THE COPENHAGEN METRO CIRCLE LINE—TUNNELLING AND STATION CONSTRUCTION CHALLENGES IN URBAN CONDITIONS

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ABSTRACT

The paper will describe challenges for design and construction of the tunnels and stations in soft ground conditions in an urban environment for the Copenhagen Metro Circle Line. The project consists of 15.5 km metro line with 17 underground stations. The ground conditions are 10–15 m of glacial deposits overlying a limestone, which are fissured and include hard layers of flint. The stations will be constructed as Cut & Cover structures using top-down construction technique and retained within a station box of either secant piles or diaphragm walls. The tunnels located in the glacial deposits and in the limestone will be constructed using closed face TBM's of either EPB or slurry type. As many of the old buildings in Copenhagen are founded on wooden piles which will deteriorate if exposed to oxygen, there are requirements for not lowering the groundwater table. One of the major challenges for the project is to control the groundwater during tunnel and station construction. A system of combined dewatering and recharge of groundwater in places in combination with grouting will be utilised. The paper describes the challenges in selection of construction methods dealing with the strict requirements for groundwater control, noise and vibrations and settlement control. The project is tendered as a design and construct project during summer/autumn 2010 and construction contract signed in January 2011.

THE CURRENT METRO SYSTEM

Copenhagen is the capital of Denmark with a population of approximately 1 million inhabitants. In 2002 the first metro line was inaugurated. The first metro line is a driverless, fully automated system. One extension was added in 2004 and a branch-off line extending to Copenhagen Airport was opened in 2007. The system currently in operation is 23 km long. 8 km is under ground. It has 17 stations of which 9 are below ground.

Cityringen—The New Lines

The idea of adding to the system was conceived shortly after the work on the first line had begun. It was published by Erlandsen in the proceedings of the inauguration seminar for the first metro line (Johansen and Erlandsen 2002). In 2005 Metroselskabet (formerly Ørestadsselskabet) was asked by the Ministry of Transport to carry out a programme study for providing further metro services to central Copenhagen. The study

Figure 1. Proposed alignment of Cityringen

was based upon Erlandsen's ideas and further substantiated by comprehensive traffic analyses, alignment, and socio economic investigations.

In 2007 the Cityringen Act was passed in the Danish parliament. At the same time a law establishing Metroselskabet (The Copenhagen Metro Company) as a new entity was formed. Metroselskabet is owned by the Danish state (50%), the municipality of Copenhagen (42%) and the municipality of Frederiksberg (8%). The task of Metroselskabet is to own and operate the existing metro and to build the new Cityringen.

In 2007 Metroselskabet tendered for consultancy work for the development of the system. A joint venture lead by COWI of Denmark and with Arup of England and Systra of France won the contract and has since then developed the conceptual design, prepared the tender documents for the construction contracts and assisted in tender evaluation and contract preparation for the Civil Works. The Cityringen line shall consist of two single track tunnels each approximately 16 km in length, 17 underground stations with island platforms, two crossover facilities and three construction and ventilation shafts. In addition, Cityringen will include an automated control and maintenance centre (south of the line) at Vasbygade built for operation and maintenance of the system. The existing and proposed metro lines are shown as Figure 1.

"More of the Same" as Principle for a Programme Study

After some initial difficulties, the driverless metro system quickly became popular. As basis for the study a principle of "*More of the Same"* was applied:

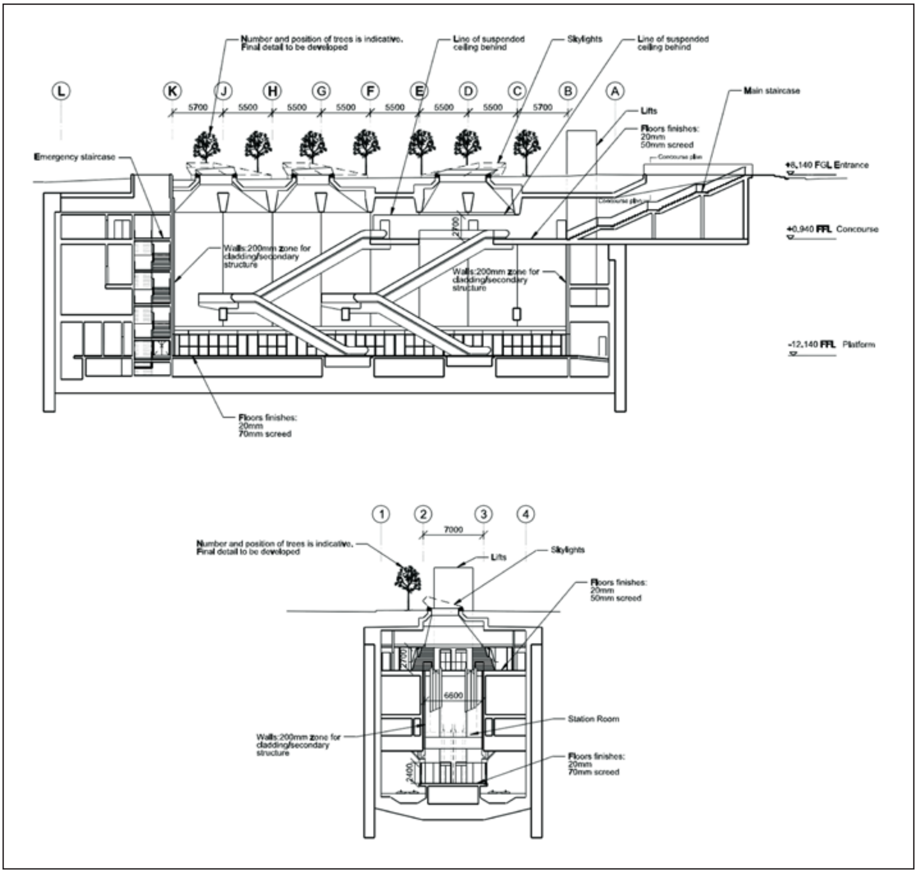

Figure 2. Longitudinal and cross section of station location at Nuuks Plads

- Short Cut & Cover box stations with straight, daylight lit central platforms fitting into the city squares. The box station is packed with all passenger, mechanical, electrical, signaling and power supply installations for the station and the adjacent rail sections.
- The platform height shall be identical to the platform height of the existing metro.
- Twin tube bored tunnels with structural gauge identical to the structural gauge of the existing metro.
- 3 car articulated train with door module matching station module.
- Fully automated train system.

The entire line will be below ground with stations conceptually identical to the deep underground stations for the metro in operation. The deep underground stations for the existing metro are built in Cut & Cover, using a top-down approach (Figure 3). A longitudinal and cross section of a deep underground station is shown on Figure 2.

Applying this principle in the planning process meant that the elements of the system became easier to analyse, place, plan and estimate for cost, simply because experience with these components was readily at hand from the first metro stages. Analyses of the lessons learned from the construction, the implementation and the operation

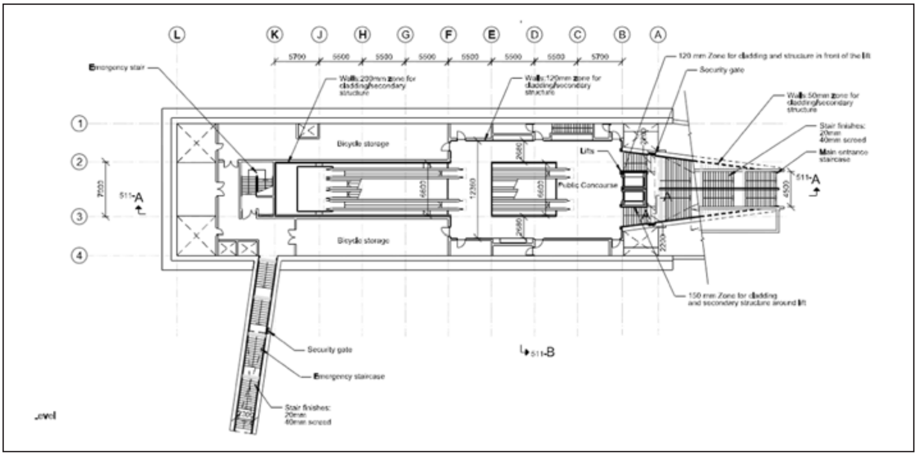

Figure 3. Plan underground station location at Nuuks Plads

of the system were part of the study and the later planning, design and tendering of the system. Examples of specific application of lessons learned are that stations in Cityringen will have two rather than one lift and that fixed stairs have a decreased slope for improved accessibility for all passengers.

Cityringen is two lines in one: A circular line supplemented by a pendulum line servicing the eastern portion with the double amount of trains. As shown on Figure 4 it will tie the net of public transportation together and enable passengers to travel across central Copenhagen in new ways. There will be interconnections to the existing metro lines as well as the S-trains from the suburbs and the regional train services. Traffic models estimate that the new lines will have 72 million passengers per year. It is physically separate from the existing metro lines, it will have its own fleet of rolling stock and its own control and maintenance centre.

Tendering and Contract Split

The dominating contracts for constructing the Cityringen metro system are Civil Works and the Transportation System. Preceding these major contracts, a number of contracts for consultancy services, geological investigations, utility relocations and building modifications have been procured.

The Civil Works for the Cityringen project was tendered in a North, a South or a North + South in one design/build contract. The North/South contract split was made to coincide with the geological setting as mentioned below. The Owner had no predefined bias for two or one contracts. The competition was carried out following EU rules in a negotiated procedure. A division of 60/40 percent for price versus technical score was set before tendering. Four consortia were pre-qualified and three proceeded to deliver a final bid. The Civil Works contract was signed in January 2011.

The Transportation System contract was tendered in parallel with the Civil Works. It comprises delivery of rolling stock, rail infrastructure, the control and maintenance centre, systems integration as well as operation and maintenance of the new metro lines for five years after commissioning with an option for further three years in accordance with EU rules.

Following these main contracts, the Owner Metroselskabet has decided to tender the architectural finishes, the works at the transfer stations and the station surface area works following further detailing of the design. The idea is to have further control of the

Figure 4. Conceptual plan of Copenhagen Metro showing Cityringen and the transport system of Copenhagen (M1, M2 existing lines: M3, M4 proposed Cityringen)

passenger experience. The Owner intends to develop this design in parallel with the Civil Works and the Transportation Systems contractor's design.

The architectural finishes contracts will be tendered at a later stage and handed over to the Civil Works contract as nominated subcontractors. A provisional sum has been set within the Civil Works contract for this.

For the station surface areas a campaign of dialogue with local residents was carried out in the summer of 2010. It has resulted in a catalogue of ideas and requests for the functions at the surface areas near the station entrances. The coming design of the surface areas is carried out in close cooperation with the municipalities. The surface area works will be tendered at a later time in one or more contracts.

GROUND CONDITIONS

The accurate determination of the geotechnical and hydrogeological conditions along the Cityringen alignment is fundamental to the design and safe construction of the various Cityringen structures. To provide sufficient data to allow the tender design, and to provide the design and build contractor with sufficient information to allow a solid basis for the pricing of the contracts, an extensive geotechnical and hydrogeological investigation has been undertaken with associated laboratory and in situ testing and monitoring to identify the ground and groundwater conditions. It is also envisaged that during the construction phase the contractor will undertake further investigations at those locations where he feels additional information is required.

Site Investigations

In order to assess the site conditions in detail, targeted site investigations were 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 tests, 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
- Advanced laboratory testing on soil and rock

The above site investigations and concurrent evaluations have been carried out in parallel with the tender design. Hence, it has 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 groundwater 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.

Soil Conditions

The current geotechnical investigation and the knowledge gained from previous investigations showed that the ground conditions along the alignment of Cityringen comprise a quaternary sequence of meltwater sands and tills resting on Danian

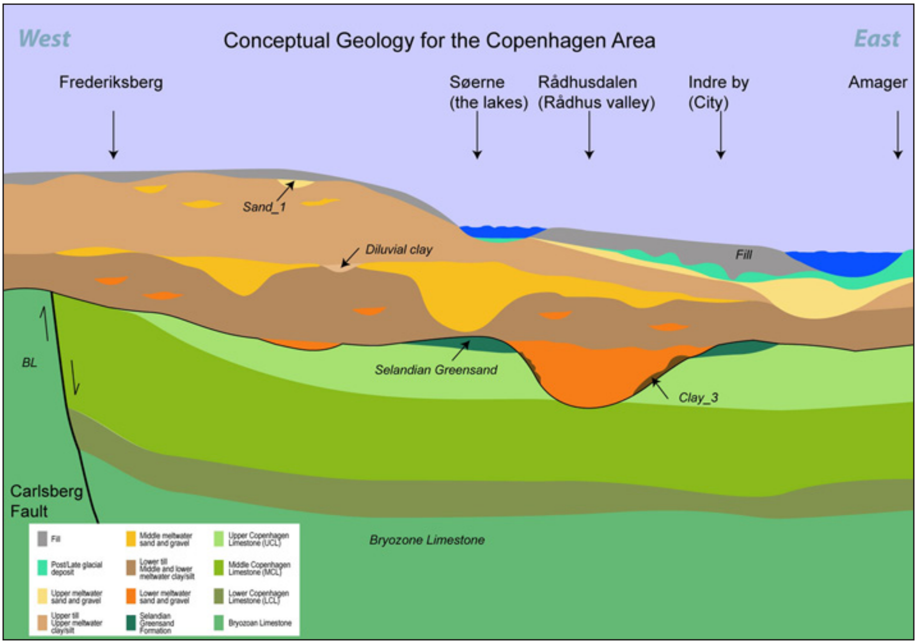

Figure 5. Conceptual geology for the Copenhagen area

limestone. The quaternary deposits are overlain by fill and post- and late-glacial deposits. Deposits belonging to the Selandian (Middle Palaeocene) Greensand Formation are also found locally subjacent to the quaternary deposits.

The fill layer is of varying thickness, with thick deposits found in areas with previous moats, lakes and canals, as well as old clay pits and sand/gravel quarries.

In the quaternary deposits two layers of till are observed, an upper till unit and a lower till unit, separated by meltwater sediments. Locally the two till layers constitute a contiguous layer e.g., as seen in the Frederiksberg area. The tills are typically heavily over-consolidated, very stiff to hard sandy clays.

Three meltwater layers have been identified. The upper meltwater unit is of very limited extent, the middle meltwater unit is separating the two till units, and the lower meltwater unit is mainly observed as coarse grained sediments filling erosion valleys in the project area.

Across much of the alignment the quaternary sediments are directly underlain by the Copenhagen limestone of Danian age. However, Selandian Greensand deposits are observed locally adjacent to quaternary deposits within the southern part of the alignment.

The Copenhagen limestone is a fractured soft rock which has some similarities to fractured chalk. Based on geophysical logging, the Copenhagen limestone has been subdivided into three sub-units, upper, middle and lower Copenhagen limestone. The upper Copenhagen limestone is horizontally bedded with layers of different hardness and thickness from a few centimetres up to 1 m. Flint occurs in beds of 0.2 to 0.4 m thicknesses, occasionally up to 1m in thickness and can be followed continuously over long distances (Figure 5).

The pre-quaternary surface is characterized by meltwater erosion valleys, incised in the limestone surface. The interface between the quaternary deposits and Copenhagen limestone takes one of two forms, these are:

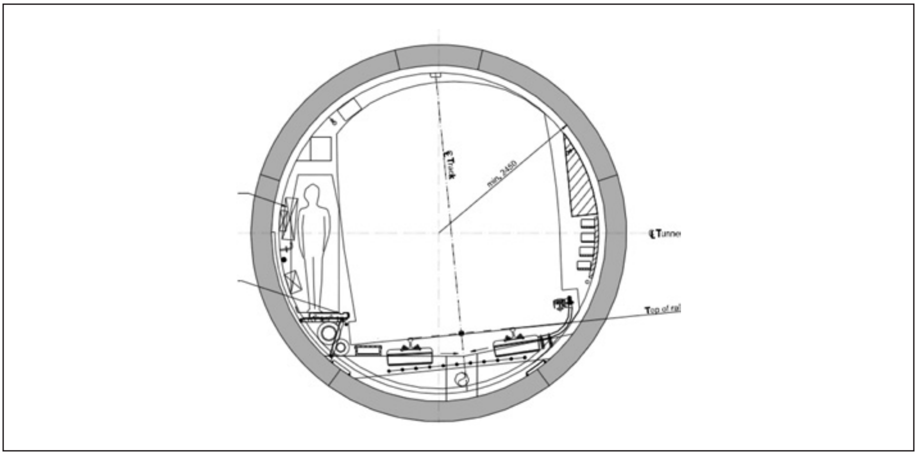

Figure 6. Section through the running tunnel

- Limestone glacially disturbed, which is limestone that shows evidence of glacial disturbance but where the original structure is preserved, i.e., it is more fractured than lower in the limestone.
- Limestone that is unaffected by glacial disturbance.

TUNNEL

The “standard” running tunnels are single track tunnels constructed using TBM’s appropriate to the ground conditions. The tunnel linings have a minimum internal diameter of 4.9 m. The single tunnel lining is formed by prefabricated universal rings with tapered segments allowing the tunnel to follow the alignment. A ring consists of six segments, including two counter key segments and the key segment. The thickness of the segments is assumed to be in the range 275 to 325 mm. The prefabricated segmental linings are either traditional reinforced concrete or steel fibre reinforced concrete, or a combination of both. Sealing of the segmental lining is achieved by fixing gaskets within the grooves of each segment. Grout holes are provided within the units to allow secondary grouting of the tunnel lining. The primary grouting of the annulus around the tunnel rings is achieved by grout lines integral with the tail skin of the TBM (Figure 6).

The tunnelling will be within the limestone and glacial soils. The tunnelling in the southern section is predominantly in the limestone, whereas the northern alignment is in glacial deposits, limestone and mixed conditions giving more difficult tunnelling conditions. It should also be noted that although the tunnels in the southern half of the alignment are generally in limestone, often the tunnels rise as they approach or leave the stations. In several cases the tunnel next to the stations are bored within mixed face deposits with corresponding larger amounts of ground movements. This is the case for instance close to Kongens Nytorv, Rådhuspladsen and København H. The ground conditions along the tunnel alignment are shown in Figure 7.

TBM tunnelling for the Cityringen will face ground conditions such as limestone with layers of flint, glacial deposits (till, clay, silt, sand, gravel, boulders etc.) and mixed zones. The water table is above the tunnel lining. TBM tunnelling by EPB machines in limestone, as in most of the southern part of the Cityringen, is assumed to be relatively unproblematic with regard to face stability, ground loss, groundwater control and settlement. This is based on previous experience with the earlier Copenhagen metro projects. Although there are some areas of glacial deposits on the southern section

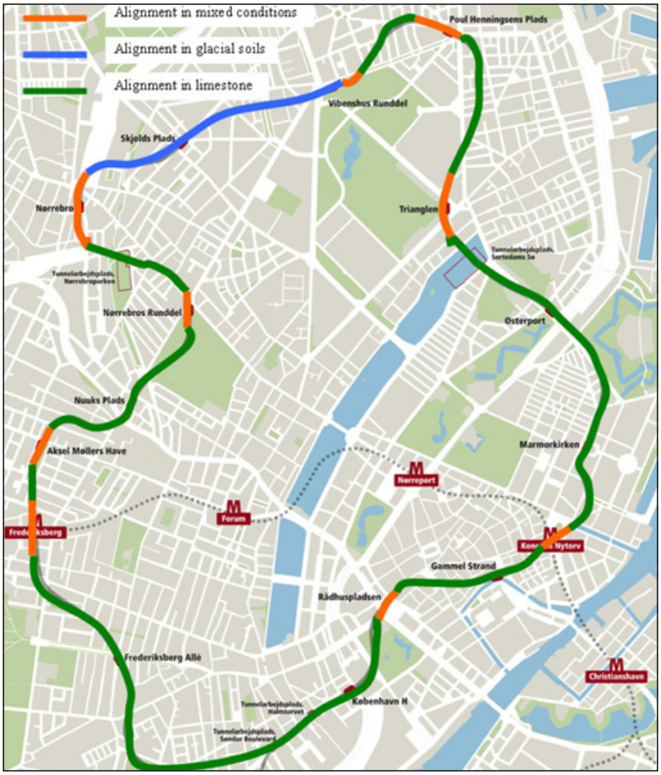

Figure 7. Ground conditions along the tunnel alignment

of the alignment, it is assessed that this does not change the balance away from an EPB machine. However, the TBM type for tunnel sections in glacial deposits and in mixed zones, as will be encountered in the northern section of the Cityringen, is more complicated. The tender documents described that either EPB TBM with a secondary face support system or a slurry type TBM with a double chamber system using a compressed air-cushion could be considered for the mixed face ground conditions and the glacial deposits. The successful contractor has chosen to operate EPB TBMs for the full circle.

STATIONS

The station concept is a development of the deep stations on the existing metro lines and most stations design follow the existing station design as far as possible, but each is modified as necessary to suit local conditions. Essentially, the station structures are built as Cut & Cover structures.

Under the design and construct contract Metroselskabet I/S as the Owner has fixed the station positions and orientations, together with the platform levels, concourse levels and other main geometry.

The basic concept for the deep stations is that they are an underground rectangular box with a main entrance at one end which incorporates two passenger lifts from platform level to ground level and ventilation fans, tunnel draught relief shafts and a fixed stair secondary exit at the other end. Generally, the perimeter retaining walls of the rectangular box are formed utilizing deep retaining walls.

Each station box is 64.4 m long but the width of the box is determined by the passenger requirements which define the width of the platform. The deep station platforms are either 7 m or 9 m wide. Therefore the overall width of the deep stations is either 20.4 or 22.4 m. The station grid is based on a 5.5 m module.

The roof structure of the station have a minimum groundcover of either 0.5 m, 1.0 m or 1.5 m below the ground level depending on the use of the surface areas; for example road or plaza areas, tree planting or erection of circus tents.

The station roof structure consists of 1.1 m wide × 2.0 m deep reinforced concrete beams positioned on the station grid lines i.e., 5.5m c/c spanning the full width of the station box with a 400 mm thick roof slab spanning between the main beams.

The upper surface of the roof slab is laid to falls and waterproofed by a waterproofing membrane and protected by a 100 mm thick concrete screed. Movement joints are not provided in the roof structure. The slab soffit forms the containment to a warm dry and well ventilated station concourse space.

Within the box there is only one level of horizontal structure at intermediate level which provides permanent support to the deep retaining walls. There is a ground bearing reinforced concrete base slab which also provides long term propping action for the retaining walls. The base slab supports the central island platform structure. There is no under slab drainage or compressible layer beneath the base slab. The general excavation depth of the stations is approximately 24 m below existing ground level.

The station box is envisaged as being built using top-down construction methods.

Prior to start construction works for the stations, diversion of utilities has been completed.

The stations are to be constructed in the close vicinity of existing buildings and structures. Construction methods have been chosen in order to control the groundwater and to limit the impact on existing buildings and structures from settlement to an acceptable level. Further, considerations have been given not to spread existing contamination of the ground water and to protect groundwater resources. The groundwater control system and the building damage assessments are further described in a later section. Before commencement of excavation, a monitoring system must be implemented to measure and interpret wall deflections, axial loads in the slabs and ground settlement as well as the effects of ground movements on adjacent buildings and structures.

As mentioned above the main principle is to construct the station within a box of retaining walls. The retaining walls need to be sufficiently stiff to minimize movement and to be watertight to reduce groundwater inflow through the wall to the construction pit. The retaining walls must extend to a sufficient level to cut off the groundwater flow from the side and below the retaining walls to the construction pit. The depth will depend on the local geological strata and the location of the flow zones. Experience from the existing metro shows that where the station box is constructed with the base slab in the middle Copenhagen limestone a depth of 5 m below track level should generally be sufficient to ensure cut-off of ground water. Based on assessment of water flow from flow logs and pumping tests in boreholes, the toe level of the retaining walls has been specified in the contract.

The main entrance, emergency exit stairs, ventilation ducts and grilles extend to the outside of the station box and require shallow excavations with retaining walls outside the station box. For four stations (København H, Kongens Nytorv, Østerport and Frederiksberg) there are transfer tunnels to existing stations. These excavations generally extend to a depth of 7–8 m below ground level, corresponding to the concourse level of the stations. Depending on the local hydro-geological conditions and the vicinity of existing structures these excavations may be supported by pre-drilled sheet piles, king post piles or in the special cases by secant piles or slurry walls. Excavation under

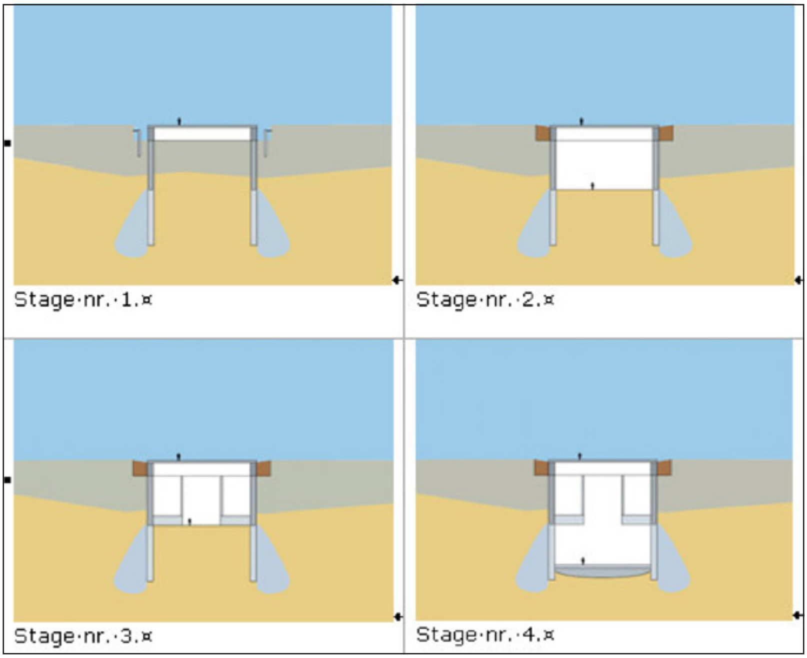

Figure 8. Typical construction method for deep station

the water level and casting the base slab wet may also be a possible solution in case groundwater can not be controlled in another way.

The typical construction sequence for a deep station is shown in the pictures in Figure 8. In Stage 1 the guide walls for the installation of the deep retaining wall are installed.

Before start of the excavation a groundwater control plant is established at the worksite. During excavation and construction groundwater will be pumped from wells and pump sump located inside the station box. The water is cleaned and recharged, through wells placed in the vicinity of the construction pit, to the primary aquifer as required in order to avoid unacceptable groundwater drawdown around the construction pit.

Excavation takes place to below roof level. The concrete at the top of the deep retaining walls is cut back using silent non-vibration tools to allow for casting for the capping beam, the roof beams and roof slab. This forms a rigid connection to the deep retaining walls.

In Stage 2 the excavation inside the station box proceeds to the level of the underside of the intermediate level beam. Temporary propping and bracing are installed in order to control wall deflections. During excavation the dewatering inside the station box is kept to a level below the excavation.

In Stage 3 the reinforcement for the intermediate level beams is placed and hangers are connected from the intermediate level beams to the roof beams. The intermediate level beams and cross beams are cast.

In Stage 4 the excavation proceeds to the underside of the base slab and a blinding layer is cast. Reinforcement is placed and the concrete for the base slab is cast in one continuous operation. At this stage the station is ready for receiving the TBM's.

The construction of the internal structures above the intermediate level can proceed in parallel to the above mentioned works.

When the TBM's have passed and are still in operation, the casting of inner walls, decks and platform can be done.

SPECIAL CONSTRUCTION RESTRAINTS

Groundwater Control

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 or adverse effects to water supply. Therefore, a focused strategy for identifying and handling the risks through comprehensive urban hydrogeological surveys is necessary. 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 zone 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, e.g., by spreading of the existing contamination plume.

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 watertight 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 9. 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.

Basis for Design

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.

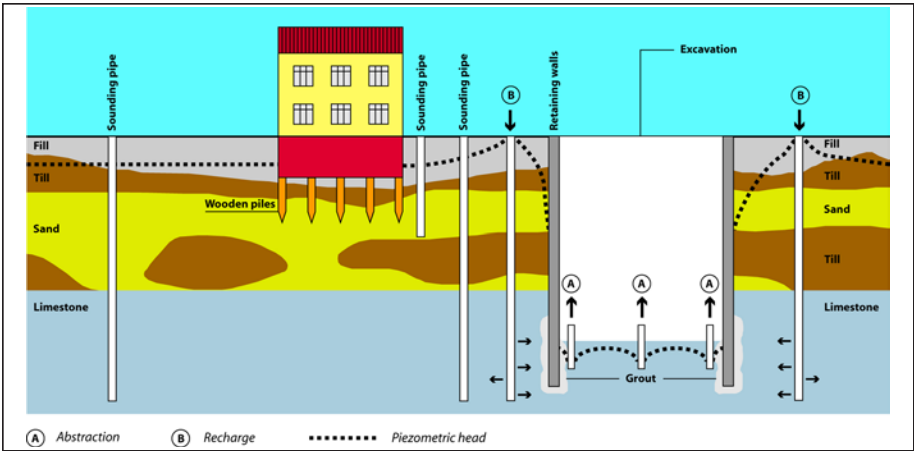

Figure 9. Principle of groundwater control in Copenhagen

Building Damage Assessment Process

The tunnels and stations of Cityringen will be located adjacent to and beneath buildings which have a great variety of ages, spanning from the Medieval times to present. Sections of Cityringen are located below the city centre of Copenhagen. This area contains many buildings dating from the 16th to the 18th century which may be affected even by minor changes in the in situ ground conditions. In relation to the older buildings, there is great variety in form and original function. These vary from "simple" dwellings for wealthy craftsmen and tradesmen to quite grand houses for trading companies and palaces for the wealthy. The newer buildings are mainly less distinctive dwelling houses, office buildings and other commercial buildings. Outside the city centre, Cityringen will also pass below modern buildings. Generally, these buildings are of complex structures, sometimes extending over large areas.

In such an urban environment building protection measures, including monitoring, settlement control and the installation of mitigation measures, are critical to the station and tunnel works. An initial assessment of building damage has been undertaken at tender design stage to assess the damage to buildings along the line of the Cityringen. The building damage assessment undertaken at this stage comprised of two aspects which were namely building registration and a building risk assessment. The two main aspects are discussed below.

Building Registration

A general registration of building data and condition of buildings within an approximately 100 m wide zone along the alignment, taken as 45 m on either side of each track centre line has been undertaken. At construction sites for stations and shafts the boundary of the area for registration of building data and condition was approximately 40 m from the retaining walls of the construction pit.

A building register, "Building database," has been developed. The building registration database includes the following:

- Registration of the cadastral number in the land register and address for buildings within the area for investigations together with a brief note about the conditions of accessible facades including a few photos.
- Collection of information from the municipality building registers for selected buildings in the area of registration and investigation.

Table 1. Volume loss for settlement cases

Case Ground Conditions	Limestone		Mixed Face, Glacial Soils	
	Volume Loss	Settlement Trough Value 'k'	Volume Loss	Settlement Trough Value 'k'
Worst credible	0.15%	0.25	2%	0.5
Most likely	0.15%	0.25	0.8%	0.5
Best	0.15%	0.25	0.5%	0.5

- Approx. 1 building every 100 m of the alignment, where the TBM is expected to be operating in competent limestone
- The majority of the buildings inside the approx. 100 m wide investigation and survey zone for the rest of the alignment, i.e., tunnelling in glacial deposits or in transition zones between glacial deposits and the limestone.

Maps have been prepared showing listed buildings, churches and other buildings of high conservational values located in a zone approximately 400 m centered around the alignment. Maps have also been prepared showing buildings within the building registration zone.

Building Risk Assessment

The building risk assessment process was based on a staged approach. The sequential process has identified the critical buildings along the alignment using the building and geotechnical information available at tender. This allowed a means of scoping the extent of required protection measures and allowed a cost estimate for building protection. The main stages of the building risk assessment can be outlined as follows.

For the Stage 1 assessment a settlement analysis was undertaken to determine the ground movements above the entire alignment of the Cityringen. The settlement analysis was undertaken using the computer programme Xdisp (Oasys 2010). The fundamental parameter that underlies all empirical methods of estimating tunnelling settlement is the volume loss. Volume loss can be defined as the ratio of the additional volume of excavated ground removed over the theoretical volume of the tunnel (Table 1).

Stage 1 comprised a screening process using the 'worst credible' volume loss. In this stage the effects of building foundation on the pattern of settlement are ignored. The screening comprised the identification of any structure where the predicted settlement from bored tunnels is less than 5 mm and the predicted slope is less than 1/500, do not need be subject to further assessment. All other structures shall be subjected to a Stage 2 risk assessment. For the Stage 2 assessment all the structures identified in Stage 1 and subject to settlements were assessed using a limiting tensile strain approach (Burland et al. 1977; Burland 1995; Mair et al. 1996; Burland and Boscardin and Cording 1989). This method takes into account the tensile strains in the ground and uses a simple idealised model of the building. The Stage 2 risk assessment assumed that the buildings followed the greenfield surface settlement profile calculated in stage 1 and again was undertaken using the XDisp programme (Figure 10). The damage category of the building was determined in accordance with the limiting tensile strange ranges as shown in Figure 11.

From the Stage 2 assessment a list of identified buildings with special concerns, or listed buildings with a damage category greater than 1 for 'worst' case volume loss, or a normal building with a damage category greater than 2, have been compiled. At tender stage this list was used to identify buildings where building protection may be

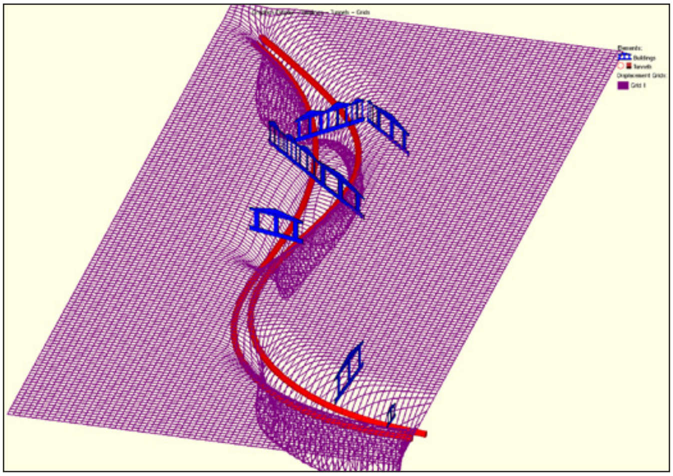

Figure 10. XDisp building damage model showing building facades and settlement trough

Category of damage	Normal degree of severity	Limiting tensile strain (ε_{lim}) (%)
0	Negligible	0–0.05
1	Very slight	0.05–0.075
2	Slight	0.075–0.15
3	Moderate*	0.15–0.3
4 to 5	Severe to very severe	> 0.3

*Note: Boscardin and Cording (1989) describe the damage corresponding to ε_{lim} in the range 0.15–0.3 per cent as "moderate to severe". However, none of the cases quoted by them exhibits severe damage for this range of strains. There is therefore no evidence to suggest that tensile strains up to 0.3 per cent will result in severe damage.

Figure 11. Relationship between category of damage and limiting tensile strain (ε_{lim}) (after Boscardin and Cording 1989)

required, allowing a means of assessing the contractor's proposed works during tender evaluation.

During the contract design phases the contractor will be required to undertake a similar staged assessment. The buildings identified at the end of Stage 2 will be required to undergo a final stage of assessment to provide an estimate of the damage and identify which buildings require protection to mitigate against the effect of subsidence damage. This final stage is expected to include a structural survey to determine the structural form and condition of the building, followed by an analysis of how individual elements of the building would be affected by the predicted settlement. The method, extent and detail of the analysis will be determined on a case-by-case basis and may include, inter alia, an analysis of the soil/structure interaction, structural behavior, and the possible effects of differential stiffness of the foundation. This detailed assessment will be used to identify and design suitable mitigating measures to protect the buildings and their foundations.

Prior to commencement of the construction works, the Civil Works contractor is also required to carry out detailed investigations to determine the types of structures and foundations of the buildings within the construction influence zone. The contractor is required to undertake building condition surveys and damage assessments for all structures/buildings (within the potential settlement zone above the tunnels along the entire alignment).

Controlling Ground Movements

Settlements resulting from tunnelling well into competent limestone are expected to be negligible.

In glacial deposits, and especially in zones with mixed faces, it is assumed that additional measures are required to keep the surface settlements at an acceptable level. Settlements caused by tunnelling are mitigated by:

- Alignment optimisation
- TBM design
- TBM operational management
- Monitoring and systematic early follow-up
- Soil improvement, structural strengthening, compensation grouting, permeation grouting, freezing, temporary bracings etc, and
- Construction of lateral and superior barriers (e.g., piling, pipe roofing etc.)

CONCLUDING REMARKS

The Cityringen project has since the passing of the Parliamentary Act in June 2007 developed from a programme study into a construction contract signed in January 2011. Design and construction methods have been developed to cope with the requirements for maintaining the groundwater level during construction and to minimise the risk of damage to existing structures and buildings. Construction works will start during 2011 and by 2018 the citizens of Copenhagen will be able to travel with the new Cityringen metro line. When the Cityringen enters into inauguration, the majority of the citizens living in central Copenhagen will have less than 600 m to public transport by rail. The Cityringen will thus assist in improving the quality of living in Copenhagen by reduction of surface transport and CO_2 omissions.

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