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# Tunnel investigation and groundwater control

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# Tunnel investigation and groundwater control

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# Preface

This report presents, in a condensed form, the results from a research programme on tunnel investigations and ground water control. Although the starting point was related to Norwegian conditions, the problems are the same elsewhere and the findings generally applicable. We thus hope that this English edition will be of value to other professional dealing with planning and construction of transportation tunnels in rock.

# Summary


The results from this programme have provided new information about methods to improve tunnel planning and construction, and is especially important to areas where lowering of the groundwater table may cause severe damage to the surface and man-made structures.

### The programme were divided into three projects:

**A:** Investigation methods. New geological and geophysical methods were tested for their potential to locate the direction of joints and weakness zones at depth, and the leakage potential, as well as efficient mapping of regional structures. The methods were found to be valuable supplements to traditional procedures. Completed tunnels were studied in order to see if there were any relations between investigation efforts and problems during excavation, with the aim to establish the type and appropriate amount of ground investigation on a given tunnel project. This has resulted in general guidelines depending on the complexity and project phase of the tunnel.

**B:** Environmental concerns. The vulnerability of the environment, especially related to changes in the groundwater table caused by the tunnel construction, is evaluated with the aim to develop methods to quantify accepted levels of leakage into a tunnel. Procedures and guidelines for various conditions are presented.

**C:** Pre-grouting techniques. A specific grouting technique and strategy utilizing thick cement grout is developed. This technique and strategy is a result of evaluation of grouting performances in several recently built tunnels, and has proven to be efficient and give better control on the amount of water draining into a tunnel.

# Contents

# 1 Introduction

Norway holds a long tradition in building transportation tunnels. There is a total of 915 (850 km) road tunnels on the road network, 315 km railway tunnels and 45 km metro tunnels. With a few exceptions, these are all tunnels in rock.

The generally good rock quality in Norway has made drill and blast the main method of tunnelling. Ground investigations are performed to locate joints, faults and weakness zones in order to evaluate the stability and the leakage potential of the rock mass. The ground investigations traditionally also include geophysical mapping, core and percussion drilling from the surface as well as exploratory drilling at the tunnel work face.

In the later years one has become aware of the environmental consequences of changes in the groundwater system. Tunnel projects with heavy water inflow during and after construction have caused significant damage to surface areas. As a consequence, a research and development programme focusing on improving the quality of ground investigation and groundwater control was initiated.

### It was decided to concentrate the efforts on three main subjects:

**A:** Investigation methods. The suitability of advanced geological and geophysical methods in locating the direction of joints and weakness zones at depth, as well as the leakage potential of the rock.
**B:** Environmental concerns. The vulnerability of the environment, especially related to changes in groundwater level caused by the tunnel construction and the leakage into the tunnel.
**C:** Pre-grouting techniques. Improving the grouting technique and strategy to obtain better control on the amount of water draining into a tunnel.

The programme involved the Norwegian Public Roads Administration, the National Rail Administration, the Research Council of Norway, as well as several contractors, consultants and research institutes.

*Figure 1*
*The Lunner tunnel, built at Rv 35 north of Oslo.*

# 2 New methods for tunnel investigation

New methods, with the potential of locating and investigating zones that may be problematic to tunnel excavation are tested. The type of methods range from satellite and aerial investigations to geophysical (geo-electrical) investigations below the surface. The main part of these tests were performed by the Geological Survey of Norway.

The new investigation methods have the potential of providing more detailed information about the relative rock mass quality and water-bearing zones below the surface. Results from both new and traditional methods were evaluated. The tests of different investigation methods in the same area and during tunnel construction provided a direct comparison of the methods, and a precise evaluation of their ability to locate water-bearing zones in the depth.

The main test site was the area above the Lunner tunnel near Gardermoen Airport north of Oslo. The 3.8 km long tunnel is situated below a nature reserve, including a lake. For this reason the requirements for water ingress to parts of the tunnel was set to 10 – 20 litres/minute/100 m (water leakage after pre-grouting). The tunnel opened in 2003. The second test site for the new investigation methods was above the Jong – Asker tunnels, two railway tunnels 2.7 and 3.7 km long, just west of Oslo. Due to risk of settlements which could cause damage in the densely built-up area, the requirements for water ingress was set to between 4 and 16 l/min./100 m. This construction project will be completed in 2005.

The aim of investigations for tunnelling is to obtain the information that is necessary to establish the excavation procedures, the design of the appropriate rock support, water sealing and costs in good time before the tunnel construction is under way. The new methods have proven to be useful alternatives and supplements to traditional methods, especially in areas where it is of great importance to obtain detailed information about rock mass quality and water-bearing zones. The methods are user-friendly and the costs are generally lower than for the existing methods. The results and evaluations of the specific methods are summarized below.

## 2.1 Borehole inspection

The optical televiewer (OPTV) is basically a video camera which is lowered into a borehole

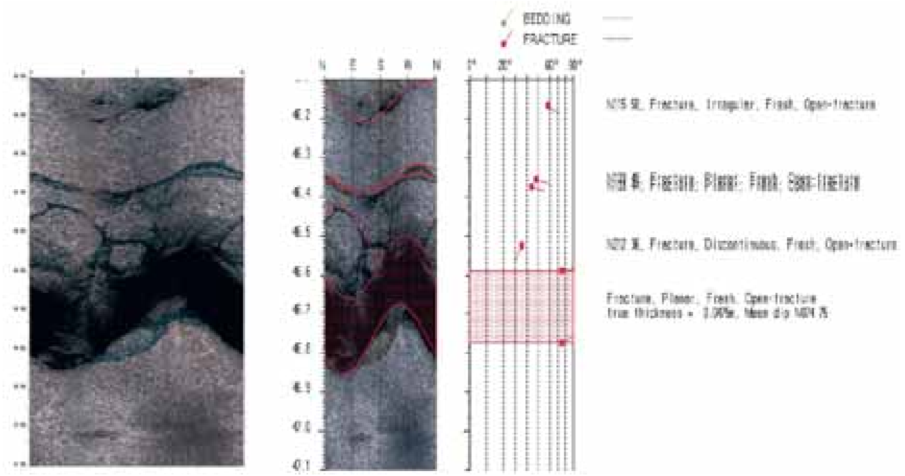


*Figure 2*
*Optical televiewer recording of a borehole, showing a 360° picture of the borehole wall with its structures and an analysis of the individual joints.*

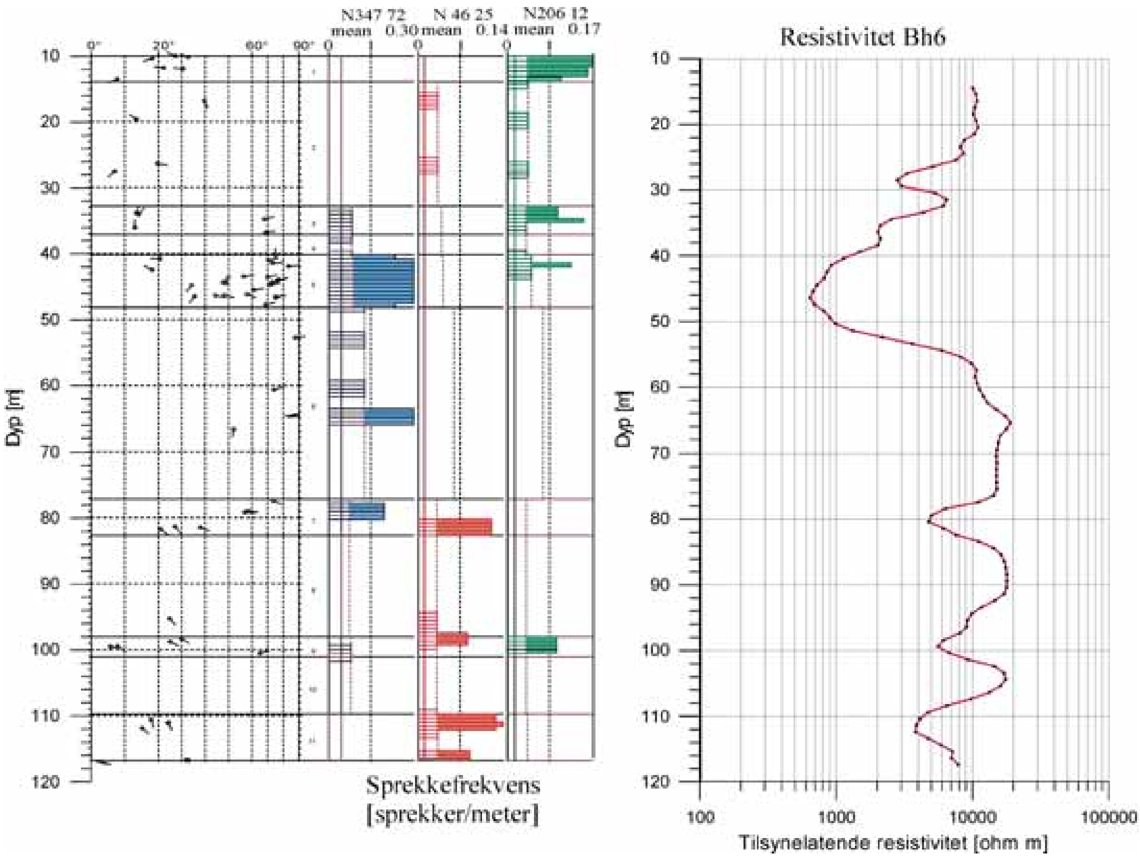


*Figure 3 Left: Example of presentation of data from OPTV logging along a borehole, with joint frequency and location of different groups of joints.*
*Right: The diagram presents resistivity measured by probe in the same borehole, showing good correlation between the joints located by OPTV and zones with low resistivity.*

of 70 – 160 mm in diameter. It provides detailed information about rock type boundaries and orientation and character of structures through a 360$^{o}$ picture of the borehole wall (Figure 2). Instruments within the OPTV record the frequency, strike and dip and opening of the various structures cutting the borehole, and statistical analysis of the data is presented in diagrams (Figure 3). The OPTV can be used as an alternative to core drilling and logging.

Additional inspection methods are probes which are lowered into boreholes with continuous logging of geophysical parameters which can be interpreted to reflect rock mass quality or potential for water leakage. For example, measurements of changes in temperature and electrical conductivity of the water may indicate open joints with inflow of surface water. Variations in natural gamma radiation may reflect variations in mineralogy (rock type boundaries). Similarly can probes measuring electrical conductivity of the rock mass identify possible weakness zones along the borehole (see example in Figure 3).

Hydraulic test pumping of boreholes is useful for identifying water bearing joints within the borehole, and may be an alternative to Lugeon-testing. The results give the potential for water leakage where the tunnel cuts these fractures and subsequently help to evaluate the need for pre-grouting.

## 2.2 Two-dimensional (2D) resistivity

Two-dimensional resistivity provides a view of the physical properties of the rock mass below the surface, this has not been possible by using traditional methods of investigation. The resisti-

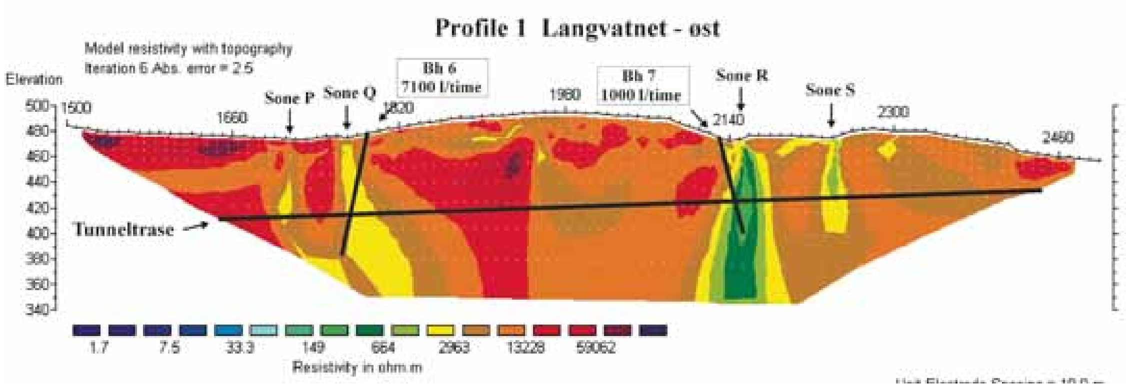


*Figure 4 Resistivity profile from a section of the Lunner tunnel. Zones of low resistivity are further examined by borehole logging.*

vity is measured by electrodes attached to cables lying on the surface. By processing the data, an image (2D profile) of the subsurface resistivity is obtained down to a depth of 120 m (Figure 4). However, the best resolution is achieved at depths down to 50 – 70 metres. The results can be interpreted in terms of rock mass condition: high resistivity indicates good quality rocks whereas zones of relative low resistivity may be correlated with jointed rock masses or weakness zones. The interpretation of the results depends on a good geological knowledge of the area from field investigations and other methods.

The tests which were carried out in this project show the exellent potential of 2D resistivity in tunnel investigation. With this method it is possible to locate zones that may cause problems related to stability and inflow of groundwater, and in far greater detail than traditional refraction seismic. The position of the zones relative to the proposed tunnel can be traced, and boreholes for further inspection of the critical zones can be established exactly in order to obtain the maximum amount of relevant information.

Measurements above the Lunner tunnel gave very good results, the profiles show clearly zones which correlated well with mapped structures both on the surface and inside the tunnel during excavation, as well as with borehole logging in the area. In other locations (Jong-Asker) some of the limitations of this method became clear. The lack of distinct results was probably due to both a generally low resistivity in the ground, and a high density of technical installations in the Jong-Asker area. As a rule, this method seems to work well in areas with a generally high resistivity in the ground; above 5000 ohmm.

## 2.3 Geophysical survey from helicopter

Geophysical survey from helicopter was carried out over the area where the Lunner tunnel is situated. Magnetic, radiometric, electromagnetic and VLF (very low frequency) electromagnetic data was collected. For all these methods, faults and weakness zones in the bedrock may appear as linear or curvilinear anomalies, also in areas covered with sediments and vegetation. Confirmation of the specific structures is done by field geological and geophysical mapping. The helicopter survey thus provides an efficient method for mapping of regional structures which may influence the tunnel excavation.

## 2.4 Mapping by digital analysis

Digital topographic maps were tested for applicability to register regional geological structures. The digital topographic data is combined with other digital data such as satellite- or aerial photos and maps. By processing these data it is possible to locate lineaments that may represent rock boundaries, weakness zones or faults.

An example from the Oslo region show regional lineaments produced by digital analysis (Figure 5). The lineaments appear clearly on the map, also in areas covered with urban settlement and infrastructure. Thus, this method also provides

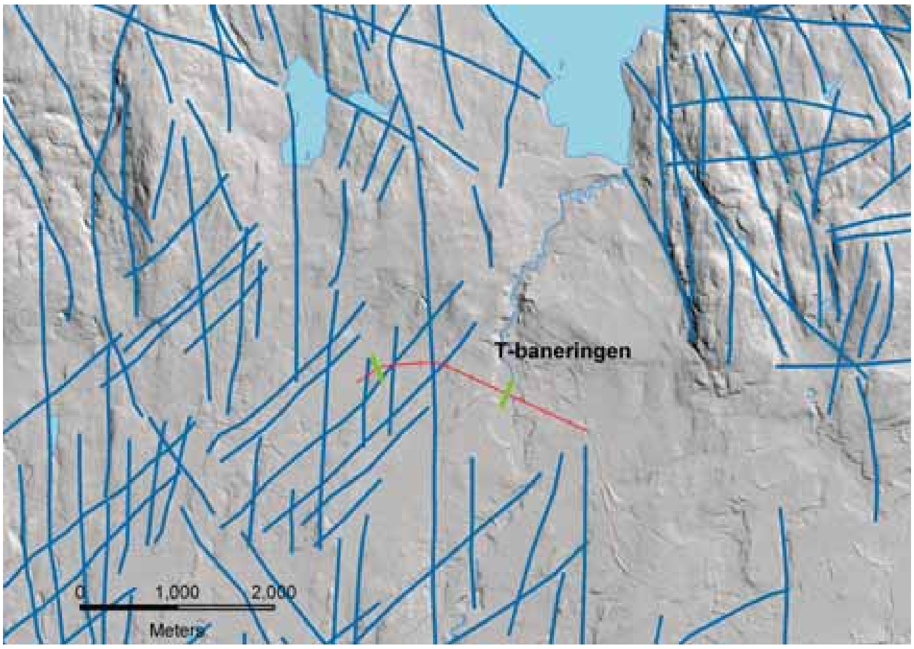


Figure 5
Lineaments produced by digital analysis from the area near the Metro tunnel (T-baneringen) in Oslo.

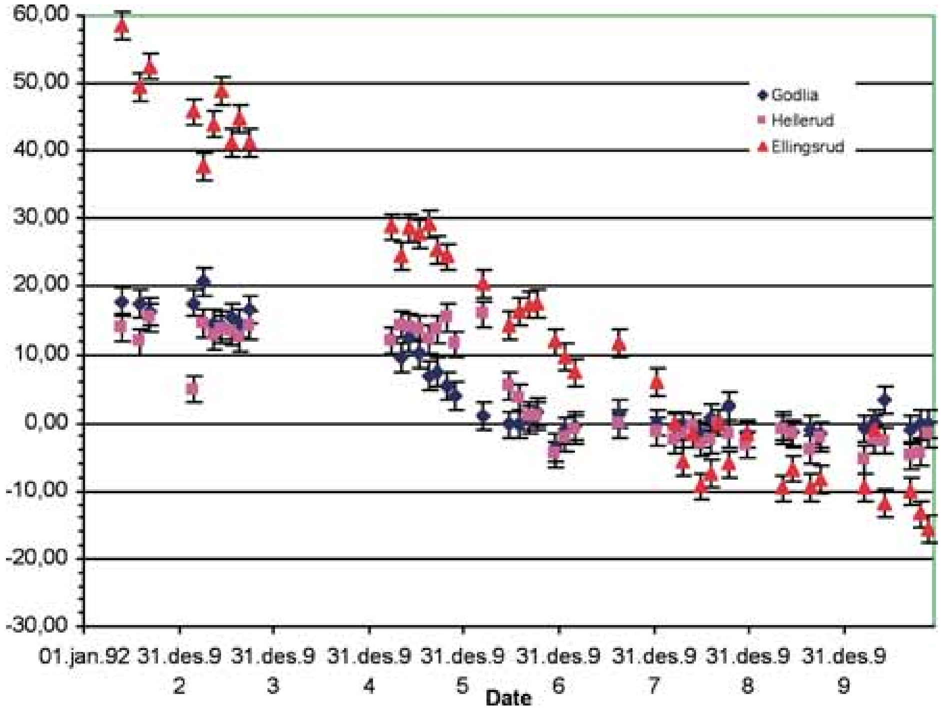


*Figure 6 Example of settlements over time of three buildings above the Romeriksporten tunnel. One building, at Ellingsrud (red triangle), shows a natural continuous settlement in the period 1992 to 1999. Two other buildings (Godlia and Hellerud) were unaffected until about 1995 when the tunnel excavation progressed below these houses. For about one year they suffered a settlement of 15 mm until the leakages in the tunnel were finally under control.*

important information about regional structures which is useful at an early stage in the tunnel planning, especially in densely built-up areas.

## 2.5 Radar interferometry

As part of this project, satellite-based radar interferometry is evaluated as a method to identify and monitor settlements during tunnel construction. Satellite images are available from the period 1992 to 2001 and further on from 2004, and provide very detailed historic data. Vertical displacements down to mm-scale are registered with this method. An example from the area above the Romeriksporten railway tunnel, which suffered significant environmental damage during tunnel construction, was used as an illustration. Recordings from before, during and after tunnel construction show both buildings that were affected directly by the construction, and buildings that had suffered a regular subsidence over a long period of time, unaffected by the tunnel (Figure 6). One of the advantages with this method is that it is possible to monitor a large area in detail, instead of displacement measurements on selected buildings only. The potential for daily or weekly monitoring of an area during a future tunnel excavation is not as good, since data are collected at an interval of 35 days.

## 2.6 Measuring While Drilling (MWD)

Measuring While Drilling is a relatively new technique to register rock parameters ahead of the tunnel work face during drilling. The instruments are installed on the tunnel drilling machine, and provide automatic registration of selected parameters. These data are then interpreted according to a pre-set scale which is calibrated for the specific project. Examples are registrations of relative joint frequency of the rock mass and variations in hardness (Figure 7).

The method is still under development and is in use on several new tunnel construction sites. It is a good supplement to engineering geological mapping in the tunnel. MWD also helps to secure the documentation of data from the tunnel excavation, and will improve the communication between work shifts.

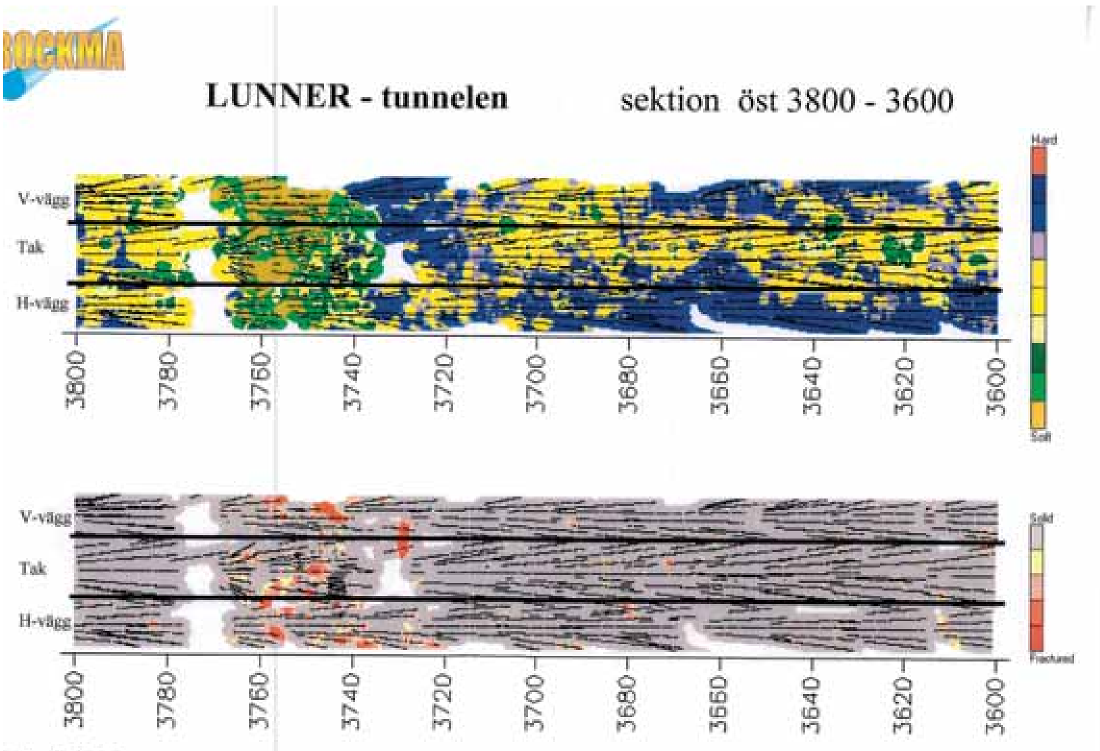


*Figure 7 Examples of registrations during tunnel drilling. Relative rock hardness (top), and relative fracturing (bottom) in roof and walls along a 200 m section of the Lunner tunnel.*

## 2.7
## Refraction seismic modelling

Seismic refraction is widely used in tunnel investigation, especially for sub-sea tunnels. The method measures the seismic velocities in the underground, and the velocities may be interpreted in terms of rock mass quality. Some of the limitations with this method are well known, for example are interpretation based on the assumption that the velocities increase downward – which is most often the case. Furthermore, the method will only provide seismic velocities in the uppermost few metres of the bedrock surface.

The Norwegian Geotechnical Institute carried out refraction seismic modelling to illustrate that the standard interpretation of the available data can be inaccurate. Synthetic seismic models of a rock surface with a sharp depression without a weakness zone below were presented in a blind test to a professional interpreter of seismic data. In each case, a vertical weakness zone was positioned below the depression (Figure 8). This is a common interpretation of this type of feature, the ambiguous data leads to interpretations that tend towards the worst case scenario. For a more realistic interpretation, two possible situations could be described from the data. Further improvements of the seismic refraction method would be techniques to extract more information from the available data.

A second model, illustrating a loose cable lying over a cliff similarly leads to interpretations that do not reflect the actual situation, for example is a weakness zone placed below the steep cliff. This interpretation can be improved by a more accurate mapping of the sea-floor topography prior to the refraction seismic measurements.

To obtain more precise information about possible weakness zones, seismic tomography can be used. This method produces a two-dimensional image of the seismic velocities in a profile between the sea floor and the borehole, alternatively between two boreholes.

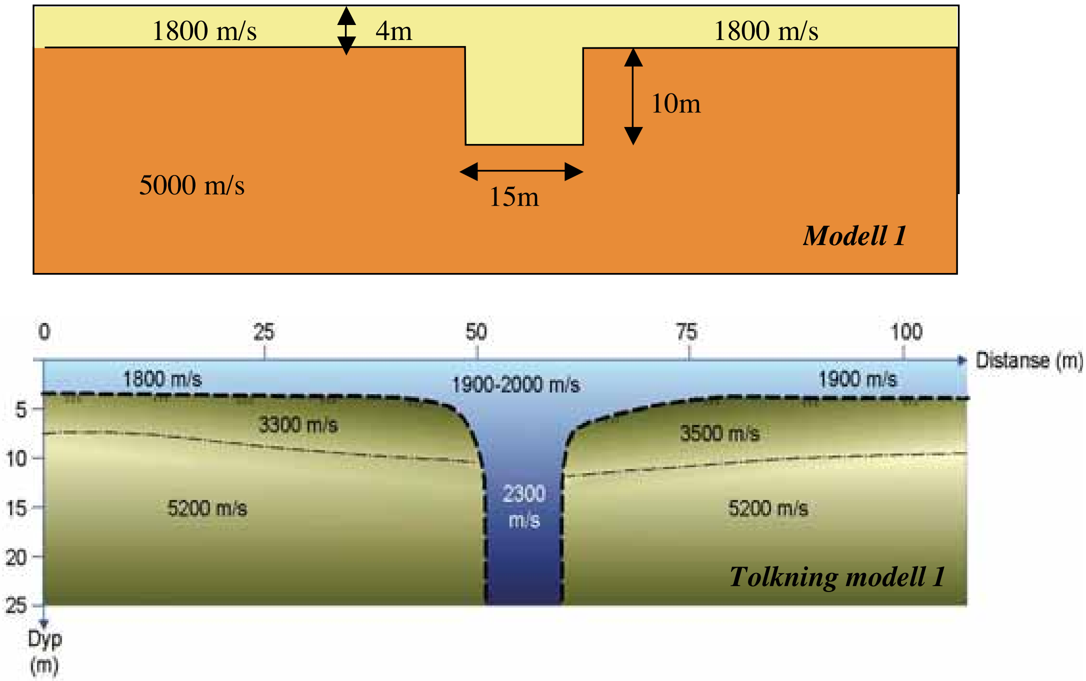


*Figure 8 Example of a synthetic model (top) and the interpretation of the model data (bottom) with a major weakness zone located in the depression. Seismic velocities higher than 5000 m/s generally represent good rock mass qualities. Weakness zones usually have velocities lower than 4000 m/s.*

# 3 Adequate investigations for Norwegian conditions

21 selected Norwegian tunnel projects have been analysed to work out recommendations on the appropriate amount (cost) of ground investigations for tunnels and caverns with today's requirements to the projects. The degree of difficulty in collecting information on the ground quality has been applied in the evaluations performed. In addition, the requirements to the safety of the actual project during construction and use, its influence on the environment, plus risks for encountering unpleasant tunnelling situations determine the project's investigation class.

The definition of investigation class is based on the guidelines in the Norwegian Standard NS-3480 'Geotechnical planning'. In NS-3480, the geotechnical project class is defined based on evaluation of a damage consequence class and degree of difficulty of the project. The same principle is used in Eurocode 7, which defines three geotechnical categories.

In summary, the investigation classes which is developed in this project is defined by the following two parameters (Table 1):

- Degree of difficulty. This reflects the engineering geological conditions, extent of weathering, overlying sediment deposits, water or urban settlements, accessibility to perform field observations. The different elements are weighted and given a value reflecting low, moderate or high degree of difficulty. This corresponds to the complexity of the ground in terms of tunnelling and the type and extent of investigation needed.
- Demands to the structure. This parameter reflects stability, possible risks during excavation, possibility to affect or damage the environment, such as vegetation or buildings. The elements are weighted and given a value reflecting low, moderate or high demands during construction and operation.

The analysis of the 21 selected tunnel projects according to this system resulted in the recommended amount of investigation for each investigation class, presented in Figure 9.
For a standard Norwegian road tunnel the recommended, appropriate total amount varies between 2 and 10 % of the cost for blasting and mucking out included rig (20 – 30 %). For sub-sea tunnels this value varies between 5 and 15 % plus 2 to 5 % for exploratory drilling ahead of the tunnel working face during construction.

*Table 1 The investigation classes (A, B, C, D) determined from degree of difficulty and demands to the structure. These parameters are deduced from evaluations of various elements (not given here)*

| Definition of INVESTIGATION CLASS | | a. DEGREE OF DIFFICULTY a1. Low | a2. Moderate | a3. High |
|---|---|---|---|---|
| b. DEMANDS TO THE STRUCTURE | b1. Low | A | A | B |
| | b2. Moderate | A | B | C |
| | b3. High | B | C | D |

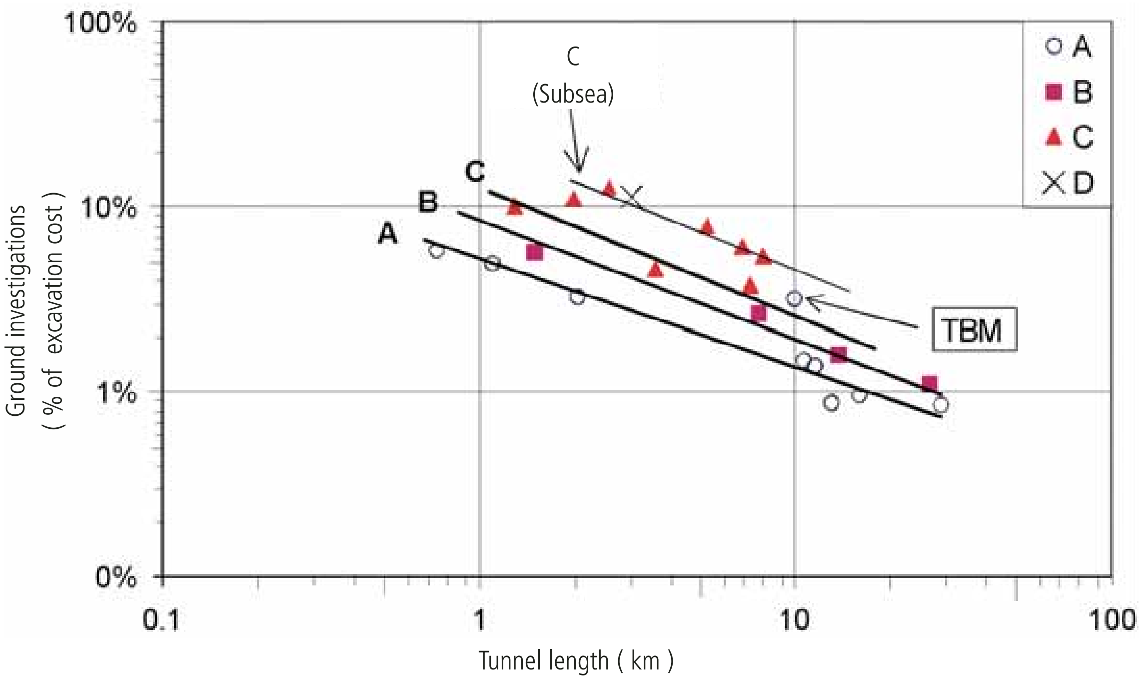


*Figure 9 Recommended amount of investigation (costs) for the investigation classes (A, B, C and D), given as percentage of cost for blasting and mucking out included rig, relative to tunnel length.*

The requirements to the accuracy of the cost estimates in the various stages of planning (Table 2) determine the amount for each of the four investigation classes defined.

It is important to stress that ground investigations cannot reveal all structures in the ground; therefore it is always possible to encounter unexpected conditions. The new geophysical investigation methods have made it possible to achieve more detailed information about the ground conditions, which contribute to more precise cost estimates. Well planned and executed investigations increase the knowledge of the ground and thus reduce the probability for unforeseen problems.

*Table 2 Approximate amount of investigation for each planning stage, and the demands for accuracy in the cost estimates for each phase*

| PROJECT PHASE | INVESTIGATIONS | |
|---|---|---|
| | Demands to accuracy of cost estimate | Distribution |
| Initial stage | ? | 1 - 5 % |
| Preliminary plan | ± 30 - 40 % ? | 7 - 15 % |
| General planning | ± 25 % | 15 - 35 % |
| Zone plan | ± 10 % | 25 - 60 % |
| Construction plan, Tendering | ± 10 % | 10 - 30 % |

# 4 Tunnel leakage and environmental aspects

The background for initiating the research programme was severe tunnel leakages during a specific construction project, the Romeriksporten railway tunnel towards Gardermoen Airport. The leakages caused damage on the surface, both to vegetation (Figure 10) and to buildings. The aim of this sub-project was to study the effects of groundwater leakage and develop procedures to quantify maximum allowable water inflow to a tunnel based on the possible or acceptable impact on the surface environment. The studies were carried out by the Norwegian Geotechnical Institute, the Norwegian Institute for Nature Research, the Norwegian Centre for Soil and Environmental Research and Norconsult.

The work involved a study of the correlations between water leakage into tunnels, changes in pore pressure and damage to the environment, both to vegetation and water sources and to urban structures. The acceptable amount of water inflow into a tunnel in a specific area can be determined by studying the correlation between a number of parameters. These include the water balance in nature, hydraulic conductivity of the rock mass and overlying sediments, the potential for settlements, the vulnerability of the vegetation and grouting procedures.

## 4.1 Numerical modelling

Modelling may be used to simulate the hydrogeological conditions before and after tunnel excavation, and to evaluate the relative importance of the different parameters used in the models. In this way, important information about the groundwater conditions may be provided in an early stage in the planning process. The hydraulic conductivity of the bedrock in Norway is generally low, with groundwater flowing along joints and weakness zones. The usefulness of numerical flow models will depend on realistic geological and hydrogeological input data and the boundary conditions established for the model.

*Figure 10*
*The tarn Puttjern which is situated above the Romeriksporten tunnel. It was nearly drained due to tunnel leakages, and later, due to response from neighbours, restored with grouting and permanent water infiltration (Photo: L. Erikstad).*

Several models are available for simulating water flow in jointed rock masses. Two main types were tested in this project to simulate groundwater flow, groundwater drawdown and the effects of sealing the tunnel:

- o Two-dimensional models, where the rock mass is modelled as a homogeneous material with average hydraulic conductivity
- o Three-dimensional model of water flow in a fracture network, providing a more detailed image of flow in the rock mass.

## Experiences from 2D modelling

Several example studies were performed to simulate groundwater flow and the effects of tunnel leakage and sealing in a homogeneous rock mass, in order to test the applicability of this type of model. A zone of low hydraulic conductivity around the tunnel in the model represents sealing of the tunnel by cement injection. The study shows that to avoid lowering of the groundwater table of more than a few metres, the leakage must be kept at 1 - 3 litres/ minute/100 metres tunnel. This will require a high degree of sealing effort, corresponding to a very low hydraulic conductivity of the sealed zone.

A second approach involves analysis of a local area with hydrogeological parameters and the interaction with overlying sediments included in the model. In a preliminary study the model was built to illustrate a typical landscape situation with, in a vertical section, bedrock in a local depression or valley bottom, overlying sediment layers and a water saturated area on top representing vulnerable nature elements. Simulations were performed to study how water inflow to a rock tunnel will affect the vulnerable surface area. The simulations were performed with varying hydraulic conductivities of each of the layers in the model. The results indicate that relatively small changes in the groundwater table may have an impact on the water saturated zone on the surface. The thickness and type and hydraulic conductivities of the individual sediment layers are the most important parameters. For example, a clay layer will seal off the groundwater and cause less water inflow. The relative position of the groundwater table adjacent to the local depression will also affect the amount of water inflow into the tunnel.

## Experiences from 3D modelling

A 3D discrete fracture network model was used to investigate the groundwater flow and to predict water inflow to a tunnel during excavation and after cement injection. The model was built by the Norwegian Geotechnical Institute using the computer program Napsac, which takes into account the heterogeneities existing in the rock mass.

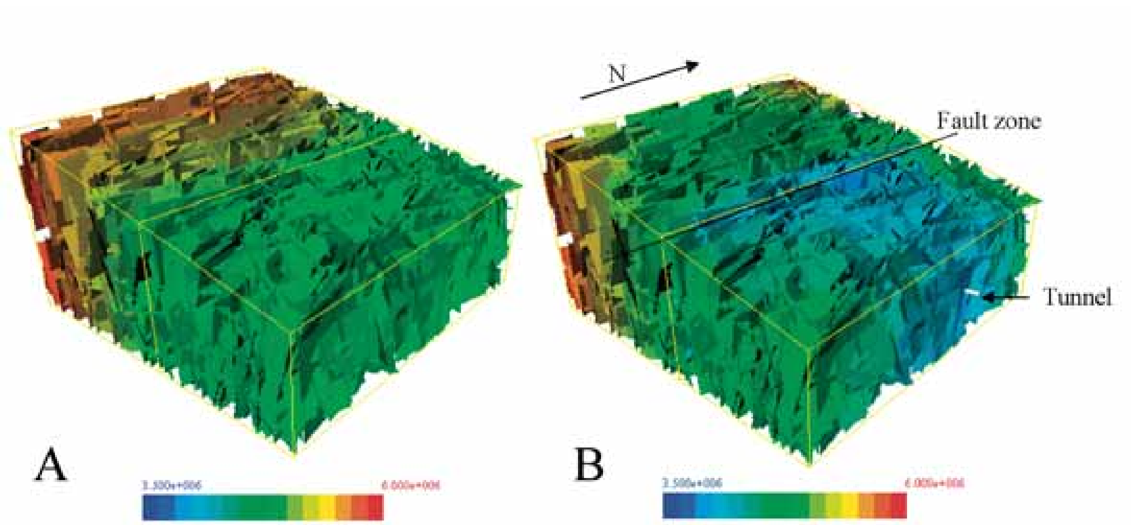


*Figure 11 Example of presentation of the steady state pore pressure distribution in a section of the Lunner tunnel.*
***A:*** *The pre-tunnel situation, with geological data and the model fracture network.*
***B:*** *Modelled effects of pore pressure change after tunnel excavation. The water will tend to flow towards low-pressure areas (blue).*

The Lunner tunnel was chosen as a field case because of its part in the research project and the large amount of data available from the field investigations. The numerical model covers an area of 550 m x 550 m along the tunnel (see Figure 11). It includes a fault zone which represents the boundary between hornfels and syenite. Joints and faults observed during the field mapping are included in the model, as well as results from borehole investigations and Lugeon-tests. Small-scale joints were statistically modelled, and used to generate a discrete fracture network.

The model provides a three-dimensional image of the water flow in the rock mass, and more accurate results compared with results obtained from 2D models. The limitation of the 3D model is the need for computer power, which in this case have put limits to the size of the area of investigation. Saturated transient and steady state calculations were performed to predict the amount of water leaking into the tunnel. The results from the simulation show that water inflow is high, with a large drawdown of groundwater. This is mainly caused by the fault zone which contribute significantly to the fracture network in the model.

The effects of cement injection of the tunnel was modelled by reducing the transmissivity of joints cross-cutting the tunnel. The results show that a reduction in the leakage rate is observed only after a significant reduction in transmissivity. An extensive injection of the fault zone was shown by comparison to be more effective than a moderate injection along the whole tunnel, although the leakages tend to increase on both sides of the injected section of the tunnel. Before cement injection a leakage rate of 900 l/min./100 m was predicted in the fault zone, with a significant drawdown of the groundwater table, which would in effect drain the model. Reducing the transmissivity in the fault zone by a factor of 200 will result in a leakage rate of 50 l/min./100 m, and a lowering of the groundwater table of 5 m.

Details of this study are found in Cuisiat et. al (2003). The simulations have so far indicated the potential for this type of numerical tool in tunnel planning. Further analyses are needed before this 3D model is ready for use on a major tunnel project.

### Tunnelling effects on the groundwater table

The effects of tunnel excavations on the groundwater table was shown by collecting data from a number of wells in the close vicinity of recently built tunnels. As would be expected, groundwater drawdown becomes less significant away from the tunnels. Changes which are caused by the tunnels are not observed beyond 200 to 300 metres from the tunnel axis. The available data shows, however, no clear correlation between leakage into the tunnels and the measured groundwater drawdown. In general, leakages of more than 25 litres/minute/100 m tunnel causes significant drawdown of the groundwater table (more than 5 to 10 m), and a leakage rate of 10 l/min./100 m or less causes a groundwater drawdown of 0 - 5 metres.

## 4.2 Accepted leakage in natural landscape

In order to evaluate the impact a tunnel excavation may have on the environment, it is necessary to assess the value of the surface environment, its sensitivity to a drawdown of the groundwater table and the risks of damage. The areas most vulnerable to damage due to drainage are identified as those having a groundwater table which is directly feeding water-dependent vegetation and surface water. The vulnerability increases with smaller size of the precipitation area. Changes in the groundwater table may also cause disturbance in the chemical balance of surface water due to erosion and oxidation of dried-up sediments, which can lead to a concentration of ions, salts and particles in the body of water. The vulnerability must be evaluated on the basis of practical use of the water source, the biodiversity and the presence of water-dependent vegetation.

A mapping programme with systematic registration of the vegetation above several tunnels with documented leakages was carried out in the course of this project by the Norwegian Institute for Nature Research. The aim was mainly to aquire new information about the relation between damage to vegetation and tunnel leakages. Systematic field mapping were not performed previous to the excavation of these tunnels, and the mapping programme thus focussed on the registration of visible

*Figure 12*
*Partly drained lake above the Tokke hydropower tunnel. Seasonal leakages cause significant variations in the water level. (Photo: A. Often).*

damage. Surprisingly little damage to the vegetation was recorded in this mapping. Some effects of drainage are easily identified such as ground settlements and dried-out ponds (Figure 12), but for the most part damage to the vegetation is not evident. It was concluded from the study that this may be due to the fact that the actual damage is unsignificant or is healed, that damage to certain species is undetectable due to lack of pre-tunnel investigation or that the scale of detail in the registration is not the appropriate for this type of investigation.

The areas most sensitive to groundwater drawdown as a result of tunnel excavation are generally quite small compared with the area above the total length of the tunnel. A method is proposed to locate potentially vulnerable areas and to classify the vulnerability of nature elements at the early stages of tunnel planning. The method involves an initial identification of the potentially sensitive areas from regional mapping. Features such as local depressions in the terrain are isolated, as these often contains water-dependent vegetation. The vulnerability of each area identified is then classified by the size of the local catchment area, for example calculated from digital hillshade models, and field mapping of the local geology and hydrogeology.

The method is well adapted to the most common geological situation in Norway, with a relatively thin layer of soil lying on top of crystalline magmatic or metamorphic rocks.
Local depressions in the terrain usually coincides with lineaments such as weakness zones in the bedrock, and this combined information is of importance both in finally establishing the tunnel route, decision of the excavation procedures and in the planning of sealing measures to protect the most sensitive areas.

The evaluation of acceptable changes on the surface environment involves a definition of the value of sensitive vegetation or surface elements along the tunnel route. In addition to economic value, the (non-monetary) values can be classified in terms of: 1) Nature, including biodiversity, 2) Recreational, and 3) Importance to local communities. The value of each element is graded according to a pre-set scale, for example according to local, regional or international interest, or high to low value.

The accepted impact on the surface is not determined by the leakage rate, as a relatively low leakage may cause severe damage in more sensitive areas. The accepted consequences will be defined by the value of the area, for example a high value implies a low acceptance level. The level of acceptance for each area may be converted into a maximum allowable leakage rate along the respective sections of the tunnel.

## Procedure to determine accepted leakage rate in sensitive landscapes

The recommended procedure for establishing leakage requirements or accepted impact in relation to consequences for the environment is summarized as follows:

- Overall analysis of vulnerable areas. Combined with a general risk assessment this gives an overview of the probability of changes and the size of the impact. This forms the basis for more detailed analyses of selected areas.
- Both a regional overview and details of specific areas are needed. Detailed investigation is performed for the vulnerable elements.
- Define a value for each of the vulnerable elements
- Describe the accepted consequences based on the obtained value
- State a figure for accepted change in the groundwater table, or water level in open sources.
- State a figure for accepted water ingress to the tunnel. Evaluate both with regard to the length of the tunnel and for ingress concentrated to a shorter section of the tunnel (least accepted change).
- Define a strategy for possible adjustment of the tunnel route, tunnelling method and measures to seal the tunnel, in the areas where tunnel leakage is likely to cause unaccepted changes or damage.

## 4.3 Accepted leakage in urban areas

The requirements on maximum water inflow into tunnels in urban areas are related to possible soil settlements which may cause damage to buildings and other surface structures. Experiences from Norway, collected by the Norwegian Geotechnical Institute, show that the risk of damage is highest in areas where the building foundations are placed on soft marine clay deposits. Groundwater leaking into a rock tunnel can cause significant reduction in the pore pressure at the clay/rock-interface, which leads to consolidation processes in the clay and subsequent settlements. This situation with marine clay deposited on bedrock is found in the Oslo region, which represents the most heavily populated area in Norway. Data from measurements on pore pressure reduction at the clay/rock-interface and leakage rates are compiled from a number of rock tunnels excavated in the region; for roads, railway, metro and sewers (Figure 13).

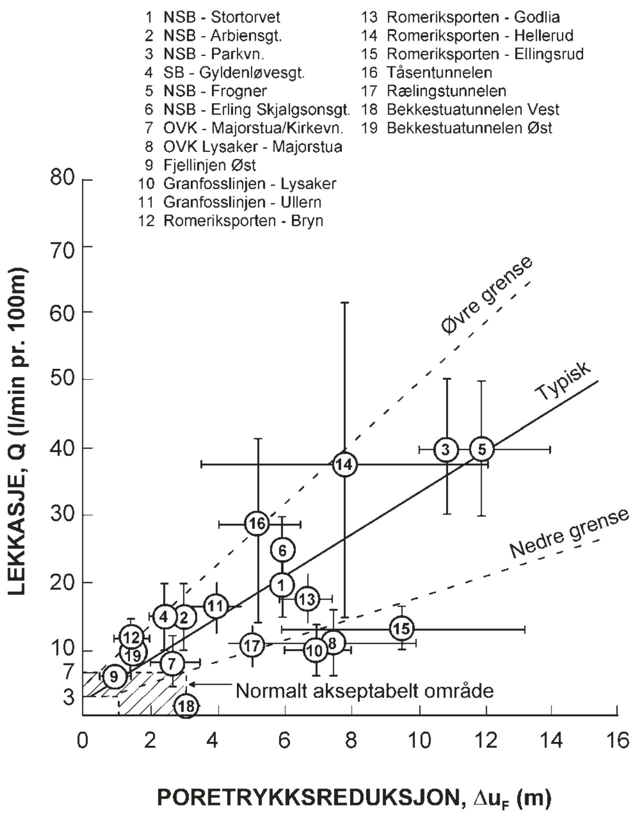


*Figure 13 Correlation between pore pressure reduction $\Delta u_F$ (m) above existing tunnels, and leakage rate, Q (in l/min./100 m). The data forms the basis for a recommended acceptance level for leakage in this type of rock/clay-underground, shown by a characteristic area (hatched).*

From the data in Figure 13 it is possible to predict the pore pressure reduction in clay deposits caused by a tunnel excavation. The data forms the basis for the recommended procedure to establish maximum allowable water inflow into a tunnel. The data indicate that an acceptable limit to the leakage rate should be 3 - 7 litres/minute/ 100 metres tunnel, which corresponds to a pore pressure reduction of 1 - 3 metres (Figure 13).

The pore pressure reduction decreases with distance from the tunnel, with an average of 2 metres per 100 m horizontal distance from the tunnel. The measurements are locally affected by the thickness of the sediment deposit, sediment types, joints and weakness zones present in the rock and the extent of cement grouting in the tunnel. The study shows that systematic grouting is necessary to fulfil strict leakage requirements. There is a clear correlation between the grouting procedures used in the tunnels, the amount of grout cement used, lenght of the boreholes and the resulting hydraulic conductivity in the rock above the tunnels. Recently excavated tunnels generally shows better results in terms of fulfilled requirements, mainly due to improved grouting techniques and materials.

The potential for consolidation settlements in the sediments in relation to pore pressure reduction can be determined from soil sampling and laboratory analyses. Clay deposits generally contain small amounts of water and the groundwater table will not be influenced significantly by leakage. Drawdown of the groundwater table is shown to occur mainly in areas where the clay deposits have a limited extent or where the clay deposits are shallow.

An accepted maximum settlement is related to the value and the type of type structures on the surface. For example, two major construction projects in Oslo have requirements to maximum settlements in the sediments above the tunnel excavation sites of 10 mm and 20 mm respectively, in order to keep the possible influence on surface structures to a minimum.

## Procedure to determine accepted leakage rate in urban areas

The recommended procedure for estimating requirements for leakage rate is based on the measurements of pore pressure changes in the clay/rock-interface:

- Specify accepted maximum consolidation settlement in the ground above the tunnel
- Produce a map of soil cover, type and thickness, along the tunnel
- Calculate settlements in terms of pore pressure changes for any sediment/clay-filled depression identified
- Identify buildings exposed to settlements at the vulnerable sites, and calculate maximum allowable pore pressure change for this area
- Establish requirements for sealing of the tunnel based on the acceptable pore pressure change above the tunnel.

# 5 Techniques for groundwater control

Techniques for groundwater control are studied in this project, with the aim of improving conventional techniques and development of new methods. Safe and efficient methods for sealing are of special importance in tunnels with strict requirements for water ingress. The best method by far, for sealing rock mass to reduce groundwater ingress to tunnels, is cement grouting ahead of the tunnel work face (pre-grouting). The project activities included studies of grouting strategies for pre-grouting of tunnels, procedures for both systematic grouting and grouting adapted to difficult geological conditions and complex tunnel design, as well as procedures for time efficient grouting. In addition, the project evaluated natural sealing processes and water infiltration.

As a result, a specific grouting strategy is systematized, based on tests performed on site during tunnel excavation, laboratory tests and a compilation and evaluation of grouting performances in several recently built tunnels. The improved grouting strategy is very efficient and give good control on the amount of water ingress to the tunnel after grouting. Also, the grout materials used are environmental friendly cements.

A major part of the work in this sub-project was monitoring of grouting procedures and practical tests of grouting strategies in ongoing tunnel construction projects: T-baneringen (Metro tunnel in Oslo), the Jong-Asker railway tunnels and the road tunnels Hagan and Lunner just north of Oslo.

## 5.1 Laboratory testing of grout cements

Laboratory tests were performed for the documentation of the properties of cement types used in tunnel grouting, and an evaluation of the usefulness of performing laboratory tests on these materials. Testing of cements was performed by conventional laboratory methods, using the actual cement types used in the grouting of the Metro tunnel. In summary, the tests showed that water/cement-ratios (w/c-ratios) higher than 1.0 result in too long hardening time, the control of the actual w/c-ratio is best done by measurements of density, and only fresh cements (newly produced) should be used. Test results gave no indications that the temperature of the cement during grouting is of importance, but the temperature of the injected rock may inflict on the hardening process.

A significant part of the project was the construction of an apparatus for testing injection properties of grout cements. This work was carried out by SINTEF. The apparatus consists of two parallel glass plates pressed in contact with each other, one of the plates has tracks which simulate joints. Cement suspensions are injected between the glass plates and instruments register the inflow (penetration) capacities of the cements. The aim of this test model is to provide comparative results for different cement types, under similar and controlled conditions. The test model was not able to provide results during the time span of the project, but is under further development to become ready for commercial use.

## 5.2 Grouting strategies

The project group carried out a test programme in cooperation with the builder and contractor of the Metro tunnel in Oslo, in connection with the grouting procedures during tunnel excavation. The aim was to confirm the grouting technique that most efficiently provides sufficient sealing of the rock mass.

The Metro tunnel is 1240 m long and part of the new Metro Ring system in Oslo. The rock overburden of the tunnel is between 5 and 25 metres, and with a cover (0-20 m) of sediments (clay). Due to risk of settlements in the clay causing damage to buildings, the requirements for water ingress to the tunnel after grouting was between 7 and 14 l/min./100 m, and grouting was performed for most of the tunnel. The tunnel was completed in 2002. Tests of materials and grouting methods were carried out along different sections of the tunnel construction site adjusted to the rock mass quality, rock cover and demands for water inflow (see Figure 14).

Some of the tests and results are listed below:

- An evaluation of grouting procedures proved that systematic pre-grouting of the tunnel is more efficient than sporadic grouting. Sporadic grouting involves adjustment of the procedure based on results from measurements of water leakage in probe holes, and the risk is that water will seep towards non-grouted sections of the tunnel. A systematic grouting schedule is both more time efficient and it gives far better and more reliable results.
- A water/cement-ratio lower than 1.0 is necessary to provide rapid and sufficient sealing, the ratio may be as low as 0.5. This was also confirmed by the laboratory experiments. Silica additives to the grout mix and improved pumping capacity make injection of this thick cement grout possible.
- A low water/cement-ratio requires high pressure pumping, up to 10 MPa, which 'kick' the grout into the finer joints and assures that the rock mass close to the tunnel is sealed.
- Different types of cement grouts were used under similar rock mass conditions and requirements for water ingress. In this particular tunnel, no difference in the results from standard cement and microcement was recorded.
- Tests were performed of optimum grouting time consumed compared with the total excavation time and the result of grouting, by adjusting the work procedures. The most time efficient procedure would be a fast construction progress, with the criteria for water ingress fulfilled from a single round of grouting. The adjustments proved very efficient when working through good rock mass quality and not so strict sealing requirements.

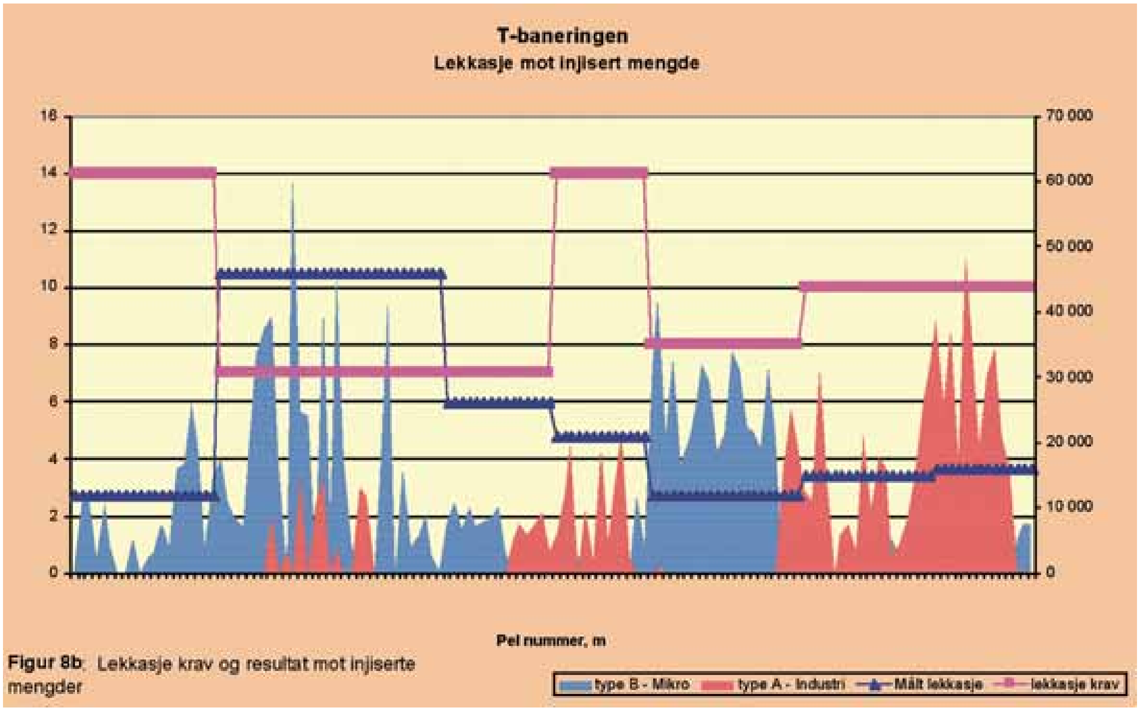


*Figure 14 Example of results of the grouting of the Metro tunnel: water leakage and amount of grout cement along the tunnel route. Horizontal lines: red= pre-set requirements for leakage (in l/min./100 m), blue= measured water ingress after grouting. Amount of cement grout used: blue= microcement, red= standard cement.*

The procedures which were followed during excavation through a particularly difficult weakness zone with strong water inflow is also well documented. The zone is 50 metres wide and needed special attention on grouting procedures and rock support. The requirements for water ingress to the tunnel as a whole was fulfilled, with an average of 4.3 l/min./100 m. The exception was the weakness zone, where water leakage is up to 8 l/min./100 m. As a result, water- and frost protection measures are reduced for parts of the tunnel.

### Documentation of grouting procedures: mapping of experiences

A selection of eight newly built tunnels (7 in Norway, one in Sweden) are examined with regard to experiences from grouting of the tunnels. The mapping procedure involved interviews with on-site personel representing both owners, builders, consultants and contractors. The selection criteria for these tunnels were strict requirements for water inflow (2-20 l/min./100 m), and carefully planned and well documented grouting strategies. The experiences with different types of rock, the grouting strategies under various conditions, equipment, materials, performances and final results are mapped and compared. The detailed results from the mapping is listed in tables which have proven to be of significant importance when planning the grouting strategy for new tunnel construction projects.

The general conclusions from the experiences are comparable to the experiences from the Metro tunnel, such as the advantage of systematic, cement-based grouting, low water/cement-ratios and high pressure pumping, as well as careful supervision of the grouting procedure with adjustments to improve both efficiency and a safe result. These conclusions form the basis of the recommended pre-grouting procedure ('Active grouting', see below).

## 5.3 Natural sealing processes

In Norwegian tunnels, water ingress tend to decrease with time. In most cases this could only be caused by natural sealing. Laboratory

*Figure 15 The Tanum tunnel (Jong-Asker railway). Markings of injection holes in the tunnel work face.*

experiments were carried out by Aquateam with the aim of tracing the sealing mechanism and to find out if this mechanism can be put to practical use in tunnels. Water samples from a selection of tunnels were analysed; sub-sea tunnels and one land tunnel. The main results show that the water leaking into the tunnels is rich in particles of iron, and contain lesser amounts of calcium, barium and manganese.

Laboratory testing showed that oxygen injected to sand columns containing $Fe^{2+}$ caused oxidation to $Fe^{3+}$ and subsequent deposition of the iron, the rate depending on the particle size within the column. The results of these tests are interesting, but further tests are needed to find out if water leakages can be reduced by accelerating natural sealing processes.

## 5.4 Water infiltration

Groundwater infiltration is used to control the pore pressure temporarily during excavation of tunnels. The reduction of pore pressure in sediments due to water leakage into a tunnel may cause settlement and significant damage to the surface areas and to buildings. In this project, experience from water infiltration over 20-30 years is compiled in a report from the Norwegian Geotechnical Institute.

The conclusions from the evaluation are that infiltration holes must be placed in bedrock, and established as result of good knowledge of the hydraulic conductivity of the rock mass and the nature of sediment deposits. Wells placed in sediments are unpredictable and have occasionally caused severe problems due to erosion. Furthermore, water infiltration should be used as a temporary measure during construction only. All of the permanent installations that are in use today were not planned as such, and had to be kept in function due to insufficient sealing of the tunnel or underground structure. These installations do not guarantee that the pore pressure is maintained and are costly due to the unforeseen, long term, 'indefinite', operation and maintenance.

## 5.5 Pre-grouting techniques

Theoretical and empirical background for high-pressure grouting

A theoretical and empirical background for high-pressure grouting is assembled for this project by N. Barton and Associates. The report describes the problems, and some solutions, concerning pre-injection in jointed and faulted rock masses ahead of tunnels. The application of very high pressure pre-injection for sealing and improving the stability of tunnels, has focussed

*Figure 16 Grouting in the Hagan tunnel syenite*

attention on the need for quantitative explanations of grout take volumes and on the effects on the rock mass, of the 5 to 10 MPa injection pressures. The report provides explanations of joint properties and change when the rock mass is subjected to high-pressure grouting of thick cement grout.

In conclusion, there is practical evidence and empirically-derived support for increased seismic velocities, increased deformation modulus, reduced deformation, reduced permeability, and reduced tunnel support needs as a result of successful high-pressure pre-injection with stable cement grout.

## Rock mass quality

The quality of the rock mass will determine the choice of grouting strategy. The rock masses that are most common in the bedrock of Norway are here divided into four groups based on experiences from engineering geology and their general properties during grouting. For each group, the number of injection holes, length of holes, water/cement-ratios and cement types are recommended, as summarized below.

The rock mass is divided into the following categories:
A. Open joints with little or no clay filling, found most frequently in sandstones, quartzites, syenites, granites. The hydraulic conductivity of the rock mass is relatively high, and the rock mass has low resistance to grouting. In general, few and long injection holes are used, and low water/cement-ratios.
B. Jointed rock mass with joints partly filled to produce local channels. This situation is frequently found in gneisses, which represent a major part of the Norwegian bedrock. The joints are typically filled with clay minerals weathered from feldspar minerals. The rock mass is less easy to grout, and the injection strategy must be adjusted to the local rock mass condition. The procedure is generally an initial high w/c-ratio (c. 1.0) and relatively low injection pressures, towards a final low w/c-ratio and high pressure pumping (up to 10 MPa). The high injection pressure is important in order to establish communication between joints.
C. Dense, plastic rock masses represented by metamorphic rocks such as mica schists, phyllites and greenschists. Joints are typically filled with clay, and have small channels occuring on narrow joints. The hydraulic conductivity of the rock mass is low, and grouting may be difficult. In order to grout the small and scattered channels, many short injection holes are needed. An initial high w/c-ratio (c. 0.9) and microcement is used, with a final lower ratio and high pressure pumping.
D. Rock masses with extremely open joints as a result of fault zones or karst. Tunnelling in these rock masses will require extraordinary efforts, for example injection of coarse masses. It is important to locate these zones at an early stage so that the grouting procedure may be properly planned.

## 'Active grouting'

A recommended procedure for pre-grouting is presented, based on the results from this project combined with the compilation of well documented and successful grouting results in various rock masses. The foundation for the application of this grouting strategy is an understanding of rock mass quality, grouting pressures, cement properties, the amount of cement and cement additives used, the geometry of the grouting fan and the number of injection holes in the tunnel work face.

- Low water/cement-ratio combined with high pressure pumping is the main condition for successful grouting. The w/c-ratio should be as low as practically possible (down to 0.5) in order to obtain a marked pressure loss away from the tunnel. This assures that the cement is concentrated close to the tunnel. The pressure build-up in each separate hole must be constantly surveilled, with adjustments of the w/c-ratio based on the observations. The pressure build-up should increase steadily to allow a smooth cement inflow, and with a final injection pressure as high as is possible (10 MPa is the maximum capacity of most of today's pumps).
- The type of cement is adjusted to local geological conditions, both standard cement and the fine-grained microcement are used. Additives of superplasticizers and silica increase the flow stability of the cement grout. It should be noted that with the cement grout mix and the pump capacity for handling dense masses, there is no longer need for the highly toxic chemical grouts.
- The tunnel is to be grouted from the sole and upward. In this way, the water is pushed up and away from the tunnel. The grouting is most efficient when using many

holes and as long holes as possible. The holes must be placed both circling the profile and in the centre of the work face. The geometry and the length of the holes in the grouting fan must be adjusted to the local conditions. An initial situation with many holes is recommended, with an adjustment based on observations and adaptations to the rock mass condition on the site. Use of modern injection rigs with two or more separate grouting lines increases the efficiency.
- Systematic grouting where the leakage requirements are strict have proven to give the best results. Where the rock mass quality is favourable, the grouting procedure may be adjusted to a more time efficient 'factory' performance.
- A successful sealing, with little or no water leakage into the tunnel will reduce the need for water- and frost protection and rock support measures.
- Continuous supervision, control and adjustment of the grouting procedure as well as an experienced professional crew is the key to a successful result.

In conclusion: It is possible to build technically very complicated tunnels with total control on the groundwater by using systematic cement-based grouting ahead of the tunnel working face, based on the principles of active grouting. This is of particular importance in areas where the tunnel construction is not to cause unwanted environmental consequences.

# Participating firms in the research and development programme (2000-2003):

Norwegian Public Roads Administration (www.vegvesen.no)
National Rail Administration (www.jbv.no)
Geological Survey of Norway (www.ngu.no)
Norwegian Geotechnical Institute (www.ngi.no)
Norconsult AS (www.norconsult.no)
Multiconsult AS (www.multiconsult.no)
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Research Council of Norway (www.forskningsradet.no)
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# Publications:

The results from the research programme are presented in a total of 40 reports, and are summarized in five Publications from the Norwegian Public Roads Administration, Directorate of Public Roads (Statens vegvesen Vegdirektoratet). These are available in Norwegian only.

**Publications:**

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