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Two adjacent railway tunnels underneath the historic city of Mainz

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ABSTRACT: Different challenging tunnel projects in the downtown area of the city of Mainz in Germany are presented. These tunnels run parallel in a distance of 4 m to max. 50 m. The tunnels were built in soft soil conditions consisting of filling, clay and marl layers of the Tertiary. The paper presents the different construction techniques, the calculation methods for the two tunnels as well as the results of measurements for the New Tunnel Mainz. The experience for the construction of this tunnel and the results of the measurements were the basis for the chosen construction and calculation method for the rehabilitation of the Old Tunnel Mainz, which is currently under construction.

1 INTRODUCTION

The New Tunnel Mainz had been constructed in the years 1998 to 2001 directly adjacent to the existing Old Tunnel Mainz. This old tunnel built in 1884 is currently being rehabilitated, converted and enlarged during the next years. Due to the small overburden of both tunnels and sensitive structures on the ground surface challenging and unique tunnelling techniques were chosen to guarantee the stability and serviceability of the tunnels and of sensitive structures. In addition calculation methods and results from geotechnical measurements are presented in the following. The situation of the tunnels is shown in figure 1.

2 GROUND CONDITIONS

The geological condition is mainly characterized by the tertiary strata (Miocene) of the Mainzer Basin. The Tertiary strata sequence consists of an alternating sequence of marly clays, chalk marl, sandy silts (hydrobia silts, hydrobia oyster shells) and sands in an alternating sequence with chalkstone banks (fig. 2). The chalkstone banks are partly compact/massive to weathered. The consistency of the in-situ ground is stiff to semi-solid, turning into soft/paste-like if water intrudes. The groundwater can be found up to the level of the floor/upper edge of track; otherwise there is only local stratum water of little importance.

3 OLD TUNNEL MAINZ

3.1 Construction

The Old Tunnel Mainz was erected in the years 1881 until 1884 as one continuous double track tunnel. The tunnel has an horseshoe shape and the lining consist of sandstone with a thickness of approx. 0.9 m. The German core center tunneling technique was used to built the Old Tunnel Mainz with an overall length of 1200 m. The German core center technique (fig. 3) uses partial drivings, mostly sidewall drivings. Due to the bad condition of the tunnel, especially the masonry and to improve the smoke venting system, a 300 m long and up to 26 m deep open cut was built in the early 30ies of the last century, which divides the tunnel nowadays into the Tunnel Mainz Central Station and the Tunnel Mainz south (fig. 1/2).

The Old Tunnel Mainz consists of the following structures:

- Tunnel Central Station: 663 m
- Open cut: 300 m
- Tunnel Mainz South: 246 m

4 CONSTRUCTION OF THE NEW TUNNEL

4.1 Construction techniques

Parallel to the existing Old Tunnel Mainz, the New Tunnel Mainz was built in the years 1998 to 2000.

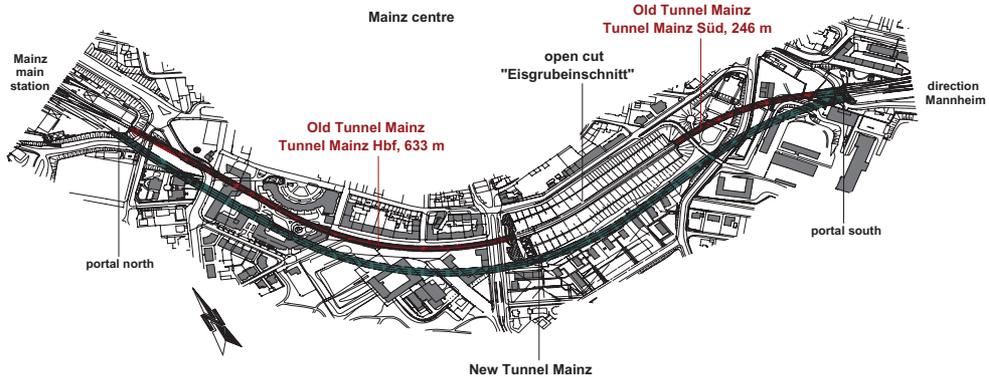


Figure 1. Plan view tunnel situation (Quick et al. 2001).

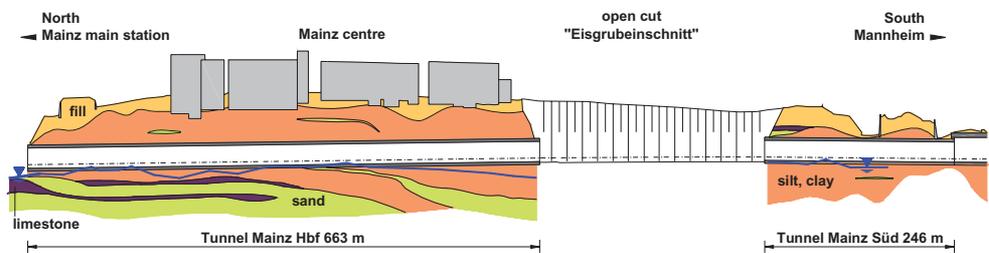


Figure 2. Geotechnical longitudinal section—Old Tunnel Mainz.

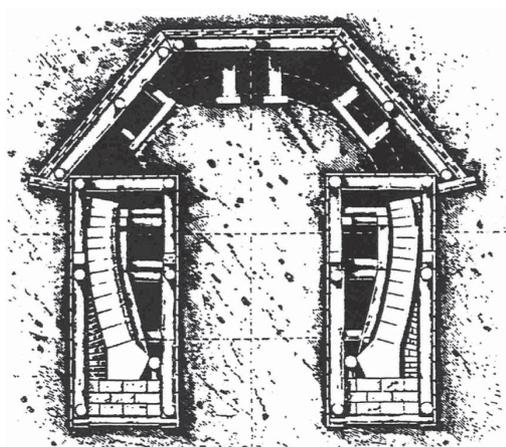


Figure 3. German core centre technique—Old Tunnel Mainz (Maidl 2004).

The new 1250 m long double track railway tunnel with a low overburden of 10 m to 23 m runs under buildings including a hotel with basements up to 10 m under ground level. Moreover, there are old (Roman) underground hollow spaces (gallery systems) to be undercrossed.

The clearance between the Old Tunnel Mainz and the new one varies between 4 m and 50 m (fig. 4).

Regarding ground conditions, existing settlement-sensitive structures and the possible influence on the Old Tunnel Mainz the excavation of the New Tunnel Mainz had to be carried out only with little deformation. Hence, an universal shotcrete tunnelling method with side wall drifts followed by the excavation of the calotte and core/bench was chosen as construction method (fig. 5).

The distance between the side wall faces and the final lining (ring closure) was limited to less than 100 m and in particularly sensitive parts to 50 m. The distance between the calotte face and the ring closure of the preliminary support was restricted to 30 m. Apart from the usual measurements in tunnelling additional securing measures were applied in areas of settlement-sensitive structures. They are as follows:

- Horizontally injected steel pipe roof shelter (strengthening of the longitudinal rock bearing arch) (fig. 5). The roof shelter is placed in the upper area of the face. The length of the drilling is 20.5 m. The minimum overlapping to the next roof shelter is 3 m. The advantage of

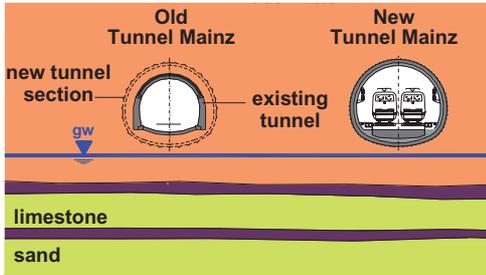


Figure 4. Geological cross section.

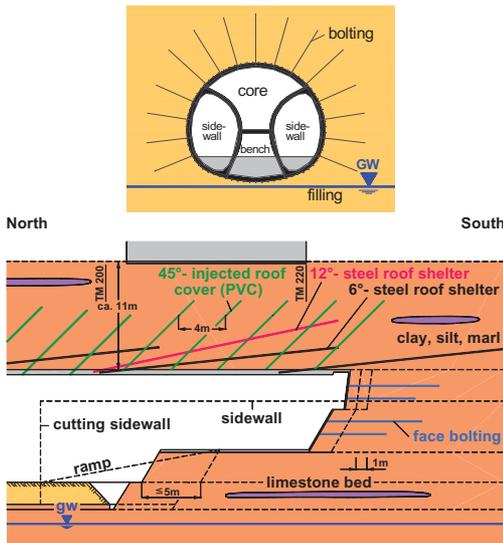


Figure 5. Undercrossing of a hotel; driving concept and securing measures (Steiger et al. 1999).

this technique is quite very obvious; a widening of the roof area to place the drillings is not necessary.

- In order to prevent any dilatational effect above the tunnel roof, 45 degree inclined, grouted PVC-fans are installed in continuous distances of about 5 m.
- Injections from the ground surface, pre-installed injection systems under the foundation of buildings as well as systematic face boltings within the tunnel are applied additionally in order to minimize deformations. All these measures together in connection with prior determined combinations of available measures were the basis of a successful driving with little deformations under settlement-sensitive structures.

4.2 Calculation method

For proof of the stability and serviceability 2D- and 3D-numerical calculation were carried out by means of the Finite-Element-Method with the program Abaqus (figs 7, 8). Continuum elements were used for the soil, where as beam elements for the lining. For the realistic simulation of the soil an elastoplastic soil behaviour was chosen (Quick et al. 2001). The modified Drucker-Prager material law with cap was implemented. The yield surface of this elastoplastic model is not constant in the principal stress space. It can expand due to plastic straining. Furthermore it distinguishes between different stiffness for loading, unloading resp. reloading.

For the calculation of the preceding deformations as well as to account for three dimensional arching effects around the unsupported tunnel the alpha-method was applied (fig. 6). The principle of this method is to reduce the stiffness of the finite elements which are to be removed in the next calculation step. The reduction causes changes in the initial stress field and therefore leads to preceding deformation. In case of the sidewall and calotte drivings the factor is set to 0.5. This assumption which controls mainly the preceding deformations was verified by measurements (fig. 11). In any case the evaluation of the factor α is difficult and is mostly based on experience.

The 3D-finite element model was created by extruding the 2D-mesh. Under respect of the construction procedure the length was chosen to 100 m (fig. 8).

4.3 Monitoring

Regarding the extraordinary situation to undercross several settlement-sensitive structures with only low overburden in soft ground an extensive geotechnical monitoring program had been carried out. At the surface the deformations due to tunnelling are measured in close distances by levelling as well as deformation monitoring systems, working on the principle of corresponding tubes. Figure 9 shows the measured surface settlements

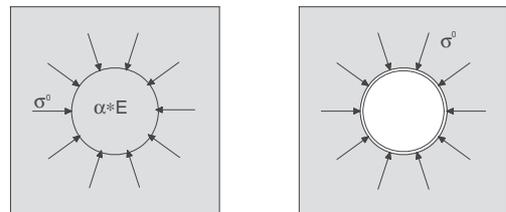


Figure 6. Principle of the alpha-method (Quick et al. 2001).

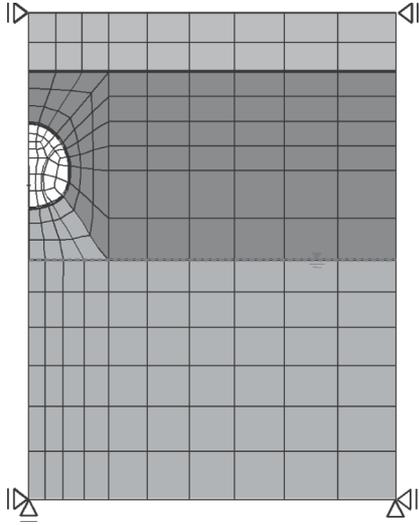


Figure 7. 2D-finite element mesh of the New Tunnel Mainz.

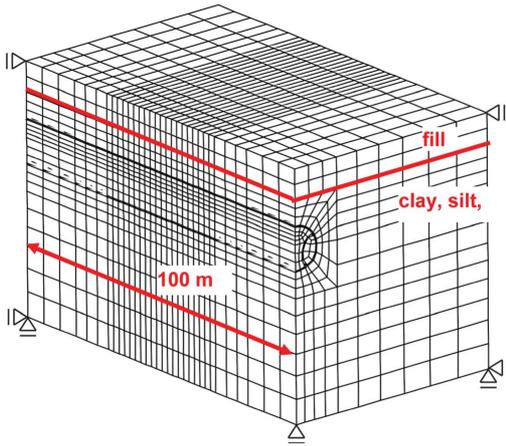


Figure 8. 3D-finite elements mesh of the New Tunnel Mainz.

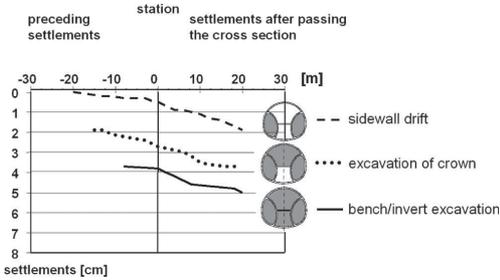


Figure 9. Measured surface settlements due to drivings (TM 117).

due to the driving at station TM 117. The surface settlement adds up to 5 cm. The settlements measured at the ground surface along the tunnel (fig. 10) were in most areas between 1.5 cm and 2.5 cm in average; at the very beginning of the driving additional securing measures—as described prior—have not been applied; the settlements at surface reached up to unacceptable 11 cm.

Figure 10 shows the surface settlements under respect of the different drivings (sidewall drift, excavation of crown etc.) at station TM 117. This station is close to the portal north (fig. 1). Most of the measured surface settlements are related to excavation of the sidewall drifts and the crown, while only a smaller amount of settlements arise from the bench/invert excavation.

Figure 11 shows the comparison between the measured roof displacements of the tunnel and the calculated roof displacements at station TM 117. The results of the 2D-calculation show a good correspondence with measurements regarding the

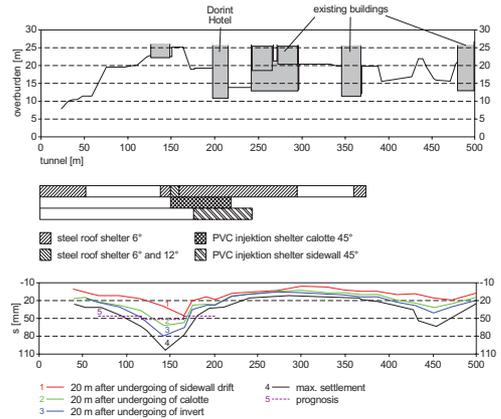


Figure 10. Surface settlement at surface due to tunneling.

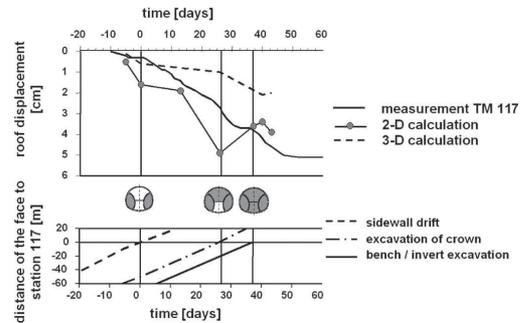


Figure 11. Comparison of measurements and calculations (roof displacements).

preceding displacement as well as the displacements due to the excavation of the sidewall drifts and the crown. However the calculated heave of the roof due to the excavation of the bench/invert does neither match the measurement nor the expected ground behaviour (fig. 11). For such soft soil conditions it is therefore in some cases necessary to increase the reloading-stiffness of the finite elements below the tunnel, in order to reduce the calculated heaving of the tunnel.

5 REHABILITATION OF THE OLD TUNNEL

5.1 Construction technique

The rehabilitation and enlargement of the Old Tunnel Mainz is going to be done under respect of the experiences of the New Tunnel Mainz. The partial loose ground (old back filling) around the Old Tunnel is improved by injections. In the first step the old filling around the tunnel is injected. Voids will be filled, improved by injections (bulk filling). For this 10 drillings up to a length of 2.5 m in a longitudinal distance of 1.5 m are carried out (fig. 12).

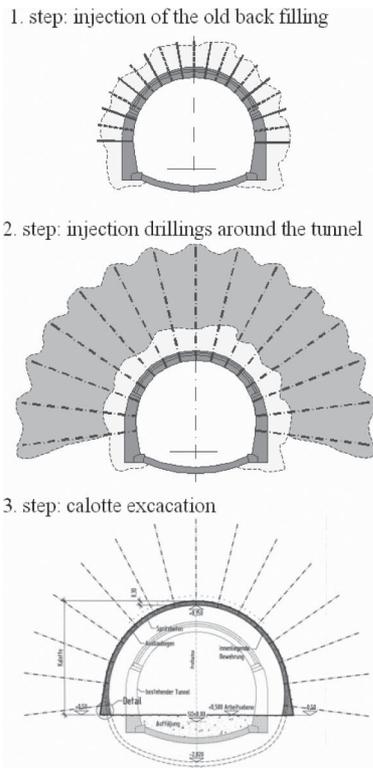


Figure 12. Tunnelling technique—Old Tunnel Mainz.

In the second step up to 8.5 m long injection drillings around the tunnel to activate a support ring are drilled. These two ground improvement steps are done under protection of the existing Old Tunnel. Subsequently the calotte driving in shotcrete method with an additional forepiles takes places. For the stability of the preliminary lining of shotcrete with a thickness of 0.30 m a widening of the calotte footing was established. In the final construction step the invert is excavated and the preliminary ring closure is achieved.

The distance between the face of the calotte driving and the preliminary ring closure with shotcrete is limited to less than 12 m.

5.2 Calculation method

For the design and the proof of the serviceability of the tunnel and the mentioned structures 2D- and 3D-numerical calculation are carried out with the program Plaxis. The numerical calculations regard all construction phases as well as the former excavation of the Old Tunnel Mainz and the New Tunnel Mainz. In order to create realistic results the material law of Hardening Soil with a yield surface, which is not fixed in the principal stress space is used. The yield surface expands due to plastic straining. In addition the material law can distinguish between different stiffness for loading and unloading resp. re-loading.

To account for the three dimensional arching effect of the unsupported enlargement of the Old Tunnel Mainz the beta-method is applied under respect of the used calculation program. The principle of this method is described in 3 steps (fig. 13):

1. Generation of the initial stress field $-\sigma^0$.
2. De-activation (excavation) of the tunnel clusters without activation of the tunnel lining and generation of (1-beta) reduced forces, which can be done by a reduction of the ultimate level of the full calculation step.
3. Activation of the tunnel lining.

The beta-value was obtained by an iterative back analysis of the New Tunnel Mainz. The predicted surface settlements of the 2D calculation for the ground surface amount to approx. 2 cm (fig. 14).

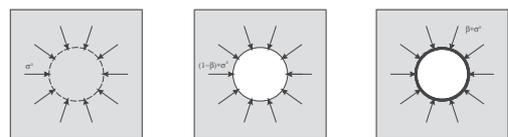


Figure 13. Principle of the beta-method.

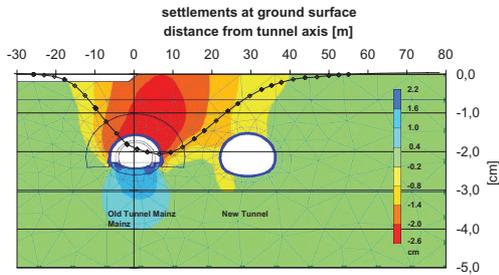


Figure 14. Calculation results—Old Tunnel Mainz.

5.3 Monitoring

The rehabilitation of the Old Tunnel Mainz is accompanied by an extensive monitoring program within the tunnel and on ground surface. For a quick interpretation of the data three levels of settlement limits for different areas under respect of the overburden and the existing structure were defined. On the basis of pre-defined measures such as an additional temporary shotcrete invert settlements can be slowed down and reduced to guarantee the stability of the existing structures.

6 CONCLUSION

The presented tunnels in the inner city of Mainz in soft soil conditions show a variety of different measures in the ground for the drivings in order to meet the requirements of the serviceability of existing buildings. 2D or 3D calculations were carried out to predict the displacements. It is shown that the evaluation of the input parameters and the calculation methods is complicated but decisive for the calculated results. Hence, every tunneling project must be accompanied by an intelligent

monitoring program to observe the impact on the environment due to the drivings and to ensure the stability and serviceability of the tunnel and neighboring structures as well as to generate data for possible back-analysis in order to improve the calculated results and to verify the assumptions. The paper shows also numerical approaches with different material laws and calculation methods. These different approaches can all lead to tolerable results, if methods are used properly and the input parameters are evaluated appropriately.

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