Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY
© 2024 the Authors
ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-633
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ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Groundwater control during metro construction in urban areas – the Cityringen experience

Contrôle des eaux souterraines lors de la construction d'un métro en zone urbaine - l'expérience de Cityringen

E. Paulatto
Metroselskabet, Copenhagen, Denmark

L.M. Markussen
Rambøll, Copenhagen, Denmark

J. Damgaard
COWI, Copenhagen, Denmark

F. Petrella, J. Flink*
Arup, Copenhagen, Denmark

**jenny.flink@arup.com*

ABSTRACT: Groundwater lowering in the inner city of Copenhagen, Denmark, is generally not permitted due to the sensitive nature of the foundations of existing buildings, and to avoid spreading existing groundwater contamination. Outside the inner-city, groundwater lowering is often undesirable due to risks towards settlement of infrastructure, nature and contamination. To ensure dry conditions during construction of shafts and other large excavations, and to protect nearby buildings as well as the environment, groundwater control systems have been established in each of the 28 underground stations/shafts of the Cityringen metro, including the Nordhavn and Sydhavn extensions. The temporary groundwater control systems have comprised of cut-off walls and a network of pumping and recharge wells. There is often a notable discrepancy between the discharge rates predicted by modelling in the design phase, and those measured during construction. Possible explanations for this discrepancy include differences between the modelled design and the actual constructed dewatering system, quality of the cut-off wall, inadequate ground investigations or misinterpreted results, pressure-dependent ground permeability and uncertain assumptions regarding anisotropy. This paper describes the basis for the dewatering activities and the outcome of the three-dimensional (3D) groundwater models developed during the detailed design and compares this with the observed groundwater monitoring data. Inconsistencies between the design and observed behaviour of the groundwater control systems are reviewed and the potential reasons are investigated.

RÉSUMÉ: Le rabattement de nappe dans le centre-ville de Copenhague n'est généralement pas autorisé en raison de la nature sensible des fondations des bâtiments existants et pour éviter la propagation de contamination existante des eaux souterraines. A l'extérieur du centre-ville, le rabattement de nappe est souvent indésirable en raison du risque vis-à-vis d'affaissement d'infrastructure, des zones naturelles et de la contamination. Pour garantir des conditions sèches lors de la phase de construction de puits et d'autres larges excavations, et pour protéger des bâtiments avoisinants ainsi que l'environnement, des systèmes de contrôle des eaux souterraines comprenant à la fois des parois étanches et un réseau de forages de pompage et de réinfiltration ont été établis dans chacune des 28 stations souterraines/puits du métro « Cityringen », incluant les extensions Nordhavn et Sydhavn. Il existe souvent un écart notable entre les débits de pompage prédits par modélisation dans la phase de conception et ceux observés pendant la construction. Les explications possibles pour cet écart comprennent des différences entre le design modélisé et le système de rabattement de nappe construit, la qualité de la paroi étanche, des investigations inadéquates du sous-sol ou des résultats mal interprétés, une perméabilité du sol dépendante de la pression et des hypothèses erronées concernant l'anisotropie. Cet article décrit le fondement pour les activités de rabattement de nappe et le résultat des modélisations 3D d'écoulement des eaux souterraines développées pendant la conception détaillée, et compare cela avec les données de suivi de niveaux des eaux souterraines observés. Les inconsistances entre la conception et le comportement observé des systèmes de contrôle des eaux souterraines sont examinées et les raisons potentielles sont étudiées.

Keywords: Groundwater control; 3D groundwater modelling; Copenhagen metro; limestone, urban hydrogeology.

1 INTRODUCTION

The expansion of the metro network in Copenhagen has taken place over the last 12 years, has entailed the construction of 28 underground structures (stations and shafts), with abstraction and recharge of groundwater via dedicated groundwater control systems. A large amount of data has been collected in the monitoring database (Kronos) that was in operation during and after construction. This paper aims to analyse the information gathered, and then give a first evaluation of the substantial discrepancy between the yield rates predicted by modelling in the detail design phase and those measured during construction. This paper also offers some explanations and hypotheses that can be further confirmed and extended in future ad-hoc papers/studies. Previous publications on this topic include Bonde et al. (1997), Raben-Levetzau et al. (2004), Bock and Markussen (2007) and Markussen et al. (2019).

2 COPENHAGEN GROUND CONDITIONS

The geology of Copenhagen, see Figure 1, comprises glacial clay till and meltwater sand/gravel deposits overlying Paleocene limestone (Copenhagen Limestone and Bryozoan Limestone). This geology forms the main geological unit in which the metro tunnels and stations are constructed.

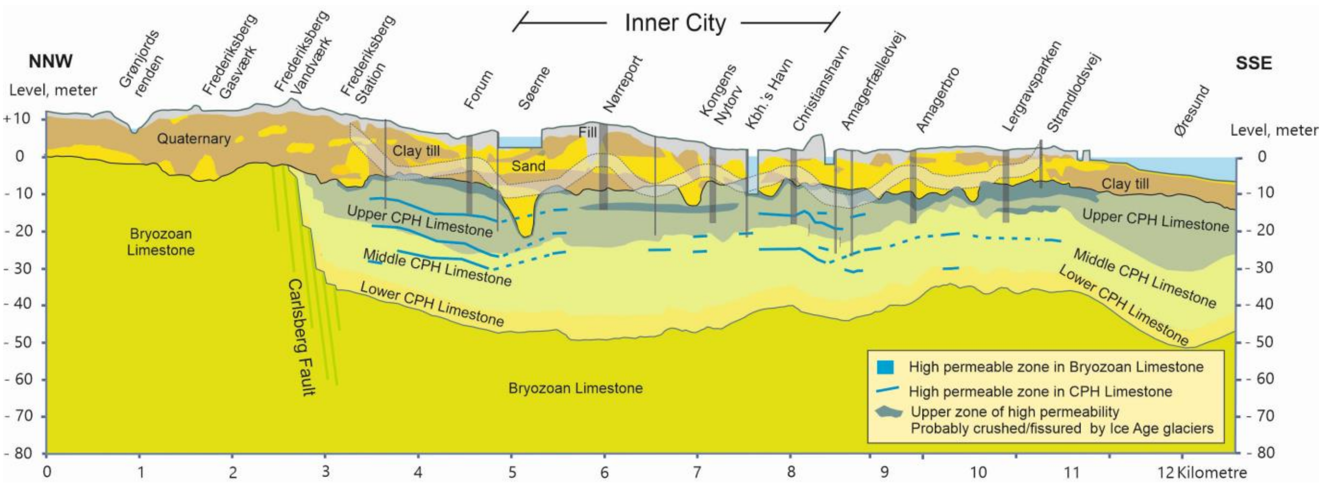

Figure 1. Copenhagen ground conditions in a profile along the M1 metro line.

The primary aquifer in the region is the upper part of the limestone, together with sand and gravel deposited directly above the limestone. The average hydraulic conductivity of the limestone generally falls in the range from 10^{-6} m/s to 10^{-4} to m/s with the majority of the flow occurring in fractures. The piezometric level of the aquifer is typically a few meters below the ground surface. Secondary aquifers are present in the overlying glacial and marine sand and gravel deposits and within the fill. Because the metro stations are situated below the groundwater table, significant dewatering works have been required for their construction.

There are several NNW-SSE oriented faults and folds in the region, the most notable in Copenhagen being the Carlsberg Fault and the Svanemølle Fault. These are known to have significant impact on limestone transmissivity (Frederiksen et al., 2002).

The primary aquifer is a source for domestic water supply with abstraction taken place in the Carlsberg fault zone where the water bearing-capacity is high. Parts of the metro alignment lie within the catchment zone associated with this abstraction.

3 COPENHAGEN METRO

The Copenhagen metro is a light rail system running 24/7 within the municipalities of Copenhagen, Frederiksberg and Tårnby. There are presently four operational lines. M1 and M2 opened in 2002 with further extensions completed in 2003 and 2007. Seventeen stations were then added in 2019, together with the M3 'circle line' (referred to as Cityringen, i.e. CR). Two of the M4 line stations opened in 2020 (referred to as Nordhavn, i.e. NH) while the remaining five stations are under construction and due to become operational in 2024 (referred to as Sydhavn, i.e. SH). This paper focuses on the M3 and M4 underground stations, and describes the temporary dewatering required to enable their construction.

The typical underground station footprint in plan is 60x20m though larger footprints are needed for crossovers or run-over tracks. The typical excavation depth is between 18m to 25m, though a few CR stations and shafts are as deep as 35m such as the Marmorkirken and Nørrebroparken stations.

4 GROUNDWATER CONTROL SYSTEM

The city of Copenhagen was founded more than 800 years ago. It is situated at the coast, and large parts of the inner city are founded on fill as the city reclaimed land from the sea. Many residential and public buildings are old and are often listed as historical monuments. The old harbour, and the many lakes and canals, form an important part of the city identity.

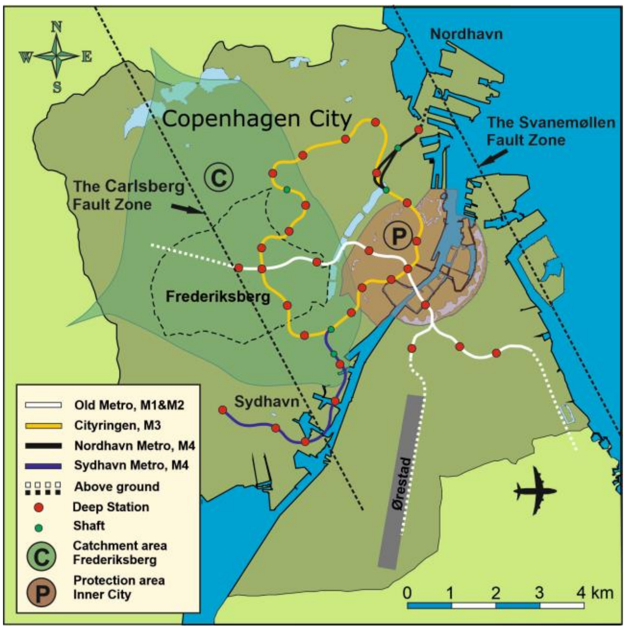

Figure 2. Copenhagen metro system.

Dewatering of deep excavations can cause:

- Settlement damage to buildings which are founded directly in fill.
- Damage to buildings which are founded on timber piles or other wooden constructions.
- Draining of city lakes
- Damage to urban drinking water interests due to pollution spreading and saltwater intrusion.
- In 1991 the Copenhagen city authorities decided to limit groundwater lowering in the entire inner city area where the risk of settlements and deterioration of wooden foundations is greatest, see Figure 2. In this area, any lowering of the upper groundwater to more than 0.3m above sea level is not allowed.

To ensure dry conditions in excavations during metro construction, and to avoid groundwater lowering in the surrounding area, a groundwater control system was established for each deep excavation. The system comprised of cut-off walls and a network of pumping and recharge wells; see conceptual layout in Figure 3.

Groundwater levels were primarily controlled by the installation of impermeable reinforced concrete secant pile cut-off in the quaternary layers and the upper part of the limestone, constructed to below excavation level. This provided a complete cut-off in the glacial layers and resulted in seepage into the excavation only occurring from the limestone. The actual cut-off depth was determined by results from pumping tests and flow logs combined with groundwater modelling.

The amount of water pumped from the sites had to be balanced by pumping back a similar amount of abstracted water into the limestone outside the secant pile wall, via the construction of recharge wells.

Monitoring was an important part of the groundwater control operation. The purpose of monitoring was twofold. Firstly, the monitoring was necessary for the actual groundwater control. Regular monitoring of groundwater levels in monitoring wells, combined with data on dewatering pumping and recharge volumes were necessary to evaluate the effect of groundwater lowering. These data were also a necessary input to the calibration of the groundwater model. Secondly, an efficient system of regular reporting to the authorities was necessary both to meet demands and to ensure efficient and professional communication with the authorities. The monitoring used the Kronos monitoring database system developed by Geodata (Rabensteiner et al. 2015).

5 DATA SET SUMMARY

Ground investigations (GI) were planned by Metroselskabet (MS) and/or their consultants to form the basis for concept design, Environmental Impact Assessment (EIA) and tender design. All the metro projects were tendered as “design and build” and therefore the contractors have often supplemented with additional GI.

For a standard station on CR, NH and SH the dewatering-related GI typically included three cored boreholes to well below the base of the excavation, one or two long-duration pumping tests, complete with multiple observation wells, three short duration pumping tests and four flow logs. These were typically made both in open hole and in the screened borehole. The GI was interpreted by both the consultants and the contractors.

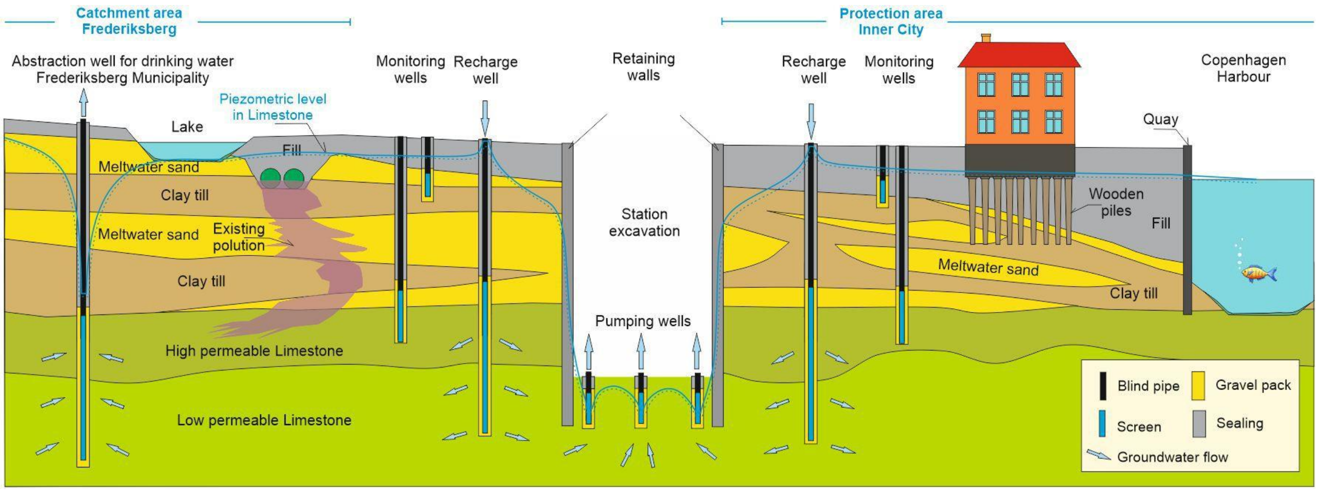

Figure 3. Typical dewatering system for metro station/shaft construction in Copenhagen.

For approximately half the stations on CR, the contractor supplemented the GI with additional boreholes and one long-duration pumping test. For NH and SH only limited additional investigations were made by the contractor.

Both MS's consultants and contractors developed their own 3D groundwater models for EIA, tendering and detailed design respectively. All models were calibrated in transient mode against the long duration-pumping tests. For CR and SH the consultant used GMS Modflow, while the contractor used Feflow for CR and GMS Modflow for SH.

The consultant used the models to determine the required minimum depth of retaining walls, expected yields, requirements of recharge rate, and locations to be reserved for recharge etc.

The contractors used the models as part of their detailed design of the dewatering system with respect to quantity and location of pumping and recharge wells, expected yields to be used for the design of water treatment, and authority applications.

6 COMPARISON OF YIELD RATES

The simulated yields (from Hydrogeological Design Reports) and measured yields (from Kronos) for the 28 underground stations/shafts were compared. The relationship between the two datasets is presented in Figure 4 and Figure 5. The yields refer to the total pumped yields from all pumping wells at the different locations.

The impact of factors such as required groundwater lowering, transmissivity, depth of cut off walls below the excavation, quality of cut off walls, limestone excavation depth, number of pumping tests, size of excavation etc. was assessed.

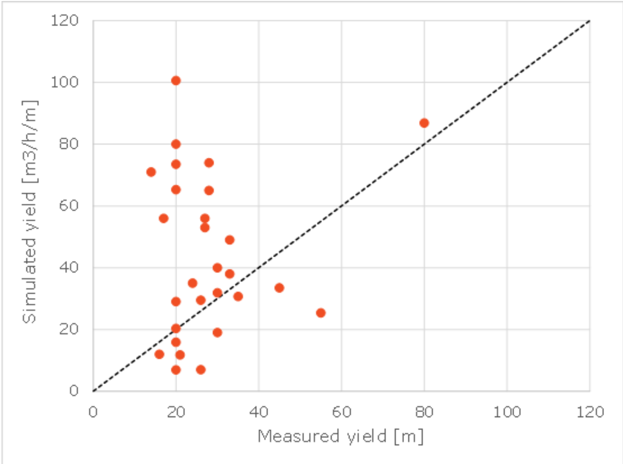

Figure 4. Relationship between simulated and measured yield.

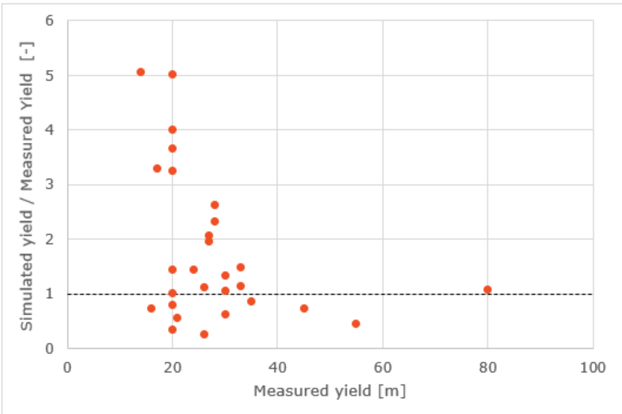

Figure 5. Relationship between simulated / measured yield and measured yield.

Figure 6 depicts the simulated and measured pumping yields when plotted against groundwater lowering.

As can be seen in the figure, the recurrent measured yield is c.20-30 m^3/h, seemingly independent of the required drawdown. The simulated yields are more variable but (besides a few exceptions) and often significantly higher than the measured ones.

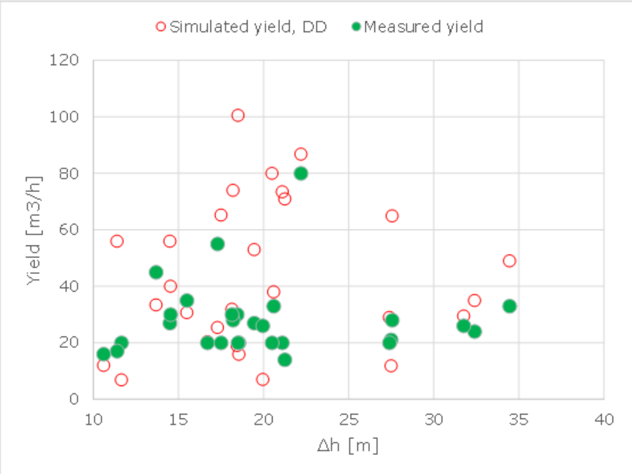

Figure 6. Relationship between simulated/measured yields and groundwater lowering.

In Figure 7, the pumping yields per meter of drawdown are plotted against groundwater lowering. No observable relationship can be seen between the yields and required drawdown.

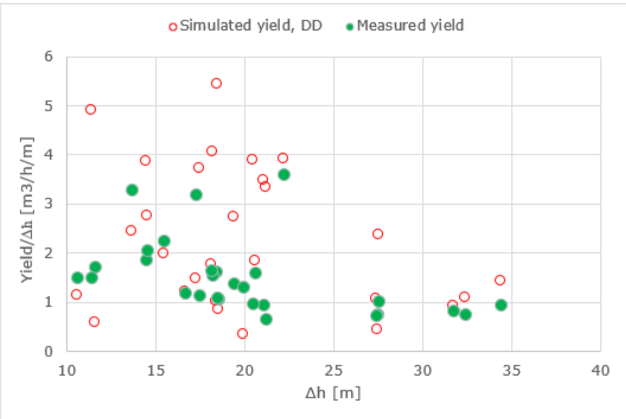

Figure 7. Relationship between simulated/measured yields per meter of groundwater lowering and groundwater lowering.

Similar to the lack of clear relationship between yield and required drawdown, no observable relationship between the yields and the other assessed factors was found.

7 DISCUSSION

A possible explanation for the recurrent 20-30 m^3/h measured yields may be that the deeper limestone, below cut-off level, is relatively homogenous across the whole Copenhagen area, in the locations where the underground metro stations have been built. The inflows are therefore steady once the upper glacially disturbed and more permeable part of the limestone is cut off. It shall be noted that the type of limestone formation being dewatered (e.g. Upper Copenhagen Limestone, Middle Copenhagen Limestone or Bryozoan Limestone) has no clear impact on the yields.

The measured yields for three stations/shafts, Mozart's Plads (45 m^3/h), Enghave Brygge/Ørestedsværket (55 m^3/h) and Sluseholmen (80 m^3/h) stations of the SH extension, exceeds the standard range. Possible explanations for the higher inflows at these locations may be proximity to geological structures (faults) and/or to the harbour.

Though no clear relationship between excavation size (area) and yield can be observed from the dataset, most excavations are of similar size with the exception of Enghave Brygge/Ørestedværket, which is twice the size of the other stations/shafts, and size is therefore likely to be part of the reason for the higher yields in this location.

At Mozart’s Plads, another reason for the observed higher yields is inflow to the adjacent shallow excavation which contributed significantly to the overall yield. Investigations and dewatering design for shallow excavations in addition to the main shaft dewatering should therefore not be overlooked.

The data analysis shows that there is a notable discrepancy between simulated and measured yields. The horizontal to vertical permeability ratio (K_v/K_h) utilised in the simulation models is a key factor to estimate yields. In the Cityringen models, the assumption has typically been that K_v is a factor of 5 or 10 less than K_h which typically equates to K_v in the order of 10^{-6} m/s. Based on pumping tests and modelling of limestone in Malmø, which is similar to limestone in Copenhagen, the K_v value in the limestone has been estimated to be $3x10^{-7}$ m/s (Citytunnelkonsortiet, 2000). This could explain the deviation between simulated and measured yields. Another possible explanation is pressure dependant permeability, i.e. water bearing fissures contracting when the pressure is reduced, as postulated by Markussen et al. (2019).

8 CONCLUSIONS

Following the review of dewatering systems for the construction of 28 underground metro stations/shafts in the central part of Copenhagen, it is noted that the measured yields are relatively steady, around 20-30 m^3/h, with no observable relationship between the yields and factors such as transmissivity or required drawdown. This may be due to the deeper limestone below cut-off level being relatively homogenous. With this in mind, determining the depth to less permeable limestone e.g. through flow logs, is considered key to assessing the required cut-off depth and thus achieving manageable yields.

The size of excavation, proximity to geological features and the harbour, are likely to be contributing causes to inflows exceeding the standard range.

Uncertain assumptions regarding anisotropy and pressure dependent permeability may explain the deviation between simulated and measured yields. Additional studies are planned to determine what 3D model parameters need to be adjusted for the models to better match the measured yields.

Despite the observed inconsistences between simulated and measured yields, 3D groundwater modelling remains a powerful tool to design groundwater control systems and provides an essential requirement to obtain the permits required by various authorities to carry out dewatering in urban areas.

ACKNOWLEDGEMENTS

The authors would like to thank Vincent Collin from COWI for translating the abstract into French.

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The paper was published in the proceedings of the 18th European Conference on Soil Mechanics and Geotechnical Engineering and was edited by Nuno Guerra. The conference was held from August 26th to August 30th 2024 in Lisbon, Portugal.