# SEGMENTAL LINING TOLERANCES AND IMPERFECTIONS

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**Keywords** : tunnel segmental lining, tolerance, imperfection, offset, ovalisierung

## INTRODUCTION

Segmental tunnel linings are nowadays in massive application on numerous projects around the world. The lining will be used through the application of some type of the TBM machine and special attention has to be paid on the quality and overall performance of tunnel lining during phases of production, transport, installation and tunnel operation. Beside required level of material quality it is also necessary to provide the quality assurance that covers the geometrical dimensions and fitting of segments into segmental lining rings (Kolic, Bodivit 1998). The quality of geometrical segment dimensions is usually checked comparing measured segment dimensions with theoretical geometry of each separate segment. Compared dimensions have to be within prescribed geometrical tolerances and within allowed range of imperfections (AFTES 1999, BTS 2000, BTS 2004, STUVA 2001).

During all last years by almost all projects that have been constructed the sizes of tolerances and the amount of imperfections has been overwritten from the last constructed project. Such prescribed tolerances were usually very far away from the reality due to their very strict requirements on segmental lining dimensions that were even beyond the possibilities that the segment material requires. These very strict, small and unreal deviations from theoretical values (ÖVBB 2005, Friebel 2008) have asked for the necessity to investigate real range of sizes within segment lining tolerances and allowed imperfections are to be defined for different types of segmental linings and different tunnel sizes in various conditions.

## TOLERANCES

Tolerances are to be defined as allowable geometrical deviations from theoretical prescribed geometrical sizes of one separate segment. They have to be defined based on the type of the segmental lining and influences on the lining during development of different project phases. Tolerances will be estimated independently one from another and they will be defined for distinct separate segment dimensions. Usual and mostly measured segmental dimensions are shown on the figure 1.

Therefore several main segmental dimensions are defined and will be measured mainly only after the end of the production phase. They are listed below as :

- Ub – perimeter segment length
- Db - diagonal chord length

- As - secant length between two radial joint surfaces
- t - segment thickness
- B - segment width
- Fe - joint face parallelism of one joint surface
- Pp - parallelism of two ring (circumferential) joints
- Wa - deviation angle from theoretical planed segment angle
- Ao - deviation from theoretical position of openings for connectors
- Dg - depth and width of waterproofing profiles

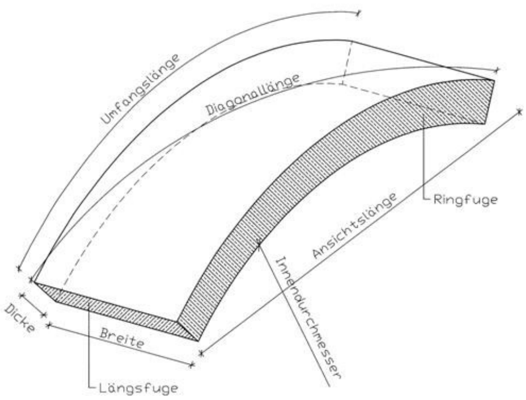


*Fig.1 Main measured segmental dimensions that require definition of tolerances.*

***Single-Pass and Double-Pass Segmental lining***

Based on the functioning of these two different types of lining systems their tolerances will also be appropriately defined.

Single-pass segmental lining systems could be used as watertight and water-permeable lining systems. Single-pass segmental lining that are water permeable have relatively lower requirements regarding geometrical tolerances. The tolerance size and therefore the accuracy of production enable bigger deviation from theoretical geometry. In comparison to them single-pass watertight linings require far bigger production accuracy as they have requirements regarding placing of the watertight profile and accurate placing of neighbouring segments in radial and ring joints.

Double-pass segmental linings are using segments as outer water-permeable lining. Therefore they are constructed without watertight profile and usually without connectors. Therefore requirements on the geometrical segment accuracy are not so high and the only watertightening that is required is against the inflow of the backfill material.

***Definition of Tolerances for Segments***

Definition of segment tolerances has been developed investigating all steps that have the influence on the final segment size. Therefore presented approach derives its sizes on influences and requirements that are described as partial influence on tolerances through (ÖVBB 2009):

- tolerances for moulds
  - where we differ between tolerances for steel moulds (more often in use) and concrete moulds (rare in use)
- tolerances due to the deformation of segments
  - deformation through temperature (in analysis used range dT= from -30°C to +45°C)

- deformation through shrinkage (used 60-70% of final shrinkage, at 70% humidity)
- deformation through creep (low influence, could be neglected)

- tolerances due to the deformation from storage, transport and installation
- tolerances due to the influence of connectors and gaskets
- tolerance due to the segment production procedure ( at least the size of a mould tolerance)

Final definition of tolerances are combining results of deformations of above mentioned influences and defining min/max combination of segment deformation as the basis to define the size of allowable tolerance for each measured segment size :

$$dL = dT + dSw + dH\ (+\ dEg) \qquad \textit{(Equation 1)}$$

… where separate values are equal to :

| | |
|---|---|
| dL | sum of deformation of some measured segment dimension |
| dT | deformation through the temperature |
| dSw | deformation through the shrinkage |
| dH | deformation through the segment production (at least mould Tolerance) |
| (dEg) | deformation through dead weight (when acting unfavourable) |
| T | suggested allowable tolerance |

Therefore based on analysis in equation 1 suggested tolerance size for some segment dimension will be equal to :

$$T > dL \qquad \textit{(Equation 2)}$$

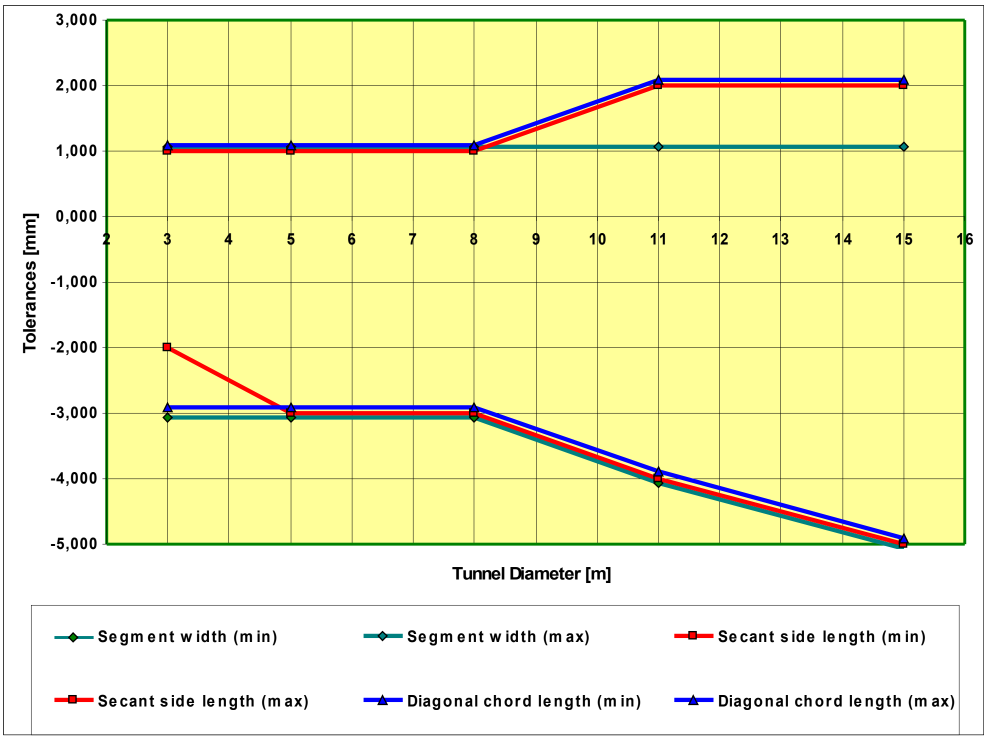


*Fig.2 Development of tolerances for some segment dimensions for tunnel diameter sizes in the range of 3.0 – 15.0 m.*

Analysis of calculated values of segment deformations and values of suggested allowable tolerances for some of segment dimensions for different tunnel diameters in the range from 3.00 to 15.00 m have been shown on the fig.2. Diagrames are showing development of tolerance values for min and max values. Minimum values for tolerances have the (-) minus sign and are typical by the production of segments due to the predominant influence of shrinkage and temperature. Maximum values for tolerances have (+) plus sign and have smaller absolute values, are not typical for the production of segments are if the y happen they are caused by higher temperatures on storage or by mould imperfections. However both values for tolerances are necessary for the successful quality assurance procedure for segmental tunnel lining. Examples of analysis and therefore suggested values of tolerances shown on figure 1 have been defined for different tunnel diameter sizes but for one-pass lining with gaskets and connectors.

If we try to evaluate segment deformations for two-pass lining having segmental lining as outer lining. Influences of temperature and shrinkage are remaining the same as by the one-pass watertight lining but production tolerances dH are far more bigger.

| **Din = 8.00 m 6 pcs., t = 0,30 m B = 1.30 m** | **Segment size [m]** | **dSw Eps = 0.00032 [mm]** | **dT T = –30°/ +45°C [mm]** | **dH Min/Max [mm]** | **Deformation Min/Max [mm]** | **Tolerance Min/Max [mm]** |
|---|---|---|---|---|---|---|
| Diagonal chord length | 4.5361 | –1.45 | –1.36 / 2.04 | –1.0 / +3.0 | –3.81 / 3.59 | –4.0 / +4.0 |
| Perimeter length | 4.3459 | –1.39 | –1.30 / 1.96 | –1.0 / +3.0 | –3.69 / 3.57 | –4.0 / +4.0 |
| Width | 1.3000 | –0.42 | –0.39 / 0.59 | –1.0 / +2.0 | –1.81 / 2.17 | –2.0 / +3.0 |
| Thickness | 0.3000 | –0.10 | –0.09 / 0.14 | –0.0 / +2.0 | –0.19 / 2.04 | –0.2 / +2.5 |
| Secant view length | 4.0000 | –1.28 | –1.20 / 1.80 | –1.0 / +2.0 | –3.48 / 2.52 | –4.0 / +4.0 |
| | **Secant view length** | | T = –10°/+10°C | | | |
| parallelism of one joint surface | 4.0000 | - | *–0.40 / +0.40* | –0.00 / +0.500 | –0.40 / +0.90 | –1.0 / +2.0 |
| parallelism of two ring joints | 4.0000 | - | *–0.80 / +0.80* | –0.00 / +1.00 | –0.80 / +1.80 | –2.0 / +3.0 |
| | **Width** | - | [°] | [°] | [°] | [°] |
| deviation angle from theoretical planed segment angle | 1.3000 | - | for 1 plane *–0.018° / +0.018°* | for 1 plane –0.000° / +0.022° | for 1 plane –0.018° / +0.040° | for 1 plane –0.05° / +0.05° |

*Table 1 Two-pass tunnel lining for water-permeable outer lining for the tunnel with the inner diameter Din = 8.00 m*

Examples of analysis of segment deformations are showing that tolerances have to be separately defined for each specific project and have to answer to the project requirements and diverse influences on the segmental lining. Therefore examples that are presented are giving just a rough overview of sizes, methods and results that could be gained during such analysis.

***Programme of Measurements***

In order to check all interesting segment measures one programme of measurements has to be established. Measurements could be performed using steel templates or could be performed with surveying instrument in the form of 3D measuring. Steel templates should be checked and tested several times during the measurement. Surveying 3D measurement cost usually far more and is establishing artificial 3D “model surfaces” based on measured points. Disadvantage could happen when some of points on the model surface has not been measured but “modelled”. In addition at the beginning of segment prefabrication it is necessary to check overall ring geometry on a test-ring, usually without gaskets and connectors (ÖVBB 2009).

## IMPERFECTIONS

In comparison with tolerances, imperfections are geometrical deviations from the theoretical ring geometry (Baumann 1992). Mostly mentioned imperfections are segment offsets and ring ovalisation, but we should also mention different types of eccentricities that may happen during the installation phase. The influence of all eccentricities have to be analyzed within the design project phase and it has to be observed and measured during installation and tunnel drive project phases (Schneider 2001, DB 2002).

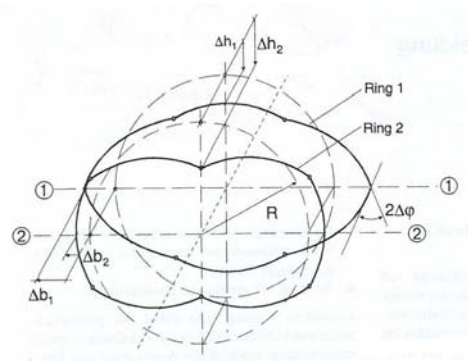


*Fig.3 Ovalisation of two adjacent rings (Baumann 1992).*

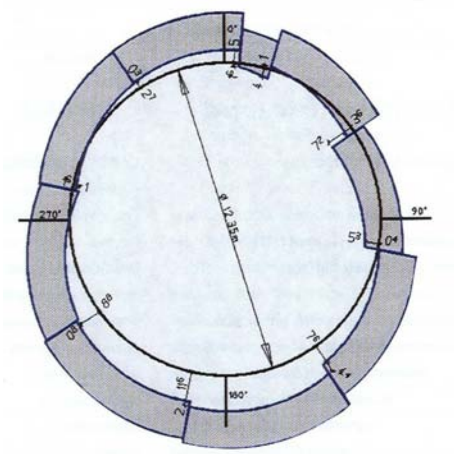


*Fig.4 Segment offsets in one ring (Baumann 1992).*

### *Ovalisation and offsets*

Both imperfections may have completely different values from project to project and their size depends on the type, purpose and the size of the segmental lining and tunnel diameter. Generally is known that both imperfections get the contact area between adjacent segments in contact smaller. Therefore overall experience is showing that by the ovalisation the rotation angle between two joint surfaces may not be bigger than 3-5 $‰_0$ (promile). The usual size of the offset varies if we use watertight or waterpermeable lining and is in the range form 0-15 mm for watertight linings and 20-50 mm for waterpermeable linings. However, allowable size of imperfections should be defined separately for each specific project and its requirements.

### *Eccentricities*

Imperfections are happening in different eccentric forms on segmental lining during different project parts as prefabrication, storage, transport and installation in the tunnel. Already during the storage of segmental lining after the prefabrication in production halls segments are placed in large storage places. It is possible that due to the eccentric placing of segments one-on-another due to the differences in the location of supporting clads between segment layers additional bending moments appears that may lead to unplanned cracks or deformations (fig.5). Such influences are especially important by long segments that we meet by big tunnel diameters.

Far more influence on segmental lining has eccentric action of thrust shoes (fig.6) or eccentric distribution of thrust pressure (fig.7) on the lining. Eccentric pressure action may cause the need for additional reinforcement and could even be a dominant factor for the dimensioning of segmental lining especially in a soft or mixed ground conditions. Eccentric placing of segments into a ring could cause also different lining quality problems by pressure concentration and spalling or bursting of concrete at the contact area of adjacent segments. Therefore is beside the measures that provide the quality during segment prefabrication important to provide appropriate quality control during installation procedure.

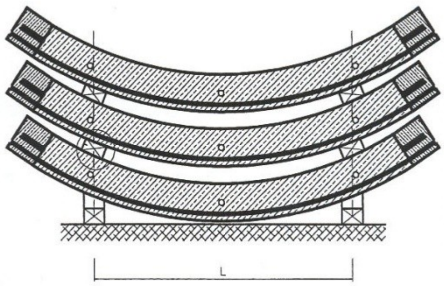


Fig.5 Segment storage (Kolic, Bodivit 1998)

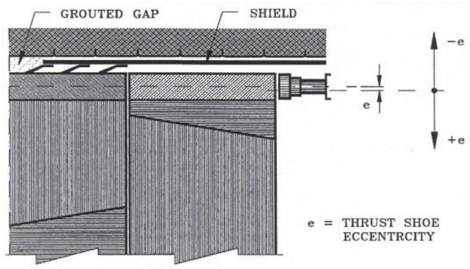


*Fig.6 Eccentricities of TBM thrust shoes on the lining during the shield drive (Kolic, Bodivit 1998).*

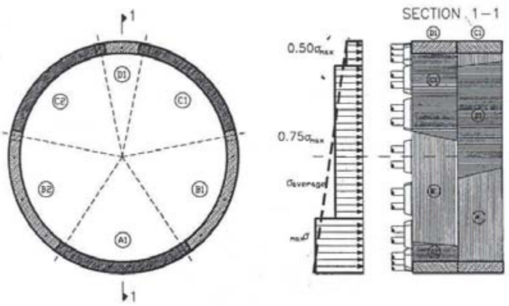


*Fig. 7 Eccentric pressure of TBM thrust shoes on the segmental lining (Kolic, Bodivit 1998).*

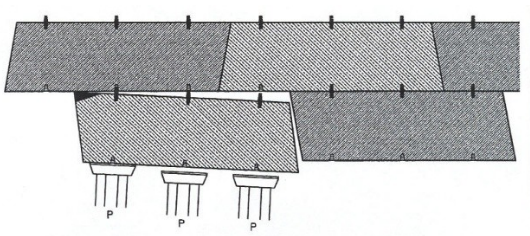

*Fig.8 Eccentric placing of segments in a ring during the shield drive (Kolic, Bodivit 1998).*

### *System Requirements and the Range of Tolerances and Imperfections*

Beside the analysis and the methodology that was presented for the definition of segment tolerances we may understand that some lining systems do not need the level of lining quality that is provided with the analysis. Sometimes it is only important that the allowed imperfections enable the installation of the segmental lining even if the ovalisation or offsets are bigger.

This usually happens with waterpermeable double-pass linings with no connectors and especially with big size tunnel diameters. Therefore we may speak generally about the 3 main groups of system requirements : geometrical, statical and functional system requirements.

| **Tolerance or imperfection size** | **Allowable size** | **Remark** |
|---|---|---|
| Offset in radial joint | +/- 35 mm | due to the segment thickness 25 cm possible |
| Ovalisation in inner diameter | +/- 70 mm | 10 ‰ |
| Offset in ring joint | +/- 50 mm | due to the segment thickness 25 cm possible |

*Tabelle 2 Geometrical system requirements for a double-pass waterpermeable segmental lining with no connectors, with diameter Din= 7.00m (no gasket).*

One example for the outer lining of a double-pass lining has been shown in the table above as an example that geometrical system requirement is enabling much more space in a placement of segments for the outer lining system where the watertightening will be provided conventionally by a membrane between linings and the final inner lining will be casted-in-place.

| **Tolerance or imperfection size** | **Allowable size** | **Remark** |
|---|---|---|
| Offset in radial joint | +/- 12 mm | due to the screw diam. 24 mm and hole dia 36 mm |
| Ovalisation in inner diameter | +/- 60 mm | 5 ‰ |
| Offset in ring joint | +/- 12 mm | due to the screw diam. 24 mm and hole dia 36 mm |

*Tabelle 3 Functional system requirements for a single-pass watertight segmental lining with straight-screw steel connectors dia.24 mm with tunnel diameter Din= 12.00m (gasket b= 50 mm).*

Next example shows that allowable imperfections are far more strict in the case of far bigger tunnel diameter that has functional system requirements that are limited with the gasket or connector requirements. Even for such big diameter size the system requirement asks for limited deviations from theoretical ring system geometry.

## CONCLUSION

Tolerances and system imperfections are phenomena that are immanent to the tunnel drive with the segmental lining. So far they have not been investigated and analyzed in detail despite very often application of segmental linings. Approach and methodology presented are trying to evaluate these values and are for the first time presented within the work in mentioned references (ÖVBB 2009) and in this article in a shorter size.

Tolerances have to have prescribed values based on material requirements and on different system requirements as well as on the required production quality level.

Imperfections have values based on system immanent limitations, system requirements and on overall installation quality level policy.

The intention is to define real sizes for tolerances and imperfections on each future segmental lining project in order to support required quality assurance and minimize additional construction and maintenance costs.

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