The Application of FEFLOW in the Copenhagen Metro Project

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ABSTRACT: FEFLOW is being used to design and evaluate the consequences of groundwater lowering strategies for 21 new metro stations and shafts on the Copenhagen Metro. The new metro line runs through dense urban areas and groundwater handling during construction is an important issue. The metro stations and shafts are situated in both limestone and quaternary layers with large parts below the water table and 95% to 100% of the extracted water must be re-infiltrated. A large amount of geological and hydrogeological data was available from the Metro pre-investigations and from other previous investigations in Copenhagen. A large hydrostratigraphical model incorporating all available geological knowledge for the larger Copenhagen area was set up and together with 3D construction information forming the basis for the hydrological FEFLOW models. All data on transmissivity and hydraulic conductivity was combined into an updated limestone transmissivity map and transmissivity was distributed vertically in the limestone based on flow log data. Additional hydraulic conductivity data from e.g. Lugeon tests was incorporated locally around construction sites as voxel models using 3D gridding. The models (stationary) were calibrated against head observations using PEST and by hand and validated both as stationary and dynamic models against pump test data. For each station and shaft the needed pumping and recharge rates were calculated for different design options which included depth of cut off walls, well screen intervals, number of pumping and recharge wells, grouting quality, bottom plugs etc. The inflow distribution when pumping from screened wells was also computed and evaluated in comparison to pumping from the bottom of an open pit. Transport of existing pollution was evaluated from particle pathlines.

INTRODUCTION

The Copenhagen Metro is extended with the addition of a city circle line (in Danish “Cityringen”) that runs through dense urban areas of downtown Copenhagen and surrounding areas. The Cityringen circle line is a completely new underground metro line, planned with 17 new underground stations and 4 shaft/ramp constructions (one access ramp to an above ground control and maintenance center (CMC-area), one tunnel ramification site and two tunnel machine worksites). The stations and shafts will be connected with two parallel running tunnels, each approximately 15.5 km long. The construction of the Cityringen circle line was started in 2010 and the line is planned to be up and running in 2018 (Metroselskabet, 2012). The alignment of the Cityringen circle line is shown in Fig. 1.

Stations and shafts are situated in both limestone and quaternary layers with large parts below the water table. To ensure proper building conditions during the construction period a temporary dewatering setup for each station or shaft is necessary.

According to design requirements and with reference to the Building Act of Copenhagen, the contractor has the responsibility to design and implement temporary groundwater control measures during the construction period. This is enforced to ensure that the design is restricting groundwater lowering outside the construction site and the amount of inflow to a minimum (Metroselskabet, 2009).
Inside the inner city of Copenhagen this means that groundwater lowering outside the construction sites (the periphery of the recharge wells) will not be accepted and that 100% of the discharged water should be re-infiltrated. This is due to a range of reasons e.g. foundations of old sensitive buildings and impact on existing contaminations in the area.

At a number of locations monitoring systems for saltwater intrusion shall be established to minimize the risk of salt water intrusion to the primary groundwater aquifer of Copenhagen (limestone) and hereby possibly affect fresh water supply wells in the area.
In neighboring areas outside the Inner City only minor lowerings are accepted and a minimum of 95% of the discharged water should be re-infiltrated. All construction sites will be heavily monitored during

the construction period for groundwater levels in monitoring wells, yields and infiltration quantities from pumping/ recharge wells and groundwater chemistry.

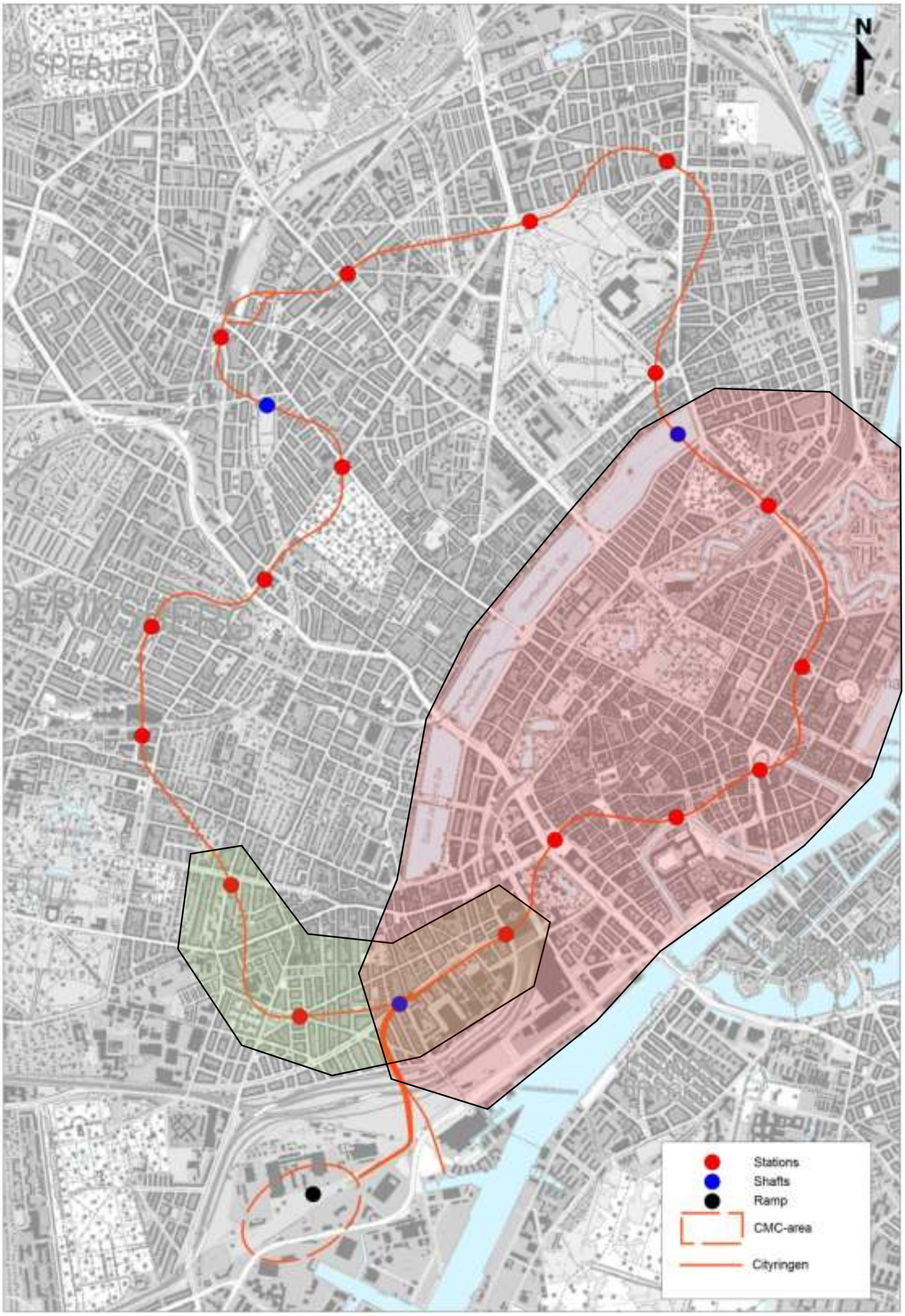

Figure 1: Alignment of Cityringen circle line, Copenhagen. Scale is 1:25.000. Red area shows inner city areas where 100% recharge is required, while green area define stations and shaft where monitoring for saltwater intrusion shall be established.

In the design of the planned dewatering/ recharge systems and evaluations of effects and consequences on the surroundings, a number of 3D FEFLOW groundwater models have been set up to help understand the hydrological system at all building sites.

The aims of the FEFLOW models are to document, to the employer and the authorities, that the suggested groundwater control strategy will be sufficient and furthermore to estimate the expected inflow and recharge at the excavation sites as well as drawdown in both primary and secondary aquifers and potential impacts on existing soil and groundwater contaminations in the areas. The models were also to be used for optimization of the dewatering design, e.g. levels of cut off walls, locations of dewatering and recharge wells, screen intervals and distribution between pumping from screened wells and open pumping/ pump sumps.

OBJECTIVES

The objective of the present paper is to make an overall description of the setup of the above mentioned models and illustrate a possible approach for FEFLOW groundwater models in relation with large scale construction sites/ tunnel projects.

GROUNDWATER MODEL SETUP

21 groundwater models have been set up for 21 construction sites along the alignment of the new Cityringen circle line in Copenhagen. All models have been built in the FEFLOW 6.0 model code. The model areas are all situated in the inner area of Copenhagen and surrounding areas. Some of the construction sites have overlapping model domains.

Geological and hydrogeological background/ input data

Large amounts of geological, geotechnical, geophysical and hydrological data have been available for the project from previous metro pre-investigation and ongoing additional soil investigations. This includes data from over 500 boreholes conducted specifically for this project, geological samples, grain size analysis, strength measurements, advanced geotechnical lab tests etc. Previous data from other project not related to the metro project was also included.

Likewise a wide range of geophysical logs (including flow logs), seismic investigations, hydrological pumping and recharge tests (capacity tests, short 1 hour tests, step tests, long term pumping tests and infiltration tests), Lugeon and Lefranc tests have been made available during the project.

Hydrostratigraphical model

All these data have been applied to a regional hydrostratigraphical model with 12 layers. The upper 6 layers all represent quaternary fill, sand and till layers, while the lower 6 layers is Selandian Greensand, a fractured part of Upper Copenhagen Limestone (HP UCL), Upper Copenhagen Limestone (UCL), Middle Copenhagen Limestone (MCL), Lower Copenhagen Limestone (LCL) and Bryozoan Limestone. In some local areas all layers may not be present (GEO, 2011). In Table 1 the setup for the hydrostratigraphical model is shown.

In addition to the main layers, a number of additional layers are added to the models. To ensure the correct application of hydraulic parameters, a thin buffer layer has been added at the top and at the bottom of each aquitard layer and calculation layers have been added to ensure numerical stability in layers of great thickness and to enable the setting of boundary conditions e.g. at cut off walls, excavation bottom, lakes, port etc. In general the models have between 45 and 65 layers, largely depending on the complexity of the modeled shaft/ station/ ramp and the local hydrological conditions.

Layer no.	Geology
1	**Fill and Late/ Postglacial sediments**
2	**Upper Sand**
3	**Upper Till**
4	**Middle Sand**
5	**Lower Till**
6	**Lower Sand**
7	**Selandian Greensand**
8	**Upper Copenhagen Limestone fractured (HP UCL)**
9	**Upper Copenhagen Limestone (UCL)**
10	**Middle Copenhagen Limestone (MCL)**
11	**Lower Copenhagen Limestone (LCL)**
12	**Bryozoan Limestone**

Table 1: Main hydrostratigraphical layers

A precise topographical DTM model (1.6 meters resolution) of the Copenhagen Area has been used at the top of the model, while the bottom of the models is defined 30 meters below the top of the Bryozoan Limestone.

Finite element grid

The finite element grid has been constructed to ensure sufficient calculation elements around areas with expected steep head gradients, areas with large differences in hydraulic parameters and areas around construction elements (stations/ shafts) and point elements (pumping and recharge wells). On the other hand the number of cells had to be kept to a minimum to reduce calculation time. The model grids had in total between approximately 4.5 and 7.5 million elements.

The mesh generation algorithm used for all models is Triangle (J.R. Shewchuk, 2005) which is recommended for complex setups of polygons and points/ lines. The finite element grid is generated as a quality mesh with a minimum angle of 30˚ and fulfills the Delauney Criterion. In Fig. 2 an example of a finite element grid from a station excavation is shown.

Boundary conditions

The model domains take their outer boundary conditions (BCs) from natural boundaries such as no-flow BCs (flow lines perpendicular to groundwater potential contours) or lines of equal head (constant head BCs). Net infiltration rates are applied at the top of the models throughout the model domains and vary from 30 mm/yr. to 250 mm/yr. depending on the type of surface and thus the infiltration to the saturated zone.

To control flow through the lake embankments and lake bottoms, fluid transfer BCs are applied at the water-land interfaces. The same method is used between the water-land interface at the harbor and at the bottom of the harbor where a semipermeable clogging layer has been recognized and applied in the model.

Pumping wells are implemented as multilayered well BCs with fixed pumping rates or as fixed head BCs depending on the type of simulation/ construction. No pumping wells have screen intervals below the cut off level of the slurry walls or secant pile walls surrounding the excavations to minimize inflow.
Open pumping/ pump sumps are implemented as fixed head BCs.

If a cavern excavation is included in the model (attached to stations or shafts), the boundary conditions are implemented as fixed head BCs (pressure = 0) on walls, roof and floor of the cavern. The caverns are surrounded by grouted sediments to reduce inflow, see also Fig. 3 where principle sketches of different station/ shaft designs are shown.

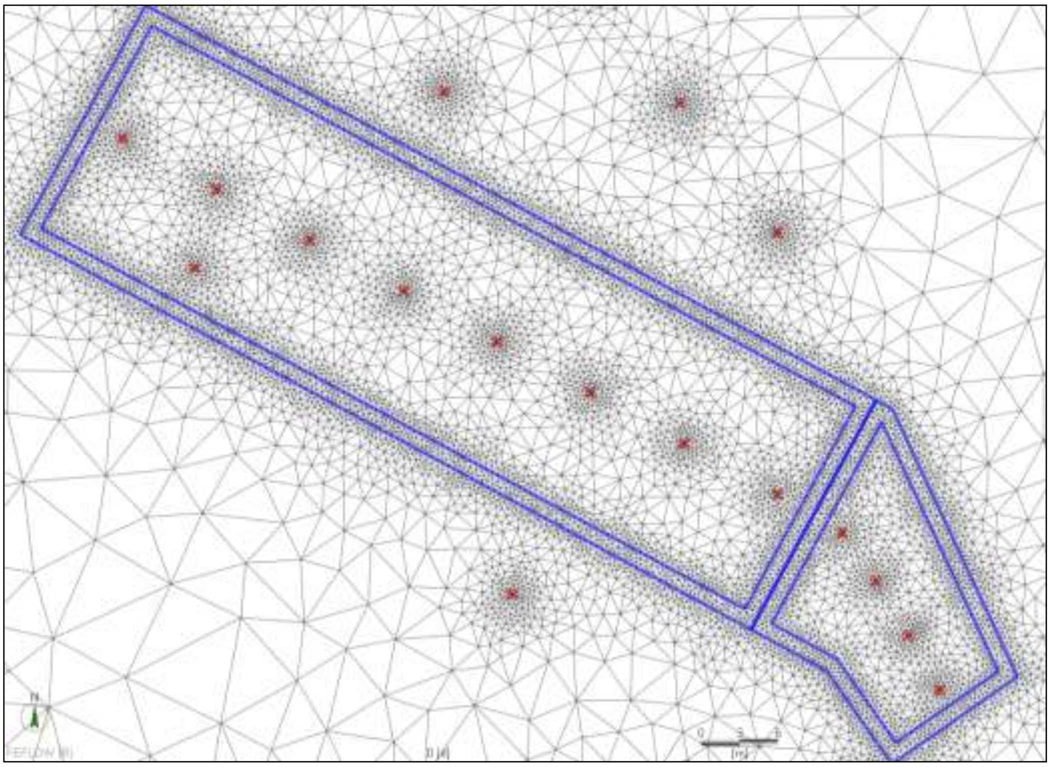

Figure 2: Example of a finite element grid from a station excavation.

Recharge wells are distributed outside the shaft areas and implemented as multilayered well BCs with fixed injection rates. The screens are most often applied from the top of the limestone aquifer to the bottom of the cut off walls. The expected recharge rates are estimated from steps tests, recharge tests and long term pumping test carried out in the area. Based on experience a degeneration loss must be expected and therefore the number of recharge wells are adjusted to meet the expected conditions.

Leaky sewers, other pumping wells (water supply) or other and permanent drainage of constructions in the Copenhagen area like basements, railways and tunnels etc. are also included in the models.

Regional and local hydraulic parameters

Hydraulic conductivity in the quaternary layers is spatially distributed based on experience and PEST/ hand calibration. Additional grain size analysis, pumping tests and Lefranc tests have also been incorporated in the models for the quaternary sand units. All data on transmissivity and hydraulic conductivity for the limestone was combined into an updated transmissivity map and transmissivity was distributed vertically in the limestone based on flow log data. Additional hydraulic conductivity data from e.g. Lugeon tests was incorporated around construction sites as voxel models using 3D gridding. The voxel models are only applied locally, and cover areas from 100 to 200 meters from the shaft, where the data density is sufficient and where many investigation wells have been made.

In the uppermost fill layer, the anisotropic difference between the horizontal and vertical hydraulic conductivity was set at 10, while for the sand, limestone and till layers the anisotropic difference were set at respectively 10, 10 and 2. An exception is the fractured part of the Upper Copenhagen Limestone (HP UCL) where the anisotropic difference is set to 5. The anisotropy factors are based on experience and results from pumping tests. In Table 2 typical ranges for hydraulic conductivity are shown. Note that Copenhagen limestone is intersected by a complex fault system, including the

Carlsberg fault system that supply a large part of Copenhagen's fresh water, which means that some areas have very high water flow rates.

Table 2: Typical hydraulic conductivity ranges distributed in the models

Model layer	Kxy (m/s)	Kz (m/s)	Anisotropy (Kxy/Kz)
Fill/ postglacial	$1{\cdot}10^{-4}$ - $1{\cdot}10^{-7}$	$1{\cdot}10^{-5}$ - $1{\cdot}10^{-8}$	10
Upper Sand	$5{\cdot}10^{-4}$ - $1{\cdot}10^{-6}$	$1{\cdot}10^{-5}$ - $1{\cdot}10^{-7}$	10
Upper Till	$5{\cdot}10^{-8}$ - $1{\cdot}10^{-9}$	$2.5{\cdot}10^{-8}$ - $5{\cdot}10^{-10}$	2
Middle Sand	$5{\cdot}10^{-4}$ - $1{\cdot}10^{-6}$	$1{\cdot}10^{-5}$ - $1{\cdot}10^{-7}$	10
Lower Till	$5{\cdot}10^{-8}$ - $1{\cdot}10^{-9}$	$2.5{\cdot}10^{-8}$ - $5{\cdot}10^{-10}$	2
Lower Sand	$5{\cdot}10^{-4}$ - $1{\cdot}10^{-6}$	$1{\cdot}10^{-5}$ - $1{\cdot}10^{-7}$	10
Selandian Greensand	$1{\cdot}10^{-4}$ - $1{\cdot}10^{-6}$	$1{\cdot}10^{-5}$ - $1{\cdot}10^{-7}$	10
HP UCL	$1{\cdot}10^{-3}$ - $5{\cdot}10^{-7}$	$2{\cdot}10^{-4}$ - $1{\cdot}10^{-7}$	5
UCL	$5{\cdot}10^{-4}$ - $5{\cdot}10^{-8}$	$5{\cdot}10^{-5}$ - $5{\cdot}10^{-9}$	10
MCL	$5{\cdot}10^{-5}$ - $5{\cdot}10^{-8}$	$5{\cdot}10^{-6}$ - $5{\cdot}10^{-9}$	10
LCL	$5{\cdot}10^{-5}$ - $5{\cdot}10^{-8}$	$5{\cdot}10^{-6}$ - $5{\cdot}10^{-9}$	10
Bryozoan Limestone	$5{\cdot}10^{-5}$ - $5{\cdot}10^{-8}$	$5{\cdot}10^{-6}$ - $5{\cdot}10^{-9}$	10

Building structures

Both secant pile walls and slurry walls (cut off walls) are used in the project and defined around the station, shaft and ramp excavations. The conductivity (Kx, Ky and Kz) of the cut off walls were assigned a presumed low value defined by the contractor. Layers inside the shaft, cavern and ramp areas were defined with a very low conductivity of 1 x 10^{-20} m/s to simulate the empty space and to avoid short circuit between the pumping wells in the shaft and the boundary condition nodes of the cavern. A more realistic drawdown cone around the pumping wells was also achieved. Grouted areas around caverns were assigned different hydraulic conductivity values between 1 x 10^{-5} and 1 x 10^{-7} m/s and manual sensitivity analyses of the conductivity of the grouted area and hereby the quality of the grout have been conducted.

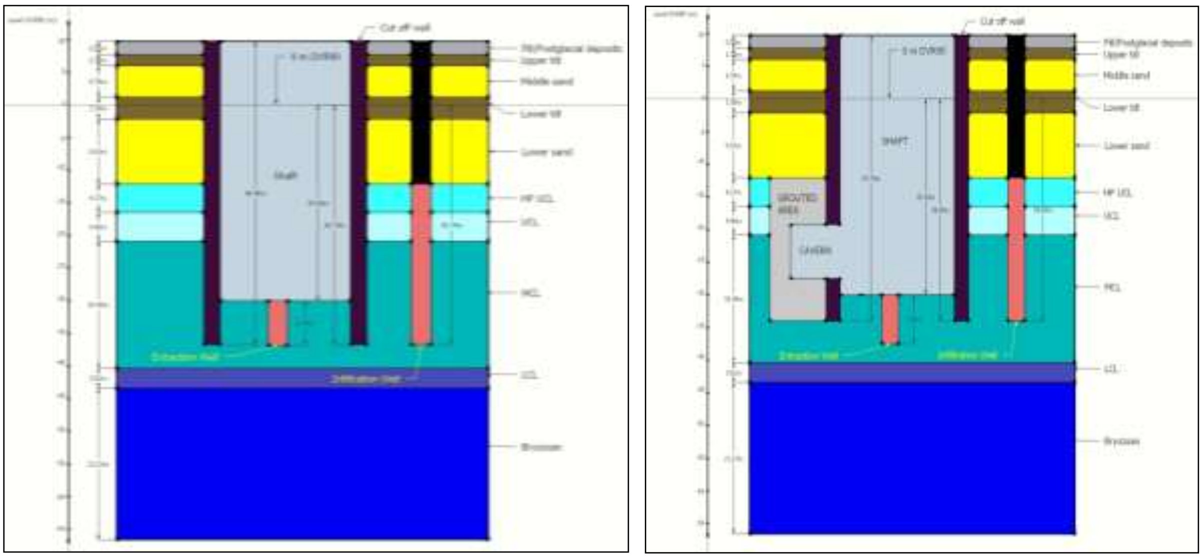

Figure 3: Principle sketches of two different station designs. Left: A station excavation with shaft, cut off walls (slurry walls or secant pile walls), extraction well and infiltration well. Right: With an attached cavern and grouted area.

Calibration and validation

The models were calibrated manually and by PEST (J. Doherty) against field-measured head data. Field data were obtained from tender material, synchronized water level measurement projects in the Copenhagen area and from the public database Jupiter, managed by GEUS (Geological Survey of Denmark and Greenland) (GEUS, 2011).

Stationary models were validated against a second set of field-measured head data (split-sample method) obtained during synchronous point measurements taken around the excavation sites.

Transient flow validations of long term pumping tests have also been performed at all sites to test the models ability to reproduce the observed properties of the primary and secondary aquifers in the areas.

Scenarios description

A number of scenarios were created and tested as stationary and transient confined flow models. First, a basis run of the models without any construction elements were conducted (scenario 1). The main purpose of scenario 1 was to check that the overall hydraulic heads in all layers inside the model domain and especially around the shaft area were simulated appropriately. An initial head for calculation of drawdown for the following scenarios were also archived.

Thereafter scenario 2 was created with construction elements like cut off walls, excavation areas, caverns etc. Scenario 2 was run a number of times with different pumping rates until the stated groundwater level inside the shaft was achieved together with recharge rates equal to 95% or 100% of the total pumping rates. Simulated head and drawdown are presented and forward pathline simulations are performed from sites with contamination that may have an impact on the groundwater quality. The pathline simulations were computed to visualize the impact of the dewatering on the contaminated sites.

The pathlines were calculated with the assumption of a fixed effective porosity and all pathlines was initiated at the top of Limestone. Finally quantifications of inflow and recharge rates are reported to the contractor.

In a following scenario 3, which is a dynamic run of scenario 2, the recharge system was stopped for a period of 14 days. The aim of scenario 3 was to present a worst-case drawdown scenario to the authorities simulating a breakdown of the recharge system.

Additional scenarios have been set up and conducted for a number of models regarding sensitivity analyses of grouting parameters (grouting quality), alternative design options like depth of cut off walls, well screen intervals, number of pumping and recharge wells, bottom plugs etc.

In situ large scale tests

Before excavation of the stations/ shafts below the groundwater table, but after the construction of the cut off walls (slurry walls or secant pile walls), the groundwater control system design is tested through an in situ large scale test carried out at all construction sites.

During the large scale test all pumping/ recharge wells and the connected distribution system, water treatment facilities, contamination control facilities and the monitoring system are tested. If any inconsistency is found between the model results and the in situ large scale test, the groundwater models may have to be updated based on the results of the tests.

SUMMARY

Modeling of a large-scale construction project with FEFLOW has been very successful. Especially the discretization of the complex building structures has been satisfactory. One challenge has been the constant update of hydrological knowledge from ongoing additional soil investigations and incorporation of new station designs. The project is still ongoing and so far only one large scale test has been conducted. Whether these in situ tests will affect the model approach is still to be reviewed.

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