Rehabilitation of old masonry tunnels – challenges and possibilities

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ABSTRACT: The Reicholzheim tunnel on the single-track line 4920 from Lauda to Wertheim had to be rehabilitated, since the existing tunnel lining, made of mortar sandstone blocks, is in a structurally poor condition. To rehabilitate the tunnel, the existing masonry shell was reinforced with a self-supporting reinforced concrete inner shell. The low clearance profile required partial removal of the masonry. Due to the vibration-sensitive structure and high rock strength, the milling work had to be carried out on the basis of a separate safety concept including high-pressure water cutting. To secure unstable areas of the vault, CFRP safety devices were installed. Due to the partly non-existent back-fill and the narrow time window during night-time closures, special requirements were placed on the concreting. As the responsible design-review-engineer, the design and compliance with the railroad regulations with regard to the innovative safety and rehabilitation measures were also challenging.

Keywords: Tunnel rehabilitation, masonry shell, sandstone, CFRP safety devices, railroad regulations.

1 PROJECT OVERVIEW

On the non-electrified, single-track line 4920 from Lauda to Wertheim, the existing Reicholzheim tunnel between rail km 28.242 and 28.785 had to be rehabilitated over its length of 543 m during night-time closure periods. The tunnel is a facility of Deutsche Bahn (DB) Regio Netz Infrastruktur GmbH West Franken Bahn. The horseshoe-shaped tunnel, completed in 1870, is located in the municipality of Wertheim (Waldenhausen district) in the Main-Tauber district at the foot of the Mühlberg mountain. The surrounding rocks are predominantly clay-bound sandstones with low to medium rock strengths.

The existing tunnel lining of mortar sandstone blocks is in a structurally poor condition. This is reflected in washed-out joints, breakouts, spalling, cavities, efflorescence and leaks in the form of water seepage. To maintain operational safety for rail traffic, parts of the vault were therefore temporarily secured. The portal structure, protected as historical monuments, have also become unstable and were temporarily secured by means by ground anchors. Due to the structural condition, annual special assessments are necessary and repair is mandatory.

Figure 1. Existing shell of mortared sandstone blocks [source: Boley Geotechnik GmbH].

For the rehabilitation of the tunnel with its horseshoe profile, the existing tunnel lining made of natural stone had to be reinforced by a self-supporting reinforced concrete inner lining in cast-in-place construction (Antony C. et al. 2021). The new inner lining was initially planned with a thickness of 35 cm in the ridge area and 45 cm in the elm area. It was founded on the existing rock on both sides via strip footings. To allow installation of the new inner lining, the existing masonry had to be removed in some areas. To seal the tunnel against strata and seepage water, a roof sealing made of a geomembrane was planned. The geomembrane was to be connected on both sides to a new drainage system that also had to be constructed.

Due to the high importance of the section for regional passenger traffic, a large part of the work was to be carried out at night. A particular challenge in planning and execution was therefore the limited time frame, as all construction works had to be carried out during the nighttime closure periods.

2 SPECIAL CHALLENGES DURING EXECUTION

The masonry mortar is heavily weathered in some areas or completely decomposed and washed out. Due to the poor condition of the mortar, several sandstone blocks came loose from the masonry structure during milling works in the tunnel roof. As the appointed EBA (federal rail agency) design-review-engineer, we were immediately commissioned by the client to assess the condition of the vault in consideration of the safety of rail operations during the day. In Germany all designs for rail structures need to be reviewed by an EBA approved design-review engineer (the so called *Prüfingenieur)*. The design-review engineer performs the structural and/or geotechnical analysis of the designs to confirm that all design standards are fulfilled.

At the time of the inspection, the masonry vault apparently showed no fresh deformations of the overall profile. The high degree of opening of the joints as seen from the tunnel floor and the number of flaws in the freshly milled area were clearly less pronounced on closer inspection. Since the masonry blocks were only roughly hewn, they showed a corresponding interlocking or wedging over the depth of the joints. On the basis of the assessment, the conclusion was that, at the time of the inspection, the masonry bond was considered predominantly stable and therefore no acute risk to the stability of the structure was to be expected (Antony C. et al. 2021).

To prevent hazards to rail operations, an immediate placement of perforated plates and plaster indicators was arranged to monitor any movement in the masonry (Balbi G. et al. 2021).

Figure 2. Loosened and temporarily secured sandstone block [source: Boley Geotechnik GmbH].

During the examination of locally opened joints, it was also found that there was likely no backfilling material behind the masonry. This resulted in significant difficulties in further planning and design.

In the course of investigations, it was also found that the sandstone blocks used in the masonry had a significantly higher strength than the surrounding rock (unconfined compressive strengths of 150 MPa vs. approximately 30 MPa). Rocks from other regions had obviously been deliberately used for the lining of the tunnel. While the sandstone of the surrounding rock has a clayey bond, the masonry blocks have a siliceous bond. Due to the high strength of the masonry blocks and the low strength of the mortar as well as the apparent lack of backfilling, it was decided that only low-vibration removal methods should be used in the tunnel roof.

In order to be able to continue the work, a safe procedure was required, which included two different methodologies. Loosening by means of high-pressure water (HPW) cutting was successfully tested as a low-vibration method, but this was associated with a high cost and an unfavorable surface finish and/or necessary reworking (Breuning V., et al. 2011).

Figure 3. Surface of the masonry after tests with HPW cutting
[source: Holzhäuser Ingenieur Consult GmbH].

Carbon fiber-reinforced polymer (CFRP) panels and bars with epoxy adhesive were used to secure unstable blocks and masonry areas, however, this also proved to be very time-consuming.

The high strength of the sandstone made it difficult to insert nails with a bolt gun, which presented another problem during the attachment of the geomembrane. A concept with drilled-in dowels was presented but not implemented for economic reasons.

3 CHALLENGES IN DETAILED DESIGN

In order to significantly reduce the extent of the removal work on the existing shell and to avoid having to work on particularly critical areas of the masonry, the contractors proposed to reduce the planned thickness of the inner shell in the ridge from 35 to 30 cm.

However, RIL 853 stipulates a target thickness of 35 cm. In consultation with DB on the interpretation of the RIL, it was decided that from the point of view of the infrastructure manager ("Anlagenverantwortlicher") and the design-review-engineer, a reduction in the shell thickness in accordance with the RIL could be agreed upon. Ultimately, it was possible to design the inner shell predominantly with minimum reinforcement and in accordance with RIL 853.

The reduction of the inner shell thickness also allowed for the increased application of a sprayed mortar lining. In the original planning, it was envisaged within the scope of a special internal approval (UIG) that the insertion of a sealing support between the existing masonry and the geomembrane could be dispensed with. However, it became apparent during the execution that sufficient surface roughness could not be produced with the solution methods of milling and high-pressure water cutting. It was therefore decided to apply a leveling layer of sprayed mortar, which acted as a sealing support. An additional advantage of the sprayed mortar layer was that it made it much easier to insert the nails for the geomembrane's anchoring (Balbi G. et al. 2021).

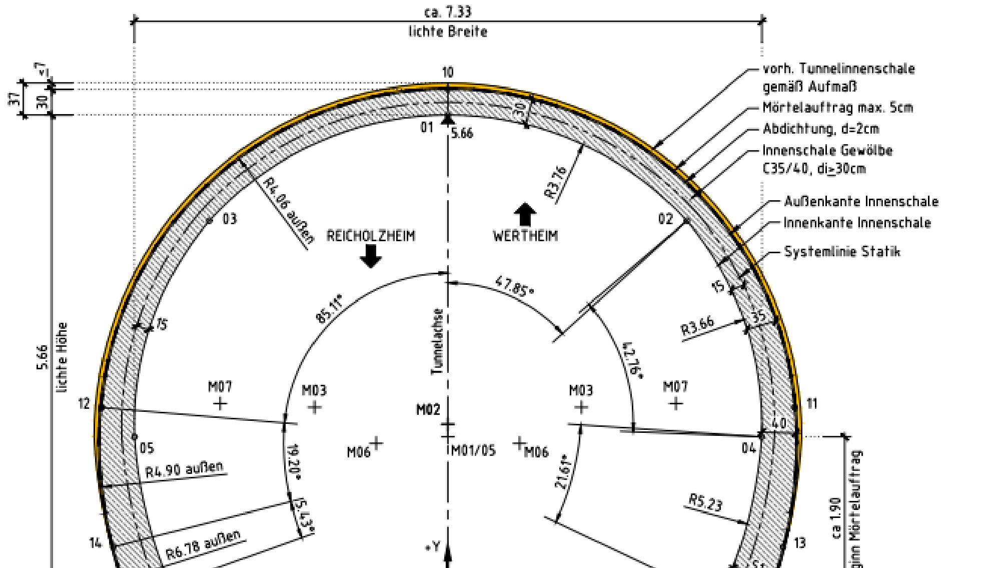

Figure 4. Cross section of the inner shell tapering towards the tunnel roof [source: müller + hereth GmbH].

Due to the possible lack of backfill, the existing masonry was only approved for a low concreting pressure of the inner shell to be produced according to the design specifications. It was assumed that the limit values could be complied with by means of appropriate concrete formula and production speeds. However, during the detailed design phase, it turned out that due to the tight time schedule and the required strengths for removing the formworks, it was not possible to implement sufficiently slow concreting speeds.

In consultation with the design-review-engineer, it was decided that the overall system of masonry, geomembrane and spray mortar lining had sufficiently high resistances to withstand the expected concreting pressures. In the end, the production of the inner shell could be carried out successfully.

Figure 5. Tunnel portal with temporary retaining system [source: Boley Geotechnik GmbH].

The tunnel portals are no longer stable due to the age of the structure and the slope movements near the surface. In the area of the portals, temporary retaining systems were therefore constructed consisting of a waling beam with rock nails. Due to the requirements of monument protection, the securing means are to be replaced by a permanent and non-visible retaining system.

From the design-review engineer's point of view, the planning is problematic because integrating the existing nails into a new system cannot meet the criteria for durability as per manufacturers specifications. The development of the stress conditions while working on and around the prestressed nails could also not be predicted with sufficient certainty. In addition, there were problems due to the confined space conditions required in the area between the anchoring.

A detailed design is therefore currently being finalized, which envisages a complete replacement of the existing system. To do this, the slope behind the portal walls must be secured by installing new rock nails in a u-shaped concrete structure before the existing rock nails can be removed. The masonry is then tied back into the concrete structure via vertically drilled CFRP-anchors.

4 CONCLUSION AND OUTLOOK

The rehabilitation of old masonry tunnels poses great challenges to those involved, among other things due to the numerous uncertainties of the existing structure. Due to the often deteriorated state of the structures, which complicates the exploration, as well as insufficient as-built plans, the estimation of the structural conditions can only be based on numerous assumptions. However, the load-bearing capacity of structures built with profound engineering knowledge and craftsmanship should not be underestimated either.

Despite the same type of stone, the strength of the rock formation cannot be simply applied to the strength of the masonry blocks. Experience with brick masonry should by no means be transferred to natural stone. Due to the high strength of the masonry, the possibilities for removal work may be severely limited. This can result in an enormous additional securing effort, especially if rail operations are to stay uninterrupted. In the case of high strengths, the application of a sealing support is recommended due to the surface condition after the necessary removal and the simpler attachment of the geomembrane. Because of the current regulations and from the point of view of technical construction, the application of a sealing support is therefore recommended.

The tight time frame combined with uncertainties about the condition of the existing masonry and backfill lead to conflicting requirements for concreting a new inner shell.

When preserving monument protected structures, it is advisable, even for temporary measures, to minimize the outward visibility of the retaining system. Particularly regarding durability, the replacement or rehabilitation of the retaining system should be taken into account from the outset during the planning stage (Eder M. et. al.).

Experience with the Reicholzheim Tunnel has shown that a detailed design planning is required in order to be able to adequately meet the challenges of timing and construction. Finally, the possible presence of protected species and the associated restrictions on construction methods and time schedules must also be taken into account (Draschitz C. et al. 2011). Due to the detailed level of planning required, it is therefore also recommended that an EBA approved design-review engineer is consulted at an early stage.

After identifying construction and scheduling problems, it must be discussed whether the costs, safety requirements and scheduling effects of the measures are in proportion to the desired maintenance of rail operations (Gabl Th. et al. 2017).

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REFERENCES

Antony C., Balbi G., Condic T., Fromm H., Gey M., Helmberer A., Jüngst C., Matt R., Reitenberger S., Schlebusch M., Seywald C., Tanner U., Urbanski J., Weller I., West T., 2021. Derzeitige Konzepte, In: *Sachstandsbericht 2021 „Erneuerung von Verkehrstunneln unter Betrieb", STUVA-Arbeitskreises "Tunnelerneuerung unter Betrieb (TuB)".*

Balbi G., Breuning V., Condic-Marinovic T., Eder M., Jüngst C., Matt R. Saelhoff G., Schlebusch M., Seywald C., Urbanksi J., Weller I., West T., 2021. Innovative Lösungsansätze, In: *Sachstandsbericht 2021 „Erneuerung von Verkehrstunneln unter Betrieb", STUVA-Arbeitskreises "Tunnelerneuerung unter Betrieb (TuB)".*

Antony C., Balbi G., Breuning V., Eder M., Gey M., Jüngst C., Loser P., Paprotny N., Reitenberger S., Schindler F., Schlebusch M., Schmidt N., Seywlad C., Tanner U., Urbanski J., Vycudil K., Weller I., 2021. Beispiele aus Planung und Ausführung – Erfahrungen, Herausforderungen und Empfehlungen, In: *Sachstandsbericht 2021 „Erneuerung von Verkehrstunneln unter Betrieb", STUVA-Arbeitskreises "Tunnelerneuerung unter Betrieb (TuB)".*

Draschitz C., Gabriel R., Pagliari,G., Simon S., Steiner H., 2011. Planungsgrundsätze zur Regelung der Schnittstelle zwischen Bauherrn und Planer, In: *Sachstandsbericht 2011 „Sanierung von Eisenbahntunneln", STUVA-Arbeitskreis „Tunnelsanierung".*

Breuning V., Chabot J. D., Draschitz,C., Edelmann T., Heisterkamp H., Pagliari G., Preißinger H., Schlebusch M., 2011. Bauverfahren und -methoden sowie Erfahrungen und Projektbeispiele zur Sanierung und Erneuerung von Eisenbahntunneln, In: *Sachstandsbericht 2011 „Sanierung von Eisenbahntunneln", STUVA-Arbeitskreis „Tunnelsanierung".*

Breuning V., Edelmann T., Heisterkamp H., 2011. Entwicklung von technischen Ansätzen geeigneter Verfahren zur Sanierung und Erneuerung von Eisenbahntunneln, In: *Sachstandsbericht 2011 „Sanierung von Eisenbahntunneln", STUVA-Arbeitskreis „Tunnelsanierung".*

Gabl Th., Jüngst C., Pucher M., Reichl Ch., Schlebusch M, West T., 2017. Strategien und Konzepte für die Instandhaltung, In: *Sachstandsbericht 2017 Instandsetzungsstrategien und -verfahren für Verkehrstunnel, STUVA-Arbeitskreis „Instandsetzung von Verkehrstunneln"*

Eder M., Gabl T., Jüngst C., Reichl C., Schlebusch M., West T., Weller I., Wolf C., 2017. Handlungshilfe für Instandhaltungskonzepte, In: *Sachstandsbericht 2017 Instandsetzungsstrategien und -verfahren für Verkehrstunnel, STUVA-Arbeitskreis „Instandsetzung von Verkehrstunneln"*