Proc. 30th ITA World Tunnel Congress, Singapore May 2004, Vol.2:1327-1335

Site investigation results versus tunnelling conditions – a study with emphasis on water leakage based on Norwegian cases

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ABSTRACT

Two tunnels are studied, the Lunner road tunnel, located approximately 40 km North of Oslo, and the Skaugum railway tunnel in suburban Oslo. The 62 m^2 Lunner tunnel is 3.8 km long and had breakthrough in October 2002. The 104 m^2 Skaugum tunnel is still under construction, with planned breakthrough in April/May 2004. In this paper the results from the different site investigations are discussed and compared with what has been experienced regarding water leakage in the two tunnels. Particular emphasis is placed on discussing what the different investigation methods may give of information, and what limitations there are.

1. INTRODUCTION

This work is a part of the NFR (Research Council of Norway) R & D project “Tunnels for the citizen”, which has main focus on problems represented by large uncertainties concerning the permeability of the rock mass. When planning tunnels the main uncertainties are often connected to where water leakage will appear, how much water may flow in, and what problems the water may cause.

Two tunnels are studied, the Lunner road tunnel, located approximately 40 km North of Oslo, and the Skaugum railway tunnel in suburban Oslo. Both projects are located in the so-called Oslo Region, which is a geologic region of about 100,000 km^2 with rocks younger than in the surrounding Precambrian areas. See Figure 1 for a geological sketch of the Oslo Region. In a North-South direction its length is 200 km, reaching from the outer southern part of the Oslo fjord to the Lake Mjøsa district in the North. Its width varies between 35 and 65 km. The Oslo Region contains a sedimentary sequence of Cambrian, Ordovician and Silurian rocks as well as sediments and plutonic and volcanic rocks of late Carboniferous and Permian age.

2. INVESTIGATION METHODS

The Lunner- and Skaugum tunnel are thoroughly investigated, prior to as well as during excavation. The owners have carried out “traditional” investigations and in addition, the R & D project “Tunnels for the citizen”, have done some extra investigations to test and gain experience with different investigation methods which have not been in common use in Norway.

The pre-investigations carried out by the owners have been: desk studies of available geological information including air photos, detailed surface mapping (structural geology), refraction seismics and core drilling. These methods are well known and will not be described here. The main extra investigations have been: geo-electrical methods and geophysical measurements including flow measurements in boreholes. Since the latter investigation methods are not common in Norway the principles are explained below in some detail. The Geological Survey of Norway (NGU) has done most of the investigations for the R & D project.

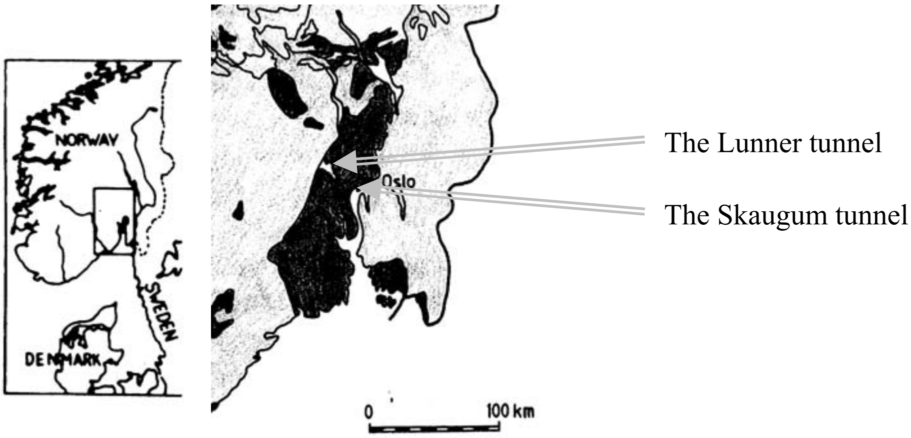

Figure 1: Geological sketch showing the Oslo Region.

2.1 Geo-electrical methods

The purpose of Continuous Vertical Electrical Sounding (later called CVES) is to determine the subsurface resistivity distribution by measurements on the surface. By gradually increasing the distance between current and potential electrodes, information from deeper and deeper parts of the subsurface is collected. The cable and monitoring system are developed at the Lund University, (Dahlin, 1993). Different electrode configurations have been tested, and so far the Wenner configuration seems preferable when it comes to noise and time consumed. Low resistivity can indicate jointed rock mass and increased conductivity, but it can also be electrical leading minerals such as sulfide and oxide or clay minerals. Maximum depth for the resistivity measurements is 120 m, but best resolution is achieved in the uppermost 50 to 60 m.

2.2 Geophysical measurements in boreholes (borehole logging)

Holes with a nominal diameter of 145 mm are bored by percussive boring. Experience has shown that the boreholes should be allowed to stand for minimum 2 weeks, to reach stable conditions and obtain good visibility. In this project three probes from Roberston Geologging are used, see Figure 2. To initiate the measurements a probe that provides a continuous, depth based measurement of temperature and conductivity of the water and natural gamma in the rock is used. The results give location of zones of different water quality, and identification of zones of in-flow/out-flow.

The second probe is an Optical Televiewer Probe (OPTV). This gives a detailed and orientated image of the borehole wall by using an optical imaging system. Traces of various geological features are recorded on the imagery, so that for instance bedding, fractures and different types of veins can be identified. Fractures with aperture from 0.5 mm and up are easily detected. Based on the registrations it is possible to obtain a complete feature analysis including dip, strike, frequency and fracture aperture along the borehole. The third probe is a electric logging probe, measuring the resistivity of the rock mass down the borehole.

To conclude the geophysical measurements in the boreholes, hydraulic testing of the boreholes is done. A pump is submerged in the borehole (pump location varies depending on the groundwater

Figure 2: Left: Picture of the three probes. Upper right: detail of optical televiewer with hyperboloidal mirror, lower right: a probe is lowered into the borehole.

table, but is typically 15 to 20 m below the groundwater level). During pumping flow rate in the borehole is measured (as revolutions per minute, RPM) with a high sensitive flowmeter probe. Measurements are done both down and up the borehole, and based on the results inflow along the borehole is calculated, indicating location of water bearing zones or fractures. Data from the submerged pump (pump out rate) together with changes in groundwater level during pumping can indicate the well capacity.

3. THE LUNNER TUNNEL

The 62 m^2 and 3.8 km long Lunner road tunnel had breakthrough in October 2002. The rock cover of this tunnel varies between 20 and 230 m. For environmental reasons sections in the tunnel have strict inflow criteria of only 10 or 20 l/min·100m. During excavation large water leakages were encountered.

3.1 Geology

The Lunner tunnel is located approximately 40 km North of Oslo, geologically it lies in the Oslo Region, crossing the boundary between the sedimentary sequence (Cambrian, Ordovician and Silurian rocks) and the plutonic and volcanic rocks (late Carboniferous and Permian age). The rocks along the tunnel can be divided into four rock types: hornfels (contact metamorphism of limestone and shale), syenite, different volcanic rocks and sandstone/conglomerate. Figure 3 shows the distribution of the rock types along the tunnel. Some intrusive dykes cut through the rock mass, but are not shown in the Figure.

The hard and fine-grained hornfels is heavily jointed compared with the blocky and moderately jointed syenite. Regionally the joints are N-S striking with steep dip. In syenite and the volcanic rocks a joint direction with strike NW-SE and steep dip is almost as frequent. Several weakness zones have been identified, all with the same directions as the dominating joint directions. A major zone of weakness is found in the hornfels-syenite contact.

3.2 Investigation results

A lot of investigation have been carried out for this tunnel project, (NGU, 2001-2002) and (Geomap, 1997), and it is not possible to describe all details of the investigation results in this paper. The section between profile numbers 2,220 and 2,561 is however particularly interesting because the largest water leakage was encountered here and a lot of site investigations were carried out, see Table 1.

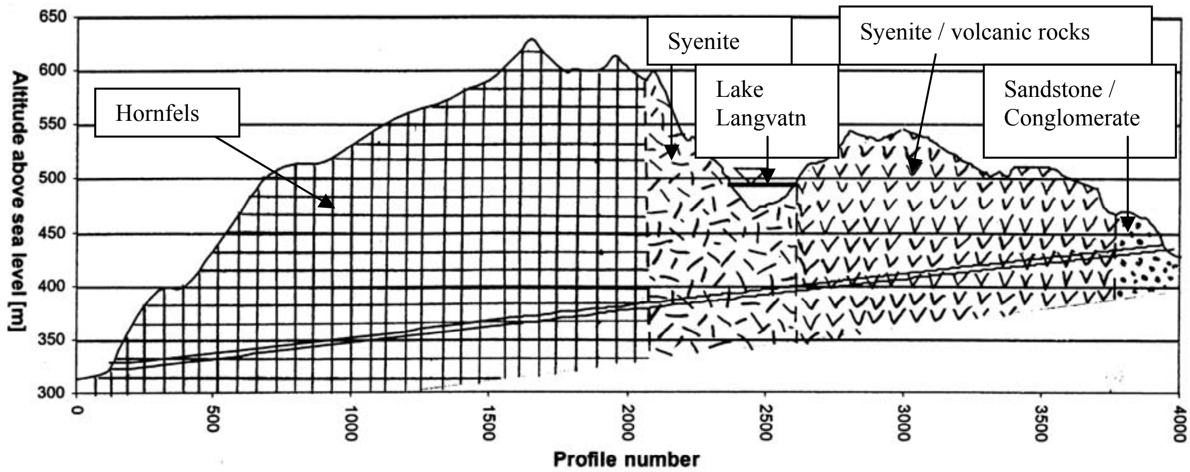

Figure 3: Simplified geological longitudinal profile of the Lunner tunnel. The direction of the tunnel is approximately E–W.

The resistivity measurements show different resistivity levels for syenite and hornfels. In syenite the resistivity is 5,000 ohmm or higher and in hornfels it is less than 5,000 ohmm. This most likely is due to the fact that the hornfels is much more jointed than the syenite.

3.3 Geological conditions and water leakage encountered

The hornfels-section was almost completely dry; only between profile numbers 1,780 and 1,820 water was encountered in a jointed zone. At the boundary between hornfels and syenite (profile number 2,220) one pre-grouting round gave as much as 2,500 l/min. High water leakage was encountered in the syenite throughout the section under Langvatn (profile numbers 2,220 – 2,561). The boundary between hornfels and syenite is a major weakness zone (fault) with clay filled joints. The water leakage came in small channels in the clay filling, and caused a lot of water inflow, and difficult conditions for pre-grouting. A total inflow of 16,325 l/min in a section of 341 m (between profile numbers 2,220 and 2,561) was measured here in pre-grouting holes.

In the eastern part of the tunnel water leakage was encountered in some sections, but not as much as in the section between profile numbers 2,220 and 2,561.

Table 1: Summary of site investigations between profile numbers 2,220 and 2,561.

Profile number	**Site investigations**	**Results with comments**
2,220 – 2,561	Refraction seismics, 4 profiles of 115 meter	2 low velocity zones (3,300 and 3,900 m/sec) in the western part of Langvatn and close to the western shore.
	Core drilling including Lugeon testing, 1 hole ~450m	100 m of poor to extremely poor and 250 m of good quality rock mass. Lugeon value up to 4.25, but mostly less than 1. Main rock boundary intrusive and not particularly jointed. Poorest rock mass quality expected between profile numbers 2,250 and 2,400.
	2-D resistivity measurements. One profile S and one N of the tunnel.	2 low resistivity zones seem to reach the tunnel depth. One zone (40 ohmm) correlate with the boundary between hornfels and syenite, the other (1000 ohmm) is in the northern part of Langvatn.
	Borehole logging and hydraulic test pumping. 4 boreholes close to the boundary between hornfels and syenite.	Poor rock mass quality, with jointed and crushed zones. Two boreholes collapsed at the lowest parts. 250 ohmm registered just above the collapsed section. Well capacity at the two boreholes 7 and 13 m^3 /hour.

Table 2: Expected versus encountered water leakages in a section of the Lunner tunnel.

Profile numbers	**Prognosis**		**Water leakage in the tunnel**	
	Inflow, this section	Inflow (l/min·100m)	Inflow, this section	Inflow (l/min·100m)
2,220 – 2,270	120 l/min	240	6,781 l/min	13,562
2,270 – 2,310	40 l/min	100	665 l/min	1,663
2,310 – 2,390	440 l/min	550	3,397 l/min	4,246
2,390 – 2,561	85 l/min	50	5,373 l/min	3,142

3.4 Site investigation results versus tunnelling conditions

Based on the results from site investigations a prognosis, "best estimate", for water leakage was made before the tunnel was excavated, (Holmøy, 2002). The prognosis for the section between profile numbers 2,220 and 2,561 is shown in Table 2, and the respective inflows in the tunnel are also given.

The Table shows that the amount of water leakage was much higher than expected. The location of major leakages were however mainly as expected. A peak in water leakage was encountered between profile number 2,220 and 2,270 (expected due to low resistivity and results from borehole logging). The section between profile numbers 2,270 and 2,310 shows a little decrease in water leakage, but still high inflow. Between profile numbers 2,310 and 2,390 high water leakage was encountered (expected due to results from core drilling, resistivity measurements and refraction seismics). In the eastern part of the Langvatn the prognosis was 50 l/min·100m, but the encountered water leakage is approximately 60 times as much. In this section the rock mass was a weakly jointed syenite, with open joints. The core drilling indicated good quality rock mass in this section, with Lugeon values less than 1, indicating moderate water leakage. The assumption that water leakage often comes in connection with weakness zones was not the case here.

4. THE SKAUGUM TUNNEL

The 104 m^2 Skaugum railway tunnel is under excavation, with planned breakthrough in April/May 2004. This paper will discuss the results until 15^{th} July 2003. The tunnel is one of two tunnels between Jong and Asker in the western part of Oslo. The rock cover varies between 3 and 100 meters. For environmental reasons and due to the risk of harmful settlement of buildings on surface (densely built-up areas), very strict criteria concerning water inflow in the tunnel were defined. Inflow criteria vary from 4 to 16 l/min·100m (water leakage after pre-grouting). To meet these inflow criteria it have been decided to carry out continuous pre-grouting in the tunnel.

4.1 Geology

The Skaugum tunnel is located in suburban Oslo, and geologically in the Ordovician and Silurian sediments, predominantly shales and limestones, of the Oslo Region. The sediments were compressed from NW during the Caledonian folding, and folds and faults were formed with gently dipping foldaxis towards ENE or WSW. Two main directions of cracks is registered, one parallel to the foliation; strike ENE-WSW dipping towards NW, and one perpendicular to foliation; NW-SE. Permian igneous dykes (diabase and porphyry syenitic) cut through the sediments. The widths are varying from a few centimeters up to several tens of meters.

4.2 Investigation results

At present (15^{th} July 2003) tunnel excavation from the central adit has reached profile numbers 20,100 and 22,500, and the investigation results from this section are presented below.

Based on the desk studies of available geological information, including air photos, and detailed surface mapping a major fault zone seems to strike almost parallel to the tunnel. This main fault zone is expected to cross the tunnel around profile number 20,960. The same fault zone is expected to have a branch crossing the tunnel around profile number 22,030. The section between 22,000 and 22,500 (later called the Skaugum area) is within an urban area and mostly covered with soil, and more extensive site investigations were therefore necessary. Core drilling, refraction seismics, electrical measurements and borehole logging was carried out, (Norwegian National Rail Administration, 2001) and (Dalsegg et al., 2003).

Four refraction seismic profiles were shot, but no main fault zone was recognised. Instead several low seismic velocity zones were registered (velocities between 2,500 to 3,500 m/sec). These zones are indicated in Figure 4.

Based on the results from the refraction seismics a 200 m core-drilling hole perpendicular to the tunnel was carried out. The hole is crossing the tunnel at profile number 22,025. The rock mass from the core drilling consists of alternating shales and limestone. Filling in the joints consists of calcite and silt, some clay is registered in the lowest 50 meters. No major weakness zone was registered.

Three CVES profiles have been carried out in the Skaugum area. The results show a general resistivity level from 1,000 to 4,000 ohmm. A low resistivity zone (down to 20 ohmm) between profile number 22,120 and 22,200 was registered, and the zone seems to continue below the tunnel level.

Borehole logging was carried out in a borehole located approximately 75 m West of profile number 22,030. The borehole is 118.5 m long, and the end of the borehole is a few meters above the tunnel level. The optical televiewer showed that the borehole is most heavily jointed in the lowest part. Joints with aperture are observed at 28, 44.2 m and 59 m. The conductivity of the water changes at 8.5 and 28 m, and this can indicate water-bearing joints. The resistivity measurements in the borehole show an average resistivity of 500 to 600 ohmm, with local zones down to 200–300 ohmm. Several joints and fractured zones are indicated as low resistivity zones, and these are verified by the optical log. The hydraulic testing gave a well capacity of approximately 2m^3/hour, with water leakage from joints at 28, 38, 44, 52, 59 and 66 m.

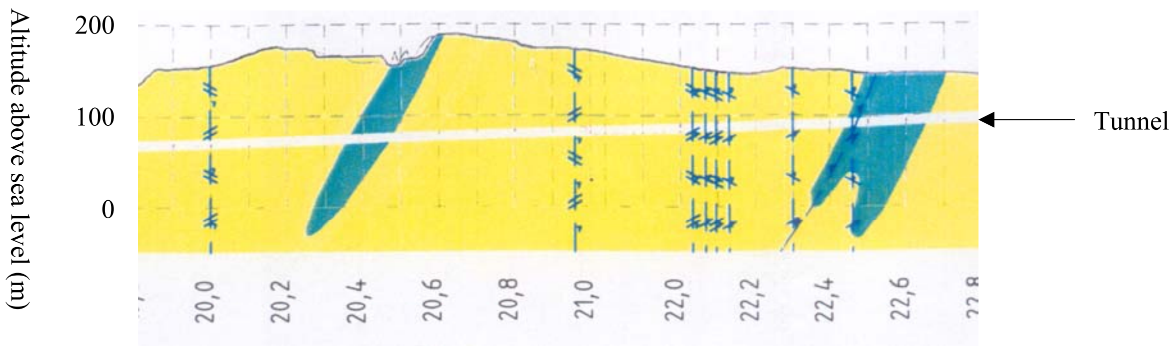

Figure 4: Longitudinal profile of a section of the Skaugum tunnel. Dark colour indicates the Bærum-group and brighter colour the Oslo-group. The direction of the tunnel in this section is close to N-S.

4.3 Geological conditions and water leakage encountered

The amounts of water given below refer to water leakage from all pre-grouting holes at one pre-grouting round, consisting of 48 holes of 24 to 28 m. The water leakage is therefore water encountered before any pre-grouting was carried out.

The rock mass quality in average has been poor to fair, with Q-values between 2.5 and 10. Fractured rock mass with some clay and calcite has been encountered, and in a few weakness- and fault zones the rock mass has been crushed in the central part (2-5 cm). Generally the central parts of the fault zones have had some clay filling, and water has come in the fractured zone adjacent to the fault. No major stability problems have been experienced.

Generally the water leakages of the pre-grouting rounds until now have been less than 100 l/min, but in some sections more water has been encountered. In Table 4 these sections are listed together with a short description of the geology.

Three of the sections mentioned with water leakage are connected to a synclinal boundary, where the rock mass in the synclinal belongs to the Bærum-group and the rock mass outside belongs to the Oslo-group, see Figure 4. The rock mass is limestone in both groups, in the Oslo-group the limestone is nodular and somewhat more jointed than the limestone in the Bærum-group.

4.4 Site investigation results versus tunnelling conditions

The low resistivity zone between profile numbers 22,120 and 22,200 could indicate jointed rock mass and water leakage, but in this section the rock mass is fair to good with Q-values from 6 to 13, and almost no water. Two crushed zones (width less than 1 m) with clay on some joints are registered between profile numbers 21,970 and 22,054. In the same section water leakage of 360 l/min was measured for one pre-grouting round. This agrees with the refraction seismics that indicate several weakness zones between profile numbers 22,000 and 22,130. The conditions encountered between profile numbers 22,000 and 22,200 in the tunnel were generally better than expected. The zone encountered is smaller and have no major water leakage, especially compared to the low resistivity zone registered. A closer look on the geology is needed to see if there is a natural explanation to the extremely low resistivity levels.

Two low velocity zones (10 and 25 m wide) were registered close to profile numbers 22,300 and 22,450. Between profile numbers 22,375 and 22,435 water leakage were encountered in a heavily jointed section connected to boundaries between different geological layers. This confirms experience from other projects in similar rock mass, showing that water leakage is encountered at densely folded areas and boundaries between geological layers. More joints will appear in such sections, and different competency in layers can give sliding between layers and apertures leading to water leakage.

The hydraulic testing was carried out approximately 75 m away from the tunnel. The distance makes it difficult to compare the hydraulic test pumping in the borehole with water leakage conditions in the tunnel.

Table 4: Water leakages of selected pre-grouting rounds between profile numbers 20,320 and 22,435.

Profile number	**Water leakage of one pre-grouting round**	**Geological features**
20320 – 20360	389 l/min	Boundary to a synclinal Different competency of the geological layers
20440 – 20520	860 l/min	Boundary to a synclinal Different competency of the geological layers
20600 - 20670	100 l/min	Poor rock quality, crushed zone with clay, folded section
21884 – 21910	52 l/min	Diabase dyke, jointed rock mass adjacent to dyke, clay filled joint
21970 – 22054	360 l/min	Moderately jointed rock mass, crushed zone plus clay on some joints, massive sandstone observed
22375 - 22435	1112 l/min	Heavily jointed section, clay filled joints, adjacent to a synclinal

4. ACKNOWLEDGEMENTS

This paper is based on results from the R & D project "Tunnels for the citizen". The author acknowledges all parts involved in the project, for being helpful and sharing all necessary information needed to write this paper.

5. CONCLUDING REMARKS

The main conclusion based on this study is that the importance of understanding the geology can not be overestimated. Thorough study of available geological information and detailed geological mapping is the first and most important investigation. In both tunnels discussed here the highest amount of water leakage has occurred at the boundary between different geological layers / rock types.

In the planning of site investigations and in interpretation of results, it is of great importance to be aware of what the different investigation methods are actually measuring. Zones with electrical leading minerals and/or clay will give lower resistivity than zones with open and water bearing joints. It is also important to combine the resistivity measurements with other site investigations to understand what the anomalies indicate. More data and testing in different rock types are needed to fully understand the results from the resistivity measurements.

The borehole logging and hydraulic testing always will represent only a small hole in a big volume of rock mass, and it is therefore important to locate the borehole where it can give most valuable information. This normally is close to the tunnel alignment. A problem with boreholes, both percussive- as well as core drilling, is the tendency to collapse when the rock mass conditions are getting poor.

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