Recent experience in the design and construction of underground metro works by use of sprayed concrete

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Introduction

In the last years a strong preference is observed worldwide in transferring public transport in the underground space. Typical examples are accesses corridors of the railway network to city centres, road arteries, and metro projects. Modern cities expand rapidly, while demands for faster, and environmentally sustainable transport increase simultaneously. Nevertheless, large construction projects, especially in densely populated areas, are accompanied by various problems such as the disruption of surface traffic and land use, the prevention of services and business operation, increased noise and dust levels. Moreover complications arise as regards with excavations in vicinity or even in intersection with existing buildings and underground structures, utility networks, and findings of high historical and cultural significance. Therefore, the citizen (eventually the user and in fact the owner of a public infrastructure works) is directly affected by the way these are planned, designed, and constructed.

Under these circumstances, tunnels with a sprayed concrete support (known in different regions as SCL – Sprayed Concrete Linings, NATM – New Austrian Tunnelling Method, or SEM – Sequential Excavation Method) often present an efficient construction approach, due to the flexibility it can offer in the geometry of underground spaces, the construction and site logistics, the management of unforeseen underground conditions and obstacles, and the management of impacts due to tunnel induced ground deformations and settlements during construction. The present paper demonstrates recent experiences of the author in the design of sprayed concrete underground works in dense urban environments. In particular, the following projects are presented:

- The London Underground Bank Station Capacity Upgrades (BSCU), and
- The temporary works of the Parliament and Lyon Stations of the Ottawa Confederation Line

Bank Station is a London Underground (LU) station located in the City of London financial district. It is a key interchange served by five lines, namely the Northern (NL), Central (CL), Waterloo & City (W&C), and the Docklands Light Railway (DLR), and at the Monument end of the same station complex, the District and Circle lines (D&C). Currently Bank station suffers from heavy passenger congestion during peak hours for boarding, alighting and interchanging between the different lines. The Bank Station Capacity Upgrade (BSCU) is a large scale underground station expansion project intending to increase capacity and to account for future forecast demand at Bank/Monument Station, maximise savings in journey times, provide step-free access to Northern and DLR lines, and improve emergency fire and evacuation protection measures for the station. The upgrade includes the provision of a new ticket hall at King William Street Northern and DLR lines and a series of new tunnels of a total length of approximately 1200 m, including a new southbound running and platform tunnel for the Northern line, concourse tunnels, cross passages and escalator barrels. These additional tunnels are constructed mostly through Sprayed Concrete Lining (SCL) techniques. The paper presents, indicative aspects of the project, and some main concepts in the lining design and the impact assessment.
procedure for the existing underground structures of the station. The paper also focuses on the extensive modelling campaign with 3D non-linear Finite Element (FE) models, representing the staged construction of the BSCU works, and helping to assess the interactions with the existing assets as well as to optimise the design of the tunnel support structure.

The Confederation Line forms part of Ottawa’s light rail transit, which consists of 13 stops and stations. The project’s centrepiece is a 2.5km long tunnel with three underground stations leading underneath downtown Ottawa and is constructed within feet of adjacent buildings. The downtown stations, Lyon and Parliament, are two very similar caverns approximately 13m by 18m in a horseshoe configuration constructed in rock with shallow ground cover. The paper discusses the excavation method, unique construction sequencing, and equipment selection, and it also documents design and construction challenges of large caverns in very close proximity to existing buildings and varying ground conditions. Both stations are eventually integrated through direct accesses with the existing and future building developments. In order to minimize impact to the existing basements, an innovative tension tie system with a live tension and deformations monitoring has been implemented within the tunnels. In this case too, advanced Finite Element modelling exercises performed for the temporary support design and existing buildings impact mitigation measures for the station caverns that host the Lyon and Parliament stations. Besides critical 2D analyses, one set of 3D models for each station simulates the complete station cavern excavations, utilizing non-linear soil and rock constitutive laws and non-linear contact between the rock and the buildings. The models deliver calculations of the convergence, displacements and settlements due to the excavation of the cavern, and the internal forces and dimensioning of all the structural elements (shotcrete shell and tension ties).

Sprayed concrete tunnel linings in urban projects

The Sprayed Concrete Lining (SCL) method, also referred to as New Austrian Tunnelling Method (NATM) or Sequential Excavation Method (SEM), was developed in the 1950s when shotcrete was first used systematically to stabilize squeezing ground in a water diversion tunnel at the Runserau Hydroelectric Power Project in Austria. In the following years, the method was advanced in theory and practice and adapted to be suitable for virtually all ground conditions. Since its first application in an urban environment in the Frankfurt Clay in 1968, means and methods have evolved further and a substantial number of sprayed concrete tunnels have been constructed, many of them in dense urban settings, with adverse ground conditions and low overburden.

SCL tunnelling enhances the self-supporting capacity of the rock or soil by mobilizing the strength of the surrounding ground. The tunnel excavation is carried out in increments (headings and rounds), which are supported by a first layer of sprayed concrete immediately after exposure followed by the installation of the initial lining consisting of sprayed concrete. This concrete can be unreinforced, reinforced with wire mesh reinforcement, and recently steel fibre reinforcement has proven to be a desirable material in several applications. The lining has a defined stiffness to allow controlled stress relaxation around the opening, minimizing the section forces and hence allows for a cost effective structural design. In addition, various ground support, face support, pre-support and ground improvement measures may be utilized to ensure the stability and safety of the tunnelling operation and minimize settlements at the surface. For extremely unfavourable ground conditions special methods like ground freezing, tunnelling under compressed air, etc. have been developed and utilized
in the past. During construction, the deformations in and above the tunnel structures are continuously recorded, monitored and interpreted to verify the design assumptions and assess the stability and the appropriateness of the applied excavation sequence and support elements. The interpretation of the monitoring data is fed back through the design engineer to the ongoing construction and adjustments can be made if necessary.

After completion of the excavation and initial support, the waterproofing system is typically installed sandwiched between initial and final lining, consisting of either a flexible waterproofing sheet membrane, or a sprayed membrane. The final lining is then installed, which can be either reinforced cast-in-place concrete or shotcrete, depending on the length of the tunnel and the variability of the cross section. The final lining is designed to withstand ground loads, hydrostatic loads and seismic loads according to the design criteria. Traditionally the initial lining has been considered as sacrificial after supporting the excavation for a short period of time allowing for the final structure to be built. However in the last years a new design approach has developed, dictating that the initial lining can indeed form part of the final structure and share the load-bearing response, for the entire life-cycle of the structure. Such an approach is used e.g. for London Underground and Crossrail tunnels (with a design life of 120 years), and for the Brenner Base Tunnel (with a design life of 200 years); see also (Bergmeister 2006), (Bergmeister 2014), (Spyridis 2014)

Finite Element Modelling principles

As computer technology evolves, numerical modelling is an increasingly preferable solution in all engineering fields. Tunnelling, although a quite empirical engineering discipline, also finds benefit in advanced numerical models, as many recent projects have shown. A well prepared modelling campaign for an underground project can give a good and communicable description of the structural behaviour, capture sensitivities of the ground behaviour, the response of structures with complex geometries, indicate risks, and highlight issues deserving additional attention during design or construction, providing substantial aid to the project development. When it comes to the design of tunnel linings, which in most cases are elements with uniform thickness and reinforcement (or unreinforced / fibre-reinforced), this can be expeditiously performed using the so-called Capacity Limit Curves, which illustrate all design combinations of axial forces and bending moments (potentially shear forces too) juxtaposed to the envelope of the cross-section’s design capacity, providing a transparent and comprehensive graphical and numerical structural verification, as well as the design’s safety factor (Hoek et al. 2008), (Spyridis et al., 2016).

In the cases demonstrated below, three-dimensional models prepared in the Abaqus software are used. In these models, the tunnel lining and the soil/ rock around the tunnel is modelled, as shell and continuum elements respectively. The Mohr-Coulomb constitutive model (MC) is employed in the modelling approach for London projects. Despite the well recognised problems with the MC model in performing undrained analysis, MC is still reliable and attractive to designers due to its simplicity providing it is employed in a total stress analysis using undrained cohesion and stiffness increasing with depth for the London Clay subsoil. Equivalent MC parameters fit well with non-linear strength parameters per the Hoek-Brown, the Barton-Bandis, or the Power Curve criteria, and they are also suitable for the rock formations underlying Ottawa.
Indicative construction increments, during excavation and initial support

Excavation is simulated according to the construction sequences division (top heading – bench – invert), and the stepwise construction progress is also simulated appropriately. Modelling of the existing structures takes place prior to modelling the SCL staged excavation and it generally follows a wished-in-place approach with a preceding stiffness reduction. The linings and structural walls are simulated as shell elements, while both linear-elastic and non-linear models for concrete are implemented depending on the case examined. Non-linear material behaviour of concrete is simulated using the Concrete Damaged Plasticity constitutive model, in order to capture concrete’s post-cracking residual capacity. Further details of the analyses and design of the two projects discussed below may be found in (Spyridis et al. 2013), (Nasekhian et al. 2015), (Spyridis and Nasekhian 2017), (Spyridis and Fortsakis 2017).

Case Study 1 – Bank Station Capacity Upgrade

Bank station forms an interchange between six lines in the City of London financial district, which makes it a very critical interchange for the transport network. The Bank Station Capacity Upgrade (BSCU) aims to relieve heavy passenger congestion during peak hours for boarding, alighting and interchange, through increasing capacity to account for future forecast demand at Bank/Monument station, maximise savings in journey time reductions, provide step-free access from street to both Northern line and DLR. The project also facilitates interchange between Northern line, Central line and DLR, and emergency fire and evacuation protection measures for Northern line and DLR passengers. The capacity upgrade comprises the construction of a new southbound platform tunnel and associated length of running tunnel for the Northern line, connecting passageways to the existing station tunnels, and the provision of step-free access from the new entrance on Cannon Street. The total length of the SCL tunnels is approximately 1,200m with tunnel cross sections that range from 10m² up to 90m². London Underground nominated Dragados as their Design and Build contractor.
and Dr. Sauer & Partners is responsible for all sprayed concrete lining (SCL) tunnelling design and the assessment of impacts on existing station tunnels, some of which are more than 130 years old. Below, design principles as well as work carried out for the assessment and design are presented. Further details may be found in the recorded presentation of (Haig and Feiersinger, 2016)

The SCL tunnels are located at three main levels, namely the typical Central line level, the Northern line, and the DLR level. All tunnels are located within London Clay, a very well-known stiff over-consolidated clay underlying the city at depths from approximately 5m to 50m at this area. The tunnel system comprises:

- A steel fibre reinforced sprayed concrete primary lining (including initial lining - a thin layer protecting or priming the surface of the excavated face) installed as part of the excavation and support process.
- A non-fibre reinforced concrete regulating layer installed to facilitate spray applied waterproofing membrane installation.
- A spray applied waterproofing membrane.
- A steel fibre reinforced secondary lining, of cast-in-place concrete in the majority.
- A non-fibre reinforced sprayed concrete smoothing layer for sprayed secondary lining sections.

The design distinguishes two main design situations, namely the short-term (5 year) period, and the long-term period (i.e. after the final lining is installed) to the full design life of 120 years. The primary lining serves both design criteria with an adjusted safety factor, and the same durability criteria per specification as the secondary lining. The combined layer forms a double shell lining system with both linings contributing to the permanent load bearing structure, and the shared load between the two components of the lining is determined through three-dimensional Finite Element Analyses. The analysis and design is based on non-linear behaviour of the concrete linings (both primary and secondary), which accepts a linear-elastic/perfectly-plastic analysis for SFRC in tension, whereby crack width and deformation criteria apply in terms of tensile behaviour (maximum strain of 10‰). A main design outcome is the minimisation of the rebar reinforcement. The compressive behaviour is assumed linearly elastic, so as to avoid concrete crushing in any location of the lining, as this would compromise the structure’s robustness. This aim was also enhanced by a preliminary shape optimisation procedure. SFRC is grade C32/40, with fR,1= 2.5MPa and fR,4= 1.5MPa, at CMOD1 = 0.5 mm and CMOD4 = 3.5 mm respectively. The concrete cover, is calculated at c=65mm for both the extrados surface of the primary lining and the intrados surface of the secondary lining, based on concrete durability calculations.

The tunnel structures have been analysed employing a three dimensional finite element analysis as discussed in the previous sections of the paper. In summary, the following two main phases are considered in the analysis in order to ascertain the true effect of long and short term design situations experienced by both linings throughout the life cycle of the tunnel structure.

Phase 1: All the construction sequences of the SCL tunnels are simulated step by step. In this phase only the primary lining (including initial lining) is in place and surrounding soil layers are in undrained conditions. It is assumed that the design life of primary lining is 5 years at this stage.

Phase 2: While the primary lining is in place (keeping all the stress history from the construction stage) the secondary linings of all structures are installed and the long term loads are for the design life of 120 years are applied to both linings.
Overview of Bank Station Capacity Upgrade project, showing the new SCL tunnels with a sprayed concrete final lining (turquoise), with a cast-in-situ final lining (purple), and the existing underground and foundation structures (grey).

For each phase a separate Finite Element (FE) model has been established to keep the stress history in the respective parts of the combined lining experiencing the temporary loads and the permanent loads. The models capture the full excavation sequence, however special considerations have been made in order to simulate a worst-case scenario of the sequence (worst impact of the tunnels’ excavations on each other and on existing assets), in order to allow logistics’ flexibility, i.e. possibility for changes in the construction sequence without the need of repeating the analyses. An overview of the models used for the project is given in the figure below.

The model’s results were then transferred to a monitoring/action plan, which is associated to appropriate trigger values, i.e. values measured through monitoring that initiate a warning and a reaction from the site and design team. A traffic light system (green / amber / red) is the most efficient and commonly used monitoring scheme in tunnelling to denote different levels of response. The amber trigger value marks the boundary of normal behaviour, i.e. deformations below the predicted ones. The red trigger denotes deformations beyond which a review of the design and reasons for deformations greater than the expected happen. Further deformation can lead to withholding works and reevaluating the design in detail (black value). These trigger values were assessed based on a sensitivity study for selected cases, by varying the most relevant ground parameters, these being the soil’s undrained Young’s modulus ($E_u$) and the coefficient of horizontal earth pressure at rest ($K_0$). Implementing this sensitivity analysis, a capacity safety factor is assessed, which then denotes different hazard levels corresponding to deformation magnitudes (Nasekhian et al. 2016), (Spyridis et al. 2016). Finally, based on an existing tunnel assessment, critical tunnels in the very vicinity of the excavations will be constantly monitored, and also checked against predictions during construction on a trigger level basis. Construction of all SCL works will be driven mainly through a 8.5x12.5 m ellipsoidal temporary shaft at Arthur Street, while the main underground diaphragm box of the station will be constructed at the location of a demolished and then re-erected building block at King William Street. The Arthur Street shaft provides access to the underground excavation faces, but also to the disused, masonry lined, King William Street Station cavern. The latter is also used as part of the construction site, for material and mucking storage. Completion of construction is expected in 2021.
Overview of models used in the process of design and assessment of existing assets for the Bank Station Capacity Upgrade

Case Study 2 – Ottawa Confederation Line Downtown Stations

The Confederation Line in Ottawa encompasses 15 stations and stops; its centre piece is a 2.5 km long tunnel with three underground stations underneath downtown Ottawa. The construction approach for the central underground core of the project was an integral part of the project planning, and a mined construction method for the stations was chosen in order to minimize the impacts to the surface, and to reduce the schedule risks of relocating buried utilities. The Dragados - SNC Lavalin - Ellis Don JV assigned Dr. Sauer and partners with the Tender, Preliminary and Full Detailed Design of the temporary support, including execution drawings for the tunnels and three mined station caverns, adits and shafts, while construction support services on site were also provided. The main parts of the underground portion of this light rail system are the running tunnel, the downtown stations, Lyon in the West and Parliament in the East, and Rideau Station located further East towards the East Portal. The double track running tunnel is on average 15 m below the surface, and the stations are designed with side platforms and access from the street level as well as direct connections to the adjacent building basements.

The two underground stations presented in more detail herein are located directly adjacent to existing, buildings requiring detailed studies of risks during construction and risk mitigation measures. They are very similar in geometry and design and construction approach; therefore the descriptions herein are common for both stations. In order to create the underground cavity, multiple drifts with complex geometries had to be excavated, by use of a roadheader, which can handle rock of compressive strength up to 120 MPa, as well as non-natural elements in the ground, while it remains quite robust and flexible in moving toward different areas of the project.

The overburden above the cavern is approximately 7m thick with a top of bedrock level within zero to 4m of the crown, followed by soft soil and made ground. Excavation took place in formations including Shales of the Billings Formation, Lindsay and Verulam. Unconfined compressive strength (UCS) values of the rock formations range from 50 to 90 MPa and RQD (Rock Quality Designation) from 30 to 90, and a GSI (Geological Strength Index) ranging from 55 to 70.
Indicative layout, Lyon Station

Indicative layout, Parliament Station
The station caverns are approximately 180 m long, 18 m wide and 13 m high. Shotcrete linings and pre-installed pipe roofs are the standard initial support measures, supported by rock bolts where required in the design. Typically the sequential excavation construction method aims to mobilize the strength of the surrounding ground to carry a major part of its own weight. However, due to the narrow rock pillar between the excavation and the basement walls this could not always be achieved. At locations where existing adjacent building basements and foundations are below the cavern arch bearing level, the installation of tension ties was required to keep both left and right hand side arch bearings in position and thus – in combination with live tension and deformation monitoring – to minimize the impact of the cavern excavation on the basement structures. The rock pillar between the cavern and the basement walls does not allow for a complete redistribution of the stresses in the ground. Tension ties are designed to carry all horizontal loads generated by the arch in order to prevent concentrated stresses at the footing level of the arch from being introduced into adjacent building structures. The ties are also installed in the case that voids exist next to the building, or the building foundation level differs from the record drawings. Permanent concrete walls installed prior to top heading excavation function as the foundation for the cavern arch. These permanent walls, have been designed by others but so as to form part of the temporary support and withstand all vertical loads transferred from the cavern arch at the construction stage as well as to prevent rock wedges from sliding into the cavern excavation. The cross section has been optimized to minimize excavation volumes and avoid excavation in soft ground, while accommodating the required clearance for the final station layout and still providing a favourable shape to counteract ground actions. In areas where no buildings are present or building foundations are above the cavern springline, the shotcrete arch is allowed to transfer vertical and horizontal loads directly into the rock. In these sections a different, simpler excavation sequence was used. The excavation geometry is subdivided into multiple excavation steps to maintain the stability of excavation face and span, decrease the disturbance in surrounding ground and accommodate the reach of the roadheaders used.

Excavation sequence of the caverns, in the cases where tension ties are used.
The excavation and support design for the transition and the cavern is based on principles of the Sequential Excavation Method (SEM), transferred into geomechanical/structural calculations using various tools and approaches as appropriate. For this purpose, the geotechnical and rock parameters and behavior, as well as the ground loads on the initial support and the interaction between the support measures and the ground were initially evaluated. The following analyses were carried out for the design of excavation and initial support in rock:

1. Underground wedge stability analyses were performed using the software Unwedge (by Rocscience) to identify potentially unstable rock blocks or rock wedges that form around the opening perimeter and in the tunnel face. Unwedge uses a limit equilibrium approach to assess the stability of blocks around underground openings in a jointed rock mass taking into account the temporary support.

2. Face stability analyses were performed to check the stability of the tunnel face. The analyses were carried out assuming unsupported tunnel face and conservative assumptions for the geometrical and geotechnical properties.

3. Analysis of the piperoof umbrella. The pipes used as a presupport measure were dimensioned against three different failure mechanisms.

4. Two-dimensional finite element analyses using the software Phase2 (by Rocscience), modelling the ground and the support, and the rock-structure interactions were performed to simulate the sequence of tunnel excavation and initial support installation taking into account the interaction between the cavern and the buildings. Specifically, the slabs of the basements were incorporated in the models and the interface between the buildings and the soils was modelled using contact elements with zero tensile strength. The 2D numerical analyses have provided results regarding the:
   a. Dimensioning of the support shell.
   b. Dimensioning of the tension ties.
   c. Calculation of the surface settlements.
   d. Assessment of expected cavern deformations and evaluation of trigger and action levels.

5. Three-dimensional finite element analyses using the software Abaqus (by Dassault Systemes Simulia) were performed to simulate the sequence of tunnel excavation and initial support installation. Analyses were performed to address issues identified in two-dimensional finite element analyses, to refine the initial design results and for the following additional purpose:
   a. Evaluation of three-dimensional stress re-distributions in the ground
   b. Evaluation of ground – cavern arch – tension tie interaction
   c. Evaluation of openings in the temporary excavation support of the cavern

In particular for the three-dimensional analysis, the dimensions of the model have been chosen so as the boundary conditions do not influence the analysis and the dimensioning of the structures. The geomaterials were simulated using wedge elements (C3D4). The behaviour of the geomaterials was assumed to be linearly elastic or linearly elastic - perfectly plastic according to the Mohr Coulomb failure criterion. The support shell was modelled using triangular 3-noded elements (S3) with linearly elastic behaviour. The cast in-situ concrete walls of the bottom side drifts in the tension tie area were modelled using triangular 3-noded elements (S3) with linearly elastic behaviour. The tension ties have been modelled using 3D truss elements (T3D2) and their behaviour has been assumed linearly elastic.
Aspects of the 3D FE model performed for the project (Lyon Station), showing the cavern geometry, the existing basements layouts, and the internal stabilization bracing components.

Aspect of the completed excavation and temporary support of the Lyon Station cavern, showing section of the station supported with the tension-tie system at the background, and the standard excavation in distance to existing basements in the foreground.
Rock bolts have not been modelled in the analyses since their main role is to prevent local failures or the fall of specific blocks. The adjacent buildings have also been modelled using S3 shell elements with linearly elastic behaviour. The buildings are connected with the surrounding geomaterial using a special interface that follows an exponential contact constitutive law in the normal direction. This interface allows the full transfer of all the compressive stresses between the building and the geomaterial, but it has zero tensile strength and therefore no tensile stresses can be transferred. A distributed load has been applied on the foundation level to simulate the vertical loads that are transferred by the building. The tension ties have been modelled assuming a very stiff truss element which is activated before the excavation of the centre drift of the Top Heading in order to calculate the maximum tension force that is needed in order to decrease the displacements. The finite element models have used a typical mesh size (at the excavation perimeter) of 0.4 m, 700,000 – 850,000 elements and 500 – 530 calculation steps each. An overview of a typical model is given below.

Construction of the temporary supports of the two stations was completed successfully in the first half of 2016 and no adverse impacts have occurred for the existing assets around the excavation; see also (Wilhelmstetter and Karner 2016).

Summary

This paper presents limitations of urban underground transport construction projects, while it addresses particularities of underground construction by use of sprayed concrete linings, and it presents main aspects in analysis, design, and construction of sprayed concrete linings. Furthermore it demonstrates the use of sprayed concrete as a temporary or final tunnel support on the basis of two innovative projects that were recently developed in London and Ottawa respectively. Experience shows that the use of the particular method proves to be efficient in tackling various problems arising in such infrastructure projects and tight construction environments. The benefits are mainly associated with ease and speed of construction, damage mitigation of adjacent structures, as well as savings in mucking volumes and support materials.

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