XXXVIII IAH Congress

Groundwater Quality Sustainability

Krakow, 12–17 September 2010

Extended Abstracts

Editors:
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Jarosław Kania
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University
of Silesia
Press 2010

abstract id: **363**

topic: **1**
Groundwater quality sustainability

1.3
Urban hydrogeology

title: **Comprehensive urban hydrogeological survey program to optimise dewatering design and reduce risks related to large infrastructure projects — case study: the Metro Cityringen in Copenhagen, Denmark**

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keywords: dewatering, metro, site investigations, construction projects, geophysics

Large-scale infrastructure projects in urbanised centres must balance the impact to environment and existing structures – e.g. preserving historical structures - with financial and technical constraints. Lowering the groundwater table in urban areas without sufficient hydrogeological data and appropriate planning can result in general ground settlement, damage to adjacent buildings, contaminant mobilisation, and adverse effects to water supply. Therefore a focused strategy for identifying and handling the concrete risks, through comprehensive urban hydrogeological surveys when conditions require, is necessary.

SURVEY SETTING

A new metro line, "Cityringen", is being planned in Copenhagen, Denmark. The line, shown in Figure 1, comprises 15.5 km of twin-tube tunnels, 17 stations and four shafts, as well as five caverns for cross-overs and bifurcations. Deep construction works will begin in 2011, with tunnelling due to commence in 2013. Inauguration is planned for 2018.

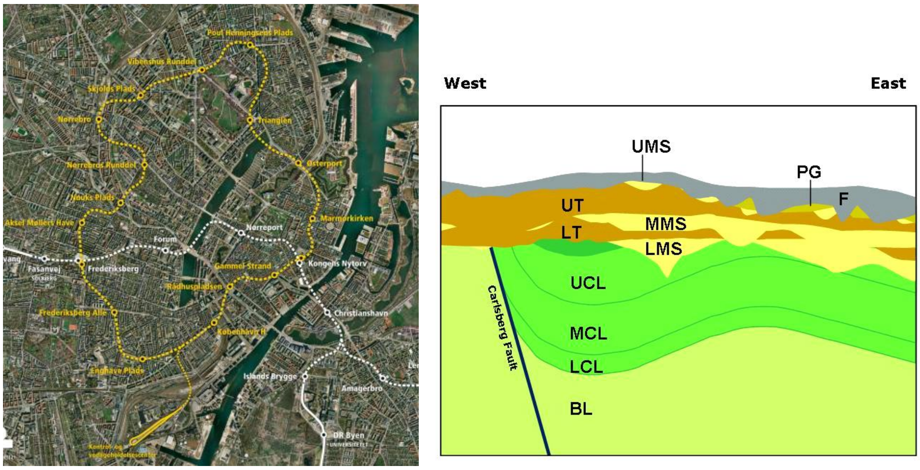

Figure 1. Overview map of Cityringen (left), conceptual geology (right). Geology is comprised fill (F) and post-glacial deposits (PG), glacia till (UT — Upper till, LT —Lower till), meltwater sand/gravel (UMS — Upper, MMS — Middle, LMS — Lower) and limestone (UCL — Upper, MCL — Middle, LCL — Lower, BL — Bryozoan)

The eastern part of the Cityringen alignment passes the inner city of Copenhagen where many buildings are old and sensitive to variations in groundwater levels. For this reason the municipality of Copenhagen has in this area prohibited any groundwater lowering outside the construction zones unless appropriate measures are taken to keep the groundwater level within natural limits. The western part of the alignment passes through a catchment for domestic water supply at Frederiksberg where a key issue is protection of the groundwater resource in terms of quantity and quality, with chemical parameters of interest being salinity/chloride, nickel and sulphate. Numerous contaminated sites — typically originating from former dry-cleaning shops, petrol-filling stations and mechanical workshops — are located close to the planned construction sites. In these instances the dewatering activities will not be allowed to alter the existing groundwater contamination regime, for instance by spreading of the existing contamination plume.

HYDROGEOLOGY OF COPENHAGEN

The conceptual geology of Copenhagen is shown in Figure1. The soils in the project area are composed of fill, underlain by Quaternary layers of alternating sand and till in varying thicknesses. The Quaternary layers are underlain by Copenhagen Limestone, CL (from the Danian period), the surface of which is generally found at 10 to 30 m below ground level. At several locations the tunnels will have to pass through the interface between limestone and glacial soils and will thus encounter mixed face conditions. The upper limestone can be locally glacially disturbed and heavily fractured down to 4 m below the top of the limestone surface.

The primary aquifer is comprised of the limestone together with meltwater sand and gravel layers when in hydraulic contact. At Frederiksberg, the primary aquifer is exploited for domestic water supply and the abstraction is the main controlling factor for groundwater levels in the western part of the alignment. The main flow within the limestone occurs in fissures and the permeability of the limestone can vary widely within short vertical and/or horizontal distances. Within the working area, one or several secondary aquifers occur above the primary aquifer. Although the secondary aquifers are partly separated from the primary aquifer by aquitards, drawdown of the groundwater level in the primary aquifer will often cause considerable drawdown in the secondary aquifers also.

RISK REDUCTION

Groundwater-related potential risks in relation to the deep construction works as such include breakdown of the dewatering system, causing e.g. risk of uplift of the bottom and/or flooding of the excavation; and large inflows from peak flow zones to open excavation in the limestone, such as caverns or adits. In terms of risks for the surrounding environment dewatering can, if appropriate measures are not taken, result in undesired lowering of the groundwater level. This may potentially lead to a range of adverse effects, including: Jeopardising existing building foundations if wooden piles get exposed to oxygen for longer periods; intrusion of saltwater from the sea or up coning of residual saltwater; increase in contents of nickel or sulphate in case deposits containing pyrite become unsaturated; and to spreading of existing groundwater contamination if the existing groundwater flow regime is altered. Other environmental risks include improperly treated water, with high contents of dissolved limestone or iron, being discharged to recipients (harbour, lakes, streams), potentially causing discoloured water in the recipient.

PRACTICAL GROUNDWATER CONTROL FOR CONSTRUCTION OF CITYRINGEN

The permanent constructions of Cityringen are designed as watertight constructions and the dewatering is thus limited to the construction phase. The practical measures to reduce the groundwater inflow to excavations during the two years of construction, and thus limit the lowering of groundwater level in the surroundings, include water-tight retaining walls to the appropriate depth in order to cut off significant flow zones and at times grouting to reduce the permeability of particularly water-bearing flow zones. In particular cases it might be necessary to resort to more costly methods, such as freezing or working under compressed air. In Copenhagen the preferred method in the latest years has been to recharge the abstracted groundwater (or occasionally harbour water) back into the groundwater aquifer. This principle is outlined in

Figure **2**. It is expected that in total 20-60 million m^3 of groundwater will have to be handled for construction of Cityringen if the appropriate measures to reduce yields, as outlined above, are taken.

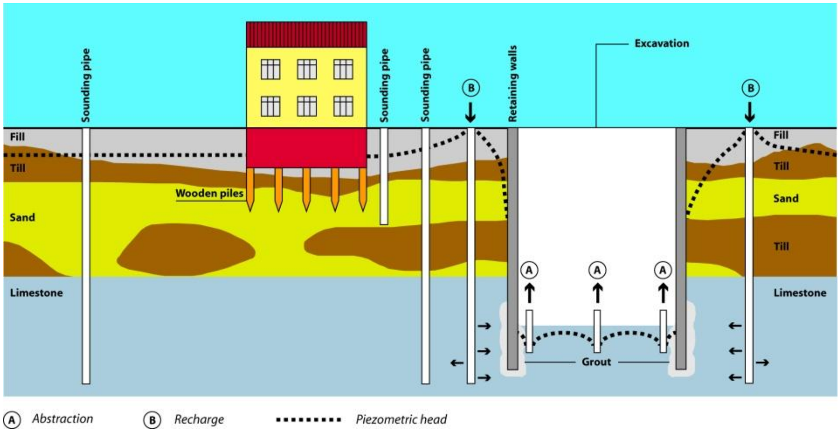

Figure 2. Principle of groundwater control in Copenhagen.

COMPREHENSIVE SURVEY AND PLANNING STRATEGIES

In light of the environmental regulations, complex site conditions and timeline the following overall strategies have been implemented:

- Extensive site investigations in order to ensure improved knowledge of the site conditions
- Integrated interpretation of the results, continuously as the data materialise, in order to improve the tender design — also by use of extensive groundwater modelling — and to improve otherwise the basis for bidding, as "Project Information".
- Dialogue with authorities in order to ensure a common understanding and to assess the likely authority requirements that the contractor will have to respect.
- Early groundwater monitoring in order to ensure proper determination of baseline groundwater levels.

SITE INVESTIGATIONS

In order to assess the site conditions in detail targeted site investigations are necessary. Extensive site investigations have been carried out for Cityringen. It has been the intention that such a high level of knowledge, ahead of tendering for detailed design and construction, will ensure that 1) less feasible design solutions will be eliminated and the tender design thus be optimised, and 2) the risk of unforeseen situations will be reduced and a solid and clear basis for the pricing of the design and build contracts will be established. It has, in other words, been the aim that surprises should be avoided. The site investigations before tender comprise the following key data:

- 374 geotechnical and/or hydrogeological boreholes with accurate geological description,
- 246 geophysical logs, including flow logs,

- 600 short duration pumping test, of 1 hour of pumping and 1 hour recovery carried out in all screens after cleaning, as well as 33 long duration pumping test, mostly of 5 days of pumping and 5 days recovery, with use of 15-30 observation wells for each test,
- Groundwater samples for chemical analysis: 101 for inorganic parameters as well as 251 for selected contaminants,
- Seismic surveys at selected sections.

The above site investigations and concurrent evaluations have been carried out in parallel with the design. It has, therefore, been possible to adjust the investigations continuously as a function of both the first part of the investigations and of the developing needs and considerations in the design.

Apart from the above site investigations a comprehensive groundwater monitoring programme has been initiated in mid-2008. The programme covers approximately 250 observation wells (screens), of which 100 are sounded continuously by use of wireless data loggers and 150 are sounded manually. Based on two years of data the contractor will have to derive target groundwater levels which he will have to operate his groundwater control scheme against, thereby ensuring that the groundwater levels during construction are maintained within acceptable ranges.

The data from the monitoring programme have also been a support in defining the design groundwater levels for the permanent constructions. However, the main factors in determining these levels have been the estimated increase in groundwater level due to the following:

- Cessation of the abstraction for domestic water supply at Frederiksberg. Comprehensive groundwater modelling has shown that such a cessation will result in increasing groundwater levels in almost the entire project area (up to more than 10 m at the stations located the closest to the well field),
- Climate change. An increase in the harbour water level of e.g. 0.5 m within the planned 100 years lifetime of Cityringen will result in significant increases in groundwater level in the entire eastern and southern part of the alignment.

INFLUENCE OF SITE INVESTIGATIONS ON DESIGN

The results of the site investigations and the concurrent evaluations served as input to Environmental Impact Assessment (EIA) as well as the conceptual design and the subsequent tender design of Cityringen. Groundwater modelling has been used extensively in the design phase in order to guide the groundwater control, such as the necessary depth of cut-off walls.

At a number of sites the design has been adjusted or completely changed as a function of the evaluated site investigations. For instance, the original design for a 180 m long cross-over cavern was lowered by several metres in order to avoid excavating into highly permeable flow zones in the upper part of the limestone aquifer. As a consequence the neighbouring future station had to be lowered as well. Another cross-over cavern, with very limited limestone cover, was changed to a cut and cover structure with deep cut-off walls as a result of the high transmissivity values determined (approximately $8 \times \cdot 10^{-3}$ m^2/s).

Along an approximately 600 m long southern section Sprayed Concrete Lining (SCL) tunnelling is alternating with cross-over and bifurcation caverns by use of the New Austrian Tunnelling

Method (NATM). Groundwater modelling, however, showed that such open excavation in the limestone along this long section — without any cut-off walls to limit the inflow — may yield relatively high dewatering yields. Therefore it was decided that the tender design should include extensive grouting carried out from a pilot tunnel, as well as sequential excavation so that only limited sections will be open and draining at any given time.

At a couple of locations in particular the site investigations showed that the surface of the limestone was found at large depths. Therefore the tender design ended up including very deep cut-off walls.

KEY FINDINGS AND IMPLICATIONS FROM SITE INVESTIGATIONS

When pumping from the limestone aquifer the drawdown in the upper sand or gravel layers was usually measured to be in the range 10–80%, i.e. highly variable but usually considerable. This underlines the need for watertight retaining walls around the excavation combined with efficient recharge in order to avoid lowering in upper layers.

The flow zones in the limestone are often not consistent within a given site. Figure 3 shows two examples where the flow zones can be either at constant levels throughout the area or heterogeneously distributed.

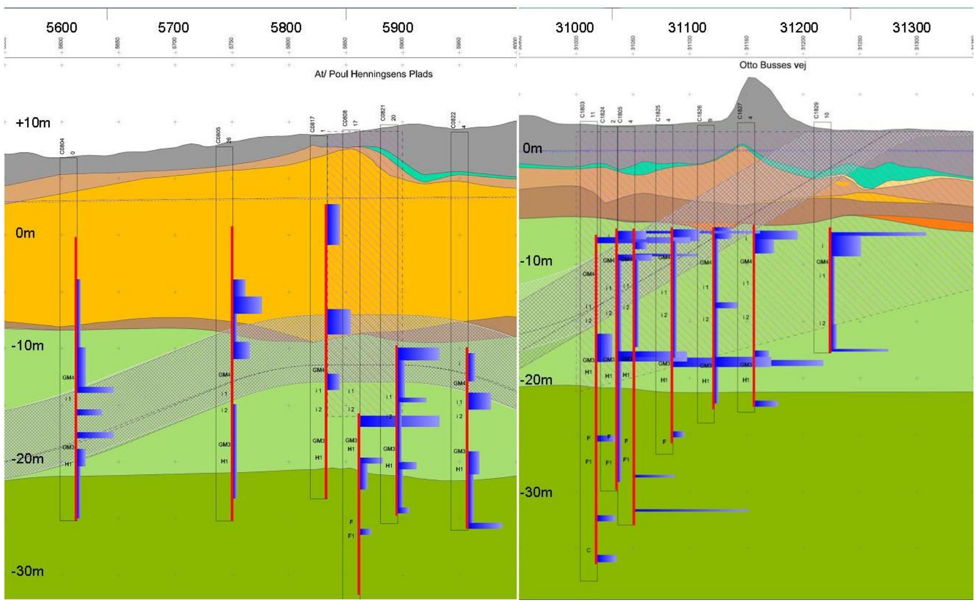

Figure 3. Examples of flow distribution: Left) Otto Busses Vej, with very even distribution, Right) Poul Henningsens Plads, with very heterogeneous distribution.

The finding that the vertical distribution of flow zones is very variable means that site-specific knowledge — i.e. from numerous good-quality flow logs — is crucial in order to be able to arrive at a proper design of the groundwater control scheme for a given site, in particular the depth of cut-off walls.

CONCLUSIONS

The comprehensive hydrogeological survey campaign carried out throughout Central Copenhagen and the subsequent continuous evaluations have resulted in a very good basis for planning and design of Cityringen. By presenting these data and evaluations — as Project Information — to the bidders for the design and build contracts it has been the intention to provide a clear basis for the contractors' tendering and subsequent work. An early dialogue with the authorities has also been undertaken with the aim of assessing, at an early stage, the expected environmental requirements to be adhered to in the design and build phase. This case study demonstrates that large scale infrastructure projects within urban centres require increasingly more comprehensive and innovative surveys to address the complex challenges to reduce environmental impact and overall risks.

International Association of Hydrogeologists

AGH University of Science and Technology

2-vol. set + CD
ISSN 0208-6336
ISBN 978-83-226-1979-0