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North East Link segmental lining lessons learnt - from design to construction

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ABSTRACT: Major tunnelling projects, ranging from metro-sized tunnels to large diameter road tunnels, have boomed in Australia in recent years. Unfortunately, due to the lack of comprehensive guidance within existing Australian or international standards specifically for tunnels, let alone large diameter tunnels, some of the typically adopted design targets may not be practically achievable in construction. Some unsuitable requirements can lead to excessive compliance effort during the construction phase. This paper aims to share some lessons learnt from North East Link segmentally lined tunnels and provide an objective review on current segmental lining design and construction processes.

1 INTRODUCTION

North East Link (NEL) is the biggest ever infrastructure investment in Melbourne's northeast. The project includes Victoria's longest and largest twin road tunnels from Watsonia to Bulleen, and a segmentally lined tunnel with a 14.1m internal diameter (ID) was designed and constructed along the majority of the alignment using the latest industry practice.

The current approach for segmental lining design in Australia is to adopt the AS 5100 Bridge Design code and various Eurocodes (building codes). The British Tunnelling Society Specification for Tunnelling (BTSS) and local state authority specifications such as VicRoads Standard Specifications are commonly required by clients for segmental lining production and installation. It is recognised there is a lack of comprehensive guidance within existing Australian or international standards specifically for tunnels, let alone large diameter tunnels. The tunnel size and precast element size can have a large influence on the lining component for production and installation, and some of the typically adopted design targets may not be practically achievable in construction. Many experienced tunnellers know a few 'tricks' to work around impractical requirements, but some unsuitable requirements can lead to excessive compliance effort during the construction phase.

This paper aims to share lessons learnt from NEL segmentally lined tunnels, focusing on the recurring issues during construction phase which can be mitigated through more reasonable design practice and specification targets. Some sections of the paper might seem disjointed due to the nature of the content. Rather than telling a single story, the paper addresses multiple key challenges that are unrelated to each other, yet each contributes to the overall puzzle. The authors hope this paper will initiate critical thinking within the industry. Instead of merely replicating past practices, some of which are commonly associated with above-ground structures, the industry should critically examine existing issues and unsuitable practices and begin considering ways for improvement.

The key discussion points in this paper include the suitability of the BTSS specified segment tolerances for large diameter tunnels and the necessity and applicability of certain concrete segment production tests. Ways to improve construction efficiency via design, and in-depth discussions on common lining installation-related issues are also considered.

2 DESIGN OVERVIEW

The segmental lining for NEL has an internal diameter (ID) of 14.1 m. The majority of the 5.0 km twin TBM tunnel alignment is supported by steel fibre reinforced concrete (SFRC) segments. Steel bar reinforced segments are utilised at various locations, primarily at cross passages, ventilation adits and ventilation shaft connections.

As shown in Figure 1, each ring consists of ten segments: seven rectangular segments, two trapezoidal counter key and one key segments. The segments are 500 mm thick and 2400 mm wide. Each longitudinal joint edge contains a guide rod and two spear bolts. Each circumferential joint edge contains two spear bolts and four shear bicone recesses, with shear bicones being installed in steel bar reinforced segments only.

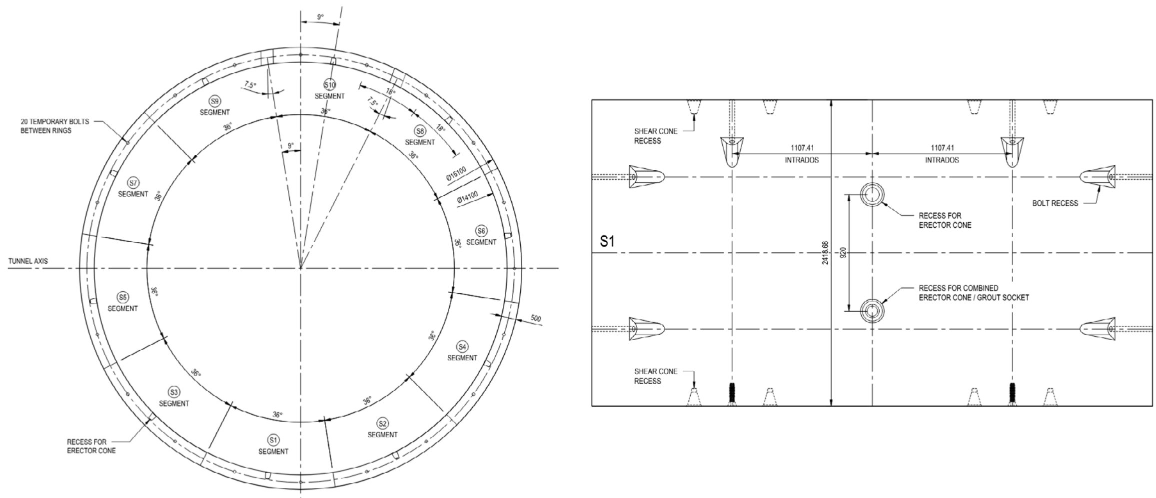

Figure 1. Elevation of erected ring (left) and developed view for a typical segment (right).

3 SEGMENT PRODUCTION

3.1 *Segment production tolerance*

Segment production tolerances refer to the allowable geometrical deviations of any segment dimension from its theoretical size. Stringent tolerance requirements are imposed on segments for quality assurance and installation accuracy to ensure lining structural and functional system consistency. Exceedance of the allowable tolerances leads to rigorous investigations into the usability of the segments. Therefore, it is important to set realistic targets for segment production tolerances.

The segmental lining for NEL is required to comply with the production tolerances in BTSS which does not make allowance for tunnel size. In fact, BTSS tolerance requirements are more suitable for metropolitan train size tunnels up to ~8m ID. NEL is one of the largest segmental lining tunnels in Australia, and all of the BTSS tolerance requirements are not practically achievable. As a result, a large number of Non-Conformance Requests (NCRs) were received during segment production. The parameter with the highest number of dimensional non-conformances is segment width. BTSS tolerance for segment width is ±1mm whilst the non-conforming segments show a shortening up to 3mm which has a significant impact on the lining circumferential joint watertightness.

The segment dimensional measurements were undertaken by 3D laser scanning. Out of 1746 measurements taken during the 2023 to 2024 production period, 41% were out of tolerance. Among these, 39% show a segment shortening of 1 to 2 mm, and 2% show a segment shortening of 2 to 3 mm. The measurements were taken when segments were a few days to a few months old. A review of the mould dimension conformances and concrete shrinkage measurement trends suggests the segment shortening is likely to be associated with drying shrinkage and thermal effects (Victoria can have large daytime temperature variations throughout the parts of the year that could contribute the dimensional non-compliance). However, the maximum drying shrinkage test result for the segments is 640 με, well within the allowable limit of 750 με based on VicRoads Specification 610. How can segments have out-of-tolerance shortening when they meet the relevant performance goals?

Table 1 presents a summary of the segment theoretical shortening for both design shrinkage and maximum test result drying shrinkage, assuming a temperature differential of 10ºC. The result shows, due to the segment size, even if segments meet the performance requirement for drying shrinkage, it is not theoretically possible for them to also meet the BTSS width tolerance requirement of ±1 mm.

Table 1. Summary of segment theoretical shortening across segment width (2.4 m).

Drying Shrinkage (με)	750	640
Shrinkage Shortening* (mm)	1.80	1.56
Temperature Differential (ºC)	10	10
Thermal Length Change** (mm)	0.24	0.24
Anticipated Total Shortening (mm)	2.04	1.80

* Strain variation of ±20% not considered
** Thermal variation of ±20% not considered

There is a need to understand the technical basis and limitations for dimensional tolerances in existing tunnel specifications as all may not be appropriate for large precast segments / diameter tunnels. Interestingly, a literature review of international published tolerance guidance was undertaken, including ITA Working Group 2 Guidelines (2019), and no specifications consider segments of this size. The author recommends that a project-specific assessment of tolerances considering concrete shrinkage and temperature differences, at a minimum, be completed for tunnel linings > 10 m diameter to minimise exaggerated demands for segment accuracy and increases in production costs. The guidance provided by ÖVBB (2011) and Kolić and Mayerhofer (2009) should be considered both for design and production verification purposes.

3.2 *Dimensional check frequency*

The segment dimensional compliance checks are typically carried out pre-production to ensure each fabricated segment mould can produce segments conforming to the specified dimensions and tolerances. During production, routine segment dimensional checks are also carried out as part of production control. The checks can be undertaken for individual segments or a combination of moulds and segments. There are no standards or guidelines in the industry for segment dimensional check frequency, and it is often left to the engineer's discretion in setting a reasonable dimensional measurement frequency and mitigation plans in the event of non-compliant results. Since the dimensional checks can be disruptive to precast production, it is in construction team's interest to reduce the checking frequency.

The authors' opinion is that more regular dimensional checks on both moulds and individual segments should be performed at the start of production for an extended period of time. The number of the checks completed needs to be sufficient for engineers to gain confidence in the adopted casting scheme, concrete mix and production controls. Relationships between dimensionally acceptable segments and other factors also need to be established. The checking frequency can be revisited after there is a consistent record of segments meeting the specified tolerances.

During the initial phase of NEL segment production, the moulds were measured twice per month for over six months, and segments produced over more than six months were also measured. Upon reviewing the whole data set, the designers observed strong correlation between acceptable segment dimensions, compliant mould dimensions and concrete drying shrinkage test results. This provided the basis for the decision to stop post-pour segment dimensional measurement, provided that:

– Mould measurements were carried out twice per month and show dimensional compliance; and
– Concrete drying shrinkage tests were carried out once per month and show compliant results.

As a mitigation plan for gross dimensional non-compliance, a representative number of samples are required to be guaranteed to be available for segment dimensional checks in the event of a concrete drying shrinkage NCR. The authors note this concession is only acceptable due to the large amount of data collected at the start of the production.

3.3 *Production tests*

3.3.1 *Fibre washout test*

One of the more frequently received CRFIs relates to low steel fibre content in SFRC segment test samples. Steel fibre content is often considered an important measurement for SFRC segments as low steel fibre content could be an indication of insufficient residual flexural tensile strengths. However, based on the test data collected, a clear relationship between fibre content and residual flexural tensile strengths is not always evident.

Figure 2 shows the available fibre content test results from March 2023 to July 2024. A few test results do not meet the target fibre contents (shown as straight lines) with Sample NP1-1153 showing the lowest average fibre content of 21.1 kg/m^3, 26% lower than the target value (28.5 kg/m^3). It is reasonable to assume the segment represented by Sample NP1-1153 would have unsatisfactory residual flexural tensile strengths.

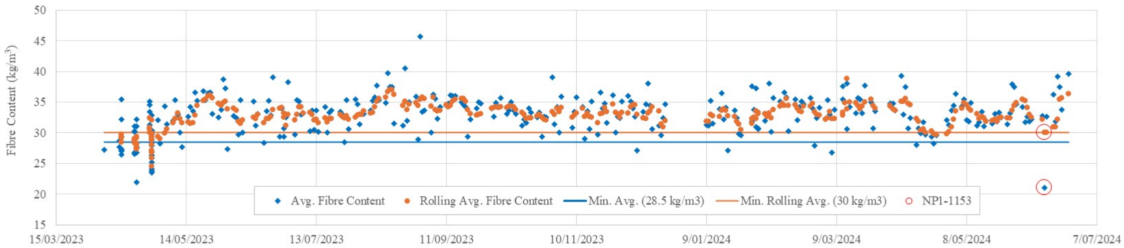

Figure 2. Fibre content test results from March 2023 to July 2024

However, the available residual flexural tensile beam test results (tested to BS EN 14651) from March 2023 to July 2024, shown in Figure 3, suggests a different story. The residual flexural strengths result for Sample NP1-1153 is relatively high within the data set, and no clear correlation is observed between fibre content and flexural tensile strengths. Note some samples exhibit strain hardening behaviour (i.e. $f_{R3} > f_{R1}$). This is beneficial for capacity as the design has conservatively assumed SFRC has strain softening behaviour which leads to lower theoretical strength. At the time of testing, the samples had reached and exceeded the 28-day compressive strength requirement of 50 MPa.

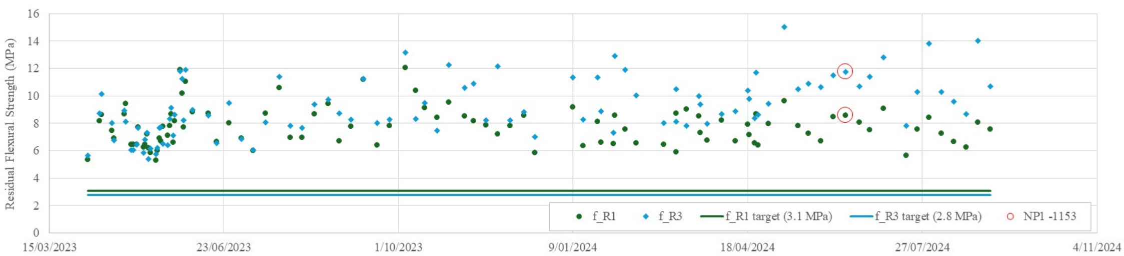

Figure 3. Available residual flexural tensile beam test results from March 2023 to July 2024.

To investigate this further, the steel fibre distribution for Sample NP1-1153, shown in Figure 4, was inspected and compared to the number of fibres protruding from both failure surfaces for available samples over an eight month period.

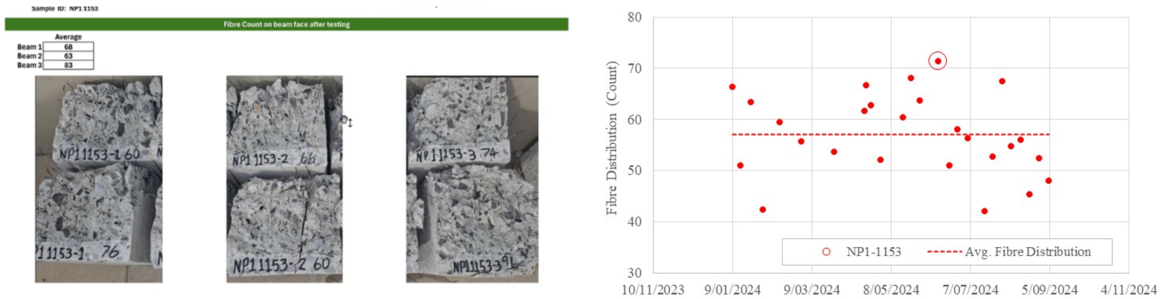

Figure 4. Fibre distribution count for Sample NP1-1153 and available fibre count results from March 2023 to July 2024.

Figure 4 shows Sample NP1-1153, with the lowest average fibre content, has the highest average fibre count amongst the available results, which is consistent with the residual flexural tensile strength test results. This suggests the potential causes of some low test results might be measurement error, sampling error or poor fibre distribution within the concrete mix.

The fibre content is measured using VicRoad Test Method RC377.01 – Determination of the fibre content of fresh concrete (wash-out method). The 3 washout samples (approx. 5 L sample volume/test) were theoretically taken near the beginning, middle and end of the pour. In comparison, BS EN 12350-1:2000 Testing fresh concrete – Sampling, which is the basis for BS EN 14651 residual flexural tensile beam manufacture/testing, says to take at least 1.5 x quantity required for fibre content tests. BS EN 14651 needs approximately 38 L concrete to make 3 beams, so approximately 56 L concrete is sampled for fibre content test. This is a significantly larger sample volume compared to the adopted washout test method and would give a more accurate concrete material behaviour compared to fibre count. The small fibre count sample size amplifies human errors in sampling, potentially selecting samples that are not representative of the batch.

In terms of the impact of uneven fibre distribution within mix, a plot of the available fibre count results versus residual flexural tensile strengths, f_{R1} and f_{R3}, in Figure 5 shows the residual flexural tensile strengths can vary significantly with the same fibre count, and even with a fibre count as low as 35, the residual strengths are well above the target performance criteria. Therefore, segments with pockets of poor fibre distribution can still exceed the target residual flexural tensile strengths.

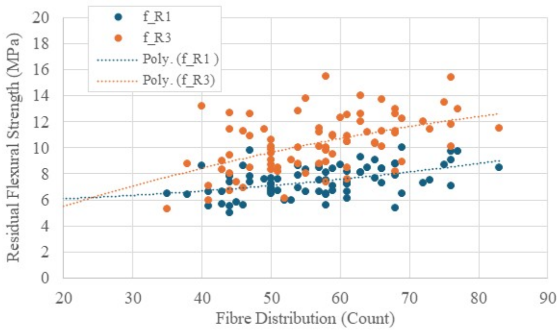

Figure 5. Available fibre count versus residual flexural strength plot from March 2023 to July 2024.

It is suggested that fibre content testing may not be necessary as a routine test as low fibre content does not always have strong association with low residual flexural strengths. The fibre content testing may potentially be replaced with the adoption of automatic batching. It is more important to ensure the steel fibres are well distributed within the concrete mix.

3.3.2 *Water penetration test target*

Water penetration testing to BS EN 12390-8 was carried out during concrete mix trials/pre-production (3 tests per mix design) and during production (3 tests per month). The Water Penetration criteria was set to 10 mm max. at 28 days testing in the project specification. Although pre-production trials demonstrated the mix achieved the strict limit of 10 mm, it is known to be difficult to measure the penetration accurately with reasonable repeatability and exceedances of the penetration limits are to be expected. It was found that the high water penetration values were confined to local areas on the sample surface which was not consistent with lower water penetration over the rest of the sample. This area of higher water penetration is likely due to poorer surface preparation and compaction around aggregate particles on the surface of the sample as illustrated in Figure 8. Water penetration testing is not specified in project requirement or referenced documents, however, has been typically introduced due to previous precedence in Victoria on recent major projects. In the authors' opinion, the requirement for water penetration testing during production should be assessed for each project by the Durability Engineer, as there are typically other forms of durability/quality testing during the trial mix stage which may produce more repeatable/reliable results.

Figure 6. High water penetration result impacted by sample preparation and presence of aggregate.

3.4 *Standardised reinforcement cage*

Steel bar reinforcement cages are generally tailored for each individual segment. The cage construction is both labour intensive and time consuming. One way to improve fabrication efficiency is to use a standardised steel reinforcement cage for segments with similar geometry.

One of the main obstacles to standardising reinforcement cages is the maximum concrete cover requirement from AS 5100.5. The code requires reinforcement provided for structural reasons to be located within 80 mm of the face for crack control. Figure 7 shows the developed layout (intrados) for Segment 1 (S1) and Segment 7 (S7). The two segments are identical except for the width due to ring taper. The difference in width is less than 30mm on one side and 17mm on the other side. Since the design cover for NEL segments is 60mm, if the reinforcement cage for S7 is to be used for S1, the theoretical cover for S1 is 75mm. The decision was made not to standardise the cage for S1 and S7 due to the concern on maximum allowable cover exceedance with construction tolerances.

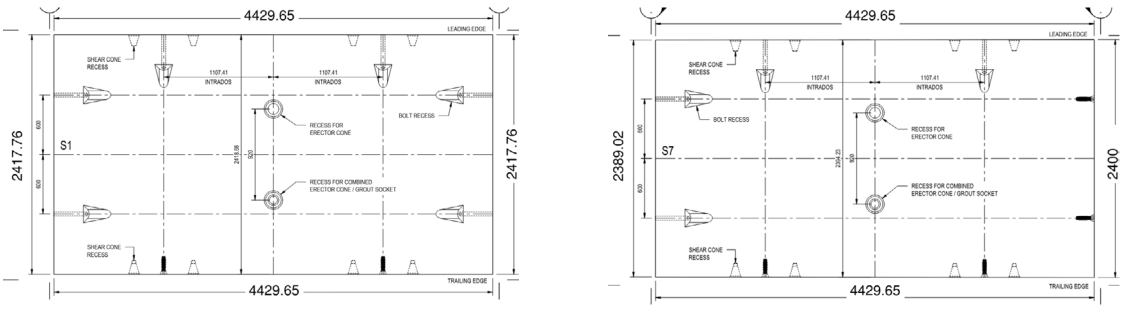

Figure 7. Segment developed layout (Intrados) for S1 (left) and S7 (right).

From a structural perspective, segments are primarily compression members and the edges of the segments are not subject to high bending moments which induce cracking. Instead of adopting a fixed value for maximum cover, it might be more appropriate to determine required cover based on strength and crack width calculations. Another consideration is the location of peak bursting stress for joint design. The bursting reinforcement is most effective when installed before or at the peak bursting stress depth from the joint face which is typically about 0.1 to 0.5 * segment thickness (d) as shown in Figure 8.

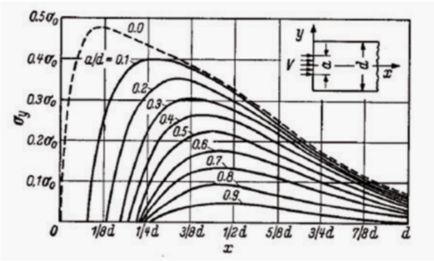

Figure 8. Tensile stress distribution at segment joints (Leonhardt,1964).

The authors' view is that standardising reinforcement cages for multiple segments is feasible as long as the appropriate analyses are undertaken to ensure adequate structural performance.

4 SEGMENTAL LINING INSTALLATION

4.1 *Ovalisation*

Deformations of the lining system are assumed to occur from two main sources: ring build deformations (including all build tolerances) and additional deformations caused by all permanent, construction and accidental loading conditions. The former is typically set to be within 0.5% of the theoretical design diameter of the ring measured on completion of ring build and grouting. The latter is based on design assumptions and calculations. A combination of these two sources of deformation results in a total maximum ring deformation/distortion for radial joint design and spaceproofing purposes. The total ring ovalisation shall not exceed 1% of the theoretical ring design diameter per the BTSS.

The current practice is to verify the ring build deformation using wriggle survey. The wriggle survey of segmental lining is typically carried out after the TBM back-up gantries have cleared the area (a minimum distance of 100 m behind the cutter head). At this time, the annulus grout has already hardened, and the segmental lining is subject to external loads from the ground and potentially via groundwater recovery. As a result, in addition to the ring build deformation, the measured ring ovalisation also includes the induced deformation from external loading, either partial or in their entirety.

To measure the ring build deformation only, the measurement should be taken when the rings are still within the TBM shield - which cannot be achieved in practice to the required accuracy. The authors' opinion is that applying the 0.5% ovalisation criteria to the wriggle survey data is conservative and will raise non-conformances which are not necessarily defects. Potentially adopting an intermediate ovalisation criteria through the approved Design Documentation would be beneficial during the construction phase. Segmental lining design for NEL adopted an ovalisation up to 0.79% for wriggle survey validation through careful considerations of ground conditions, groundwater levels and gasket performances due to joint opening.

4.2 *Segment joint steps and lips*

The out-of-tolerance step and lips for the Southbound TBM tunnel from Ring 1 to Ring 650 are plotted in Figure 9. Whilst the data shows general improvement of ring-build accuracy with time, a number of segment joints still have steps and lips in the 5-15 mm range, exceeding the BTSS requirement of 5 mm.

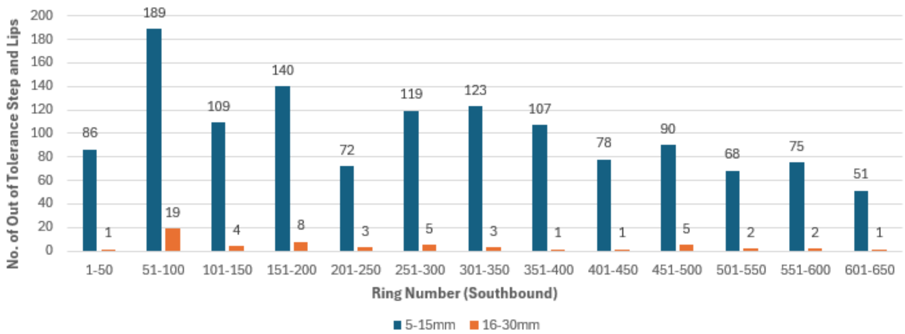

Figure 9. Example of out-of-tolerance segment joint steps and lips for Southbound TBM tunnel.

Segment steps and lips impact the as-built gasket offset which is one of the key parameters for determining gasket watertightness capacity. The gasket design for NEL requires the gasket to maintain watertightness at a test pressure of 8 bar at 6.5 mm joint opening gap with a 10 mm offset. The adopted product, Datwyler M80103 "West Gate", has the capacity to resist 8 bar pressure at 6.5 mm opening with a 15 mm offset. Therefore, segment joints with a step or lip up to 15 mm are considered to have low risk of leakage. For segment joints with a step and lip of 16-30 mm, location specific assessments were carried out considering gasket gap and groundwater level at the particular ring build location, and feedback was sought from the manufacturer.

The authors' view is that applying the 5 mm step and lip tolerance is conservative and raises non-conformances which are not necessarily defects. The step and lip criteria should be based on the specific gasket performance for the required design water pressure, and a more refined criteria through the approved Design Documentation would be beneficial during the construction phase.

5 CONCLUSION

This paper presents valuable construction and test data for NEL segmental lining. It critiques certain unreasonable design and impractical construction requirements for large diameter tunnels and suggests alternative targets. Additionally, the paper addresses recurring NCRs and CRFIs encountered during construction and offers recommendations for design improvements.

6 ACKNOWLEDGEMENTS

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