are being adopted by Bane NOR and Nye Veier, and feedback from an overall industry is generally positive.

In all phases of road projects, documentation is ordered and processed that shows how the road should be placed, designed and functioning. It is crucial for the quality of plans and execution that the NPRA orders the right type of documentation and sets clear quality requirements for its preparation.

On 22nd November 2017 the Directorate of Public Roads released a new strategy for digitalisation which deals with technology that drives changes in the future.

In the digitalisation strategy one of the main goals is to establish a standardized digital work processes that ensure a uniform implementation of the following tasks:

- Be faster and more cost-effective in digital planning construction, operation and maintenance of roads.
- Facilitate and establish open international standards and use information models (BIM) in the design, construction and management of roads.
- Facilitate that operating and maintenance systems make the most of different use data sources and digital models from the road network and constructions.
- Facilitate digital information based on data entered in one place.
- Start work to facilitate the industry and other public actors interacts with us digitally.
- We will further develop the digital-navigable road network for a digital twin of its physical road network.
- Clarify data ownership.

The corporation has ambitions through its digitization strategy, business development portfolio and regional initiatives, to implement model-based road projects (BIM). The manuals R700 subscription basis and V770 going to be merged into a new guideline where model-based practice must be the main rule in the future road projects. In 2018 the Directorate of Public Roads has initiated a project VU053 (corporate development initiative 053 "digital road projects") to work for developing of model-based working method as defined in manual V770 Model basis. The work will result in a new guideline that sets requirements for the documentation that is prepared in road projects, as well as a guide describing best practice. In addition, the project will contribute to necessary system support, training, standardization of information and to the fact that the model data is archived and can be used in management, operation and maintenance.

The project contributes to standardization work internally within the NPRA and shall follow up other relevant standardization initiatives and projects externally.

At the same time, the project will work to model the information so that it becomes machine readable and can be exchanged on standardized, open formats.

This management document briefly describes how the working methodology in manual V770 can be further developed and introduced as standard in road projects.

As a part of the NPRA's development work is to interface relevant projects, organizations and initiatives nationally and internationally that should be followed up as Cedr-INTERLINK (completed), ISO/TC-211 – Geographic information/Geomatics, Inspire, Open Geospatial Consortium (OGC), BuildingSMART Norway etc.

Figure 2.3.5 Logos for some of the projects NPRA are participating in regarding standardization of digitalisation

2.4. Bane NOR

Authors:
- *Kristin Lysebo, Bane NOR*
- *Morten Sigvartsen, Bane NOR*

Figure 2.4.1

2.4.1. Purpose and history

Bane NOR SF is the Norwegian government agency responsible for the planning, development, administration, operation and maintenance of the national railway network, traffic management and administration and development of railway property. Bane NOR has operational coordination responsibility for safety work and operational responsibility for the coordination of emergency preparedness and crisis management. Bane NOR's mission is to ensure accessible railway infrastructure and efficient and user-friendly services, including the development of hubs and freight terminals.

The agency is the result of the rail reform of the Conservative-led coalition and is organized as a state enterprise which became operational on 1 January 2017. Bane NOR and the Norwegian Railway Directorate replaced the former agency the Norwegian National Rail Administration (*"Jernbaneverket"*). Bane NOR has approximately 4,500 employees and the head office is based in Oslo, Norway.

The Norwegian railway sector has a long history that starts in 1854 when Norway got its first railway from Kristiania (Oslo) to Eidsvoll.

In 1883, the management company *Norges Statsbaner AS*, trading as *NSB*, was established, known in English as the Norwegian State Railways. On 1 December 1996 the largest structural change in Norwegian railway history in the 20th century took place - the old Norwegian State Railways was split into three separate agencies. The ownership, maintenance and construction of the track was transformed to the newly created government agency Norwegian National Rail Administration while a new Norwegian Railway Inspectorate was created to supervise all railway operations in the country. *NSB* was renamed *NSB BA* and created as a limited company, wholly owned by the Ministry of Transport and Communications.

In 1999, the railways had a positive reputation as a fast, comfortable and efficient public transport mode, largely because of the success of the Gardermoen Line, which transports passengers to the main airport.

In September 2004, it was exactly 150 years since the railway was a reality in Norway. After the anniversary year, growth in train traffic continued. Strong growth in both freight and passenger traffic has meant that central parts of the rail network have been declared overloaded. There are therefore plans for increased capacity, more tracks and larger freight terminals.

2.4.2. Tender strategy

Bane NOR's goal is to facilitate the contractor's success and establish conditions and a climate of co-operation that motivate towards continuous improvement processes and optimal performance in our infrastructure projects.

In the years to come, Bane NOR will continue to introduce several large projects to the market, and the consequence of this is increased use of EPC contracts (Engineering, Procurement & Construction).

As the main elements in Bane NOR projects are bridges, tunnels, civil work, approach zones and railway systems, the EPC contracts may include the total SoW or be divided into different elements, as one EPC contract for the substructure and one for the railway technology. In projects close to railways in operation or with complicated interfaces, the Bane NOR strategy also provides opportunities for construction contracts with engineering provided by Bane NOR.

Bane NOR will involve contractors early when suitable and has introduced tender processes such as competitive dialogue and early contractor involvement. Bane NOR strongly believes that close co-operation and a good relationship between contractors and Bane NOR are key factors to success.

Bane NOR requires that the contractors and consultants use BIM in all contract forms when building the railway projects, however they do not specify details like what software to use, but it is required that the contractor specify how they will use BIM and that they describe work processes, methods, software and so on. In addition, Bane NOR clearly states the final BIM delivery with as-built BIM models with specified object properties. Bane NOR is in the process of updating all its specifications for as-built and maintenance documentation to include BIM. One of the company´s goals is a complete digital dataflow between all parties in a project and between all Bane NOR´s internal systems including mechanical completion and maintenance database.

2.4.3. BIM and digitalisation

Bane NOR has a BIM strategy that was approved by the company´s CEO in June 2017. The strategy clearly states that all projects shall be planned and built using BIM. Project management shall be an integrated part of BIM and all as-built documentation is to be model based. The strategy further states that Bane NOR shall work actively to further develop knowledge, methods, tools and industry standards for efficient use of model bases design, construction and documentation of railway projects. Bane NOR plans to start an internal project to define the use of BIM in maintenance and life-cycle management.

The company´s large projects division started using models in 2014 and has since then implemented BIM in all of its projects. The division is responsible for designing and building over 300 kilometres new double track railway with dimension speed of 250 km/h. The use of BIM will gradually be implemented in smaller projects in the divisions for existing railway and properties.

An overall goal is to implement all disciplines in the BIM models, with the most optimal level of detail for the actual plan phase and to use BIM from the earliest plan phase through the construction phase. Bane NOR's values are to be open, respectful, innovative and engaged. These values are an important part of the goal of becoming an even more digital organisation. Several internal projects and processes regarding digitalisation are ongoing, and more will start in the coming years.

BIM models based on open standards are the main element in the digitalisation processes. By actively using BIM as the core element in the process, Bane NOR hopes to achieve better and faster design processes, more standardised and industrialised building processes and more efficient life cycle management.

Bane NOR is actively involved in new BIM work processes like ICE and VDC and encourages its consultants and contractors to use these methods, as well as requiring their use through the contracts. In addition, Bane NOR is involved in a Research and Development program for *Forskningsrådet* together with several consultants. The goal of the project is to develop a work method for the infrastructure industry that can save up to 50% in design calendar time on large projects. In Bane NOR´s new head office a BIM room to further facilitate the use of BIM in the organisation will be implemented.

An important part of the digitalisation is data flow during construction. As previously mentioned the company´s BIM strategy states that all railway projects are to be built using BIM. Hence this is included in the tender strategy where digitalisation will be achieved through tender requirements in close cooperation with the industry.

By using BIM for design and construction, Bane NOR believes in a reduction in the amount of errors due to deviating versions of drawings and misunderstandings between the different disciplines and parties in the design and construction processes.

WG TUNNEL SEALING

COMPLETE WATERPROOFING SYSTEM FOR ANY CAVERNS, SHAFTS AND OTHER UNDERGROUND FACILITIES

WG TUNNEL SEALING IS A COST-EFFECTIVE METHOD TO PROVIDE A PERMANENT SEALING OF ROCK WALLS AND CAVERNS.

Key features with WG Tunnel Sealing:

- Patented solution with extensive experience
- Tailored for each individual project and facility
- Can be uses in all types of underground facilities
- Life span minimum 50 years
- The fabric is self-extingishing and will never spread or maintain a fire
- Avoid risk caused by dripping water and humidity

Examples of where WG Tunnelsealing is installed:

- Water treatment facilities
- Parking facilities
- Sewage treatment plant
- Storage facilities
- Sporting facilities
- Power plants
- Cable tunnels
- Valve chambers
- Technical rooms
- Access tunnels
- Military installations and hospital
- Mines
- Drop protection in road tunnels

W. GIERTSEN TUNNEL

W. Giertsen Tunnel AS Nygårdsviken 1, N-5165 Laksevåg-Bergen, Norway
www.giertsentunnel.no I tunnel@giertsen.no I +47 5594 3030

3. Case studies – lessons learned

DESIGN PHASE

3.1. Ringeriksbanen (FRE16)

Author:
- *Martin Stormoen, Bane NOR*

The Ringerike Line and E16 Highway (FRE16) is one of many megaprojects in the pipeline in the Norwegian tunnelling industry. It is the largest joint traffic project in Norway, including highway and railway, administrated by both Bane NOR and The Norwegian Public Roads Administration. It consists of roughly 40 km double tracked railway line between Sandvika and Hønefoss, including a 23 km railway tunnel, establishing a new railway station by Sundvollen and several long bridges (Figure 3.1.1). Year of construction start is set to 2021. The overall goal is to build a railway and highway to tie Ringerike closer to Oslo and reduce the travel time on the Bergen Line, at the lowest possible investment cost. Such ambitions combined with demanding geological conditions has pushed forward the need for a model based interdisciplinary design phase, including geological information to be modelled.

Figure 3.1.1: An overview of The Ringerike Line and E16 Highway (FRE16). Dashed black line shows where the railway tunnel is planned, between Sandvika and Sundvollen (23 km), and between Sundvollen and Bymoen (3 km).

3.1.1. From strategy to best practice

Bane NOR has adopted a strategy for model-based design, construction and documentation. The BIM strategy sets strict requirements that can be summarized in 4 main points:

- Model-based methods and tools will be used during planning, design and construction of all railway infrastructure projects and shall be an integral part of project management in Bane NOR.
- Model-based "as built" documentation of completed projects. Guidelines and requirements for model-based documentation from consultants, suppliers and contractors. Bane NOR has the ownership of all data throughout the whole process. The models and data must adapt for future operation and maintenance of the railway infrastructure.
- Bane NOR shall contribute to development of skills, methods, tools and industry standards for an effective application of model-based design, construction and documentation.
- Bane NOR will provide key guidelines for an ICT infrastructure (software, storage media, collaboration tools etc.) appropriate for model-based design, construction and documentation.

In addition to the strategy, model-based design is further detailed through a handbook with guidelines for modelling. This supports a common set of models and processes for working with models for the large portfolio of railway projects. Table 3.1.2 lists four of the models important for the design phase.

Basis model (Grunnlagsmodell)	**Discipline model (Fagmodell)**	**Interdisciplinary model (Samordningsmodell)**	**Tendering model**
Existing situation, collected data from pre-investigations	Designed /engineered situation, divided by discipline	Compilation of all models	Adjusted model for tendering purposes

Table 3.1.1: Lists four of the most important models for the design phase.

In line with the overall strategy for model-based projects, FRE16 has pushed the boundaries for model-based design and planning in several disciplines. Further, the project has completed a highly successful phase with interdisciplinary simultaneous design, where the use of models has been critical. This governed a close cooperation between the client and the designer.

One of the most innovative models created on the project is the geology model (Figure 3.1.2- Figure 3.1.5), consisting of elements belonging to the basis model and the discipline model for geology. Table 3.1.2 shows how the elements in the geology model are structured. All elements follow a set of rules for geometry and properties. Details about the elements are compiled in Table 3.1.2.

Element	**Geometry / visualisation**	**Metadata / properties**	**Uncertainty**
• Soil- bedrock intersection • Geology (rock units) • Faults and fracture zones • Pre-investigations (drillings, geophysics, mapping) • Wells • Ground water level • Geological map • Tunnel leakage limits • Rocks mass quality	• Plane, pipe, volume, point, text • Transparency • Colouring	• Rock unit • Rock mass quality • Reference • Main identification • Width • Date completed • Responsible • Length/dip • Comment	• Main identification • Working on other parameters: - Level of uncertainty - Visualizing uncertainty

Table 3.1.2: Shows how FRE16 has structured the geological elements. Tunnel leakage and rock mass quality are the only two elements belonging to the discipline model, while the other elements sort under the basis model.

Uncertainty is a commonly discussed issue in relation to modelling geological conditions. Many share a fear of economic claims due to different real-world conditions compared the conditions presented in the basis model. Even experts are drawn to describing geological conditions with simple 2D illustrations riddled with question marks, or even simple text descriptions lacking illustrations. This is not a sensible development in the industry.

Therefore, a model must be viewed in relation to the following reports. In addition, one can visualize uncertainty in the model by describing it in the properties for an element and what source of information has led to its identification. Another way of visualising uncertainty is using different levels of transparency or defining categories of uncertainty, similarly to what is done for level of development. This issue was discussed thoroughly on the project and it was concluded that modelling the geological conditions is beneficial in despite of this.

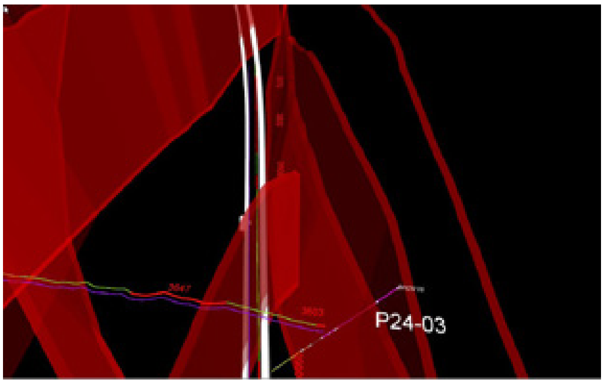


Figure 3.1.2 Illustrates how the discipline model for geology is used to visualize how the railway tunnel (white) cuts through an area with complex faults and weakness zones. Core drillings and seismic profiles are also shown.

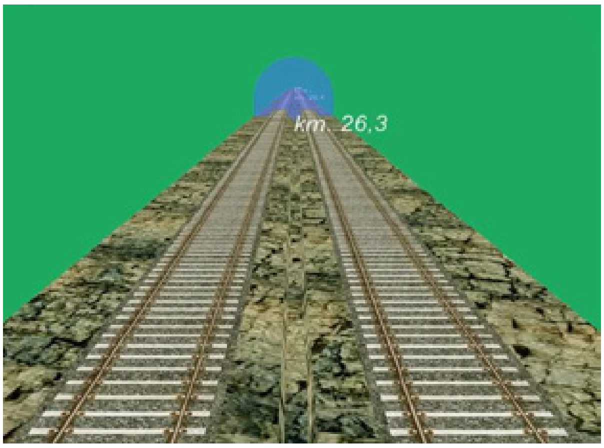


Figure 3.1.3 Shows how the discipline models can be combined to illustrate how a fault line (blue) cuts through the planned railway tunnel. The tunnel walls are colour coded to illustrate varying rock mass properties.

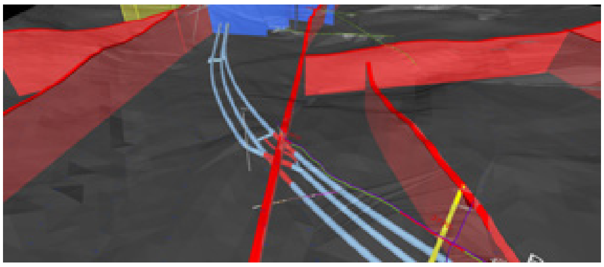


Figure 3.1.4: A complex part of the railway tunnel is shown (grey), cutting through a major fault line (red). The results from a core drilling are also illustrated.

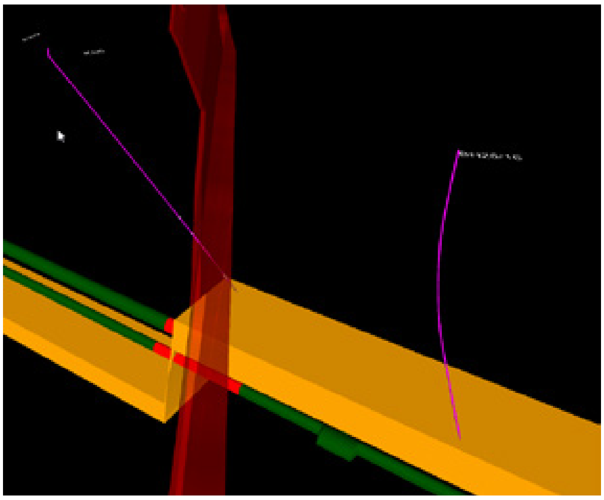


Figure 3.1.5: The railway tunnel is shown in relation to a very unstable geological unit (orange) and a major fault line (red). Rock mass properties are colour coded on the tunnel surface, where red indicates poor rock quality and green indicates good rock quality. A technical niche in the tunnel is shown and is placed with distance from the area with poor rock quality.

3.1.2. Lessons learned

A well-structured use of models in the design phase has several benefits. These benefits can be divided into measurable and non-measurable benefits (Table 3.1.3).

Measurable benefits	Non-measurable benefits
• Reduces the number of technical drawings • Reduces the number of errors and claims • The combination of models and Integrated Concurrent Engineering gives efficient processes (reduces duration of design phase).	• Better interdisciplinary design • Better communication within the project team and with other stakeholders • Better and more efficient processes

Table 3.1.3:

3.2. E18 Western Corridor Lysaker – Ramstadsletta

Authors:
- *Ausra Aalborg, Norwegian Public Roads Administration*
- *Geir Dehli, Norwegian Public Roads Administration*

E18 Western Corridor comprises of a road system from Lysaker in Bærum to Drengsrud in Asker. The first stage of the project is E18 Lysaker – Ramstadsletta (Figure 3.2.1) and is in the National Transport Plan (NTP) 2018-2029. E18 Lysaker - Ramstadsletta is currently in the design phase.

The E18 Western Corridor's vision for society:

- E18 project will contribute to more people taking the bus, cycling or walking.
- Facilitate a functional road system with good intermodal transfer points between Lysaker and Asker with urban development.
- Improved quality of life for resident and traveller.

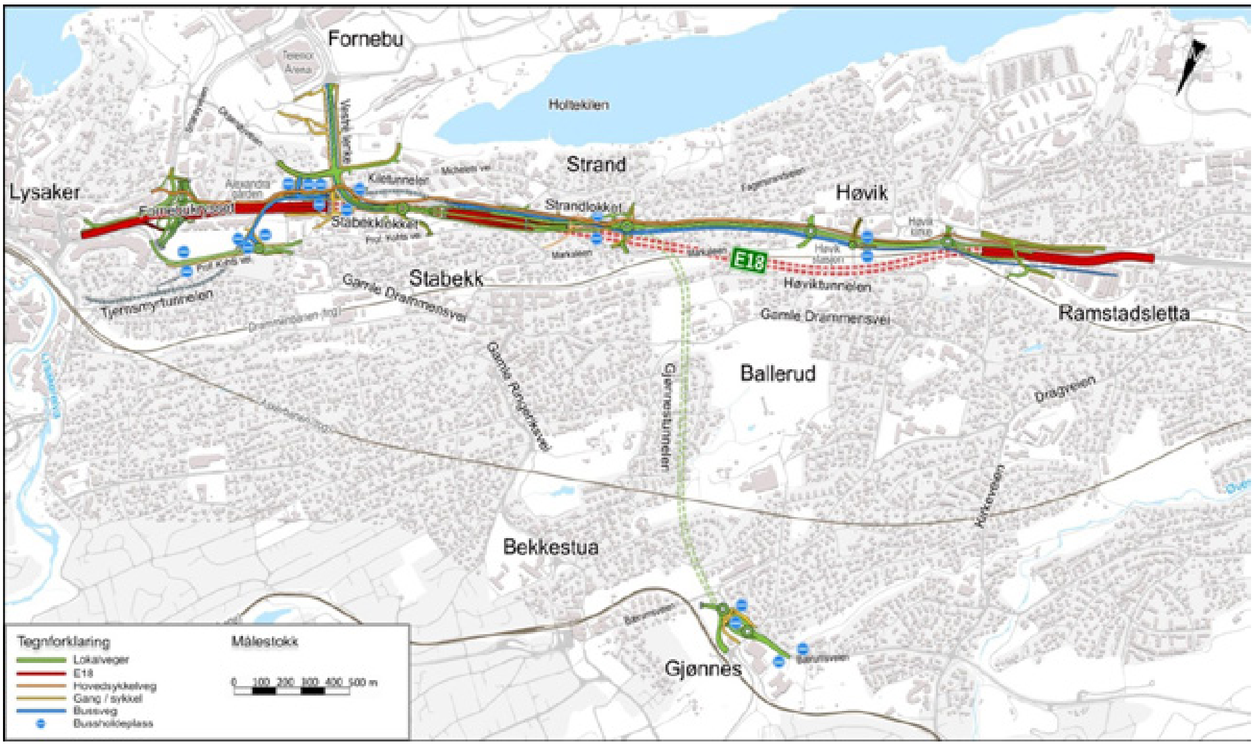


Figure 3.2.1: The first building stage of E18 Western Corridor, E18 Lysaker – Ramstadsletta.

The first stage, E18 Lysaker – Ramstadsletta, consists of 4.4 km new E18 from Lysaker to the middle of Ramstadsletta and approximal of 26 km of local, bus and bicycle roads. There is a total of 6 tunnels to be built:

- Approximately 500 metres of tunnel for E18 at Stabekk, "Stabekklokket"
- Approximately 1900 metres of tunnel for E18 from Strand to Ramstadsletta, "The Høvik Tunnel"
- Approximately 1900 metres of tunnel for a new cross-connection from E18 at Strand to Gjønnes, "The Gjønnes Tunnel"
- Two tunnels for buses, "The Kile Tunnel" (500 metres) and " The Tjernsmyr Tunnel" (735 metres).

Aas-Jakobsen is the Norwegian Public Roads Administration's contractual party and is responsible for the project management. Aas-Jakobsen AS are working with Geovita AS and NGI to ensure that the geology discipline is represented in the design phase.

3.2.1. Project Geological 3D information model

The project has developed and designed a 3D geological information model for the Høvik Tunnel. The Geological model is created in Leapfrog Works software and is implemented in the project Novapoint Quadri model (Figure 3.2.2).

According to the Norwegian Public Roads Administration manual N500 Road Tunnels, the project must as of today produce typical geological drawings in all the construction phases of the tunnels. With this model, the projects main goals for the geological rock model are:

- Use in design phase and building phase instead of the typical geological drawings (geological maps, geological cross-sections etc.).
- "As built" model: Enable model-based construction and model-based delivery to MOM (Management, Operation and Maintenance).
- Make necessary information from all phases easily available in one model.

A 3D information model provides a more comprehensive understanding of the geology in an area of study than traditional drawings. All available material and information are embedded in the model and easily available. By clicking on the material the user can see any notes, make own cross-section, and etc. It will also be possible to add links to pictures, e.g. for core logging, ERT, Seismic etc.

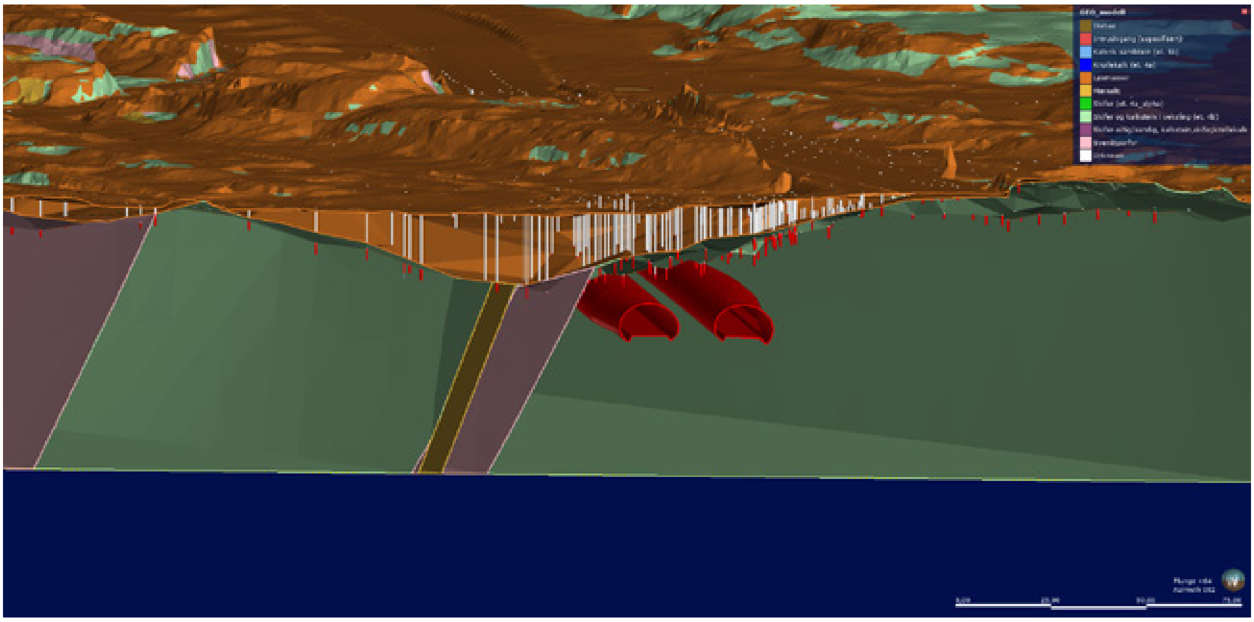


Figure 3.2.2: The model in Leapfrog Works showing drilling from terrain surface down to the rock surface. The white bars show boreholes in the soil and where the columns change color to red shows where it is drilled in rock.

3.2.2. Structure of the geological rock model

The geological 3D model is based on the same information, geophysical methods, soil surveys, field work and field observations as used for production of typical geological drawings. For the Høvik Tunnel, this includes base maps from NGU, field work, previous field work, data from other projects (the Holtekil Tunnel, Bane NOR etc.) etc. The interpreted geology of the Høvik Tunnel is given in Figure 3.2.3.

Strike and dip measurements are digitalized with GPS location. These measurements are included in the model to get a better understanding over the direction of the different lithological layers, dikes, rock boundaries, folds and faults in 3D. This information gives a better interpretation of the orientation of the different layers of rock and faults/folds. The stereographic projections are planned to be imported into the model.

With use of raw data from soil to bedrock drillings, the bedrock surface has been interpreted and modelled in 3D. Depth to rock surface, soil thickness and distance from the rock surface to the tunnel

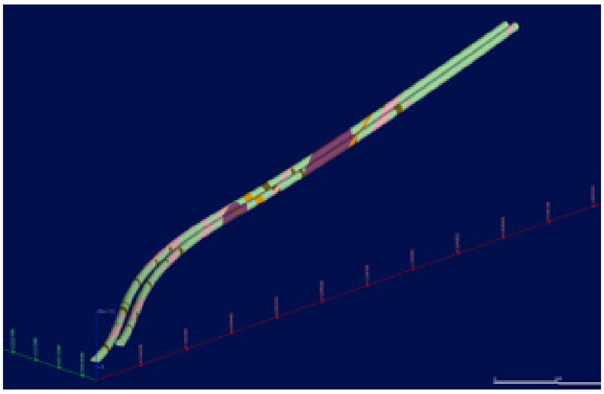


Figure 3.2.3: The Høvik Tunnel with the interpreted geology. Different geological dikes are given in red, yellow and brown. Different sedimentary rocks (shale, nodular limestone) are given in green and violet.

can be easily given from the model (Figure 3.2.2). This gives the impression and possibility to easily measure the interpreted soil thickness along the tunnel. Location of houses together with depth to rock surface model, well data and tunnel geometry, will give good indications of interpreted vibrations, possible settlements of buildings and problems with wells during the tunnel construction.

Geophysical field observations are included in the model as PDF-files with georeferencing. This makes is easier to interpret the fault- and weakness zones with another field observations, for example core drillings, and look at them together in a 3D perspective to make the best interpretation (Figure 3.2.4).

The following information is modelled for th Høvik Tunnel:

- Geological map from NGU
- New geological mapping
- Lithology, strike and dip, faults and folds observations from field work
- Interpretations
- Laser scanning (bedrock, houses, existing tunnels etc.)
- Drillings soil depths
- Bedrock surface model
- Rock surveys
- Faults and fracture zones
- Rock mass quality
- Geophysical surveys
- Core drilling
- Well data based on map data from NGU's GRANADA database

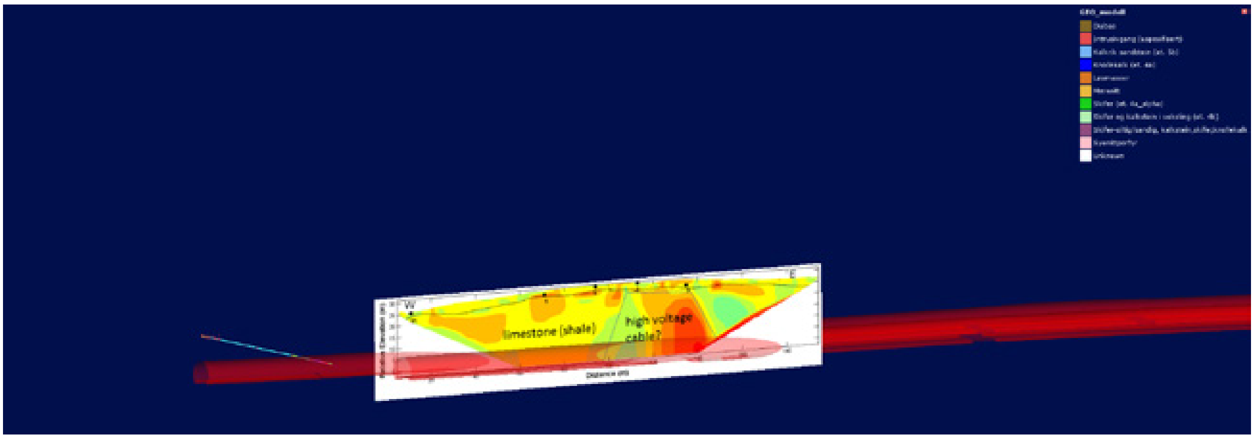


Figure 3.2.4: Core drilling, tunnel and ERT included in the model

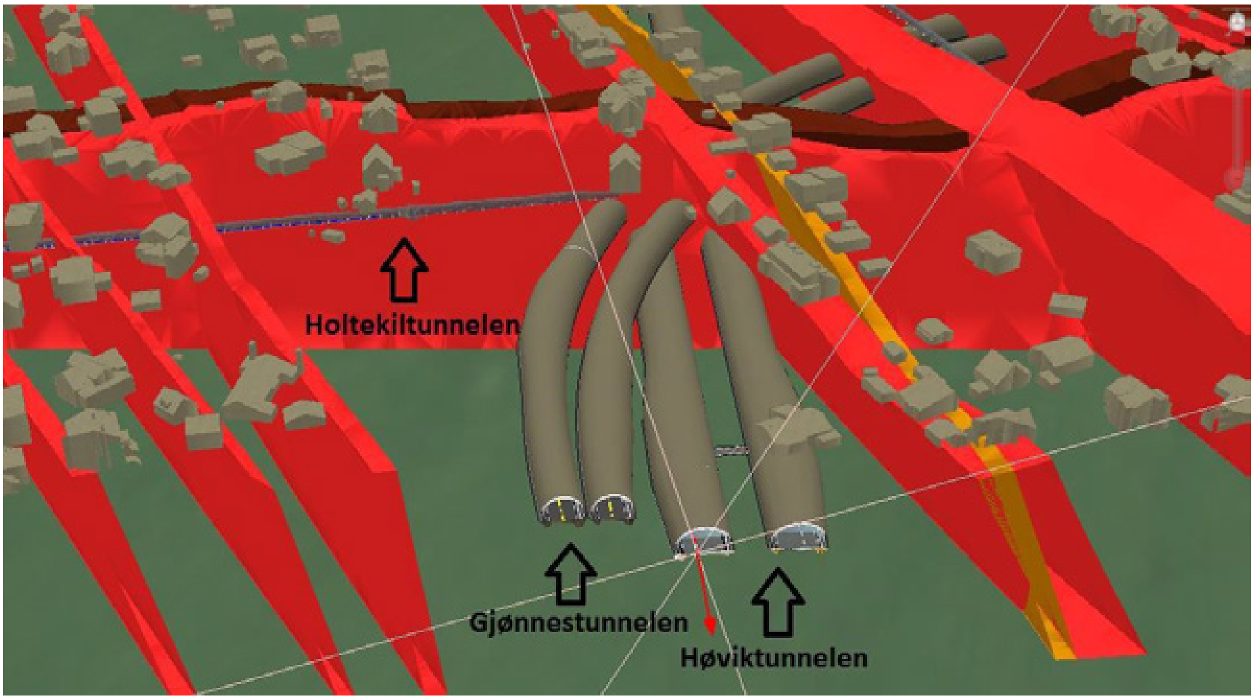


Figure 3.2.5: Geological rock model in the Novapoint Quadri. The figure show crossing of three tunnels; the Gjønnes Tunnel, the Høvik Tunnel and the Holtekil Tunnel (existing tunnel). Buildings are displayed in gray and different geological dikes in red, yellow and brown. The layer depth of soil and bedrock shale is turned off to see the tunnel crossing better.

3.2.3. Drawings

It is possible to extract drawings, with desired scale, in form of geological maps and cross-sections from the model. The model is dynamic and can relatively easily be updated with new information. Changes made to the model will be automatically reflected in drawings, which may easily be reprinted.

At the same time, it will be possible for the users to extract other products from the model, like drawings, videos etc. Users without a separate license for the program may use a separate interactive web-solution.

The project attends to produce drawings and geological maps from the model, and not make a model from drawings and geological maps. In addition, the project's Geological Report will refer to the model, and not several drawings. From the model, users can take out the drawings they require with the scale or scales that are most appropriate.

However, there are still need for some separate drawings, such as drafts for ribs of sprayed concrete, rock bolting and shotcrete, as well as drawings of tunnel entrances. As these are currently not covered by the modelling software in use.

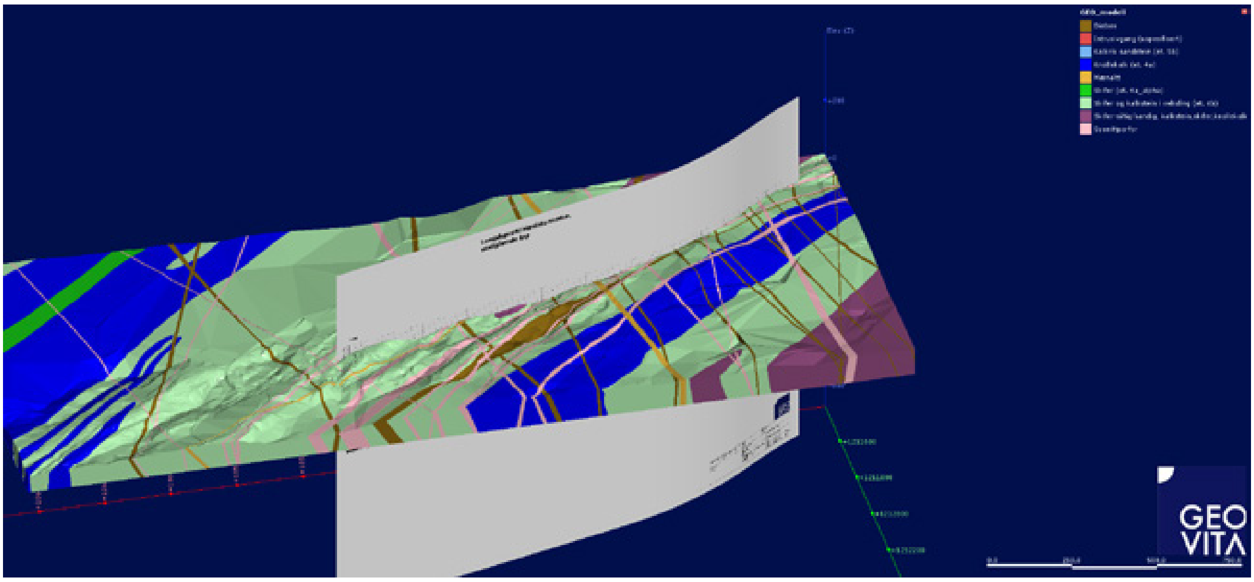


Figure 3.2.6: Length profile drawing exported from model.

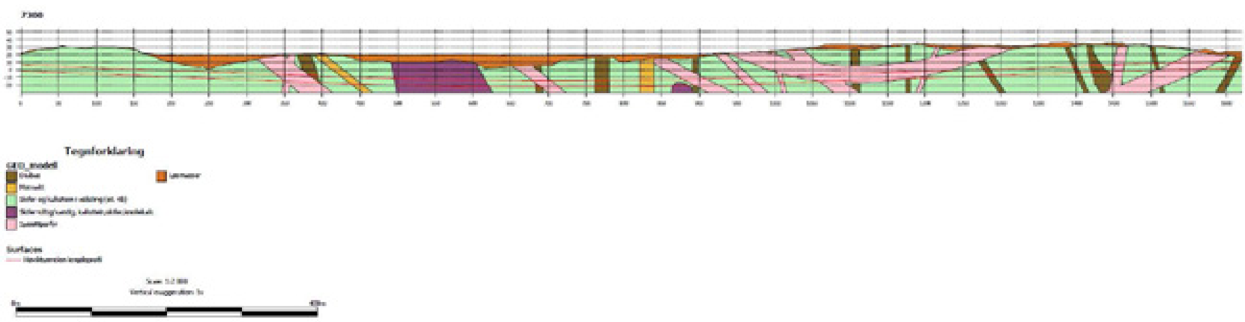


Figure 3.2.7: Length profile drawing exported from model.

3.2.4. Review

The geological rock model for the Høvik Tunnel (see Figure 3.2.8) is built on the same information as the geological drawings and presented with the same level of detail as in the drawings. The possibility to see an area with surroundings in 3D provides a new visual dimension with a more holistic impression of the geology.

A 3D geological model can give a better overview during both the design and construction phase of the tunnels and give a better interpretation and understanding of what to expect of the geology. In the model you can zoom into a problem or difficult geological area, rotate and take cross-sections easily. Layers can also be turned on and off in the model to get a better view.

Geological field work and surveys is the key for a good structure of the rock model. The more field work and surveys that are executed the better and more precise geological rock model you get.

In a geological rock model, as for the Høvik Tunnel, all information is included in one model, instead of several drawings and documents. This makes it easier to see the relationship between the tunnel and its environment. It also makes it easier to keep track of several years of research.

This is important for a complex project as E18 Western Corridor.

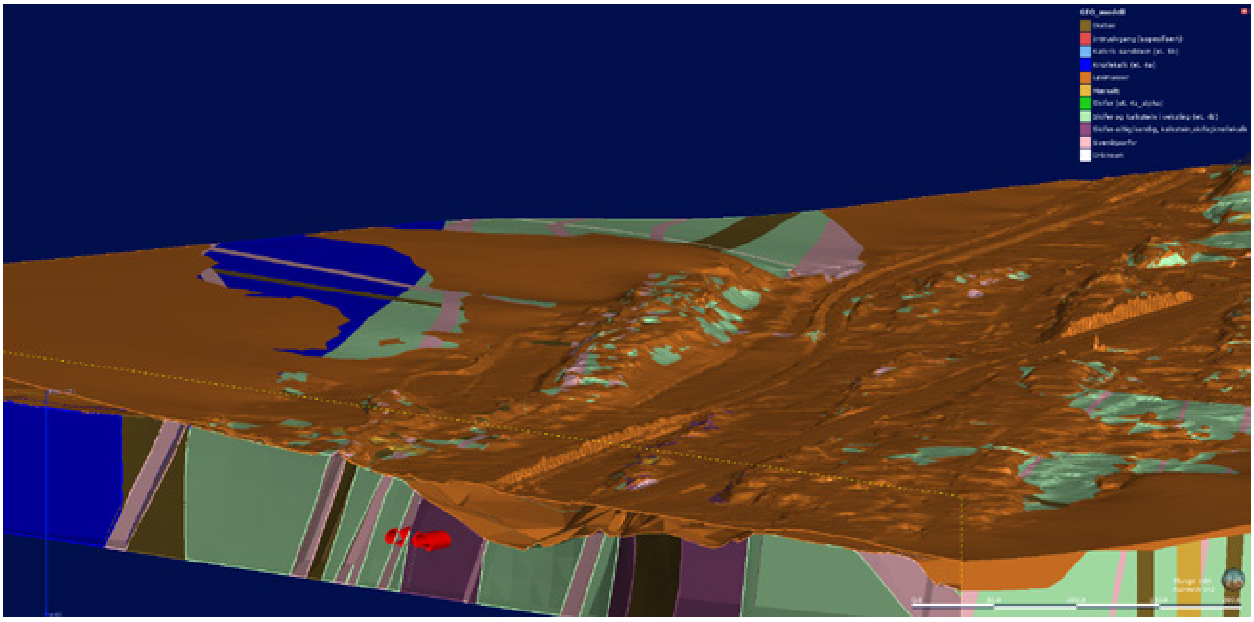


Figure 3.2.8: Geological model of the Høvik Tunnel. The Høvik Tunnel is given in red.

CONSTRUCTION PHASE

3.3. The Follo Line Project

Authors:

- *Marcus Lawton, Bane NOR*
- *Joakim Navestad Hansen, Bane NOR*

The Follo Line Project is one of the major railway projects ongoing in Norway. It is administered by Bane NOR and is due to open in 2021. It consists of 22 km of new railway, where 20 km will be underground. The tracks are being built in two separate tunnels, making a total excavation length of more than 40 km. The tunnel is mainly being excavated by double shield TBMs, with some smaller sections and audit tunnels excavated by drill and blast or drill and split (Figure 3.3.1). The Follo Line is part of a larger upgrade of the rail network in eastern Norway.

The project is divided into several different EPC contracts, with requirements for 3D-model delivers. The model was aimed to be an integrated part of the design and construction process. The purposes for the model are listed below:

- Display of information about existing facilities, terrain, geology and surface layers.
- Communication of proposed and selected design
- Basis for interdisciplinary control/check
- Verification of visibility from train to railway signals
- Verification of solution for security, emergency response and evacuation
- Ensure coordination across disciplines and contracts
- Basis for deviation control/check
- As-built documentation

3.3.1. Engineering models

The history of using models at the Follo Line Project starts many years before the start of the construction phase. The main purpose of using models, in addition to the mentioned points on the previous page, is to have an overview of what is included in the project. From an early stage, the model has been actively used for such purpose, where all the mentioned bullet points in some extension have been implemented in the work (with varying degree and detail).

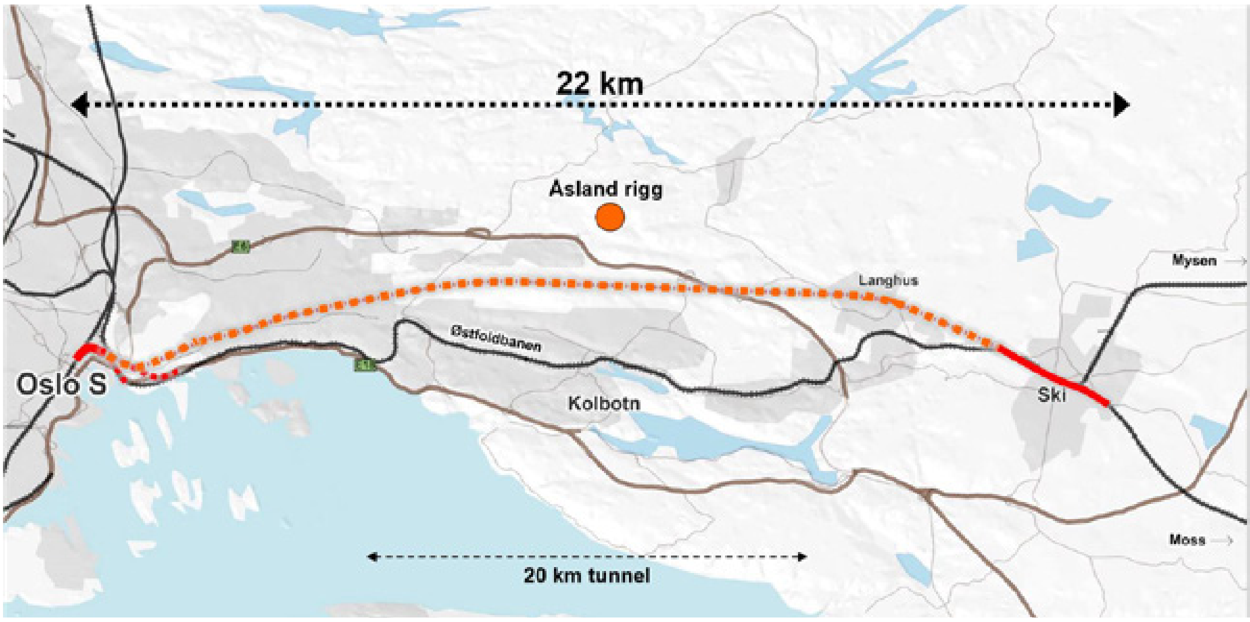


Figure 3.3.1: Excavation methods. The red and orange line displays the Follo Line. The red, solid lines illustrate the parts excavated by blasting and splitting, while the orange dotted line shows the part that will be excavated by TBMs. Notice the orange dot, illustrating where the main rig area is located.

The purpose of using models on the project was to use them to follow up the construction phases of each sub-project, link the models with other software packages and/or database systems, perform collision controls, coordinate the interfaces of the different phases and to coordinate between the stakeholders to compare the design of the different systems along the sub-projects. Later, after the completion of the construction steps, the models will be used for maintenance of the operation and maintenance division.

Models used in the tender documents was different to models that was supplied by the contractors. The original models consisted of discipline models for each subject area and 3 different assembled models (discipline model, coordination model and basic model). The degree of detail of the models varied since it was of different designs and railway engineering areas. The discipline model was certainly used most for clash control. Most of the 3D model is developed based on 2D drawings, but some tricky elements like the collar from the TBM tunnels into the CPs or the cableways from the manhole in front of the CPs into the various technical room inside the CPs were developed in 3D. The deliveries have further been divided into two different types of models; a discipline model and a coordination model (Table 3.3.1):

Discipline model	Coordination model
• Designed situation • Divided into disciplines • Updated to as-build by end of project	• Consists of all configured data collected. • Includes geological data, estimated geological conditions, as well as data collected during the construction.

Table 3.3.1: Discipline model and coordination model.

The coordination model consists mainly of geometry giving a good visualization of what is to be constructed. Some objects also contain information like tag numbers.

The use of 3D has changed a lot during the project, since the Contractor almost started from zero, but came quite far with the 3D development. The Contractor, Acciona Ghella Joint Venture (AGJV), uses 3D a lot at the Follo Line Project. Drawings are made from the 3D model, tunnel profiles are scanned, and the actual construction are later compared with the model. Some objects like rock bolts and lining segments are implemented in the model after being built, but with a large time lag and with no systematic way of including information in attributes.

3.3.2. Construction model (during excavation)

There has been a special focus on visualization of ground investigations and data collected during excavation for the project. As the tunnel is mainly being bored with double shield TBMs the possibilities for traditional geological mapping is limited. To get a best possible basis to compare predicted ground conditions to the actual, there has been an extended use of different technologies to collect geological- and machine related information, shown in table Table 3.3.2.

Method	Documentation	Description
Face mapping TBM	Visual inspection	Written report documenting rock type, fracturing, water ingress, overbreaks etc. Mapped daily.
	Photogrammetry	Supplement to the visual inspection. Generates a 3D image of the tunnel face, with the possibility to measure fracture planes
	Photos	Photographic records of each face mapping
	"Chip analysis"	When the TBM is in production, chips are collected and analysed
Probe drilling	MWD	Visualization of rock strength, fracturing & water ingress with data from probe drilling rigs.
	Optical televiewer (OTV)	Photographic record of probe hole, including deviation measurement
	Water measurements	Manual measurement of water seepage through probe holes.
Core drilling	Core logging report	Visual inspection
	Photos	Photographic record of core
	Laboratory tests	Testing of DRI, CLI and mineral content
Machine data	Data logs	TBM penetration rate, thrust force, rotation speed etc.

Table 3.3.2: Methods used to collect geological- and machine related information during construction.

All these investigations create huge amounts of data. To put it in perspective, more than 36 km of OTV images have been produced, approximately 2000 face mappings have been performed and water measurements exists for more than 8000 probe drillings. Every data input includes some information about the geological conditions, but getting the complete overview is a challenging task. In addition, there has been an extensive program of pre-investigations prior to excavation, making the "geological database" even more comprehensive. Consequently, the site geologists started to look into methods for digitalising the data and bringing as much as possible into the same model. Most of the data collected at underground projects will be georeferenced, either by real world coordinates or by positions along an alignment. This has been the basis for organizing data at the Follo Line Project.

3.3.3. Methods and resulting model

<u>Face mapping by visual inspection</u>

The purpose of performing face mapping is to gather general geological information and to get input to assess the fracture factor ks-tot. Mapping is normally performed once daily during the maintenance shift in the morning. Depending on the excavation rate there is 15-20 tunnel metres in average between each face mapping. Geological mapping of the face normally consists of the following parameters:

- Observations of rock types
- Presence of hard and abrasive minerals like quarts or garnet
- Signs of weathering
- No. of fracture set and fracture spacing, fracture plane roughness, infilling or aperture.
- If present, which fractures or weakness planes contribute to fall-out or overbreak
- Water seepage from the face
- Photos

The fractures are often challenging to map correctly through a cutterhead inspection, due to narrow workspace and relatively poor light conditions. In addition to the limited view through the cutterhead, there are only two dimensions visible at the tunnel face, which in combination with a non-functioning compass (reacting with the TBMs metals) makes it difficult to map the fractures accurately [2].

With this in mind, it was challenging to include the mappings into a model. There are solutions for digitalising face mappings sheets, and software like TUgis was looked into. With the lack of accuracy in the face mappings, a detailed modelling seemed unnecessary. A simpler approach was therefore chosen. By modelling a disk along the alignment for each mapping and enriching it with attributes from the mapping, different parameters could be visualised together with other investigations. Figure 3.3.3 show face mappings where RQD values have been coloured from high (green) to low (red). Weakness zones from the pre-investigations are modelled as brown planes. This gives a visual feedback by showing where zones intersect, compared to the predictions.

Figure 3.3.2: Geological mapping in front of cutter-head.

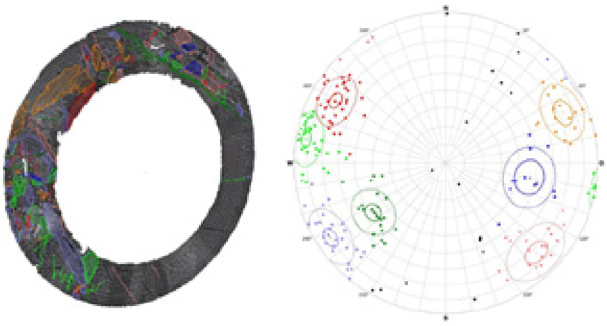


Figure 3.3.4: Interactive and semi-automatic tools for rock mass characterisation. 3GSM

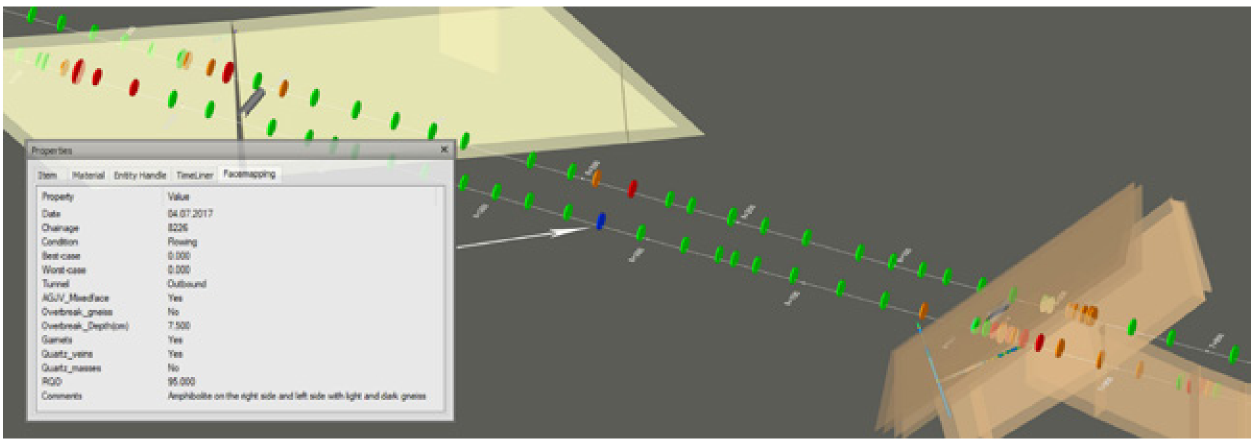


Figure 3.3.3: Face mappings displaying RQD values by colour.

The Follo Line Project have used a solution by 3GSM to create 3D imagery of the tunnel face. Photographing of the face in 3D is performed by installing an autonomous imaging unit at one of the inspection openings during maintenance shift. When the cutter head is turned, a circular video is captured. Advanced software generates scaled and oriented 3D images from measurements taken (3GSM) [3]. The result is a permanent documentation of rock mass conditions. From the 3D images it is possible to identify and measure the overbreaks and perform geological mapping, see Figure 3.3.4. The generated surface is also exportable to dxf or as a point cloud making it easy to include in a geological model.

Probe drilling

Probe drilling is performed to obtain information ahead of the TBM on geological conditions, especially weakness zones and water seepage. Probe drilling is, depending on the TBM progress, performed daily. There are 38 openings around the shield dedicated for probe and grout holes. The TBM's are equipped with two percussion drill machines for probe and grout holes drilling. The probe holes are normally drilled to around 40 m length in rock (Figure 3.3.5).

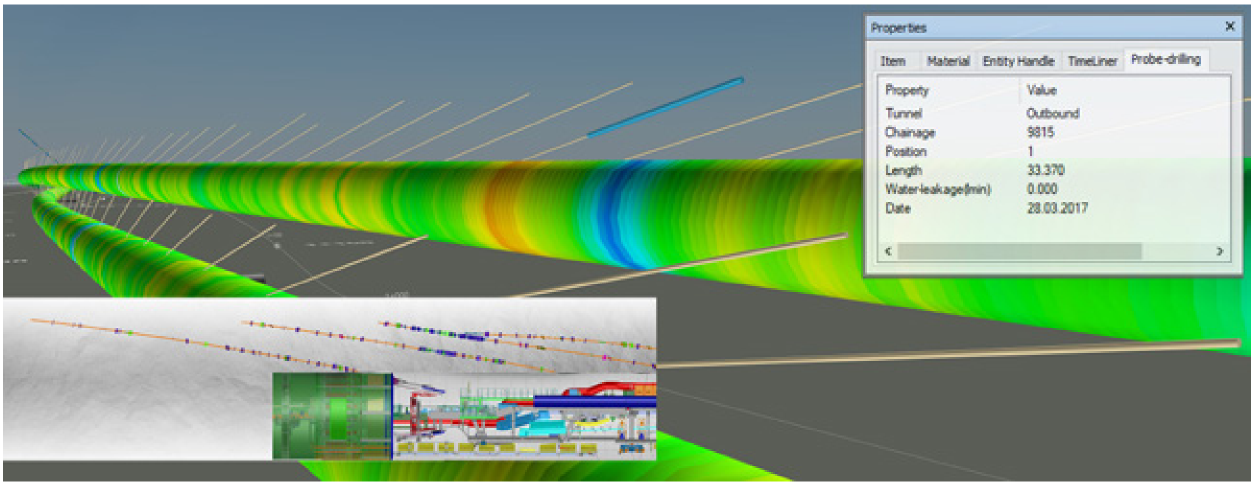


Figure 3.3.5: Model of probe drilling.

MWD is collected during drilling making it possible to detect variations in rock hardness and to discover weakness zones [3]. Although MWD can be a useful tool, the lack of compatibility with other software has been an issue. As the data is only accessible in a separate software, it is easily forgotten and hard to compare to other data. For the geological model, probe drillings have therefore been visualised as cylinders at the location of drilling. Water leakage measurements in the boreholes have been modelled as cylinders, where the radius of the cylinder indicates leakage value.

Optical televiewing

Televiewing has been done in one probe hole approximately every 20 metres, to create an overlapping series of images. The instrument for televiewing has compass and gyro to keep track of borehole orientation, Figure 3.3.6. To get a good picture the hole should be dry and therefore directed upwards. The televiewing picture has high resolution and gives good information of rock types/lithology along the hole.

Figure 3.3.6: Optical televiewer.

Open fractures are usually easy to detect, while closed fractures or fractures with small aperture can be difficult to observe in the picture. Sometimes a line of brownish colour from weathering can reveal the presence of a fracture that is otherwise undetectable in the picture. Also fractures in dark rock like amphibolites can be difficult to spot.

Fractures and weakness planes that are believed to contribute to the rock breaking process under TBM boring are marked on the picture with the software wellcad. With the same software it is then possible to decide strike and dip of these structures (Figure 3.3.7)

The logged OTVs have been modelled using output from wellcad, as well as deviation measurements. This called for creating a custom script to read the files and generate the geometry. Once the script was made, reading and importing huge amounts of data into the model became an easy task. The models are all built up by geometry and attribute data. By doing this the model also acts as a database, where fracture data or lithology statistics can be exported for selected sections of tunnel. As an example, this is a useful feature to create fracture pole plots for selected areas.

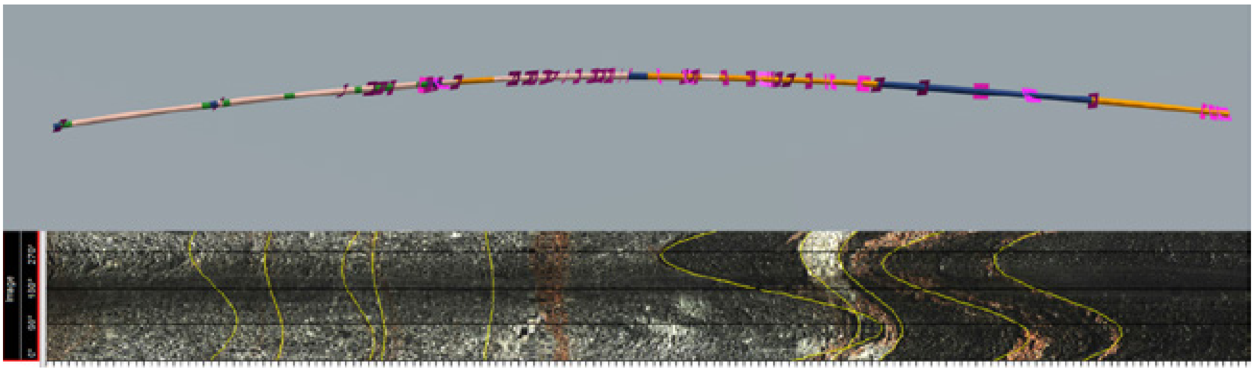


Figure 3.3.7: Picture from optical televiewing performed in probe hole.

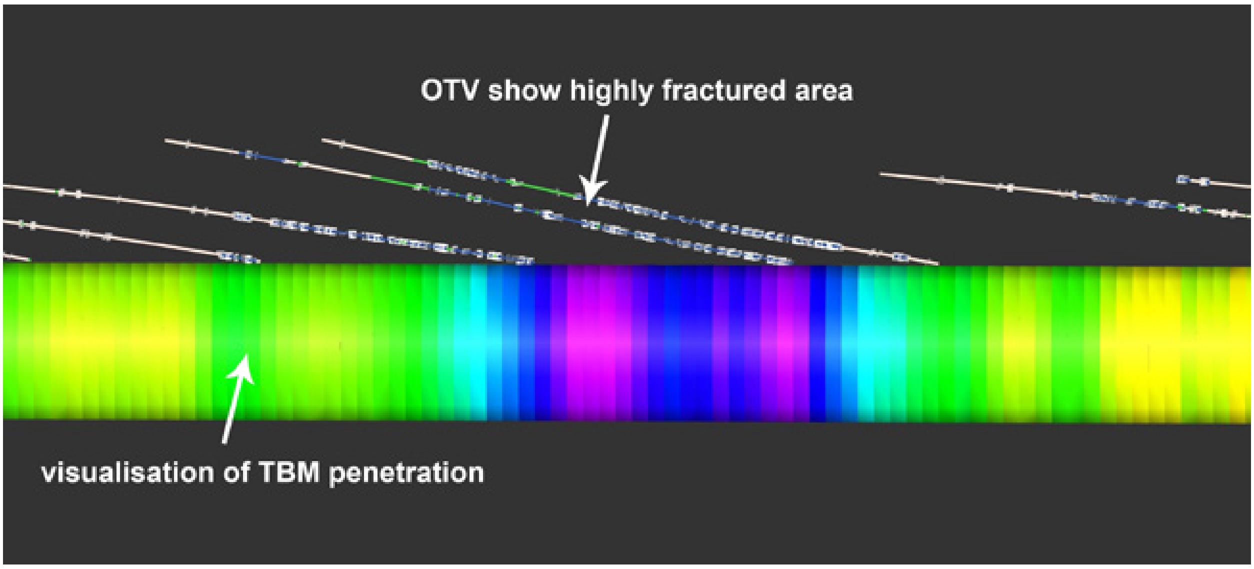


Figure 3.3.8: Model of OTV when crossing a weakness zone.

Core drilling
Core drilling is performed at the front of the TBM's on a regular basis to get rock material for laboratory testing (4 m core) and cores for geological logging (2 m cores), see Figure 3.3.9. Although modelling of core drillings from the tunnel can be done the same way as core drillings in the pre-investigations, digitalisation of the data has proven to be a time consuming job. As data from core drillings traditionally have been delivered as pdf reports, large amounts of manual labour in needed in the digitalisation process, and therefore not a focus area of this project.

Core drillings from the pre-investigations have been modelled. Parameters like RQD, lithology, lugeon measurements and fracture infill have all been added to different layers. This makes it possible to customize the model depending on the data of interest. The example in figure 3.3.9 shows how the RQD value vary when entering a weakness zone.

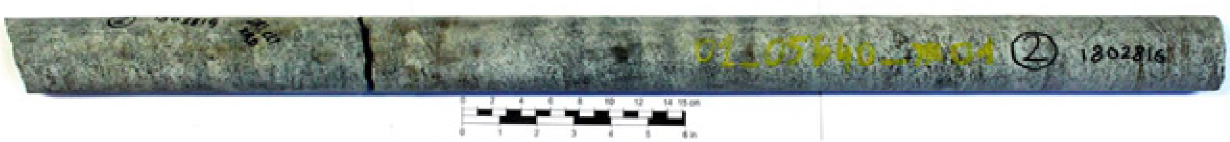


Figure 3.3.9: Core drilling from TBM. Typically 2 m.

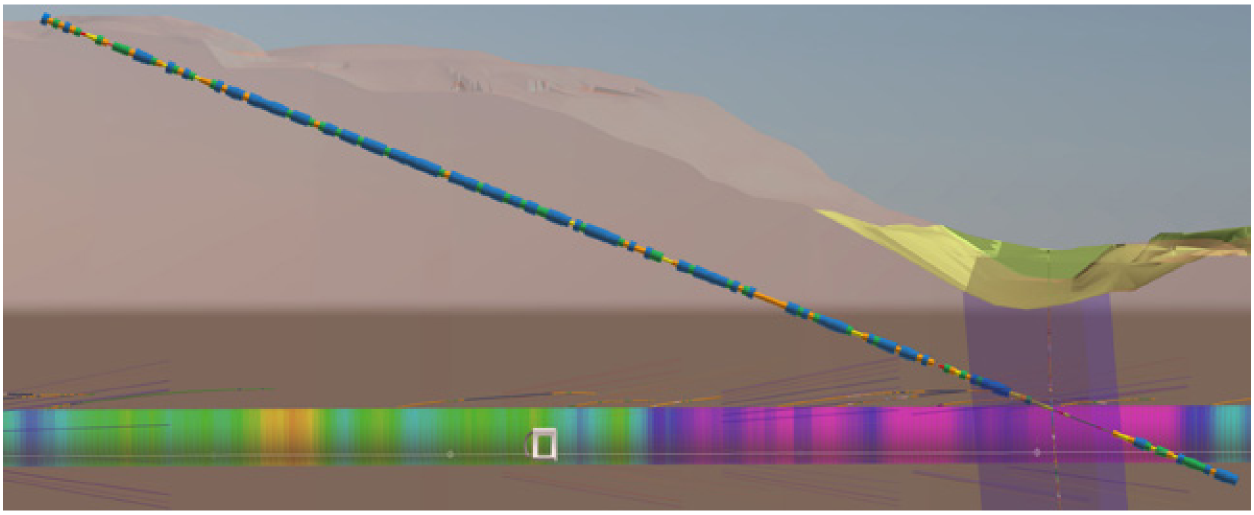


Figure 3.3.10: Model of core drilling, where cylinder radius and colour indicate value. Core drilling is here seen together with TBM progress model and probe drillings.

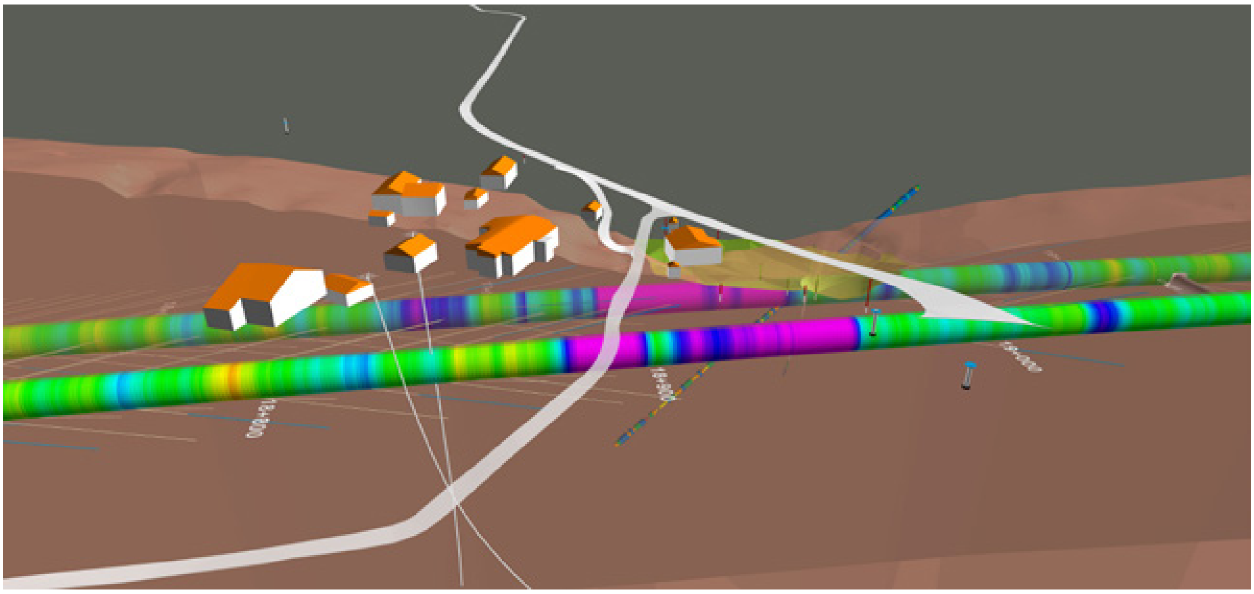


Figure 3.3.11: The Follo Line geological model.

3.3.4. Conclusion

As explained, the Follo Line Project has in certain areas of modelling achieved good results, however somewhat fragmented. The project design has been modelled to a high detail level, but there has been no real strategy on how to use this in production. Objects are built to drawings and there is a lack of input from construction to the model. As a result, the model becomes a tool for design, and not an active aid during construction as it could be. This being said, useful results have been achieved with production data. Large amounts of the collected geological data have been implemented in the model, although mostly by the persons using the data.

This can be attributed to the missing overall concept at the project start. The contracts contain a specification for 3D, which is at a rather low level. Working in BIM as such is not required, only a general 3D model and an engineering database need to be developed. Almost all the design is done is 2D and the 3D model is based on these drawings.

In order to improve this for future projects the following recommendations may be made:

- Establish in an early project phase a BIM Manager.
- Establish in an early project phase a general BIM strategy.
- Establish in an early project phase a project information system.
- Establish in an early project phase the way of information exchange.
- Establish in an early project phase unique ID codes (tags) for certain objects, which are refined with the project progress.
- Establish a strict policy for the use of these tags in the various software tools (design, schedule/planning, cost calculation).

Most important for a successful use of BIM is a close collaboration between all project members. The BIM shall be used as an integrated tool and bring people together. In order to reach this, the process needs to be explained properly to the various stakeholders [1].

3.3.5. Future work

The use of BIM in the Follo Line Project (and other projects) can be further improved. Some ideas of how to expand the use and what we would like to achieve are presented as examples below:

- Use the 3D model for evacuation simulation and training for train personnel and rescue forces like fire fighters etc.
- Connect the 3D model with completion management.
- Use the 3D model for progress monitoring (optimized for infrastructure projects)

References

[1] Gollegger, J. & Sànchez Moreno, A. (2017). *State of the art design, construction and documentation methods in infrastructure projects.* Proceedings of the World Tunnel Congress 2017 – Surface challenges – Underground solutions. Bergen, Norway.

[2] Hansen, J. N. (2018). *Comparison of existing performance prediction models for hard rock tunnel boring based on data collected at the Follo Line Project* (Master's thesis, NTNU). Available at: http://hdl.handle.net/11250/2503069

[3] Syversen, F. S. G., Grasbakken, E. & Gammelsæter, B. (2017). *Geological monitoring of Follo Line TBM project in Norway*. Proceedings of the World Tunnel Congress 2017 – Surface challenges – Underground solutions. Bergen, Norway.

3.4. E6 Arnkvern – Moelv

Author:

- *Simen Thorsen, Veidekke*

E6 Arnkvern-Moelv is a four-lane highway project by Nye Veier and is part of the new E6 between Kolomoen and Moelv which will open in 2020. The road between Arnkvern and Moelv is 24 km long and passing through one road tunnel. The appointed designer is Sweco and the appointed contractor is Veidekke.

The project is model-based. Sweco has created an integrated model using their own developed program based on Forge and Autodesk called SMaRT-Sweco Model Review Tool, seen in Figure 3.4.1. This model is web based and accessible for everyone involved in the project.

Both DWG and IFC files are used in the model, the IFC files contain metadata and attributes. To read the various files different programs are used. In the model each file is given an object code and maturity index, MMI, which indicates if an object is under development or ready for construction. The objects are also labelled with a code associated with NPRA standards which is linked to a bill of quantity system. Dropbox is used to share and distribute files on the projects. There are 18 different models in use on the project.

Several benefits with the integrated review model are listed by the contractor. It is easier to get an overview of what the models consist of and read the different attributes. All technical approvals are done using the model, which is highlighted as a great advantage. This is done by delivering the required files as a package on Eroom (online file-sharing platform). Solibri is then used by the client to check the model. A drawback with 3D models, mentioned by the contractor, is that not all objects are presented with enough detail. However, a feature in Solibri allows the user to access the required information by clicking the signs/links in the model. The user is then directly guided to the appropriate files. The Solibri model can be accessed by the construction workers and used for construction of for example bridges and concrete elements directly.

However, the above-mentioned models are not sufficient for construction of the road and tunnel. The tunnel displayed in the viewing model is a DWG export from the software Gemini Terrain and is only used to visualize the tunnel geometry, as IFC files only models closed solids, not line models which is required for constructing the tunnel. It is empha-

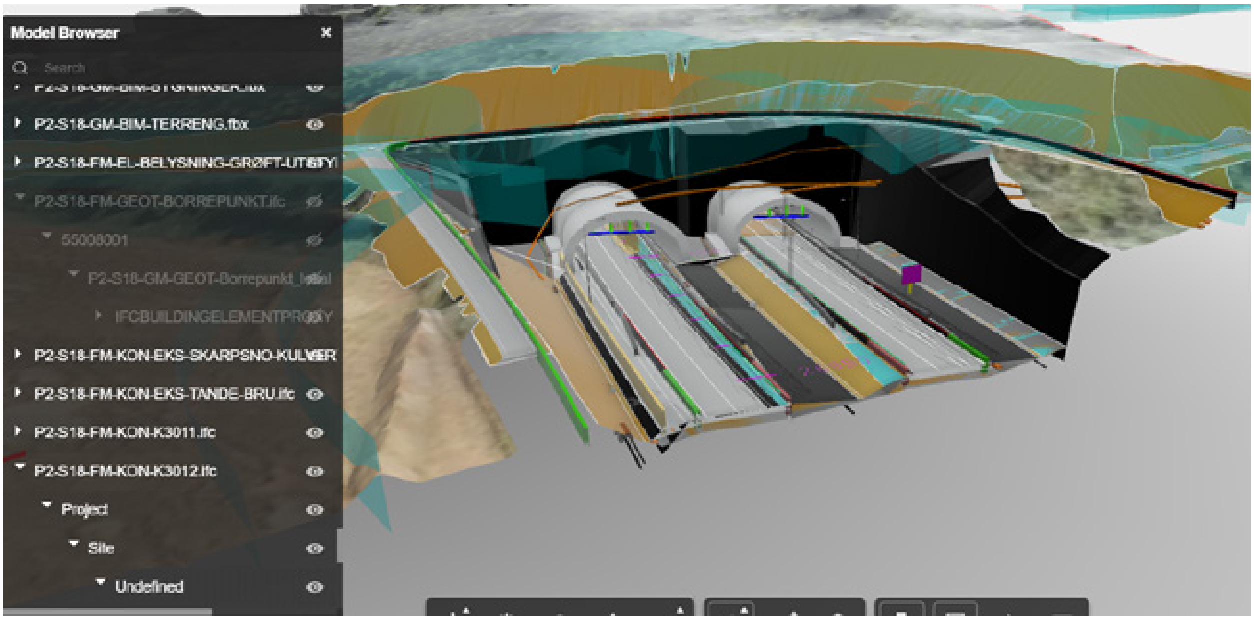


Figure 3.4.1: SMaRT model created by Sweco. Showing object and code associated with NPRA standards.

sised that the Navisworks model cannot replace VIPS and line models. The DWG import from Gemini is used to check that the model used in the drilling jumbo is correct. Novapoint is used to check that the requirements for line of sight are met. This is visualised in the web model.

A VIPS file, line model created by Sweco is therefore used by the contractor to create the required data for construction of the tunnel. The VIPS file is imported to Gemini Terrain where a 3D model of the road and tunnel cross section is generated. The Gemini terrain model is more advanced compared to the SMaRT model as it is showing both the elevation and the cross section of the tunnel geometry. This generated model is further exported as a land XML file which is imported to the computer-based guidance system used by the drilling jumbo.

Gemini Terrain can also be used to integrate other 3D models and show other elements in the project by importing DWG files. For example, concrete elements and drainage pipes are also displayed in the model as well as a 2D geological surface map from NGU.

Probe drilling

The contractor used Gemini to model and visualise the result from probe drillings, done as part of the site investigations to map presence of alum shale. This is the first time this is done one a project. The advantage of importing the measurements in Gemini is that the drillings are directly geo referenced containing all metadata such that they are displayed

Figure 3.4.2: Gemini model showing 3D model as well as data from scans with draped orthophoto.

correct according to the tunnel alignment. This can further be used to interpret the geology between the drillings. The results from the probe drillings are directly imported from spreadsheets, by specifying rules for the import in Gemini. This allows Gemini to interpret the data as points as well as read the metadata. The measurements are then visualised using the metadata, such that it easily can be observed where the level of uranium and radiation are exceeding the allowable limits. This can for example be used to evaluate if the overbreak from the tunnel excavation need to be deposited on a special landfill. The model can be seen in Figure 3.4.3.

The importance of having a software which is used for construction, that allows for integration of both the 3D geometry of the tunnel as well as geological 3D model is emphasised by the contractor. As it is

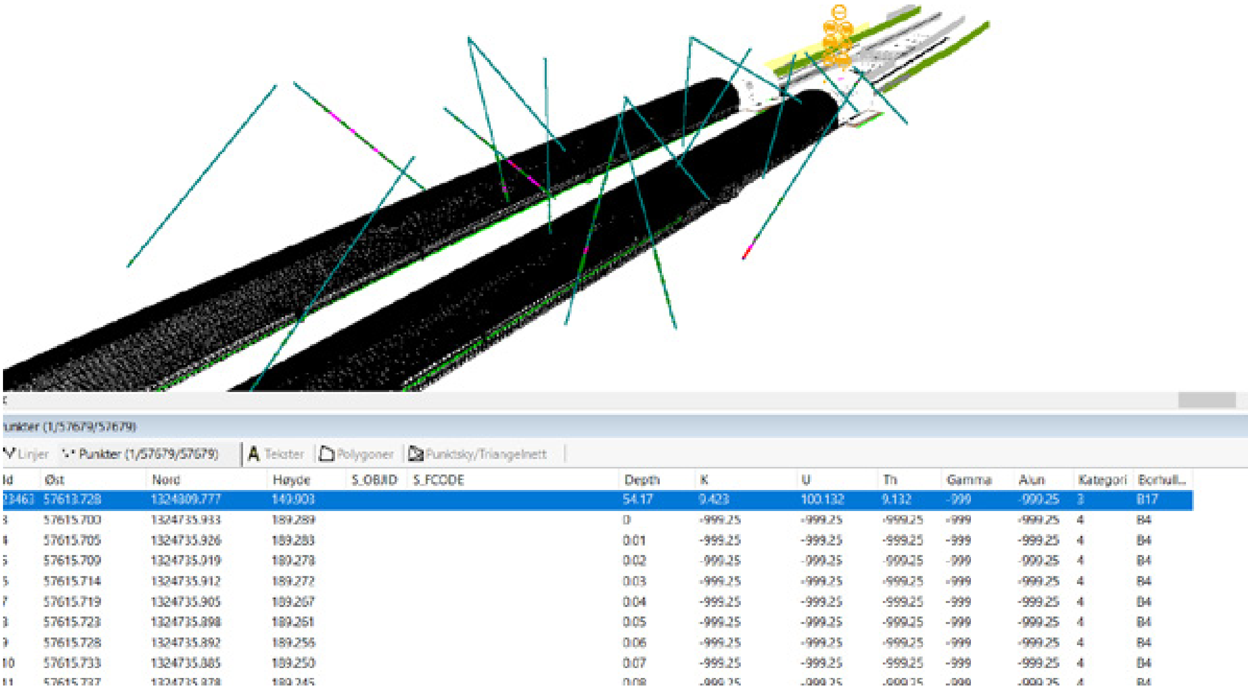


Figure 3.4.3: Gemini Terrain model displaying results from the probe drillings.

only when the two are combined, they are useful in the construction phase. The possibility of combining MWD data and a 3D model of the geology along with the tunnel alignment is mentioned as advantage by the contractor as it can be used to verify the findings/interpretations of the geology from the site investigations, however this is not done on the project.

FINALIZED PROJECTS

3.5. Vamma 12 Hydropower Project

Author:
- *Øyvind Engelstad, SN Power*

For the large hydropower project Vamma 12 under development by Hafslund Produksjon AS, Norconsult AS took the initiative to challenge contractors to perform construction directly based on BIM without delivery of 2D drawings.

Before the completion of the tender documents for construction works and supply of electromechanical equipment and hydraulic steel works, Norconsult and the project owners were in dialogue with all prequalified contractors to anchor the approach and identify needs in relation to construction based on BIM. After evaluation and contract negotiations AF Anlegg AS was chosen as the contractor for Vamma 12 HPP. In addition to price, expertise and approach to construction, the contractor was also evaluated on their attitude and approach to the utilization of BIM in the construction process. In addition to the civil works contract, a number of other contracts for the supply of electromechanical equipment and hydraulic steel works, HVAC, low voltage installations etc. were negotiated. These supplies are performed as turnkey contracts (EPC) and are therefore separately responsible for providing their design directly into a joint Coordination Model (BIM).

The approach was thoroughly founded in the contract by inclusion of specific clauses as additions and deviations to the contract standards (NS8405 for civil works and KOLEMO for other supplies). Rather than establishing rigid instructions for cooperation in BIM, a joint BIM strategy was established. Signed by all parties, cooperation, flexibility, and joint development of "best practices" are key elements. As the approach with utilizing BIM as the direct basis for construction was new to all parties, focus on flexibility and common goals was believed to be essential for success. This has also proven to be the correct approach. The intension of the BIM approach was to bring the parties closer together and secure that all participants have a common understanding of the totality and potential points of conflict as early as possible. The risk is greatly reduced as conflicts are resolved early instead of appearing as surprises during construction. Through a process of cooperation and common learning, workflows are adjusted to optimize and ensure good processes and structured access to critical information. Such a process will obviously never run without challenges but based on the strategy for BIM and focus on cooperation and common development, all parties help improve the process.

3.5.1. Virtual Design and Construction (VDC)

The utilization of BIM in conjunction with engineering and construction is as much about process and communications as it is technology. Virtual Design and Construction - VDC, has become the abbreviation for this approach. BIM is central to the process, and as Professor Martin Fischer of Stanford University said during a seminar in Stavanger in the fall of 2016; "BIM is the best tool I have found to secure that everyone is working on the same project". The phrase describes the fact that if the multidiscipline BIM (coordination model), is kept updated and shared openly in the project, one will secure that everyone can observe the evolution of the design of each discipline in concurrence with the other disciplines, enabling interdependent concurrent engineering to take place in an orderly and coordinated manner.

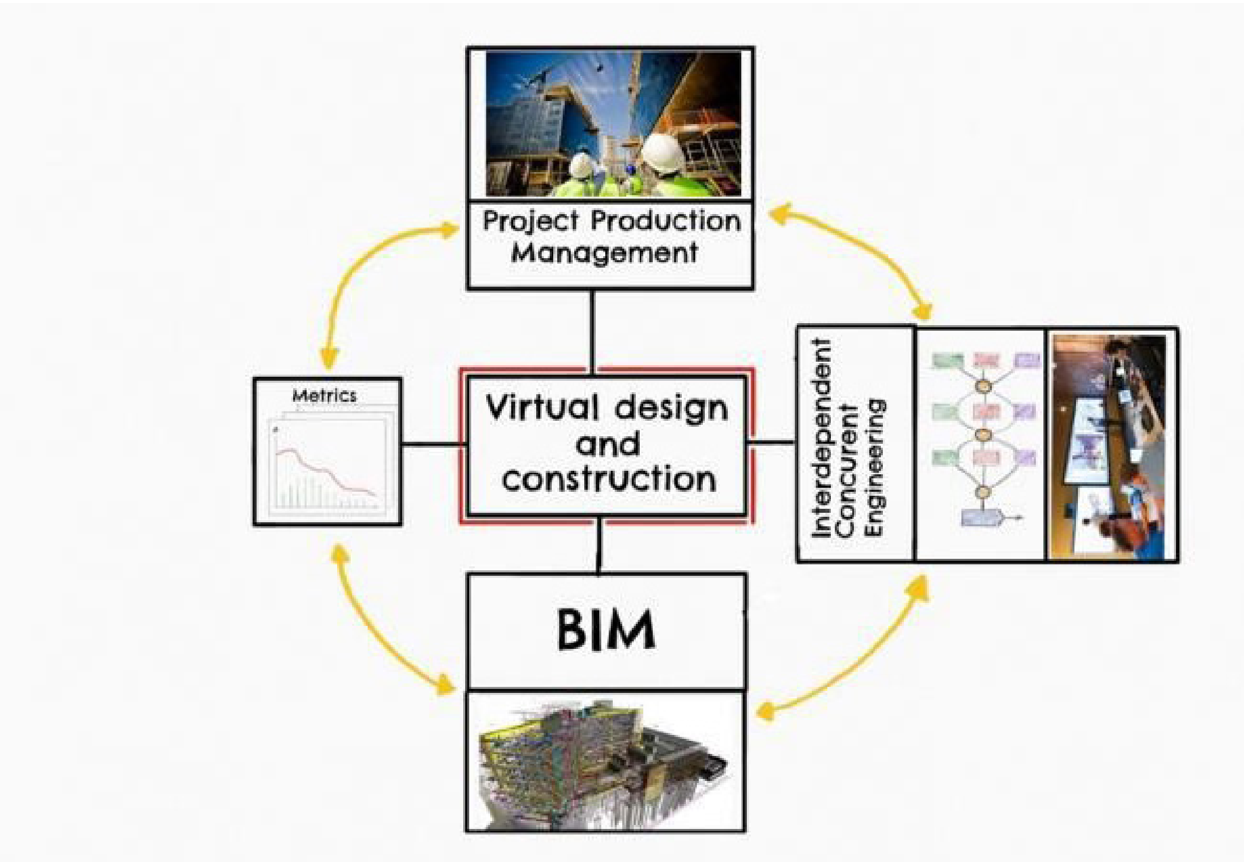


Figure 3.5.1: The elements of VDC.

This contrasts with the traditional approach where each discipline, is working separated from each other. In many projects this has led to a notion that conflicts are detected too late in the design process or in many cases during construction. The traditional approach entails lengthy processes with large amounts of requests for information (RFI) going back and forth between the parties to arrive at a fully coordinated design. The flexibility of making design changes also suffer in this process as such changes late in the process causes ripple effect into other disciplines that many times lead to extensive delays and cost overruns in the design process. In many cases the coordination has not been sufficient and end up with conflicts between different disciplines during construction. This again leads to extensive rework and bad quality of the final product. The rework cause delays and cost overruns.

VDC aim to reduce the conflict level and through “virtual construction” reveal and resolve challenges up front. The BIM is a good tool for planning and testing of constructability. When all disciplines are working into a joint coordination model, the design team can, through a structured process of Interdependent Concurrent Engineering (ICE) ensure that the interface coordination is handled continuously. To ensure an effective process, one can utilize so-called "big rooms" where all involved disciplines can meet in so called ICE-sessions and interact with BIM in the centre of the process.

The coordination model, typically shared in a cloud-based collaboration platform, secure that all parties have access to the latest versions of all discipline models merged into a joint BIM. During the ICE-sessions the BIM is always up on the screen and is utilized as the basis for discussions and clarifications. Involving the owner, designers, and contractors in the ICE-sessions secure clarification of issues and clear decision making. It brings the parties closer together to optimize the design from the point of view of operations, constructability, quality, cost, and schedule.

To be able to fully optimize time and cost, the BIM should be utilized directly as basis for construction (production at site). In this approach the contractor plan construction and harvest all necessary data (such as geometry and specifications) directly from the BIM.

3.5.2. Engineering

Norconsult utilizes a variety of tools in the design process. The concrete and steel structures are primarily modelled in Autodesk Revit, while the basis for the design done by the suppliers of electro-mechanical equipment and hydraulic steel works performed in a combination of Autodesk Inventor, MicroStation and SolidWorks. As the open format IFC is not yet adapted to these types of elements with special data requirements and complex geometry, other formats like .sat and .step are used to convert models into Revit. The coordination of all models take place in Navisworks, and it is this platform that forms the basis for communication with the contractors.

For terrain works and underground works, design in “Gemini Terreng og Entreprenør” from the Norwegian software supplier Powel is utilized. A benefit of this specific BIM tool is that it has integrated functionality specifically developed for integration with tools used by the contractor at site without a need for conversion of data. Many Norwegian contractors have chosen this tool as their BIM platform for production and thus have the required competence and experience to get full benefit out of it. The fact that Powel is a Norwegian supplier who knows the industry and is close to the process, has also been beneficial as they have contributed with continuous customization based on running demands from the projects.

A challenge when using BIM is that data is spread throughout the system (on many tabs), and it is thus difficult to separate out the data to be used as the basis for construction. To ensure that production critical information is quality assured and made readily available to the contractor, an add on to Navisworks called iConstruct was used to sort out and communicate quality-assured data for each item in the model. The contractor finds all this information available under a specific tab in Navisworks. The content of the tab varies between the different elements (formwork, reinforcement, concrete, steel work, HVAC etc.) and is based on a process involving the contractor, designer and owner.

The Norwegian standard NS3420 is used for setting up bill of quantities (BoQs) to form the contractual basis in unit price contracts. This standard has a coding system and regulates all requirements (material, process, quantity calculation rules etc.) either directly or through reference to other standards (national and international).

To secure a solid contractual connection in the BIM, Norconsult AS has developed an application to create a dynamic link between the different positions in the BoQ and the elements in the BIM.

As to ensure that the contractor is working on the correct basis, each element in the BIM is tagged with a “phase” index, and he is only “allowed” to proceed on elements tagged as “issued for construction”.

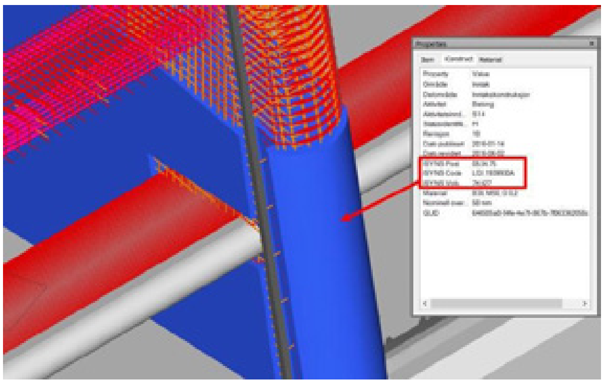


Figure 3.5.2: Information tagged directly on each element in the BIM, directly linked to the BoQ.

All reinforcement engineered in 3D in the BIM. Each rebar is thus visible to the contractor in the correct position and is tagged with position code, shape code, dimensions, centre distance and specific instructions (where relevant). No traditional bar bending schedule is published but is derived directly from the data in Revit and may be presented in various formats like MS Excel.

3.5.3. BIM for construction

The civil contractors are integrated in the VDC process and are utilizing the BIM directly for their construction planning, setting out works and construction in the field. In addition to having access to the BIM in the field office, they have installed so called BIM-kiosks in containers in the construction pits. The BIM is also published through Autodesk 360 Glue and Field and "Gemini Entreprenør" to the construction workers on iPads and "Though Books".

Figure 3.5.3: BIM as basis for construction in the field.

Data for setting out works is harvested directly from BIM using Autodesk PointLayout and Gemini Entreprenør.

For pre-fabrication of reinforcement, bars bending schedules are published in .XML format to a cloud service and downloaded and fed directly into the bar-bending machines in the workshop. Upon receiving the ready bent bars at site the reinforcement workers pick them out based on tags matching the tags found in BIM and place them in the form based on BIM (on iPad).

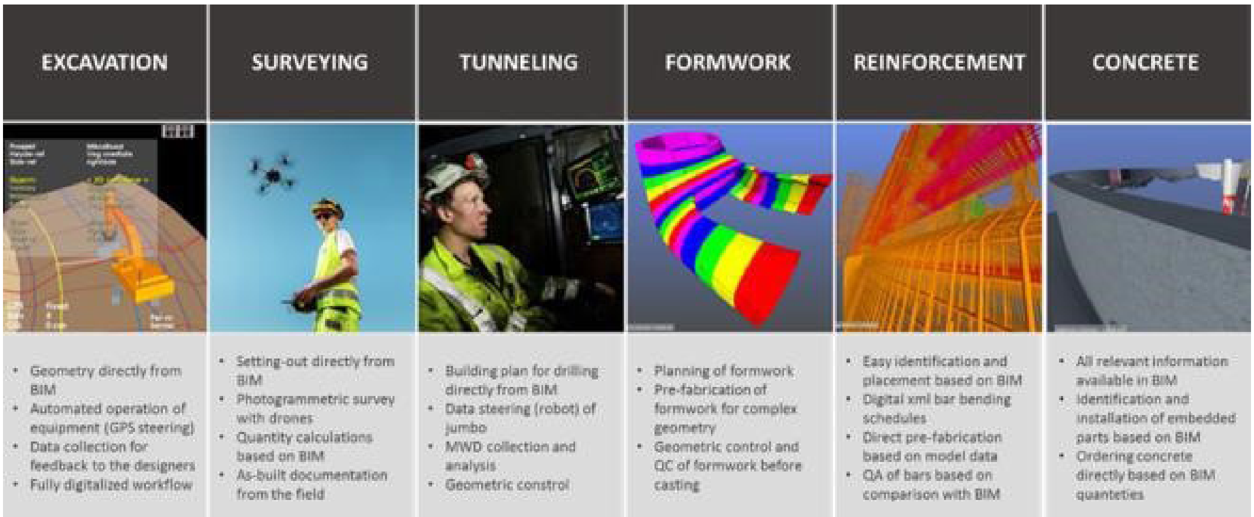


Figure 3.5.4: Contractors processes based on BIM.

3.5.4. BIM for excavation and tunnelling

For the excavation and filling works the civil works contractors feed the geometrical data from BIM into their GPS operated excavators. For the excavation of tunnels, shafts and caverns, the 3D geometry is transferred from BIM directly into the excavation planning tools to produce blasting plans that further is loaded into the Bever Control system to control the drilling jumbo. In this way data is transferred directly from design into production, reducing time spent on data handling and improving quality by deleting the re-entry of data which in many instances introduce a source of human errors.

After blasting and excavation the contractor carries out scanning of the rock surface for geometrical control. The point cloud and triangulated surfaces are also forwarded to the designer for inclusion in the BIM. Based on this the designer can make necessary adjustments of structures etc. to fit the excavated surface. Norconsult has developed tools for efficient cutting of concrete structure against the rock surface.

Comparing the scanned surface with the theoretical (designed) contour one may analyse overbreak caused by drilling and blasting inaccuracies as well as geological conditions. With high resolution scanning it is possible also to perform an automated categorization of the different discontinuities based on strike and dip. This may be illustrated in the BIM by means of e.g. colour coding. In many cases the shape of the scanned surface may also help identify the intersection between the tunnel and weakness zones etc.

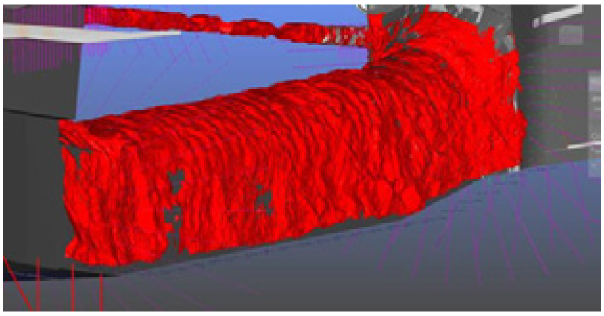


Figure 3.5.5: Scanned rock surface

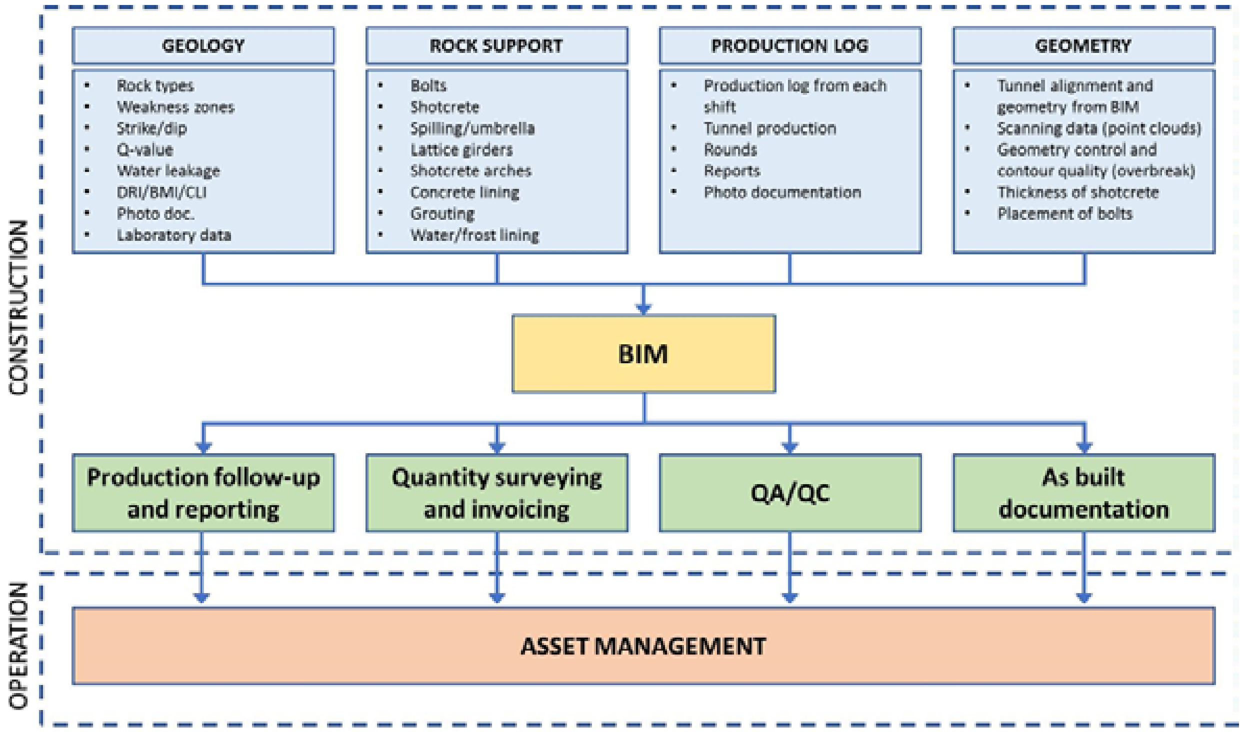


Figure 3.5.6: Data collection and analysis for tunnelling using BIM to bring all of it together.

The surface may be scanned both before and after the contractor apply shotcrete for rock support. By comparing the two scans, a map showing the thickness of the shotcrete layer may be constructed. This can be utilized as as-built documentation, quality checking (adherence to required thickness) and as basis for quantity calculations.

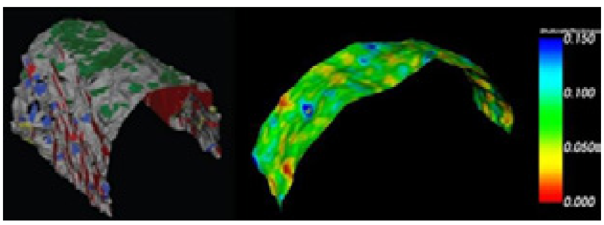


Figure 3.5.7: Automatic interpretation of strike and dip and documentation of shotcrete thickness (heat map) based on laser scanning [1].

Rock support bolts and anchors installed by the contractor may be imported directly into the model based on xyz coordinates collected form the data logger on the main jumbo or the bolting rig. Data from the MWD-log (measurement while drilling) can also be interpreted and brought into the model as a colour coded 3D volume and compared with the geological mapping as well as photo documentation from the face of the tunnel. While scanning the surface of the tunnel prior to applying shotcrete, it is also possible to collect high resolution orthophotos that may be draped on the surface of the models. If the quality of the photos is sufficient, they may act as a support in the geological interpretation and be strong as-built documentation. These data can be collected and be made available in the BIM as illustrated in Figure 3.5.6.

An example of a system that enable the projects to both do design and collect data in a good and systematic matter in BIM is Novapoint Tunnel, developed in Norway. In Norwegian road and railroad projects the clients demand that all geological and rocks support data are collected and systematically entered in such a system.

In the future, this process should be automated as much as possible, but it is important to notice that skilled engineering geologists and tunnelling workers that enter the tunnel to "touch and feel" the rock mass is of key importance when interpreting the geological situation and responding appropriately.

The system only becomes valuable if the systematization of data is utilized in an active way to improve interpretation and optimize the tunnel support to the best for both safety and cost.

3.5.5. Conclusion

Applying BIM as the basis for planning, design and as direct basis for construction has so far worked very well and helped to ensure good cooperation, data exchange and production on Vamma 12. Although experiences are very positive so far, the future will show if the industry is able to utilize the full potential inherent in the approach. BIM is a very useful tool also for underground construction. Merging data from multiple sources into BIM and using the data actively to monitor and analyse the conditions and adopting the design and construction method to the challenges has a great potential. The BIM can further be used as basis for asset management and condition monitoring. However, it is important to note that BIM is a tool, and as with all tools it takes skills and training to operate them in a good matter. Without adaptation of processes, trust between the players and focus on common goals, any system will malfunction. BIM could contribute to secure that "all parties are working on the same project, towards common goals" and would therefore be a good foundation for cooperation.

References

[1] NGI. LiDAR. 2019. [10.01.2019] Available from: https://www.ngi.no/eng/Services/Technical-expertise-A-Z/Geophysics-remote-sensing-and-GIS/LiDAR

3.6. E18 Kjørholt – Bamble tunnels (E18 KBT)

Authors:

- *Henning Ekström, BetonmastHæhre*
- *Anne-Line Kvale Ferstad, Nye Veier*

3.6.1. Introduction

The project involved the upgrade and renovation of the Kjørholt tunnel and Bamble tunnel of length 765 m and 2129 m respectively, as well as the excavation of two new parallel tunnels. The appointed contractor on the project was BetonmastHæhre. The tunnels were opened for traffic in August 2018 and was the first new road stretch completed by the client, Nye Veier.

3.6.2. Digital Processes E18 KBT

At E18KBT BIM or digital models have not been used to a large extent, mainly due to an older project-design and the that the decision of a building a new tunnel was done late in the design phase. The project is essentially drawing-based, except for DWG models for portals and VIPS for road and tunnel.

Bever Team Online

The part of the project that has had the greatest focus on digitization was the geological surveys and documentation. Where systems provided by Bever Control was used, with cloud storage for MWD data from the drill rig was collected and digital mapping of geological survey was done using tablets. With the help of Bever Team Online, both contractor and the client have been able to follow all documentation of MWD and production after each blast. This is the first time this system is used by the contractor. The contractor sees clear potential for streamlining the drill and blast process with regards to documentation. Further work on implementing the system directly into the contractors' own documentation software is advised.

Scanning density

The scanning equipment on the drilling jumbo created some difficulties on the project as it did not provide the required scanning density. Initially this was not clearly defined in the contract where only a scanning density of "as-built" scanning by 0.5 x 0.5 m was specified.

It was later determined that a density of 0.02 x 0.02 m should be used and that the tunnel profile was to be scanned before and after the shotcrete application. This created a need for different scanning equipment. Some difficulties due to equipment availability and the need for staff who had the experience to use it where encountered. Such detailed scanning also requires a large amount of data processing. This has previously been done by the contractor on other projects and it was at that time deemed to be too time consuming compared to its value for the project. Based on the contractors experience a clear plan is needed from the early stages of a project for which data that should be collected and how it should be documented and presented, with thoughts on the necessity of each.

Digital information existing tunnels

The digital data that were available from the existing tunnels consisted only of as-built scanning that was performed two years before the project started. Digital data as measurements of water and electricity systems as well as scanning of rock or shotcrete (using 0.25 x 0.25 m) from the existing tunnel, would have been useful to have on the project and in the construction of the new tunnel.

3.6.3. Digital geological mapping on face

The geological mapping is an important exercise to decide how much support the rock formation needs. Geological mapping therefore provides important information both during the tunnel excavation and for later use after project completion. During the excavation of new Kjørholt and Bamble tunnels, a digital mapping tool on a tablet was used to map geological features (Figure 3.6.1). The digital mapping tool can register geological data from site and directly import it to a digital model with no need for paper and pencil on site, which makes the processing of data faster and more accurate.

MWD

All modern drill jumboes in Norway can specify the logging data from the drill holes. This is done by using Measurement While Drilling (MWD) for each round of excavation. These data provide information about the rock mass quality. Until recently, these data have only been used to a small extent for geological mapping. The new geological mapping tool from Bever Control makes it possible to use these data directly into the mapping tool. When the geologist is on site, the information from the MWD-data is imported as a layer on the tablet and all geological features can be registered on top of the layer. The geological mapping tool enables the geologists to do a mapping that is more uniform and accurate among the different geologist working on the construction site. One important prerequisite is that the MWD-data must be available right after the drilling is done. This worked well through the online system provided by Bever Control on this project.

The users of the mapping tool were people with different experience, some had just finished university whereas others had many years of practical experience from tunnelling. Everyone found the tool/ application helpful as the mapping was done more efficient. The data was converted into Novapoint Tunnel in accordance to the requirements in the contract. The conversion to Novapoint Tunnel is an easy step in the tool.

Figure 3.6.1: Face mapping

However, as Novapoint Tunnel only presents the geological data in 2D it was attempted to present the information in a 3D model on the project. The borehole geometry, MWD-data, the geological mapping and laser scanning before and after shotcrete were included in the model (Figure 3.6.2). Due to the high density of the laser scanning it was useful in areas with complicated geology. The 0.02 x 0.02 m resolution made it possible to see features in the rock mass on a scale useful for the geologist. High resolution requires a lot of data storage and has proven to be challenging to use in the different computer programs. Related to geological mapping, a lower resolution may be sufficient.

There is a lot of potential to make the model even more useful than achieved on this project. For example, geological features should be objects and not raster-files. Q-values and text written by the geologist can also be made more readable in the model. A common belief on the project is that in order to create a good model of a tunnel project it is very important to engage and create a good collaboration between the geologists and BIM-developers.

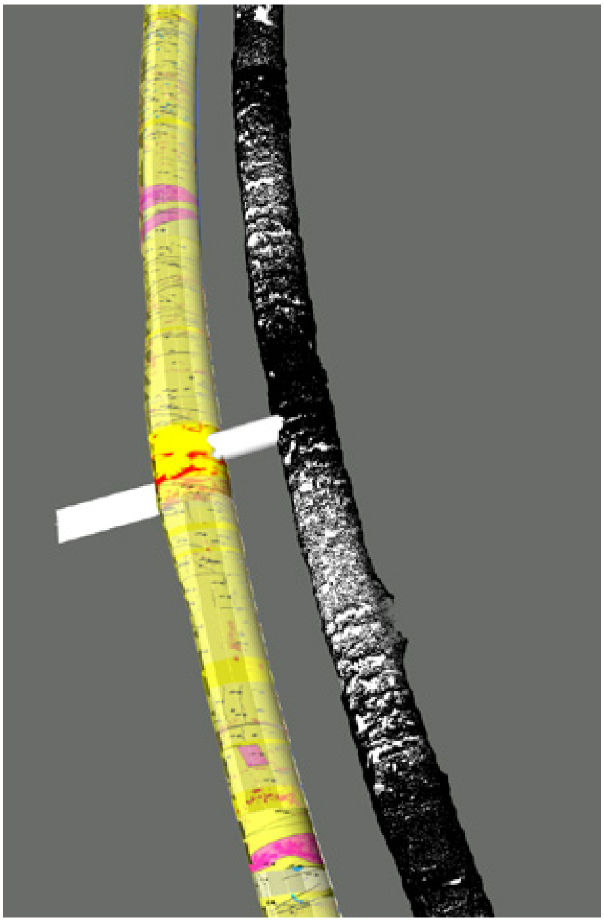


Figure 3.6.2: Geological mapping and interpreted hardness in left tunnel and scanning of right tunnel.

3.7. The New Ulriken Tunnel

Authors:
- *Torstein Standal, Bane NOR*
- *Leon Eide, Bane NOR*
- *Kjetil Andre Hellebust, Skanska*

The Arna-Fløen project for Bane NOR has been in production from 2014 and will be completed in 2022. The existing tunnel between Arna and Bergen is the busiest single-track tunnel in Northern Europe. To remove this bottleneck, a new 7.8 km parallel tunnel between Arna and Bergen is excavated by both drill and blast and TBM. Using a TBM made it possible to create a new tunnel near the existing without affecting the traffic. In addition to a new tunnel, the project is renewing Arna station. When the new tunnel is set in operation, there will be a minor upgrade of the existing tunnel.

Arna-Fløen started as a traditional 2D infrastructure project. In 2015 the project organisation decided to use 3D in planning and construction for the Arna station contract. Seeing the benefits of this way of planning, a change in existing contracts was made, and the entire project transformed from 2D to 3D. This helped coordination across disciplines. BIM models for the tunnel project and station upgrades were created using AutoCAD, Civil 3D, and Revit, together with Navisworks to collaborate with construction teams.

Sight models

Traditionally, foundations for signalling systems are installed before train operators are able to test the line of sight in the actual tunnel. This makes the necessary approvals from the railway authority difficult to obtain during construction. By using the ready models, a game-based sight model was created. This allowed for the verification of line of sight of signalling systems.

Within the game experience, train operators drove on the virtual train tracks under the supervision of engineers, who used their performance to evaluate the placement of signs and signals. The virtual environment provided a realistic scene, which is key when verifying planned constructions using actual users. Through an iterative design process, the engineers refined and optimized the signalling system. Working with the train operators gave a better understanding of their thought process and allowed the project to benefit from their experience.

Bane NOR has also gotten additional benefit from the game as a visual aid for emergency responders. By playing the game in drone mode – navigating the project from the perspective of an unmanned aerial vehicle – personnel can familiarize themselves with evacuation routes or simulate emergency scenarios.

Figure 3.7.1: Desktop Ulriken sight model

Figure 3.7.2: Driving the sight model

Figure 3.7.3: Drone mode, Ulriken sight model

Figure 3.7.4: Drone mode

4. Success factors and further development

4.1. Characteristics of successful digitalisation

From the publication some common features for successful implementation of digital tools are identified and summarised in this section.

4.1.1. Connectivity

Connectivity and streamlined data flow are the fundamentals of successful data transfer between the engineering model, the construction site and the as-built during the construction phase. Thus, it constitutes both an important basis for further utilisation of digital tools, as well as the basis for communication between the engineered model and the as-built model.

The underground environment provides some practical challenges related to connectivity, compared to construction projects located above ground. Core elements to include in an early project phase to ensure a successful data collection and efficient data flow are therefore listed below (the list is by far not exhaustive).

- WLAN. Access to wireless networks is the key to success and fundamental for the establishment of data flow from sensors to interpreters. The network must be robust and reliable. Selected examples of digital processes dependent of WLAN-connection from the tunnel:
  - Drawing-less model-based projects are totally dependent of WLAN to update their models for the tunnel workers
  - Real time utilization of MWD
  - Data transfer from scanning
  - Transfer of drill plans from the project office to the drill jumbo
  - Online, real time monitoring of e.g. TBM machine data and machine performance
  - Navigation of position-based equipment on site (e.g. drill jumbo, shotcrete rig). Systems for accurate positioning
- Cloud based solutions for storage of data
  - More robust data storage, in terms of less risk of losing data
  - Accessibility. Several users can access the same data, regardless of their location.

Highlighted benefits from establishment of WLAN connection mentioned in the publication are listed below:

- Continuous data flow between the construction site and engineering office
- Reduced costs from optimization and fine tuning of machine operations with experience from the actual conditions during construction phase.
- Improved accuracy for equipment dependent on navigation systems
- Reduced time for rigging of navigation equipment
- More accurate estimates of required shotcrete amounts (reduced costs and spill related to excess material)

4.1.2. Integration of discipline models

This publication describes the integration of different underground disciplines in one digital model, where methods for integration, which data to be included and experienced benefits from these integrations are included. The main disciplines of focus are:

- Ground conditions
- Rock support
- Production data
- Machine operations
- Water and frost protection
- Technical installations
- Environmental monitoring

BIM modelling is at a high level in the Norwegian building industry, while the underground industry is not at a level of a BIM standard as per today. BIM-modelling of the ground conditions has posed some challenges to software producers as well as engineering companies, clients and contractors. This publication provides several methods and tools for establishment of a geological BIM. Traditionally, geological mapping and documentation in Norway has been visualised in 2D maps and drawings supported by written reports. Introducing 3D models as a basis for presentation of geological data at an early project state allows the geologists to better visualise the ground conditions to the non-geologists. This in turn allows the project to utilise the data for continuous optimisation of excavation methods, probe drill concepts, tunnel alignment, location of cross passages etc.

In the construction phase, a continuous update of the engineered geological model with the actual mappings from face, enables a fine tuning of the model. From the publication it can be read that the software developers have established 3D-tool for geological mapping, operated from a smart phone or tablet. This allows the geologists on site to map the tunnel face and continuously update the 3D-model without any extra modelling from an office-based computer. While tunnel excavation is ongoing, the recording and continuous analysis of MWD-data transferred in real time from the drill rigs also constitute an important and objective input to the geological as-built model. A high level of utilisation can be achieved when MWD-data is compared to both the predicted geological 3D-model and the 3D-model from face mappings. All data combined enables the project to establish a "geological as-built"-model. A precise and continuously updated geological as-built model is an important tool for e.g. control of rock bolting, further fine tuning of pre-grout concept and control of pore pressures. A model comparing the predicted ground conditions versus the experienced conditions also act as valuable input if any contractual dispute arises.

Solutions for including position-based data as rock bolting and technical installations in the model are also described in detail in this publication. Such data are available from machine equipment with navigation systems installed. Data transfer through WLAN both minimises the risk of human errors and allows a streamlined transfer of data that can be implemented directly to the as-built BIM.

The aim for the industry is paperless projects with streamlined data transfer from the engineering phase, to the contractor in the construction phase, and back to the client. The latter in terms of an as-built model for operation and maintenance of the tunnel. However, this is not yet achieved. It can be read from the publication that the most streamlined data transfer is located within the contractor's offices; from their model to the machine computers.

A full integration of all disciplines in one model that can be handed over to the contractors, without any transformations or re-modelling, is not yet achieved. The identified keys for further integration of discipline models are:

- An efficient and clear method of expressing uncertainty. By use of metadata is suggested.
- Establishing a standard information level to be included in each discipline model
- Agree on open formats

4.1.3. Contract specifications

It is believed that the main responsibility for future standardisation and innovation lays with the clients. The industry agrees that the main objective for all digital processes is to achieve a model that can follow the life cycle of a tunnelling project; from early planning to engineering phase, throughout construction phase, before it ends up as a live model for tunnel operation and maintenance. The first section of this publication demonstrates that both software producers and Norwegian contractors can deliver such model-based solutions. However, this is not yet produced and the main responsibility for the further process is located at the Norwegian clients.

The contract requirements constitute an important basis of digital innovation and development of the industry. It cannot be expected that the contractors deliver beyond the contract requirements. Thus, regardless of the contract type, the requirements related to digital processes and model-based engineering tools must be precise, relevant and achievable. The contract specifications related to detail level must reflect the detail level required by the user. The data must also be delivered on a format that the user can utilise. This requires experienced clients and constitutes one of the most important factors for the full achievement of a digitalised, model based and paperless project. The chapter written by Norwegian clients demonstrate that a lot of work has been initiated and that they are focusing on this in their contract requirements.

Digital standards and open formats are identified as two of the most important next steps for the digitalisation of the tunnelling industry. Again, this responsibility lays with the clients. According to the idea behind the life cycle of a model, they are both receiver and user of the final product. The major Norwegian clients' involvement and sponsorship of the group "Building Smart Norway" is identified as another important step in the right direction. Building Smart is a worldwide, neutral non-profit organisation which main purpose is to achieve open, international standards and working procedures for model-based projects.

4.2. Future visions

There is an enormous potential located within areas such as: agreement on standard formats, even more efficient handling of design changes, continuous data flow from the engineering office to the tunnel site and back to the client's as-built models.

The ideas of what to include in a BIM is not the limiting factor in the tunnelling industry, neither are the tools nor the knowledge. The next step is to unite the industry, establish common BIM standards and ensure that all the levels of the supply chain are pulling the development in the same direction. The main responsibility is located with the clients.

Key points for the future development of BIM in underground engineering

- Develop a standard for implementing/using BIM on infrastructure projects
- Agree on open formats (Building SMART)
- Be able to include a model for risks and project planning.
- Ensure that the model follows the entire life cycle of a tunnel

Artificial intelligence for building smarter models.

Internet of Things for live collecting data from sensors.

Big Data for the continuous stream of large amounts of data collected in face operations.

Listed below are relevant tasks in tunnelling where the above-mentioned technologies can be applied.

- Start using machine learning models for optimization, automation and operation guidance in all kind of operations in planning phase and face operations.
- Major expansion in smart use of all the digitally collected data from:
  - sensors on jumbos, grouting-rigs, excavators etc
  - scanning and pictures from the face
  - environmental monitoring
  - digitally collected data from tunnel construction sites
- Combined use of BIM and machine learning model

What do we hope to achieve in the near future (3 – 5 years)?

- Autonomous machinery
  - Autonomous shotcrete application
  - Autonomous rock grouting
  - Driverless dumpers/excavators/loaders
- Smart maintenance – prediction of down-time in advance by using data from rig-sensors and machine learning models
- Planning operations
  - Optimized prediction-models for quantities of rock support and grouting
  - Water inflow prediction
  - Rock mass classification and modelling
- Face operations
  - Grouting optimization
  - Blasting optimization
  - Geologic mapping and rock support – guidance systems
- Operation phase
  - Smart monitoring of rock stability from sensor data

In order to succeed with these developments, we find that it is necessary to expand and further develop the cooperation in research and development from all relevant players in the industry – sharing of ideas and data. Further, we need to agree upon and facilitate a common database system in Norwegian tunnelling industry for collecting and sharing digital data. The Norwegian Tunnelling Society will continue to facilitate the process for such cooperation.

Norwegian Tunnelling Society International Support Group

NFF, Publication no. 28
Appendix 1.

The Norwegian Tunnelling Society have 1000 personal members, among those approximately 100 corporate members covering private sector, governmental agencies, research and education. Their representatives are active in the various permanent committees. One of these - The International Committee responsible for this publication - is specially supported by the core group presented below:

ANDERSENS MEK. VERKSTED A.S P.O. Box 194, N-4401 FLEKKEFJORD TEL. +47.38 32 04 20 FAX. +47.38 32 33 30	Supplier of tunnelling equipment and machinery to the international market. Shotcrete robots and computerised drill rigs. www.amv-as.no company@amv-as.no
BASF AS – Admixture Systems Gullfotdalen P.O.Box 13, 2120 SAGSTUA TEL. +47.62 97 00 20 FAX. +47.62 97 18 85	Supplier of chemical products and equipment for rock support and water control in tunnelling. arne.dokken@basf.com www.basf.com/no
COWI AS Grensevn. 88, N-0605 Oslo TEL.:+47.02694	Multidiscipline Consulting services firmapost@cowi.no www.cowi.no
EPIROC NORGE AS Berghagan 7, N-1405 Langhus Tel: +4764860300	Supplier of mining and rock excavation equipment and machinery epirocnorge@epiroc.com www.epiroc.com/en-no
FOAMROX AS Molandsveien 337, N-4849 Arendal Tel: +4791397732	Foamrox AS is a product development company specializing in fire, water and frost protection. post@foamrox.no www.foamrox.no
GEOFROST AS C.J.Hambros plass 2C, N-0164 Oslo Tel: +47 67147350	Specialized ground freezing company geofrost@geofrost.no www.geofrost.no
GHELLA S.P.A NUF Sluttstykket 2, N-1291 OSLO	Contractor
HERRENKNECHT AG NORWAY Arnstein Arnebergs vei 30, N-1366 Lysaker Tel: +47 950 02 129	Supplier of TBMs bengtsson.mats@herrenknecht.de www.herrenknecht.com
IMPLENIA NORGE AS Fornebuveien 11, N-1366 Lysaker Tel: +47 22 50 73 00	General contractor. Tunnelling Expertise. audun.aaland@implenia.no norway.implenia.com

INJEKSJON & TUNNEL-SUPPORT AS Slemmestadvn.30, N-1408 Kråkstad TEL.:+47.91 30 08 50	Supplier of equipment for grout operations ifa@its.as
LNS AS N – 8484 Risøyhamn TEL +47 76 11 57 00 FAX +47 76 11 57 01	General Contractors, Heavy construction. Underground engineering. firmapost@lns.no www.lns.no
MAPEI AS Vallsetvn.6, N - 2120 SAGSTUA TEL. +47.62 97 20 00 FAX. +47.62 97 20 99	Supplier of concrete additives for rock support and water control in tunnelling. post@mapei.no www.rescon.no
MULTICONSULT P.O.Box 265 Skøyen, N – 0213 OSLO TEL +47.21 58 00 00 Fax +47.21 58 00 01	Complete deliveries of consulting services. Energy, oil & gas, underground engineering. multiconsult@multiconsult.no www.multiconsult.no
NCC CONSTRUCTION P.O. Box 93 Sentrum, N - 0663 OSLO TEL + 47.22 98 68 00 Fax + 47.22 89 68 01	General Contractors, Heavy construction. Underground engineering. firmapost@ncc.no www.ncc.no
NMC TERMONOVA OY Torpmalmasvëgen 44, FI-10210 INGÅ	
NORCONSULT AS Vestfjordgt. 4, N - 1338 SANDVIKA TEL. + 47.67 57 10 00 FAX. +47.67 54 45 76	Multi-Discipline Consulting and Engineering services. Underground facilities, geotechnical and rock engineering. company@norconsult.no www.norconsult.no
NORMET NORWAY AS Silovn. 20, NO-2100 Skarnes Tel. + 47 476 66 476	Supplier of tunnelling equipment and concrete additives
NORWEGIAN GEOTECHNICAL INSTITUTE NGI P.O. Box 3930 Ullevål Hageby, N - 0806 OSLO TEL. +47.22 02 30 00 FAX. +47.22 23 04 48	Consulting and engineering services. Geotechnical, geology, rock engineering. ngi@ngi.no www.ngi.no
ORICA NORWAY AS P.O. Box 614, N - 3412 LIERMARKA TEL. +47.22 31 70 00 FAX. +47.22 31 78 56	Supplier of explosives and advanced charging systems. firmapost@orica.com www.orica.com
PROTAN AS P.O. Box 420, N - 3002 DRAMMEN TEL. +47.32 22 16 00 FAX. +47.32 22 17 00	Intelligent tunnel ventilation, ducts, electronic tunnel tagging systems. protan@protan.no www.protan.com
SIGICOM AB Götalandsvëgen 230, SE-125 44 ÄLVSÖ	

SINTEF **Rock and Soil Mechanics** N - 7465 TRONDHEIM TEL. +47.73 59 30 00 Fax. +47.73 59 33 50	Research and consulting services. info@civil.sintef.no www.sintef.no
SKANSKA NORWAY AS P.O. Box 1175 Sentrum, N - 0107 OSLO TEL. +47.40 00 64 00 FAX. +47.23 27 17 30	General contractor. Tunnelling expertise. firmapost@skanska.no www.skanska.no
STATENS VEGVESEN, VEG DIR. P.O. Box 8142 Dep, N-0033 OSLO	Norwegian Public Road Administration
SWECO NORWAY AS P.O. Box 400, N - 1327 LYSAKER TEL. +47.67 12 80 00 FAX. +47.67 12 58 40	Multidiscipline Consulting and engineering services. Hydropower, underground facilities, geotechnical and rock engineering. post@sweco.no www.sweco.no
VEIDEKKE ENTREPRENØR AS P.O. Box 504 Skøyen, N - 0214 OSLO TEL. +47.21 05 50 00 FAX. +47.21 05 50 01	General contractor. Tunnelling expertise. anlegg@veidekke.no www.veidekke.no
VIK ØRSTA AS P.O. Box 194, N - 6151 ØRSTA TEL. +47.70 04 70 00 FAX. +47.70 04 70 04	Supplier of rock support quality steel items e.g. the CT-bolt. post@orstagroup.com www.ct-bolt.com www.vikorsta.com
W. GIERTSEN TUNNEL AS P.O. Box 78 Laksevåg, N - 5847 BERGEN TEL. +47.55 94 30 30 FAX +47.55 94 31 15	Waterproof lining in rock caverns and tunnels. Membranes for tunnels, shafts and rock galleries. tunnel@giertsen.no, hans.larsen@giertsen.no www.tunnelsealing.com
NORWEGIAN TUNNELLING NETWORK Lavendelgången 3, SE-459 32 LJUNGSKILE TEL. + 46 768 528 750	Network of Norwegian Companies for promoting commercial cooperation involving Norwegian underground knowledge and technology internationally. post@norwegiantunneling.no
NORWEGIAN TUNNELLING SOCIETY PO BOX 2752 Solli - 0204 OSLO Tel +47 98 21 05 30	A leading national society with focus on rock engineering with governmental, private sector and individual members. nff@nff.no www.tunnel.no www.nff.no

NORWEGIAN
TUNNELLING SOCIETY

Postboks 2752 – Solli, 0204 Oslo

nff@nff.no | www.nff.no | www.tunnel.no