

Segmental Concrete Lining Design and Installation

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1 FUNCTION AND DESIGN OF TUNNEL LINING

The final tunnel lining has to withstand a variety of factors. Essentially, those are:

- From rock:
 - Ground pressures of all kinds (e.g.: dead load, swelling pressures, reduction pressures),
 - Water pressure,
 - Chemical attack by aggressive water or aggressive ground components,
 - Settlements due to poor ground conditions
- From construction conditions:
 - Annular ring grouting,
 - Transportation conditions of finished components (Segments),
 - Thrust forces, backup loads
- From utilization:
 - temperature influences from air or waste water and similar causes,
 - chemical attacks by gases, waste water, de-icing salt and similar,
 - effects caused by traffic,
 - fires in traffic structures.

These effects have to be taken into consideration in the static and constructional design of the final tunnel lining.

A sealing effect of the lining can be obtained both by the water resistant concrete type as well as the application of a waterproof skin on the exterior of the lining with in place concrete.

The planning and the production of the final concrete lining result from the interaction of tunnel cross section, geological and hydrologic conditions, excavation procedure and tunnel length.

The tunnelling industry differentiates following final tunnel linings:

- cast in place lining,

- shotcrete lining,
- in situ concrete,
- double shell lining,
- reinforced concrete segment lining,
- reinforced concrete pipes.

2 REINFORCED SEGMENTS

Tunnel lining with segments may have a single- or a double-layer lining construction. The final lining of tunnels with a double-layer lining design consists of a cast in place lining on the interior wall of the segment lining.

In a single-layer lining construction, the segments form the final lining. They must fulfil all requirements, resulting from construction conditions, rocks, groundwater conditions and utilization. Generally, the segments are reinforced pre-cast components. Only in smaller tunnel diameters and with lower quality requirements segments without reinforcement are used.

2.1 Requirements for Utilization

The requirements of the utilization of segment lining result from rock and water pressure, along with the use and the construction conditions.

High concrete strength is compelling regarding load transfers in the joints, thrust forces and the backup loads (construction conditions). Usually reinforced concrete segments are produced in concrete strength class B45, sometimes also in B55 or higher.

It should be mentioned, that the concrete of the segments in the tunnel portal area must have a high frost resistance; a high frost and de-icing salt resistance is necessary for road tunnels.

With chemical attack due to sulfate containing water (≥ 600 mg SO_4/l) or sulfate containing soil (≥ 3000 mg SO_4/kg) cement with a high sulfate resistance has to be used for the segments.

2.2 Segment Construction

2.2.1 Ring Geometry

A segment ring usually consists of five to seven segments. The ring division and the segment dimension have to be optimized according to the project-specific requirements. The ring division is among other things influenced by:

- tunnel diameter,
- max. permissible size of the segments for the intended transport,
- mechanical engineering mechanisms for installing the segments in the tunnel (erector),
- number of thrust jacks and their distribution over the range of the ring.

For the excavation of radii and to the reconciliation of inevitable deviations of the tunnel axis from the nominal line, segment rings are manufactured conical, such that the ring end surfaces are not parallel. In practice, both, the production of two opposing conical rings as well as the production of a conical ring worked satisfactorily. Each spatial curve can be produced by rotating the rings. If only one ring type is used, storage and tunneling process are simplified.

2.2.2 Longitudinal Joints

Normal ring forces, WARP moments via out-centric normal forces and transverse forces are transferred in the longitudinal joints.

The design of groove and spring in the longitudinal joint offers a good guidance for the installation and improves the possibility of transferring transverse forces.

Other joint designs, for example reciprocally convex joints or concave/convex joints, are hardly considered for final segment lining because of insufficient sealing possibilities. To avoid sealing problems (cross joints) and to increase the rigidity of the segment pipe, longitudinal joints of neighboring rings should be staggered.

2.2.3 Ring Joints

The ring joints are stressed by normal and transverse forces. The normal forces result from the thrust cylinder forces during construction and in the final state from water pressure. Transverse forces in the ring joints result from different deformations of neighboring rings.

To avoid damage due to stress peaks and to improve the load transfers, load transfer plates inserted in the ring joints have proven to be satisfactory. Also, for installation of cam and pocket systems, the use of

kaubit strips or equivalent is recommended. Practice shows that the design of groove and spring constructions clearly increases the danger of concrete chipping. If permitted, it is recommended to implement the ring joints evenly.

2.2.4 Segment Bolting and Segment Dowelling

For the installation of the segment ring and to secure the geometry, it is useful to bolt the segment connections along the longitudinal grooves and ring joints. Generally, the screw connections can be taken out again after imbedding the ring in the grout. Then, a bolted connection is no longer necessary, since the longitudinal joints are pressed into place by the ground pressure and water pressure and pre-loads are present in the ring joints created by resetting forces of the sealing section.

2.2.5 Sealing

For sealing the segmental tunnel pipe consisting of individual concrete segments, each segment is provided with a neoprene sealing frame which is glued into the corresponding groove of the ring joints and longitudinal joints. In order to avoid the opening of the seals they have to be compressed in accordance with their load deformation curve. This compression is achieved by means of the application of the thrust forces onto the seals in the ring joint, the subsequent temporary bolting of the segments and the following grouting of the annular gap.

2.3 Segment Production

2.3.1 Casting, Tolerances

Generally, segments are manufactured in an existing pre-casting plant or in special job-site plants developed for the project.

Following dimensions/tolerances are recommended:

- Segment width ± 0.6 mm,
- Segment thickness ± 3.0 mm,
- Segment floor length ± 0.8 mm,
- Longitudinal joint evenness ± 0.5 mm
- Ring joint evenness ± 0.5 mm
- Cross-setting angle in longitudinal joints $\pm 0.04^\circ$,
- Angles of the longitudinal joint taper $\pm 0.01^\circ$.

The dimensional tolerances can be defined project-specific.

2.4 Segment installation

The installation of the segments may only occur after reaching the necessary strength requirements. Directly before the installation the segments should be

inspected for damages and for proper installation of the seals. Damaged finished units may not be inserted. The segments are installed in the protection of the shield. Minor concrete flaking due to compression during the ring installation cannot always be prevented. Therefore, a concrete surface repair is generally necessary.

The ring joint grouting has large influence on the support behavior of the segment pipe. Essentially it can be distinguished between two injection methods:

- the continuous grouting of the ring gap through the tail shield of the shield machine and
- the additional grouting through the connecting piece in the segments.

In soft ground, grouting of the ring gap directly behind the shield is the current state of technology. The filling of the ring gap is volume and pressure controlled to minimize settlement on the ground surface and to embed the segment tube properly into the ground. This grouting has to be controlled such that inadmissible deformations of the segment rings can be prevented and damages on the segments are avoided.

For grouting through grout holes in the lining segments, the segments are provided with holes fitted with screwed connection pieces. They are closed during ring build by plugs. Distinction has to be made between primary and secondary grouting. Primary grouting is to facilitate the bedding of the segments in order to keep settlement during excavation as low as possible. Secondary grouting is to fill remaining cavities around the tunnel, e.g. caused by settling of the primary grout. The grouting through grout holes in the lining segments happens relatively late, so that penetrating soil - in the soft ground conditions - through the ring gaps cannot always be prevented. Therefore, grouting is not always even and a pressure build-up in the injecting material is only marginally controllable.

In hard rock, subsequent grouting through the segments or backfill of ring gaps with pea gravel and following grouting are today's state of the art. Important for the reduction of deformations and the support characteristics of the newly installed segment ring is the quick stabilization of the grout. The mortar should therefore possess good flow characteristics during the processing phase. After the injection process, it should be able to quickly tolerate high shear stresses and to accomplish consistent volume it should lose as little filter water as possible. Therefore, the "recipe" of the grout is highly important.

3 PROJECT EXAMPLE: GRAUHOLZTUNNEL (MIXSHIELD/SWITZERLAND)

3.1 *Project Description*

A slurry shield of 11.6 m diameter was used for excavating the Grauholz Tunnel in Switzerland in glacial soils below and above the groundwater table in mixed-face conditions and sedimentary rocks.

In soft ground and in rock formations with low overburden and mixed face conditions the Mixshield was operated as a Slurry Shield with bentonite supported tunnel face. In the rock sections, the Mixshield functioned as a normal open Hard Rock TBM. The TBM was a convertible machine and could dependent on the geological situation switch from Slurry Mode to Open TBM mode.

Tunneling with a slurry shield requires a watertight lining immediately behind the shield.

The Grauholztunnel was lined with a single shell liner consisting of six pre-cast elements and one keystone.

The joints between the elements are sealed by neoprene gaskets. The width of the ring was 1.8 m.

The finished tunnel has an inner diameter of 10.6 m and the liner has a thickness of 0.4 m. This leads to a shield diameter of 11.6 m.

The tail-void between the liner and ground was continuously grouted through the tail-seal.

Each meter of lining required 17 m³ of sand and gravel, 4 t of cement and 1 t of reinforced steel. The segments were cast in an 88m x 30m building working two shifts/day. During each shift, the 26 segment-casting wagons have been filled with concrete to produce some 14 m/d of lining. The segments were steam-cured at 50-55° for five hours to achieve the required strength. The production facilities were automated and have been equipped with modern handling systems. Concrete mixing was electronically controlled and the mix in the casting shell was vibrated. The minimum allowable concrete strength was 50 kN/m².

After inspection and removal of any imperfections, the segments were moved to a stockyard which could carry 250 whole rings, sufficient for about two months. Segments were stocked for a minimum of 28 days. Before they are being transported by road to the tunnel site, the segments are examined and fitted with neoprene gaskets in tongue-and-groove to seal against water flow.

The segments have been erected by an erector at the rear of the shield. A segment erector is able to carry out the following movements independently of one another: Radial extension and retraction along the

tunnel axis within the tailskin, rotation of 360° about the TBM axis, tilting of the erector head in direction of the tunnel axis and in lateral direction. A fine control of all movements is possible.

The operator of the erector was equipped with a portable erector control. He picked up the first segment and brought it into its proper position. As soon as the thrust rams gently touched down on the first built segment the erector picked up the next one. The rest of the ring including the key stone was conventionally erected. The segment connections were bolted temporary along the longitudinal grooves and ring joints. The bolts were left there until the grout was hardened.

The annulus behind the segments was grouted through grout holes in the lining segments.

4 CONCLUSION

In shield tunnel boring machines for soft ground and partly for rock formations, the support is installed with the help of an erector within the protection of the shield tail. The tunnel lining usually consists of pre-fabricated reinforced concrete segments. It is an excellent lining member with high compressive strength against both radial and longitudinal forces. It has also high rigidity and water tightness. Apart from supporting the surrounding geology, it serves in the case of most Shield TBMs as an abutment for the thrust rams. The load transfer between the lining and the subsoil is realized by grouting the annulus void at the shield tail.

The second lining, when required, is normally constructed by in-situ concrete. Usually the primary lining is designed as a main structural member against the final load, because the secondary lining is installed long after the erection of the segments.

Secondary lining is sometimes omitted to save costs when the primary lining is watertight enough or the ground conditions are favorable.

As the cost of segment shares significant portion of total tunneling cost, the type of segment should be carefully selected from both engineering and economical points of view.