ENLARGEMENT OF THE METRO STATION MARIENPLATZ

ENLARGEMENT OF THE METRO STATION MARIENPLATZ – A COMPLEX TUNNEL PROJECT BENEATH THE MUNICH CITY HALL

Holger Heidkamp, Casimir Katz
SOFiSTiK AG
Oberschleissheim, Germany

Christian Hofstetter
Schmitt Stumpf Frühauf & Partner Ingenieurgesellschaft mbH
Munich, Germany

SUMMARY

Due to the expected passenger capacity requirements for public transport during the 2006 Football World Cup, it was decided to enlarge the metro station Marienplatz, situated right beneath the Munich city hall. The finally approved concept provides for two extra tubes in parallel to the existing ones. By connecting the new and old tubes each with eleven approximately 3.10 m wide cross cuts the intended approximate doubling of the platform passenger capacity is achieved.

The close vicinity of the new tunnel tubes to existing buildings – in particular the historic city hall “Neues Rathaus” that was erected from 1867 to 1909 – puts a high demand on control and limitation of soil movements that are to be expected during the construction process. While the original bid invitation proposed a lowering of the groundwater level, the finally chosen solution uses an innovative brine freezing technique, a specific proposal made by the executing consortium.

As the analysis covers numerous non-linear construction stages involving parameter studies, it proves essential to have a fast solution technique. On the other hand, the simulation of the cross cutting process demands consideration of a complex non-linear three-dimensional problem. Aiming at the best compromise between efficiency and required accuracy a novel concept is adopted. It starts with a classical two-dimensional finite element analysis of representative cross-sections using standard and approved techniques to account for the three-dimensional stress redistribution effects during the tunnel excavation process. Then a special combined mesh generation and mapping technique is applied to create a three-dimensional model that inherits the load history induced by the tunnelling process and thus allows for simulation of the cross cut installation process.

This combined approach enables the complex analysis task to be performed within a reasonable timeframe.
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Figure 1: Animation of the completed metro station after the enlargement

1: Background

The metro station Marienplatz, situated right beneath the Munich city hall, is the most important station of the north-south metro line 6. It was taken into service in 1972. While in the opening year passenger peak loadings on the platforms (boarding, deboarding and transfer) amounted to 5800 passengers per hour, in 1989 this value had already increased to 21500 passengers per hour. For the new Munich football arena that is currently under construction, metro line 6 is the only public means of transport. This effects, that in 2005 when the new arena is in service, the expected peak load reaches 32500 passengers per hour [1]. In this context and with particular focus on the Football World Cup in 2006 the Munich city council issued the project “Bahnsteigerweiterung U-Bahnhof Marienplatz”\(^1\) and in 2003 finally contracted the consortium construction company Max Bögl Bauunternehmung GmbH and Schmitt Stumpf Frühauf & Partner Ingenieurgesellschaft im Bauwesen mbH for practical planning – the latter being consulted by SOFiSTiK AG regarding the finite element tunnelling analysis.

The finally approved concept enlarges the existing passenger platforms by means of two new tunnels in parallel to the existing ones. New and existing tunnel tubes are then connected each with eleven approximately 3.10 m wide

\(^1\) “Enlargement of the passenger platforms at the metro station Marienplatz”
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cross cuts, by this assuring the intended approximate doubling of the platform passenger capacity.

![Figure 2: Existing and new tunnel tubes beneath the Munich city hall, metro station Marienplatz](image)

The geological situation in-situ is characterised by alternating layers of tertiary sands and clays, the lower sand bed leading confined ground water. The new tunnel tubes are mainly located in the lower tertiary clay layer. The close vicinity of the new tunnel tubes to existing buildings – in particular the historic city hall “Neues Rathaus” – puts a high demand on control and limitation of soil movements that are to be expected during the construction process. According to a specific proposal made by the executing consortium, the ground water problem is handled using a brine freezing technique, where starting from pilot tunnels that are initially installed, the soil body above the crown region of the new tunnels is frosted, providing for a watertight shield above the new tunnels. With this process a spacious lowering of the ground water level is avoided and only temporary ground water relaxation in the lower sand layer is required.

![Figure 3: Schematic geological profile along new western passenger tunnel](image)
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2: Finite element simulation – requirements and solution strategy

The complex nature of the construction task imposes several particular requirements for the finite element analysis. The following construction stages need to be considered:

- In-situ stress state prior to construction activity
- Ground water relaxation (drainage)
- Installation of the pilot tunnel
- Soil freezing process
- Tunnelling process (excavation and subsequent securing by shotcrete outer lining)
- Defrosting of frozen soil body
- Drainage turning-off
- Cross cut installation process
- Installation of inner reinforced concrete lining

Due to the high demand on control of soil movements and the complex construction stage sequence both during tunnelling and installation of the cross cuts, soil-structure interaction is expected to play a significant role. Therefore, the soil body is modelled as a nonlinear continuum adopting a specific material law (Granular Hardening). This material law can be calibrated according to triaxial and oedometric test data and it accounts in particular for different stiffness in primary and un-/reloading stress paths.

![Triaxial response "Granular Hardening"](image)

Figure 4: Characteristic stress path for triaxial loading with un-/reloading sequence
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As outlined above, numerous nonlinear construction stages, in particular for simulation of the tunnelling procedure, have to be considered. This and the prerequisite to be able to perform parameter studies within a reasonable time-frame emphasize the need for a fast solution technique. Therefore, the tunnelling process is simulated by means of two-dimensional continuum finite element models of representative cross-sections under plane strain conditions, taking into account the specific material behavior of the soil in-situ. Three-dimensional stress redistribution effects are accounted for using the well-established “α”- or “stiffness reduction” method.

During installation of the cross cuts between existing and new tunnel tubes stress redistribution in direction of the longitudinal tunnel axis takes place. In this case, the amount of stress redistribution directly influences loading and therefore design of the supporting high-strength reinforced concrete frames. Moreover, due to the non force-locked butt joints between the crown segments of the existing tunnel, a stepwise cross cutting – supporting procedure is necessary. Simulation of this sequential process, taking into account the individual construction stages, requires a complex three-dimensional finite element model which includes various nonlinear effects, such as nonlinear soil behavior and in particular the contact behavior of the crown segment joints.

Aiming at the best compromise between efficiency and required accuracy for this project a novel strategy is adopted – a combined approach joining both the benefits of a fast and clearly arranged two-dimensional finite element analysis for the tunnelling simulation and the capability of a three-dimensional finite element model simulating the cross cut installation process. The connecting link between the two analyses is a procedure that not only generates the three-dimensional model from the two-dimensional one by a special extrusion technique but also maps the results of the two-dimensional analysis to the three-dimensional model – with it generating a primary state for the three-dimensional model that “inherits” the loading history induced by the tunnelling process.

Subsequently, the three distinct simulation phases are discussed in more detail.

3: Modelling the tunnelling process

As already motivated, the tunnelling process is analysed by means of two-dimensional continuum finite element models of representative cross-sections under plane strain conditions, taking into account the various soil layers in-situ and their specific material behavior.
Due to the inherent nonlinear character of the analysis it is obligatory to first generate a loading state of the model that represents the actual state prior to beginning of the construction activities. This is basically achieved by simulating the historic construction process of the existing tunnel tube – starting from a homogenous stress state. The so obtained loading state of the model then serves as the starting point for the subsequent analysis of the tunnelling process for the new tunnel tubes. From the complete analysis chain stated above two aspects shall be shortly highlighted in the following, namely simulation of the soil freezing and the actual tunnelling process.

Starting from the pilot tunnel the cooling lances are driven towards the new tunnel location in a fan-like manner. They are passed through by –40°C cold brine, serving as coolant. By this, a pore-water freezing process in the adjacent soil is initiated, finally forming a wedge shaped frozen soil body above the location of the new tunnel tubes. The freezing process implicates a remarkable temporary strength and stiffness conditioning for the affected soil regions. On the other hand significant volumetric expansion can take place, which is, however, constrained by a limiting maximum compressive stress state (Figure 5:).

<table>
<thead>
<tr>
<th></th>
<th>Sand</th>
<th>Frozen Sand</th>
<th>Clay</th>
<th>Frozen Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction angle [°]</td>
<td>37.5</td>
<td>-</td>
<td>22.5</td>
<td>-</td>
</tr>
<tr>
<td>Cohesion [kN/m²]</td>
<td>-</td>
<td>1500</td>
<td>-</td>
<td>1000</td>
</tr>
<tr>
<td>Young’s modulus primary loading [MN/m²]</td>
<td>120 (at σ = 400 kN/m²)</td>
<td>1300</td>
<td>90</td>
<td>600 (at σ = 800 kN/m²)</td>
</tr>
<tr>
<td>Young’s modulus unloading [MN/m²]</td>
<td>180</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume change, unconstrained cond. [%]</td>
<td>-</td>
<td>-1.0</td>
<td>-</td>
<td>~2.5</td>
</tr>
<tr>
<td>Max. pressure, up to which expansion takes place [kN/m²]</td>
<td>-</td>
<td>200</td>
<td>-</td>
<td>800</td>
</tr>
<tr>
<td>Actual effective volumetric strain [%]</td>
<td>-</td>
<td>0.0</td>
<td>-</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Figure 5: Mechanical properties of frozen soil

This mechanical behaviour has to be accounted for in the analysis and investigated with respect to permissible soil heavings and the generation of constraint stresses in the soil skeleton. For the actual configuration – due to the limiting compressive stress state – the freezing affected sand layer does not experience volumetric expansion. Volumetric expansion is restricted to the clay domain and amounts to an effective value of 0.14 % (Figure 5:).
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The actual tunnel driving process is then performed under the shelter of the frozen soil body. During the tunnelling procedure significant stress redistribution in the surrounding soil skeleton takes place. In reality, not only stress redistribution in the cross-section plane can be observed. In the working face region stress redistribution effects in the third direction along the tunnel axis take place, as well – resulting in a load release of the working face section. The two-dimensional simulation accounts for this effect by means of the well established so called “α”- or “stiffness reduction” method. This method involves an artificial relaxation of the sections of the model that are going to be excavated, i.e. removed from the model, during the next step – thereby the relaxation reflecting the load release effect due to the three-dimensional stress redistribution at the working face. The amount of artificial relaxation is subject to calibration and controlled by the relaxation factor $\alpha$.

**Figure 7:** Concept of the $\alpha$-method
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For Munich soil conditions it can be resorted to comprehensive experience made in the past with this method. Due to the stiffness conditioning of the frozen soil body a higher amount of three-dimensional stress redistribution is motivated – therefore, for the current tunnelling analysis with $\alpha = 0.2$ a rather low value is determined, effecting an 80% relaxation of the excavation sections prior to the actual excavation step.

4: Combined extrusion and result mapping technique

As previously discussed, the cross cut installation process requires investigation by means of a three-dimensional finite element model accounting for the sequential construction process and the limited stress redistribution capabilities in tunnel axis direction due to the non force-locked butt joints between the crown segments of the existing tunnel. In order to assure the consistency between the two-dimensional and three-dimensional model, a special technique is adopted.

The three-dimensional geometry is generated by a layer-wise extrusion of the two-dimensional model, with varying layer thickness in respect of the construction stages of the cross cut process. In the crown region of the existing tunnel tube every 2 m a non-linear interface element layer is provided, facilitating simulation of the butt joint contact behaviour.

Simultaneously, the complete set of variables representing the loading state of the two-dimensional model after drainage turning-off, i.e. prior to beginning of the cross cut installation process, is mapped to the extended model. Hence, the extended three-dimensional model not only inherits geometric attributes but also the loading state of the “parent” two-dimensional model.

<table>
<thead>
<tr>
<th>Tunnelling simulation 2D</th>
<th>Extrusion &amp; Result mapping</th>
<th>Cross cut simulation 3D</th>
</tr>
</thead>
</table>

Figure 8: Schematic outline of the mapping concept
5: Modelling the cross cut installation

Using the above described technique, a corresponding three-dimensional finite element model is generated comprising an inherited primary state that reflects the loading history induced by the tunnelling process. This primary state now serves as a starting point for the cross cut simulation. As mentioned earlier, the cross cutting process is performed in a stepwise manner, as required by the non force-locked crown segments of the existing tunnel.

The characteristic work sequence of a cross cutting process is illustrated in Figure 9:. At first, half of the final aperture is cut and supported with a c-shaped high-strength reinforced concrete frame. Prior to cutting out the remaining part of the aperture, the reinforced concrete frame is supported by three prestressed temporary steel columns. After the second half of the supporting frame is casted and force-fit connected to the first one, the temporary columns are removed. In Figure 9: each construction step is contrasted with a result plot of the corresponding finite element analysis step. From the distinct relative movement at the crown segment butt joints, especially during the second aperture process (second last picture pair), it becomes apparent that the contact interface elements are activated, i.e. no force transfer over the butt joints takes place.

Sectional forces, obtained by integration of the computed stresses over the domain of the supporting frame for each constructions step, are the basis for the supporting frame’s reinforcement design.
6: Current state of the construction process

In June 2003 the construction activities for the project “Bahnsteigerweiterung U-Bahnhof Marienplatz” were launched. As of December 2004, the tunnelling process in the eastern tube is finished and installation of the cross cuts is about to start. In accordance with the operating schedule, cross cut installation in the western tube is in process since October 2004.

During the tunnelling process accompanying measurements were undertaken, both regarding soil movements, with special focus to surface settlements, and force control in the outer lining of the newly installed tunnel tube. Comparing the measured data with the predictions of the finite element analysis, a good correspondence can be identified. This confirms validity of the choice of modelling parameters, particularly regarding the relaxation factor $\alpha$. 
the “Granular Hardening” material parameters and modelling of the volumetric soil expansion during the freezing process.

![Figure 10: Measured and computed settlements/ normal force [2]](image)

7: Conclusive remarks

The project “Bahnsteigerweiterung U-Bahnhof Marienplatz” posed a complex analysis task, involving simulation of numerous construction stages for the tunnelling and cross cut installation process within a fully non-linear context. Especially for the cross cut installation process a three-dimensional analysis approach was inevitable. On the other hand, the tight project schedule required a sufficiently fast simulation approach.

To cope with these requirements, for this project a novel analysis strategy was established by linking two-dimensional and three-dimensional finite element simulations with a joined extrusion and mapping technique. This strategy allowed the expensive three-dimensional finite element calculations to be restricted to solely the simulation of the cross cut installation process – without losing load-history information of the preceding tunnelling process – while the tunnelling process itself was efficiently captured by two-dimensional finite element computations.

In conclusion, the novel technique could successfully be applied to the project – the combined analysis approach enabled the complex analysis task to be completed on schedule. Furthermore, calculation results prove to be in good accordance with the data available from accompanying measurements.
REFERENCES


2 SCHMITT STUMPF FRÜHAUF Ingenieurgesellschaft mbH - Structural calculations "Bahnsteigerweiterung U-Bahnhof Marienplatz“, 2003-2004