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Modeling of pipe arch canopies in shallow soft ground tunnels constructed by sequential excavation methods

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Abstract

The New Austrian Tunneling Method (NATM), also referred as Sequential Excavation Method (SEM), has found application in soft ground in urban tunneling in the late 60's and has since then enjoyed a broad, international utilization in both rural and urban settings. One key element, which enlarged the adaptability of NATM tunneling in soft ground and low overburden environments enormously in the recent decade, is the application of pipe arch canopies used as a systematic pre-support measure. However, the effective numerical modeling of pipe arch canopies is still a challenge. Very often models do not fully utilize the positive effect on the surface settlements in particular when using two-dimensional techniques and three-dimensional models are required to approximate the pre-support benefits and provide guidance on the design for the pipe arch canopies. This paper demonstrates opportunities how to model pipe arch canopies and how to take credit of the positive settlement controlling effects in Finite Element (FE) modeling. Project examples will be discussed and include the Tysons Corner Tunnels, Washington D.C. and the Fort Canning Tunnel, in Singapore. This article will summarize the findings and provide guidance on how to generally adapt the approach to other projects.

Keywords: Pipe Arch Canopy, Sequential Excavation Method, SEM, SEL, NATM, Modeling, Finite Elements, FE

1 SEQUENTIAL EXCAVATION METHOD FOR SHALLOW SOFT GROUND TUNNELS

Congested urban areas have always lead to vertical growth of the urban infrastructure, with frequent utilization of the underground space. Urban underground infrastructure essentially involves complicated tunneling scenarios which may include challenges such as weak/soft ground, shallow ground cover, existing structures, irregular underground opening cross-section, etc. Generally, the New Austrian Tunneling Method (NATM), also referred as Sequential Excavation Method (SEM), is the preferred tunneling technique for tunnels of short length, over-sized or irregular cross-sections.

The application of SEM is based upon optimisation of the tunnel support system and deformation control during tunnel excavation. When used in soft ground conditions in urban tunneling, convergences and surface settlements are measured rigorously. Ground deformations start ahead of the face (pre-face) and can be reduced by controlling movements by providing a pre-support. Pre-face settlements may become more pronounced when there is shallow overburden in particular for larger tunnel openings. This paper will discuss the pre-support technique, which is commonly known as the pipe arch canopy, along with its numerical modeling aspects.

2 UTILISATION OF PIPE ARCH CANOPIES

The pre-support technique of a pipe arch canopy is based on structural beam action. A number of steel pipes are installed sub-horizontally in longitudinal direction, directly above the proposed tunnel section to be excavated. After the drilling, the installed pipes are grouted with cementitious or synthetic grouts depending on the type of ground to increase the bearing capacity of the pipe, to enhance the strength of the pipe-ground interaction, and ensure a tight pipe-ground contact. As the excavation progresses, a mechanism of supporting the overburden load by the longitudinal beam action of the pipe arch canopy as well as a radial arching effect is developed. Each pipe is bridging the excavated advance, supported by the shotcrete lining in the back and the unexcavated ground ahead. The number of pipes installed and the ground along the tunnel excavation boundary in the heading area act collectively to form a three-dimensional arch canopy. Thus, it can be seen as ground reinforcement for excavation which supports the overburden, helps to stabilize the face, reduce ground movements, and surface settlements as well.

Key decisions for pipe arch canopy design are the required number of pipes, effective length, angle of installation, and overlap length. The number of pipes required depends on the size and shape of the tunnel cross-section. Pipe arch canopies are usually installed at a very small sub-horizontal angle in the range of 3-5 degrees to create a drill niche for installation between the consecutive pipe arch canopies as well as a pipe overlap. A minimum overlap length between two pipe arches is necessary to ensure a continious pre-support. The excavation cross-section enlarges longitudinally from a typical geometry at start of the canopy to the largest cross-section at the end commonly referred to as the “saw-tooth”. This saw-tooth effect occurs concurrently (see Figure 1). The length between the two saw-teeth is called the “effective length” of the pipe arch canopy. The pipe length is derived from the effective length plus overlap length.

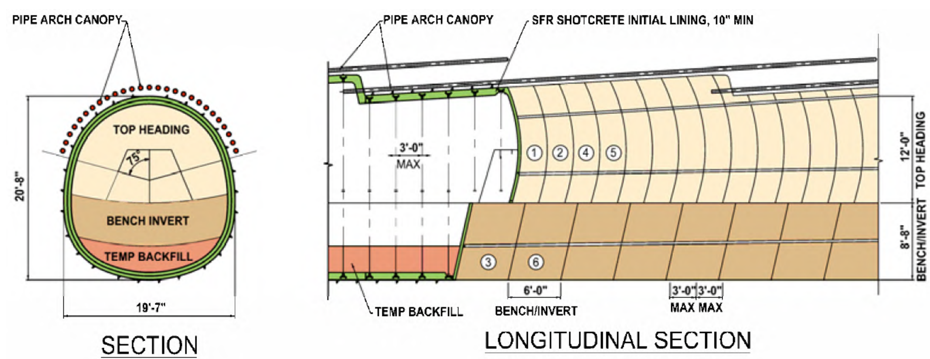

Figure 1: Typical application of Pipe Arch Canopy in SEM/NATM Tunnels

3 MODELING OF PIPE ARCH CANOPIES AND EXPERIENCES

Despite the availability of various calculation approaches, Finite Element Method has been quite frequently and efficiently utilised. In general, Two-dimensional (2D) and Three-dimensional (3D) Finite Element (FE) Analyses can be performed. 2D studies perform plane strain analysis of a tunnel cross-section using ground relaxation or similar methods to approximate three-dimensional stress-strain conditions at the heading. Meanwhile, 3D analyses models both the cross-sectional as well as the longitudinal excavation. It does not require any additional arbitrary ground relaxation or similar approaches. Phase^2 is a widely used 2D FE package, whereas ABAQUS is a commonly used 3D FE package.

There is the need to simulate the ground relaxation induced by the excavation and support process, when utilizing a 2D analysis for tunneling in soft-ground (see figure 2). Usually a softening factor - a reduction in ground elastic modulus - of about 50% is applied to the excavated region to model excavation. Softening is very critical so as not to over or under predict ground movements and ground support as well as section forces in the linings. In a 3D analysis, the excavation and support sequence is modeled and therefore does not have to be simplified. When using a 3D model, the number of elements increases dramatically, which in turn, creates a better representation of the problem. Modeling of elasto-plastic material behaviour of soft ground may cause convergence problems in the analysis and this increases the computational effort as well. Economical considerations demand simplifications to make the analysis reasonably efficient. Large variations in material behaviour in elements around excavation areas should be avoided. Symmetrical effects should be utilized.

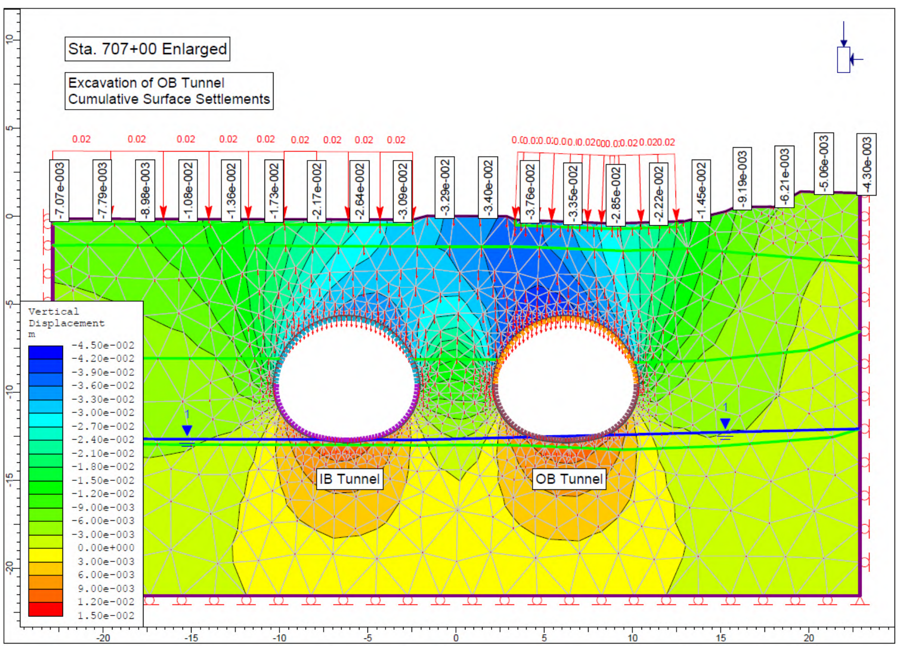

Figure 2: Plot Showing Vertical Displacement from 2D Simulation of Twin Tunnel Excavation using Ground Relaxation Approach

In a 2D analysis, modeling individual pipes leads to large variation in stiffnesses. It is more reasonable to model pre-support as a region represented by equivalent properties around the excavation boundary. This approach also provides longitudinal support action based on the consideration that plane strain analysis is performed. However, this approach requires calculating the equivalent properties for each individual case.

The approach of equivalent properties can also be utilised for 3D modeling. However, this approach provides no information for the pipe itself. If this kind of information is needed, modeling of the pipes as beam elements is unavoidable (see figure 3). In this case it is more efficient to coincide the nodes from beam elements and ground solid elements.

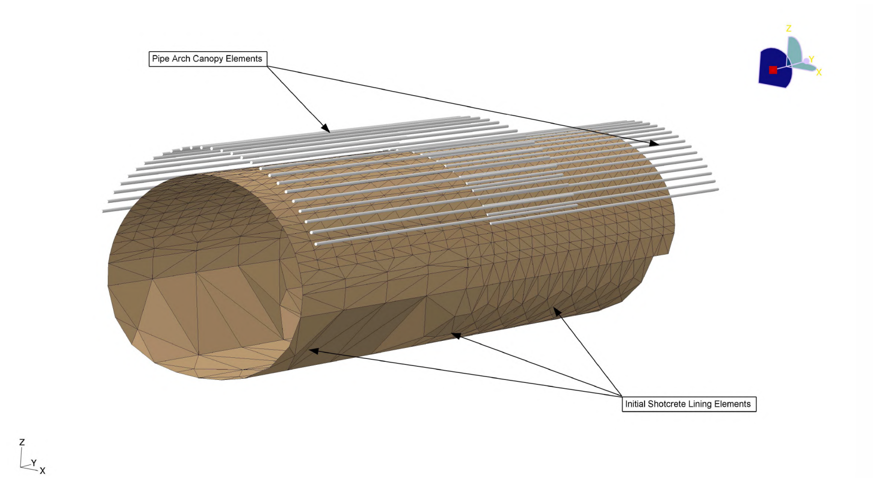

Figure 3: 3-D Model Detailed View of Shotcrete Initial Lining and Pipe Arch Canopy Elements

2D analysis does not provide any face stability results. In a 3D analysis with a simulation of the excavation sequence the face stability is inherently checked.

At times, and of course depending on hardware and high degree of model complexity in both constitutive material behaviour and mesh refinement selected, experience shows that a 3D analysis for pipe arch canopy calculations can take up to three weeks of calculation times. Thus, 2D analysis is more suitable for preliminary engineering and 3D analysis is more suitable for detailed design phases of a project.

Following are recent case studies presenting a general overview of the ground conditions and modeling approach:

Case Study 1 is refering to the numerical modeling conducted for the Fort Canning Tunnel in Singapore and is based on work of Zeidler et al. (2007). The Fort Canning tunnel is a 14.7 m high and 9.2 m wide vehicular tunnel constructed by NATM / SEM. The overburden ranged from 3.0 m to 9.0 m. The elastic modulus of ground varied from 10 MPa at top to 80 MPa at bottom, while the shear strength ranged from 40 kPa to 300 kPa. The presence of ground water produced a soft ground condition which required pre-support measures. AGF pipe arch canopy with 114 mm dia and 6 mm pipes drilled above the top heading at 400 mm spacing was used. Each pipe had effective length of 12.5 m and overlap length of 3.5 m.

A range of ground conditions were simulated by performing an uncoupled 2D analysis using Mohr-Coulomb failure criterion based plasticity and accounting radial effect of pipe arch canopy. The 2D analysis predicted 50-120 mm of surface settlement. A set of coupled 3D analysis – one with pipe arch and other without pipe arch – have been conducted. While utilising the pipe arch canopy, 90 mm of settlement was predicted. Comparing this to the 114 mm of settlement calculated without a pipe arch canopy, the tunnel pre-support caused a reduction of 24 mm (more than 20%) of settlement. During construction field measurements showed settlements ranging from 30–120 mm. It could be proved that numerical calculations were able to predict the pre-support effectiveness as well as to provide reliable results.

Case Study 2 is refering to the numerical modeling of the Tysons Corner Tunnels conducted for the Dulles Corridor Metrorail Project (DCMP) in the Washington D.C. Metropolitan Area, USA and based on the work of Gall et al. and DTP (2009). The challenges faced included soft ground, low overburden, enlarged cross-section, existing structures in the close vicinity, among others. The construction involved excavation of twin tunnels each 7.2 m high, from 7 to 9 m wide with overburden ranging from 3 m to 15 m. The soft ground conditions required systematic pre-support measures. Double and single row pipe arch canopies using ALWAG AT 114 pipes with 114 mm diameter and 6 mm thickness were constructed. The effective length was 12.8 m with an overlap length of 5.2 m. The anticipated elastic modulus of the ground ranges between 19-96 kPa with shear strength of 40 kPa.

Several 2D analyses for varying ground conditions were performed for the twin tunnel excavation. The 2D analysis did not account any pre-support installation predicting a maximum settlement of 24 mm under the worst boundaries after excavation and support of the first tunnel drift. In 3D analysis, just one single tunnel was modeled with maximum, enlarged cross-section at the end of the saw-tooth with shallowest overburden. A settlement of 15 mm was been predicted for single tunnel excavation using 3D analysis. So the more realistic modeling with the 3D analysis in combination with the pipe arch canopy effect reduced the predicted settlement up to 9 mm (roughly 37%). The construction of the tunnel was scheduled to start in Fall 2009. So comparison data from the settlement monitoring was not available at the time when the report was written.

Case Study 3 is refering to a different kind of application, namely the installation of pre-support using microtunneling. In this technique, pipes installed can have a diameter as large as 2.0 m. Though, this case study modeled 60 cm diameter pipes for a tunnel of 6.0 m and overburden of 3.0 m. This case study is a 3D analysis performed using FLAC3D based on finite difference method (FDM). It models ground with elastic modulus of 21 MPa and zero shear strength with friction angle of 21 degrees. The description is based on the work of Ahuja et al. (2008).
Individual pipes, modeled with shell elements, are connected to each other to simulate the 3D support action. The ground loss occurring due to micro tunneling during pipe installation is modeled with a multi-scale modeling of excavation diameter 6.0 m compared to pipe thickness of 10 mm. The calculation time of up to 3 weeks was involved. Surface settlements of 80 mm were observed after tunnel excavation was complete. The installation of pre-support provided more than 50 % of ground control.

4 SUMMARY

The application of pipe arch canopies used as a systematic pre-support measure enlarged the adaptability of NATM/SEM tunneling in soft ground and low overburden environments enormously in the recent decade. The effective numerical modeling of pipe arch canopies is still a challenge. Opportunities how to model pipe-arch canopies and how to take credit of the positive settlement controlling effects in Finite Element (FE) modeling were shown in general and with regard to case studies as well. 2D analyses are a useful prediction tool in a preliminary design state, however, they are not detailed enough to fully understand the full range of interaction and behaviour of the pre-support system. 3D analyses are much more detailed and a

powerful tool. Economical considerations demand simplifications to make the analysis reasonably efficient. Simplifications and the utilisation of symmetry effects are almost mandatory to make it an efficient design tool.
It is recommended to use 2D and 3D analyses concurrently to enhance the design process and reliability of the results. Based on experiences, it is known that systematic pre-support will help reduce ground deformation by controlling the pre-face movements – sophisticated modeling techniques are supporting this approach in the tunnel design as well.

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