SELECTION OF SEGMENTAL LINING SYSTEM AND REPAIR CLASSIFICATION

Jodl Hans Georg*, Kolić Davorin**

* O.Univ.Prof. Dipl.-Ing. Dr.techn. Hans Georg Jodl
Institute for Construction Process and Construction Management
University of Technology Vienna, Karlsplatz 13/234, A-1041 Wien, Austria
E-mail: jodl@ibb.tuwien.ac.at

** Davorin Kolić M.Sc. PE
Neuron Consult ZT, Pelikanstraße 18, A-4061 Pasching, Austria
E-mail: office@neuron.at

Key words: Segmental lining, durability requirements, repair classification, categories of damage, quality system, segment production, mechanical tunnel drive.

Abstract: *This document provides information for selecting an appropriate segmental lining system for mechanically driven tunnels with special focus on life span durability of the concrete structures. Important part of sustainable design for precast segmental lining are suitable concepts for handling damaged segments and damaged segmental lining. A catalogue of measures for easy identification and contractual stipulated classification of damages as well as acceptable rehabilitation is proposed. Clearly indicated contractual arrangements and quality control concepts are exemplified and should be generally stated in the tender documents but finalized chiefly in the contract.*

1. INTRODUCTION

Design and construction of segmental tunnel lining are crucial steps for building a mechanical driven tunnel with a live span of 100 years or more. Since client, designer and contractor have different roles on a project and basically different points of view to the execution preferably clear and fair contractual arrangements should be worked out. In order to avoid conflicts prevention to avoid damages should be aspired. Since damages are hardly avoidable it is necessary to dispose of practicable contractual instruments for proper damage classification and acceptable rehabilitation measures. The specifications for the quality of the precast segments and adequate proposals for striking the goal of durability in spite of unavoidable damages are major tasks in this article addressing clients and contractors as well.

2. SEGMENTAL LINING SYSTEMS

The new age of segmental lining systems starts approximately 15 years ago with several new products on international market and at the same time with the new approach to shield machine design. Basically new products have been new types of connectors and new sorts of waterproofing gaskets. The y have asked for new details of segmental lining but also for new machines having erectors able for fine tuning, easy installation and high carrying capacity. In cross section direction they are two basic systems: one-pass (Figure 1) and two-pass (Figure 2) segmental lining.

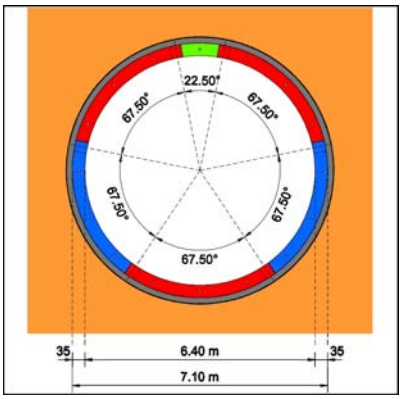

Figure 1: One-pass segmental lining system RER Line EOLE, Lot 35B Paris, France 1993 [1]

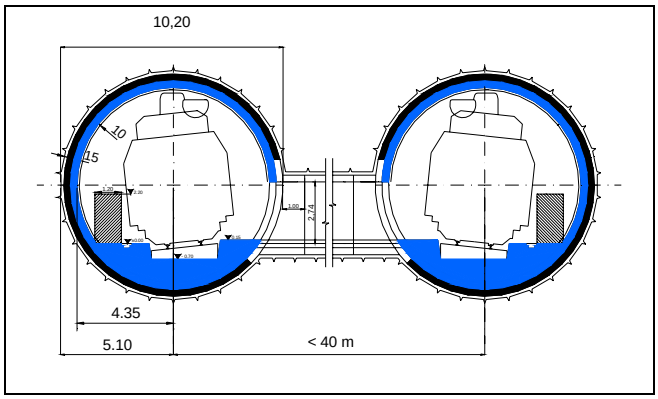

Figure 2: Two-pass segmental lining system for high-speed rail lines in Austria (tunnels Wienerwald, Perschlingtal, Koralm) in 2001-2005.

These two systems are coming basically from different approaches to durability of lining systems, from different water tightening concepts and from different understanding of underground behaviour. Requirements on design of segmental lining are therefore also different and therefore design details as well [9]. In longitudinal section of segmental tunnel lining we may differ among different ring division systems and different types of segment shapes: there are universal or parallel rings in use, segment shape differs from trapezoidal to rhomboidal or rectangular shape. All mentioned types come from a need to provide easy installation of segments connected into full

tunnel lining. Even though there are several types of linings that are more or less usual for distinct tunnel cross section sizes main requirement on all linings is to have easy and fast installation with no cracks. Therefore each tunnel will be a new challenge with a new machine and new erector and new details on segmental lining adopted to chosen connectors, gaskets, guiding devoices, drive and installation speed and accuracy.

3. DESIGN PRINCIPLES AND TRENDS

Beside all specific requirements of any new project we may depict few specific points that have seriously influenced approach to segmental lining details. One of these is for sure chamfer details on corners (Figure 3) that have been used during last 15 years on both longitudinal and ring joints. Chamfer detail enabled easier installation of segment into one ring and uses at the same time new type of gaskets that will provide watertight joint closure in the range of tolerances prescribed with improper installation procedure. They enable further imperfections of connectors what is one important moment because different types of connectors are today in use: some of them are longer than 40 years in use and others like different types of dowels are no longer than 5-10 years in application.

Next design principle or better to say trend in design uses nowadays more often hexagonal or so called honeycomb segmental lining or very big rectangular segments. Both systems are representing trends of segment application for best particular tunnel type. Hexagonal systems are nowadays in predominant use for long water supply systems in predominantly good rock conditions. It is anyhow the best solution for almost straight tunnels where very high advance speed has been expected. They are as well good solution for two-pass linings where hexagonal system acts as outer lining toward ground and may not be always high quality and capacity lining part (Figure 4).

Figure 3: Chamfer design for one- pass segmental lining on the project RER Line EOLE, Lot 35B in Paris, France in 1993 [1]

Figure 4: Honeycomb segmental lining for water supply tunnel on WYRDP in PR China in 1998 [2].

Further trend comes from growing capacity of shield machines: they are getting bigger and bigger and recent biggest diameter has reached 15.0 meters of excavation diameter on example of Groene Hart tunnel in Holland passing through soft geological formations saturated with water [4]. The

results of big-diameters tunnel trend are segmental lining that have very wide ring widths, at the moment beyond 2.0 meters. Specific point in design is that due to the tunnel size there is plenty of space to install each segment and therefore the shape of segments has returned to rectangular form, as was usual 30 years ago. Details of segmental linings are not so important any more but other details and requirements are put on segmental lining: there are plenty of new details regarding safety requirements that have asked for safety and ventilation chambers on side, numerous cross-adits, vault details or in bottom areas. However trends are showing continuous change in development of lining details and application of high quality concrete classes. Experience with sophisticated projects as e.g. SOCATOP project in France will for sure define new levels of tunnel usage and as well new requirements on segmental linings.

4. DURABILITY REQUIREMENTS

Segments for segmental lining systems of mechanically driven tunnels are usually produced in special job-site plant or in an existing pre-casting plant. The production process and the subsequent logistic chain may cause quite a number of different cases of segments transfer. The ready produced concrete elements have to be removed and handled several times before being erected to their final position as part of the final segmental lining, the so called Tübbing ring. The durability of any segmental lining system can not be measured directly but it has to meet functional, technologic, environmental and operational requirements. Most countries dispose of guidelines for precast concrete parts although the guidelines regularise mainly the segment production alone but do not cover the whole logistic chain from the mould to the segmental lining. Lack of defaults with rules for the contractual handling of damages is also to be indicated. Most tenders do not enclose any provisions of a contract regulation and a manageable procedure for defects in quality, repair provisions and their counterpart with deduction of price or similar [9].

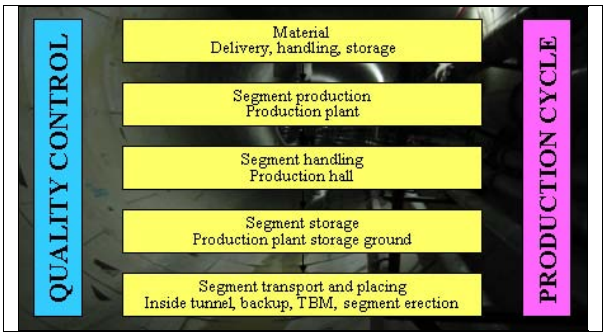

Figure 5: Segment production chain from mould to segmental lining

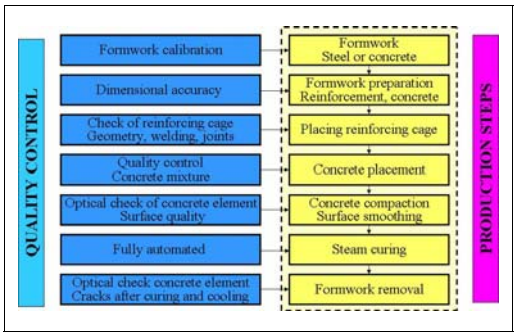

Figure 6: Segment handling in production hall

This contribution may give some ideas for detecting the possible genesis of defects during the production cycle, handling and placing of elements as well as proposals for the specification of defects which may be corrected or not. Finally a frame of quality management references are offered to be taken into consideration with public contracts for tunnel projects with segmental lining. To meet the advertised requirements and tolerances the segments have to be produced with high accuracy. The assembling of segmental lining to a closed ring of segments without stress

concentration and constant width of the joints needs precise design and preparations. The single element has to be brought to that target with a minimum of risk and a maximum of care. Production and assembling tolerances should be defined project-specific by the producer and contractor. Samples of point of references for dimensions and tolerances are recommended [11].

Category of damage	Characterisation of damage
1	Microcracks from temperature, shrinkage, etc.
2	Surface damage without bare reinforcement
3	Surface damage with bare reinforcement
4	Open, through-going cracks off mechanical impact
5	Leaky joints

Figure 7: Categories of damages [9]

Figure 8: Edge spalling [Foto Kolić]

The number of possibilities for damages on elements may be demonstrated with some figures showing the complicated application flow depending mainly on the type of segment production and of the tunnel boring machine (Figure 5). For this reason the whole production chain may be divided in two main groups of segment handling. Each production step should be monitored with great carefulness. To assure the best quality an appropriate quality management system should be installed. The main measures of quality checks are pointed out parallel to the production steps (Figure 6). This article is not concerned with the first group material manipulation because it has no effect on the state of the ready casted segments. The second group segment production and the third group segment handling remain within the segment production plant either in the precast production hall or in the storage ground which is usually located near to the hall. Production of precast concrete parts for segmental tunnel lining must be carried out with high accuracy and precision. The segment moulds and the concrete segments have to follow strictly defined tolerances which have to correspond with each other [7].

Moulds and segments have to be measured carefully. Tolerances have to be specified in tender documents and contract. The tolerance values are usually based on results of deformations caused by temperature influence, deformations due to quality of the casting and shrinkage calculation of the concrete body. Major tasks are the steady-going quality of the concrete mixture, skill and training of the workmanship and permanent quality checks. Key production steps are preparation of moulds before concreting, vibration of moulds filled with young concrete and stripping of the fresh segments. All the crucial procedures are setting the quality of the segment and the segmental lining. In consideration of this facts test rings should be made and carefully evaluated according to imperfections and deviations before starting the tunnel drive. With the process step stripping of the segments they have to be turned over for intermediate storage in the precasting hall to avoid possible damage caused by high flexural tensile stress until outside storage. After surface checks and measuring application of the sealing is made. Finally the segments are prepared for intermediate transport to the outside storage yard. The fourth group segment storage gives attention to numerous segment transportation cycles from the production hall to intermediate

storage yard. The segments get piled ready for ring erection at the outside storage yard. The fifth group shows different intermediate transport cycles to the tunnel portal area where the segments may be optionally stored again and through the tunnel to the place of segment erection within the shield tail of the TBM.

5. DAMAGE CLASSIFICATION

Tunnelling is a tough job since there are numerous possibilities for partial damage on each segment on its way from casting in the mould to placing in the tunnel. When using segmental lining in tunnelling with TBM and Shield Machines it is necessary to detect the red light of external or partial damage as soon as possible. After stripping a first optical check of the segment has to be made. Depending on compliance with the defined requirements each segment is to be distinguished between good, repairable or eliminable. Well directed measures may achieve appropriate improvement at ongoing production, storage, transport and placing of segments. The objective of this damage classification is to allow client and contractor a well disposed damage assessment balanced on relevant project conditions under defined ancillary conditions without the need to discuss on site every damaged segment whether it can be repaired or must be sorted out.

5.1 Rehabilitation of segments

Segments damaged on the way from production to erection must not being assembled in that status. Slightly or partially damaged segments can be renovated and repaired. Heavily damaged segments must be sorted out. For contractual approach according to the rules quantity and quality of acceptable damage should be defined in the contract papers respectively as well as proper rehabilitation measures permitted. The client should commit the contractor to submit a statement for proper rehabilitation for acceptance. For easy and quickly addressing of possible defects a table of damage categories may be proposed (Figure 7). These general categories should be rendered by the contractor more precisely with defined values and specified repair measures. Modern all-purpose repair mortars are available in very high quality which brings the decision for repair to a primarily economic question whether a segment should be repaired or built new.

An assortment of common damages on segments and repair measures may be discussed [9]:

- **Voids**: the porosity of the surface is conditioned by number and size of voids (determining diameter of a single void) per rated surface area. By adherence to defined maximum values no repair is required. Measure: closure of voids by stopping with cement-bound mortar and final surface smoothing.
- **Cracks**: distinction between micro-cracks or damage-cracks. Dominant characteristic is the measured crack width. Micro-cracks (in general smaller 0,2 mm) within the groove need no repair since being filled by glue. Damage cracks within the groove may be penetrated with epoxy resin of low viscosity.
- **Spalling**: spallings within the edges of the groove are conditioned by depth and defined maximum length respective. Repair of spalling segment edges is necessary when > 5 mm depth and/or > 20 mm length. When the bottom of the groove is intact the edges can be postformed by stopping with cement-bound mortar and final forming. Spalling greater 3 cm needs repair with epoxy resin reconstructing the original geometry (Figure 8).

- **Breakage**: breakages are to be distinguished as within the groove or within the contact area or within the erector cones and bolting gaps. Limitation of repair to size of depth (8, 7, 6, 5 mm) and corresponding length (50, 60, 70, 80 mm). Repair measure by stopping with cement bound mortar and final forming. Smaller breakage (< 5 mm) and those which are outside areas with defined special requirements need no repair.
- **Pockets**: careful check of the segment is necessary. Pockets must get filled like breakage when they are out of the groove basis, locally limited and do not reach the reinforcement. Repair measure by cleaning the structure reaching the intact concrete zone and filled with cement bound mortar. Segments with more than one pocket are to be sorted out.
- **Joints**: staggered joints and lateral off-set of segments after finishing of ring application. No dismantling of segments is possible. Repair measure by widening and filling the joints.

When segments are identified as being damaged and meet specified maximum damage limits contractually defined rehabilitation measures can be done. Rehabilitation measures have to correspond with categories of damage to restrict acceptable rehabilitation or elimination of damaged segments. To facilitate compliance with contractual regulations likely rehabilitation measures may be assessed to the cause of damage. The client defines general design criterias and quality standards for segmental lining and segment production which have to be rendered more precisely by the contractor in the bid and later in the contract as well. Since development of concrete technology and construction is a steady ongoing process the client should stay abreast of changes and avoid stipulation of precise numerical data but pretend clearly his functional requirements on the building.

5.2 Quality management

For providing adequate quality of the tunnel with special regard to segmental lining specifications for verification and effective control measurements are to be foreseen. The contractor has to meet contractual requirements by developing an applicable quality assurance system. Compliant quality standards requirements have to be worked out in a quality manual. The provisions due to the quality manual should be binding upon all parties of the production chain of segments. When precast-plant and production of reinforcement are not part of the site all specifications of the quality manual should be fixed within a contractually arrangement with subcontractors and suppliers. When quality measures meet contractual requirements the client approves the contractor’s quality system. The client confines himself to controlling random sampling.

5.3 Tender recommendations

The technical specification to the concrete and the segments should be detailed enough but sufficiently flexible to allow the assessment and adoption of alternative materials, design, joints and others when adequately documented. Before starting the permanent works construction it may be aimed for tendering process that pre-qualified contractors have the opportunity to settle a first stage of pre-testing the segment production to ensure the achievement of the requirements with an appropriate documentation. A selection of general tender recommendations should encourage the client to demand on the contractor providing necessary information more precisely. The points with important regard to segmental lining should be taken into consideration including a report concerning site installation. The contractor has to submit a comprehending technical report of the

segmental lining system referring to design, production, erection, sealing and quality assurance. The basic design considerations are to follow the national standards and guidelines available.

6. CONCLUSION

The life span of mechanical driven tunnels is strongly influenced by design and construction of the most suitable segmental lining system. On the way to their point of final destination each segment has to pass approximately 10 to 14 steps of intermediate handling. Each handling process holds the risk of damage to the segment. Damage of segments can not be excluded completely but considerable reduced. The client should explain his requirements in the tender but without restriction of innovation and ongoing development. The contractor has to submit a proper plan for exposure to damage on segments to be approved by the client as part of the contract. Within a quality system appropriate controlling measures have to be secured. The aim of this approach is to install a professional system for realistic and easy accomplishment of different defined damages without quarrelling about each single problem but ensuring a stainable construction with high durability.

REFERENCES

[1] Bordas A., Kolic, D., Longchamp, P.: 1995. Tunnelling in the Underground of Paris, France. Symposium "Modern Construction Methods", Brijuni Islands, June 19-21, 1995. 395-403.

[2] Kolić, D.: 2000. Quality recommendations on segmental lining for shield drive in hard rock.. Int. conference on tunnels and underground structures (eds), *Proceedings*: 355-362. Singapore: Balkema.

[3] Jodl, H.G., Kolic, D., Schlosser, W.: 2004. Planung, Herstellung und Anwendung von Tübbingen. *Proceedings Betontag 2004, Wien.* March 18-19, 2004. 23-31.

[4] Kooiman, A., Ruitenberg, J., Ballesteros, L., Bourdon, P.: 2003. High Quality Lining of World's Largest Shield Driven Tunnel. *Proceedings ITA Congress.* Amsterdam, April 14-16, 2003. 215-223.

[5] Ceresola, A.: 2001. Tübbingproduktionsanlage Lötschberg-Basistunnel Süd, Lose Steg und Raron. *Tunnel 4/2001*. 119-122.

[6] Degn, S.; Boye, Ch.: 2003. Design and construction – Conflicting stages? *Underground Construction, London; COWI publications no. 1663*. London.

[7] Girmscheid, G.: 2000. *Baubetrieb und Bauverfahren im Tunnelbau – 19 Tübbingauskleidung*. 509-521. Berlin: Ernst & Sohn. ISBN 3-433-01350-0.

[8] Johnson, M. 2003. Copenhagen Metro, Segmental Tunnel Lining Durability Strategy and the Supervision thereof. *COWI publications no. 1604.* Published by: Rail, Metro and Tunnel - 2002 - Copenhagen Metro.

[9] Working Group A-10. 2004 : *Recommendation for Segmental Tunnel Linings (Richtlinie Tübbinge).* Vienna. Austrian Society for Concrete and Construction Technology. Prepared for publishing in 2005.

[10] Recommendation. 2003. *Erhaltung und Instandsetzung von Bauten aus Beton und Stahlbeton.* Vienna. Austrian Society for Concrete and Construction Technology.

[11] Herrenknecht, M., Bäppler, K.: 2003. Segmental Concrete Lining Design and Installation. *Soft Ground and Hard Rock Mechanical Tunneling Technology Seminar*, Colorado School of Mines (CSM).