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Temporary Groundwater Control for Construction of Railway Tunnels in Copenhagen

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ABSTRACT
As part of the construction of the new high-speed railway line between Copenhagen and Ringsted, two cut-and-cover tunnels are constructed in the urban zone in Copenhagen. The tunnels are each about 1000 m long and intersect a series of known contaminated sites as well, as an area used for drinking water supply.

In order to meet the construction requirements of maintaining a dry excavation, the groundwater must be lowered between 2 and 5 m to approximately level -2 m AOD and -4 m AOD respectively. The tunnels are located in strata consisting of clay till of relatively low permeability overlying limestone of high permeability.

Given the dense urbanization and the intersection of existing contaminated sites, requirements from the authorities have focused on reducing the drawdown effects in the surrounding residential areas and minimizing the movement of contaminant plumes, in order to protect existing drinking water supply wells and basement air quality.

This paper describes how these challenges are overcome by undertaking a series of detailed preliminary hydrogeological investigations. The investigations include installation of test boreholes, pumping testing, geophysical borehole logging, water quality sampling, soil-gas sampling and air quality measurements in residential basements. Subsequently, updating and calibration of a numerical 3D groundwater model, designed to assess the different strategies and provide the optimal design of the system, was undertaken.

The selected design of the groundwater control system consists of some 100 pumping wells located inside or near the excavation, some 120 injection wells located at a perimeter of up to 400 m from the excavation, and a system of 100 monitoring wells. Both abstraction and injection is from and to the limestone aquifer. During operation of the groundwater control system, up to 700 m^3/h is abstracted, treated in activated-carbon filters and injected, thereby meeting the requirements from the involved authorities.

Keywords: Groundwater lowering, Tunnels, Authority liaison, Hydrogeological investigations,

1 BACKGROUND

As part of the construction of the new high-speed railway line between Copenhagen and Ringsted, two cut-and-cover tunnels are constructed in the urban zone in Copenhagen. The tunnels intersect a dense urban area with existing well known contaminated sites (chlorinated solvents and benzene) but also an area used for groundwater abstraction, where the main concerns relate to high nickel and chloride concentrations, that already, prior to the project, exceed the acceptable concentrations, as set by the Authorities. A stream that crosses the alignment between the two tunnels, on the border between the Municipality of Copenhagen and the Municipality of Hvidovre is classified as a protected stream.

The location of the new railway line is marked in red on Figure 1.

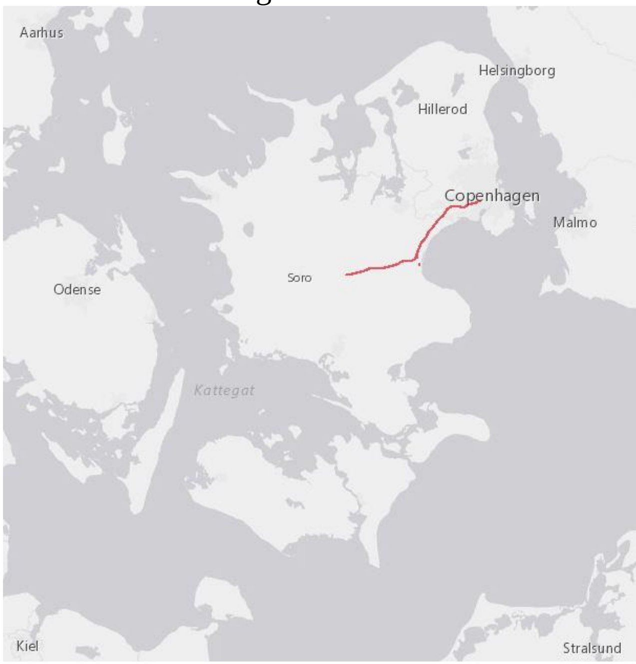


Figure 1 The new railway line Copenhagen – Ringsted.

The construction is divided into a number of tender packages of which the tender package covering two urban tunnels is the largest and most complicated.

The project owner is Banedanmark, operator of the Danish railway network.

2 THE PROJECT

The tunnels and troughs are each about 1000 m long and intersect a series of known contaminated sites, as well as an area used for drinking water supply.

Figure 2 and Figure 3 show the location of the two tunnels, investigation boreholes and existing contaminated sites.

Figure 2 Location plan showing Hvidovre Tunnel and troughs, investigation boreholes and contaminated sites in Hvidovre Municipality.

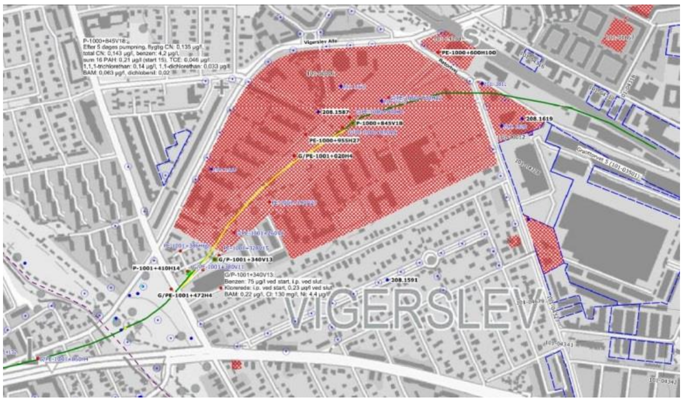


Figure 3 Location plan showing Kulbane Tunnel and troughs, investigation boreholes and contaminated sites in Copenhagen Municipality.

In order to meet the construction requirements of maintaining a dry excavation, the groundwater must be lowered between 2 and 5 m to approximately level -2 m AOD and -4 m AOD respectively. The tunnels are located in strata consisting of clay till of relatively low permeability overlying limestone of high permeability.

Given the dense urbanization and the intersection of existing contaminated sites, requirements from the authorities have focused on reducing the drawdown effects in the surrounding residential areas and minimizing the movement of contaminant plumes, in order to protect existing drinking water supply wells and air quality in neighbouring residential buildings.

This paper describes how these challenges are overcome by undertaking a series of detailed preliminary hydrogeological investigations. The investigations include installation of test boreholes, pumping testing, geophysical borehole logging, water quality sampling, soil-gas sampling and air

quality measurements in residential basements. Subsequently, updating and calibration of a numerical 3D groundwater model, designed to assess the different strategies, and provide the optimal design of the system, was undertaken.
The selected design of the groundwater control system consists of approximately 100 pumping wells located inside or near the excavation, 120 injection wells located at a perimeter of up to 400 m from the excavation, and a system of almost 100 monitoring wells. Both abstraction and injection is from and to the limestone aquifer. During operation of the groundwater control system up to 700 m^3/h is abstracted, treated in activated-carbon filters and injected, thereby meeting the requirements from the involved authorities.

3 PRELIMINARY HYDROGEOLOGICAL INVESTIGATIONS

Geological and hydrogeological investigations were carried out in order to refine the existing conceptual model of the area. The model was updated with detailed information about the borehole geology, groundwater level in the limestone aquifer, hydraulic parameters (T, S) of the geological units, and stage and flow of the Damhusåen stream where it intersects the project, between the two tunnels and on the border between the municipalities of Copenhagen and Hvidovre. The various investigations are discussed in the following sections.

3.1 Drilling investigations

A large number of geotechnical boreholes were drilled and subsequent tests conducted in the tunnel alignment area to obtain detailed design parameters for the construction of the tunnels. Where feasible, hydrogeological investigations were performed in the geotechnical boreholes. In addition, a number of wells, installed with screens targeting the primary limestone aquifer, were established outside the alignment.

The borehole-information from these preliminary investigations provided a detailed picture of the lateral variation of strata thickness: This was incorporated into a revised conceptual groundwater model.

3.2 Flow logging

Prior to completing the well installations, a geophysical flow log was performed in selected boreholes. The purpose of geophysical logging was to assess the vertical flow distribution in the limestone aquifer to optimize well design and determine the required target depth of the secant pile walls. Furthermore, flow logging results were applied in the conceptual groundwater model, and permitted separation of the limestone layer into high- and low-yielding units.

3.3 Pumping testing

Following the well completion development pumping test were carried out in order to obtain information about the hydraulic characteristics of the pumped limestone aquifer, the overlying confining clay till and the shallow aquifer, where present.

In most cases, the constant-rate pumping tests included a number of monitoring wells screened in different levels in order to assess the effects on the shallow aquifer and hence undertake an assessment on potential settlement of neighbouring buildings.

The findings of the geophysical flow logging identified two flow zones in the limestone separated by a low permeability flow zone. In order to obtain field data that would permit simulation of this in the groundwater model, 12 pumping well where installed along the alignment with an associated monitoring well about 20 m away. In each of the well-pairs, the pumping well was screened targeting the deep flow zone in the limestone, whereas the monitoring well was screened in the upper flow zone (as well as the pumped aquifer). A constant-rate pumping test was carried out in these well-pairs to obtain data for the design depth of cut-off walls.

3.4 Groundwater monitoring

In order to obtain background water levels from the project area, an online monitoring system consisting of 35 monitoring wells screened in the limestone aquifer were established. Existing wells were used where possible, but in addition, 9 new monitoring wells were drilled to provide sufficient coverage in all directions from the excavation. The 35 monitoring wells were equipped with pressure transducers and modems that continuously send water level data to a custom-designed online supervision system. The collection of background data was completed by conducting a comprehensive monitoring round where more than 100 wells in the area were manually sounded in one single day, prior to starting the groundwater lowering.

The online supervision system has been operating throughout the project collecting data.

Detailed, baseline groundwater-quality data was obtained via the following activities: literature searches of environmental site assessment reports to find historical water quality data; extensive environmental assessments, performed in 2011, including water quality sampling at the final stage of step-drawdown tests in 11 wells and 7-day pumping tests performed in 14 wells; environmental screening for contaminants and undesirable parameters, such as nickel, which started in selected monitoring wells several months prior to start of groundwater lowering activities, and finally, prior to test of the groundwater lowering and injection system, the water quality of every fifth pumping well and infiltration well, was screened.

Furthermore, residential buildings that are neighbours to a former automobile repair shop were investigated for benzene levels under the basement floors as well as in the basement, to document background concentrations prior to start of groundwater lowering activities.

3.5 Stream flow gauging

Even though the groundwater control system is based on recharging 100 % of the abstracted groundwater back into the aquifer, the contingency plan included discharging excess groundwater to the stormwater sewer system as well as into the conveniently located Damhusåen stream that intersects the central part of the project. In order to obtain an authority permit to discharge groundwater to the stream, flow profiles were gauged at an upstream and downstream location from where the stream intersects the tunnel alignment. The flow profiles were gauged every two weeks from 6 months before the groundwater lowering commenced and continued after the project started. This allowed assessing the seasonal variation in both water quality and the stream flow, as well as quantifying the groundwater discharge to the stream or recharge from the stream to the groundwater.

4 RESULTS

4.1 Geology

The borehole information from preliminary investigations was used to update the geological model. An example of the cross section is provided in Figure 4. The conceptual model consists of a fill layer of approximately 1 m thickness overlying a clay till layer between 2 and 6 m thickness again overlying the regional limestone aquifer. A shallow sand aquifer is encountered in places within the clay till layer. These sand units are generally considered to contain only limited volumes of groundwater since they are relatively thin and of limited lateral extent.

However, it is noted that where Damhusåen stream crosses the project area, the clay till layer is thin. Instead, the sand layer is sitting directly on the limestone providing a higher degree of hydraulic contact between the limestone aquifer and the stream.

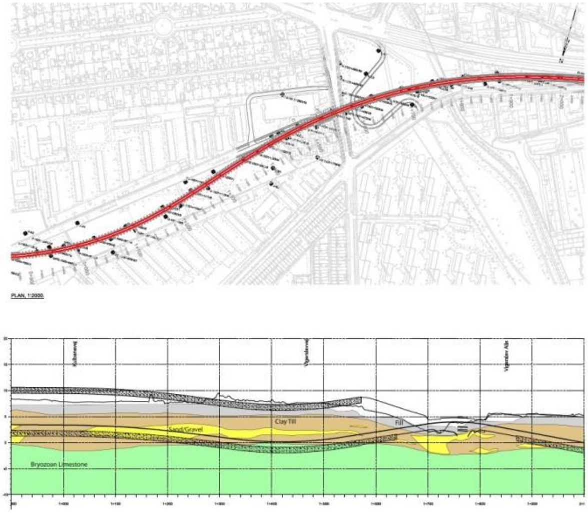
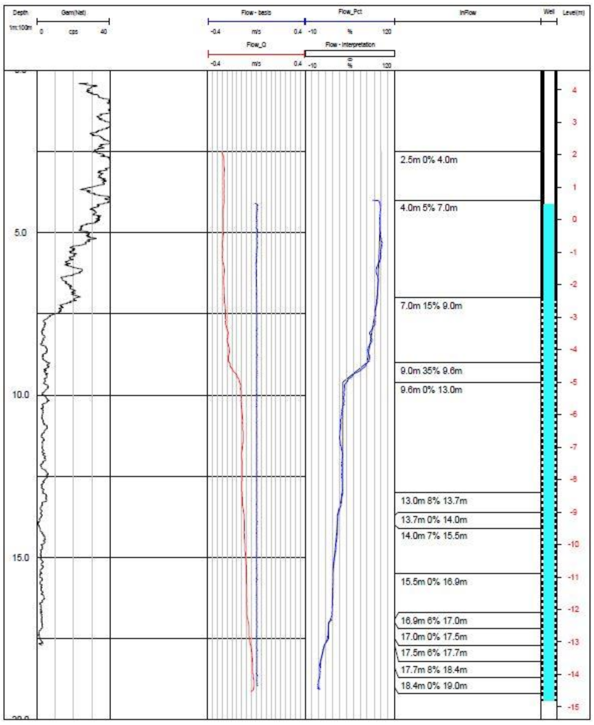


Figure 4 Example of the geological cross section.

4.2 Geophysical flow logging

The results of the geophysical flow logs indicated that the primary flow zone in the limestone is in the upper 5 m of the unit. In some of the boreholes, mainly near Damhusåen and Vigerslevparken a sand layer is encountered overlaying the limestone, making this aquifer unit high-yielding compared to the area further west in the tunnel alignment.



4.3 Pumping testing

A number of pumping tests have been performed in existing and new boreholes to assess the transmissivity of the limestone aquifer. Where the wells where considered for use as abstraction or injection, a step-drawdown pumping test followed by recovery was carried out, whereas constant-rate pumping tests followed by recovery where carried out in order to obtain information about the lateral variation of the transmissivity. Figure 5 shows an example of the density of wells used for pumping tests during the investigations.

Figure 5 Map showing location of wells used for pumping tests and flow logs around the centre of the Hvidovre Tunnel. Blue dots denote wells used for pumping tests and red dots denote wells used for flow logging.

The results show that the horizontal distribution of the transmissivity varies: the high-yielding limestone is found around the Damhusåen stream. The limestone aquifer becomes less transmissive to the west, by a factor of 5. The calculated transmissivities were used to produce a contoured map showing the transmissivity distribution of the limestone aquifer, refer to *Figure 6*. Along with the results of the geophysical flow logging, the transmissivities were applied to refine the 3D groundwater model.

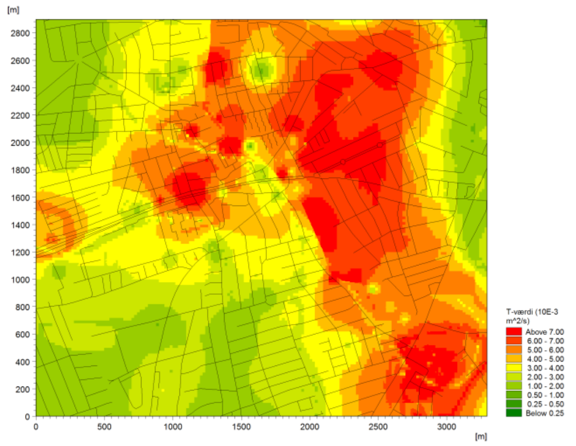


Figure 6 Transmissivity map

4.4 Monitoring

Groundwater quality

Water samples from the pumping tests in the initial investigations identified a single well with a relatively low benzene concentration.

Similarly, water samples taken from pumping and infiltration wells indicated that contamination at the former gasworks site was moderate, and that not all water would require treatment with activated charcoal. However, under the construction phase, on-going monitoring revealed increasingly high benzene-concentrations in pumping wells on site. In the end, all groundwater at the Kulbane site required treatment with activated charcoal prior to injection. Off-site monitoring wells indicated the presence of contaminated groundwater from a former gas station in Hvidovre, as well as benzene-contamination, likely from the former gasworks site, south of the Kulbane tunnel area. Mapping of existing groundwater quality, before start and during the construction phase of the project, was crucial information in our liaison with the authorities regarding permit compliance.

Stream gauging documented extreme seasonal variation in streamflow. During the warm summer period, with little precipitation, flows as low as 30 m^3/h were measured. In contrast, flows of over 2000 m3/h were observed several times each year. Flow information provided the background data for applications for permits to discharge groundwater to Damhusåen. Futhermore, frequent analysis for nickel, ammonium and barium concentrations in the stream, documented actual background levels and resulted in discharge criteria that were higher than generally accepted.

4.5 Groundwater modelling

Updating the existing groundwater model with the information obtained from the field investigations provided a strong and powerful tool in the process of preparing the detailed design for the groundwater control system. In the end, the contractor-firm to whom the contract was awarded, could implement the design, with almost no changes and carry out the tunnel construction under dry conditions. Furthermore, the model results provided the background-information regarding water quantities and pumping rates that are required information when applying for abstraction, injection and discharge permits for groundwater. The 3D model results provided an overview and facilitated an understanding of the project and its impacts that was invaluable in liaison with the authorities.

5 AUTHORITY LIAISON

In Denmark, permits regarding groundwater activities such as dewatering, groundwater lowering and injection are granted with restrictive conditions. Firstly, groundwater-authorities generally require that 90-100 % of the groundwater abstracted during a construction project be injected into the aquifer from which it was abstracted. Secondly, the quality of the water that is injected generally must comply with the maximum acceptable concentrations for contaminants and undesirable parameters in groundwater, (e.g. nickel and chloride) as specified by the Danish Environmental Protection Agency’s groundwater criteria. Typically, this condition is stipulated in permits, regardless of the existing water quality in a project area. In practice, this means that situations arise where contaminated groundwater must be treated with activated carbon prior to injection in wells that lie within a contaminant plume, for example on the south side of the Kulbane Tunnel.

Geographically, the project is divided along a north-south axis at the stream Damhusåen, which is also the border between the municipalities of Copenhagen and Hvidovre. Thus, two sets of permits for all groundwater activities were required. Furthermore, the conditions stipulated by each municipality, regarding monitoring of injection water quality, water quality in the surroundings, plus water levels reflect differences in permitting practises in the two municipalities, their drinking water supplies, and in particular, the contaminant situations in the two project areas.

Despite extensive and precise documentation of groundwater quality and contamination, prior to start of activities, groundwater contamination was strongly affected by the dynamic pumping rates, dynamic pumping strategies and by other groundwater activities in the vicinity. Here, dialog with the permitting authorities is vital to achieving the 'least poor' solution, when chemistry or water levels do not meet the conditions in a permit.

For example, in the case of the Hvidovre tunnel, injection of groundwater requires activated carbon treatment, filter-by pass for water from pumping wells that are documented clean (to improve residence times in the carbon filter system) and injection of nickel-impacted groundwater only in areas that are previously impacted (to protect an active drinking water well). This complex injection system is the pragmatic solution that addresses the following issues:

- Groundwater contaminated with heavy hydrocarbons at concentrations up to 550 μg/l;
- Costs associated with procurement, operation and maintenance of an activated carbon filter system;
- Nickel concentrations ranging up to 94 μg/l;
  Lack of satisfactory nickel-treatment solutions; and
- A groundwater injection system that was constructed prior to comprehensive mapping of nickel concentrations.

The solution meets the authorities' overall requirement that injection water within drinking water supply areas have the lowest nickel and contaminant concentrations possible. A pragmatic solution must take regard of the authorities' role and obligations, while also taking regard of what is reasonable and relevant in the 'big environmental picture'.

After documentation of benzene in the injected water, the City of Copenhagen agreed to a reduced sampling program, where 1) 'non-detect' compounds and compounds at concentrations below the EPA's maximum acceptable concentrations were omitted; 2) water samples for the priority-compound, benzene, were taken each week, at each manifold, with analysis results provided within 24 hours; and 3) non-priority compounds were analysed for only once a month.

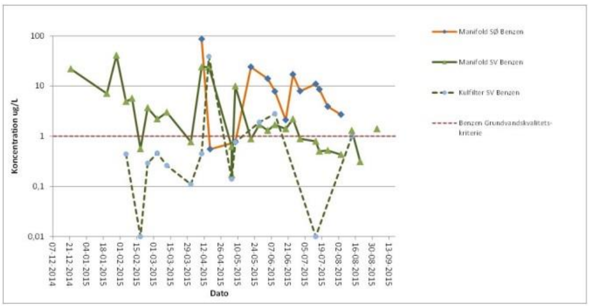


Figure 7: Benzene concentrations measured at the manifolds and after the activated carbon filter. High concentrations in April were first 'discovered' almost a month later, when the final analysis report from the extensive sampling program was released by the laboratory. The dashed line denotes the maximum concentration permitted by the authorities.

This focused and simplified sampling-program, accepted by the City of Copenhagen provides the most relevant information about the carbon filter capacity and sign of contaminant breakthrough.

Furthermore, these results are used to plan supplementary sampling at critical points, for example after each carbon filter, if there is sign of breakthrough. A rapid 24-hour analysis time facilitates a rapid response on the part of the supervising engineer and the groundwater contractor to take remedial action.

Achieving a water-sampling program that is relevant, from the consultant's point of view (can indicate when contaminate breakthrough can be anticipated, if there is contaminant spreading) and for the authorities (ensures that the water treatment system is complying with the permits) also requires an active dialogue between the supervising engineer, the contractor and the authority.

Finally, a simple and long-term groundwater quality program in offsite monitoring wells provides valuable background information regarding contaminant levels prior and during to the project. Several times these data series provided substantial evidence that groundwater activities related to the tunnel construction were not responsible for changes in groundwater chemistry.

6 LESSONS LEARNED

6.1 Detailed preliminary investigations removes a lot of the guesswork and saves money at a later stage

- The preliminary geotechnical and hydrogeological investigations and the subsequent groundwater modelling provided robust and detailed background information, which permitted alternative scenarios to be explored prior to the final project design.
- The actual groundwater lowering and injection system ultimately designed by the contractor is, with the exception of 4 supplementary pumping wells, exactly what was modelled and designed by Rambøll.
- The excellent agreement between the planned design and the actual conditions resulted in a project that is generally on-budget and on-time.
- Environmental screenings provided valuable planning information regarding groundwater treatment requirements and regarding permit applications. However, these investigations are relatively short term, and local in scope. These cannot provide an accurate picture of the contaminate conditions during a long term groundwater lowering project. Consequently, if screening results and site history indicate that activated-carbon treatment will be required, the system must be planned to be flexible and robust to allow for rapid changes in treatment strategy and even injection areas.
- A simple and long-term groundwater quality program in offsite monitoring wells provides background information regarding contaminant levels prior to and during the project. This information was invaluable in assessing unforeseen contaminant concentrations off site.

6.2 Keep it simple

One or two broad, groundwater-screening programs, performed at observations wells and on-site, provide a picture of the groundwater chemistry. Thereafter the program may be reduced, to focus on priority contaminants/compounds, that are sampled for more frequently, with rapid analysis times. A broader program can be performed once a month. A crucial link in a flexible and robust water treatment system is a frequently conducted, but simple water sampling program at critical points in the system.

6.3 Apply for authority approval as early as possible

Even though the standard processing time of applications related to groundwater lowering projects in Denmark is about 2-3 months, the experience from this project, crossing the border between two municipalities, is that it took more than one year to obtain all the required permits.

6.4 Strive for an open and inclusive dialogue with the authorities when problems arise.

Immediate and open contact to the authorities regarding the lack of compliance is the first step in achieving an agreement on a solution that considers the following:

- All possible remedial options
- Implementation timeframes
- Costs
- Technical feasibility
- The authorities' assessment of the seriousness of the situation
- Environmental ramifications
- Legal ramifications

Ideally, the groundwater contractor participates in these meetings or is in close dialog with the consulting engineer, so repercussions of any decision can be considered prior to agreement on a final solution.

6.5 Too little capacity too late

The water treatment systems and pipework must be as flexible and robust as possible. The contaminant situation, based on initial investigations, is most definitely not the situation the consulting engineer will be dealing with 1 or 2 months after start of the project.

6.6 *3-D approach to monitoring*

A tunnel alignment is basically 2D but in order to assess the effects on the environment, and meet requirements of the authorities, it is important to include borehole information from wells scattered throughout the area, at an early stage, and hence consider the project and its environmental implications in 3D.

7 CONCLUSIONS

Well-considered and thorough preliminary investigations provide geotechnical, hydrogeological and environmental information that are the cornerstone of 1) a robust project design, 2) rapid and flexible solutions to permit non-compliance and 3) in-depth assessment of project impacts.

An open and inclusive dialog with the groundwater authorities is crucial to achieving agreement on the 'least poor solution'. The bigger the project, the more likely that one, or several situations arise, where requirements stipulated in permits cannot be met.

8 Acknowledgements

This paper is prepared with the assistance of our colleague Per Beck Laursen who has been involved in the project from the very beginning and still manages to keep track of the many hydrogeological aspects of the project area.
We would also like to acknowledge the representatives of the Principal Banedanmark Martin Ipsen and Atli Runar Kristjansson for the ongoing discussions about the management of the groundwater control system throughout the tunnel construction.