Segmental linings: a vision for the future

In the Oct/Nov issue of Tunneling Journal North America[1] the authors, Anthony Harding and Malcolm Chappell described the current state of the art in segmental linings. Following this, they explore some of the areas they think segmental linings are likely to develop over the next decade.

WHILE TUNNEL LININGS have been getting bigger (see box), the thickness of linings has been going in the opposite direction in an effort to save cost and excavated volumes. The authors have seen contractors consider a lining thickness of 240mm for a 6m Metro tunnel, but settle on slightly higher thicknesses having examined risks associated with fragility of such thin linings, particularly the imposed loads and deformations at cross passage openings. It therefore appears likely that we are approaching the practical lower limit for lining thickness in many parts of the world.

The largest rings still tend to use traditional rectangular segment designs. However, at smaller diameters rectangular segments are increasingly being replaced with trapezoidal and parallelogram shapes (often called the universal ring). These rings typically build more quickly, more easily, and more accurately than their straight sided counterparts. It is likely that they will continue to be used at ever higher diameters until they are the geometry of choice except where particular project requirements dictate otherwise.

However, the geometry that warrants real development over the next decade is the hexagonal lining. Hexagonal linings offer significant productivity benefits over the traditional tapered ring, as the TBM can thrust from half of the ring while the other half is being erected (see Figure 1). In their current form they suffer from gaps that open due to imperfect ring plane (see Figure 2). These gaps tend to concentrate the hoop loads in just one half of the ring unless the gap is grouted with a high strength mortar. The gaps can also pose problems with waterproofing gaskets. For this reason their use has been confined to:

- rock tunnels where water ingress and ground loads are not an issue
- projects in Japan where high tolerance moulds and bespoke steel connectors have been employed to limit loss of plane and ensure a good fit

However, if a simple and cost-effective method for early identification and correction of ring plane can be identified then it is possible that these linings could become an attractive alternative to normal tapered rings.

An additional benefit of hexagonal segments is that it is possible to create openings by simply removing a segment or pattern of segments in a way that allows the load transfer through the remaining lining. While this would require additional reinforcement in the segments around the opening, it could eliminate the requirement for internal propping.

Allowance for internal structures
As more and more tunnels are constructed with internal structures, particularly where intermediate decks are required, cost effective solutions for the construction of the internal structures will be required. Such solutions will need to:

- connect to the lining in a cost effective and buildable way
- accommodate all the movements that might occur to the lining over its design life (including seismic)
Are tunnel linings getting bigger?

It seems that barely a few years pass before the latest world record TBM is surpassed by another tunnel of even larger diameter. This has been driven by a combination of tunnel function and constrained urban environments. Where corridors are narrow (for example due to the presence of tall buildings either side of a street), there may not be enough room for a twin bore tunnel. This problem becomes even more apparent at the portals, where significant excavated space outside the TBM perimeter is required. So what do you do if you don’t have enough width? One option is to stack the roadways within a single bore as illustrated in Figure 3, to obtain a lower overall width.

This has been successfully implemented in a number of tunnels, including the SMART tunnel in Kuala Lumpur and the Socatop Tunnel in Paris. A three lane tunnel with full height traffic lanes would require a world record size TBM, as was envisaged for the Orlovski project in St Petersburg.

Such solutions also offer benefits in eliminating cross passages – as communication between roadways can be provided with internal structures, and equipment and ventilation spaces provided to either side of the roadway. Removing the requirement to hand mine cross passages may be a significant benefit.

Materials
The predominant material in segmental linings is concrete that uses Ordinary Portland Cement (OPC) as a binder, and is reinforced either with steel or steel fibres. However, the author’s view is that there will be an increasing trend towards lower carbon, non-ferrous linings.

One way that carbon footprints will be reduced is by the replacement of OPC with geopolymer, a product that uses slag and fly ash in place of cement, activated by admixtures to produce comparable strength and strength gain rates to conventional OPC. Wimpenney and Chappell\textsuperscript{[2]} have presented research into the use of fibre reinforced geopolymer concrete for tunnel segments that demonstrates that geopolymer can achieve equivalent or better structural, durability and fire performance than traditional OPC. This technology is sufficiently mature to be adopted on a tunnel project. Critically, their research showed that the CO\textsubscript{2} required to produce and deliver the segments would be 70\% less than the OPC equivalents.

The major barrier to the widespread uptake of geopolymer has been that high volumes of concrete are required to make the cost of setting up a supply chain and manufacturing facilities economically viable. However, a typical metro tunnel contains at least 1,000m\textsuperscript{3} of precast concrete per route kilometre in the tunnel lining alone, and would easily provide sufficient concrete volume to make for a viable the business case for geopolymer. Indeed, geopolymer binder could even be cheaper, particularly if the geopolymer was to be used for other concrete on the project.

As well as material cost, geopolymer can also save money in the manufacturing plant:

- geopolymer requires almost no curing, eliminating the requirement for steam curing
- geopolymer is less vulnerable to early thermal cracking
- improved fire performance may save on micro-synthetic polypropylene fibres

These cost savings will be of interest to contractors while the reduced carbon footprint will be a concern to all in the industry and a major selling point to clients. Therefore as soon as a trial project has successfully demonstrated the effectiveness of this technology, it is likely that there will be a proliferation of projects that use geopolymer concrete in place of OPC.

Fibres
As well as changing the concrete binder, the authors also see macro-synthetic fibres becoming a frequently employed alternative to steel fibres. There is currently much debate in the industry as to whether steel fibres or macro-synthetic fibres are superior for the reinforcement of concrete segments. Both have limitations when compared to
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The single bore option does reduce schedule flexibility somewhat but this can usually be managed. Therefore where space is tight we can expect more mega-TBMs.

Will conventional tunnels get bigger?

While the mega-projects grab the headlines, the workhorses of the tunnelling industry are much smaller tunnels: metro tunnels at around 6m, cable tunnels at 2-4m, and water tunnels varying from the very smallest tunnels up to diameters over 10m. One might think that this blend of sizes might remain. However, even for normal tunnels there may be upward pressure on diameter. In metro projects the solutions developed for Barcelona Line 9 (see Figure 4), which place both tracks on separate decks within the same tunnel, offer a number of benefits outlined in Table 1. The impact of these benefits will vary from project to project, but it is likely that this kind of scheme will be the best solution for some projects.

There may be other circumstances where we can add genuine value to projects by making space for more infrastructure inside the tunnel. This will also put upward pressure on the average size of segmental linings.

Plain concrete???

Another potential area of development is the use of plain, unreinforced concrete. This may at first appear to be a retrograde step back to the earliest segmental linings, many of which were not reinforced at all[3]. However, the problem with plain concrete segments was that they proved very prone to damage during handling, even at low aspect ratios (ratio of circumferential length to thickness). In recent years aspect ratios have been increasing in order to have fewer segments in the ring, with the consequent cost and schedule benefits. So it would appear that modern requirements make plain concrete even more problematic. However there are two important recent developments that may put plain concrete back in the frame.

Firstly, increased concrete strengths and qualities mean that in many tunnels the reinforcement is not required for the tunnel in its constructed state. The hoop force in many tunnels provides sufficient resistance for the expected bending moments.

Secondly, handling systems that limit damage have become widespread, primarily to limit damage to steel fibre reinforced segments. The success of such systems is that they ensure that the segments are not cracked by the handling activities. Given that the fibres only provide additional strength after the formation of the crack, it could be argued that the systems could also limit damage to plain concrete segments even at high aspect ratios.

The key differences between fibre reinforced and plain concrete are:

- Fibre reinforced concrete provides toughness against impacts that plain concrete does not.
- In the event of a flexural failure the fibres will hold the segment together and provide residual resistance. Plain concrete segments could break into two or more pieces.

Where these obstacles can be overcome (and ground loads allow) plain concrete linings may become more common.

Connecting

As well as reducing or even eliminating steel from the main body of the segments, the
authors also expect that steel bolts will become less and less common. Push-fit plastic dowels have already replaced steel bolts on the circumferential joint in many parts of the world, and there are projects where guiding rods have been used in place of steel bolts on the longitudinal joint. Bolts are often included in designs simply because they have always been used, without regard for whether they are actually required[4]. However, resistance to the removal of bolts will continue to be eroded as more projects demonstrate that bolts are not required in normal circumstances.

Where tension across the joint must be resisted bolts could continue to be required. However, installing bolts can add time to the erection process and providing long term protection against corrosion is difficult. The authors have been working with one supplier to develop a push-fit plastic alternative to bolts in order to provide alternatives for some current projects, and have some promising ideas. Other suppliers are also looking to develop systems. Therefore in ten years’ time it appears likely that there will be no need to use ferrous elements of any kind to connect the segments.

**Grouting and sealing**

The recent and welcome adoption of cast-in gaskets is likely to turn into widespread usage in the next ten years. While it may be difficult to see any big developments in the seals incorporated into the segments, the first line of defence is usually the grouting. Tail shield grouting is very widely adopted, but still needs very careful control to ensure effective filling of the annulus. Poor filling can easily occur and requires significant secondary grouting to mitigate – if detected at all. Even where tail shield grouting operation is good some check grouting is required to verify the continued performance. Check and secondary grouting activities require additional crews handling highly alkaline materials, and can often slow progress of the TBM.

Therefore if an alternative can be found that provides an assured filling of the void (such as a low strength expandable material cast into the outside of the segments, for example), then these activities and the associated risks of material handling could be eliminated. A void filling material that is expanded could also be useful in squeezing ground if the material could absorb inward movements without overloading the lining.

**Automation**

The drive to improve both productivity and tunnel safety must be maintained if we are to push the industry forward. The gold standard for safety is to remove operatives from the work area. Meanwhile the quality of segmental linings and TBM performance is subject to quality of workmanship. Automation of the tunnelling operation has the potential to remove operatives from the tunnel, while maintaining or improving quality and productivity.

The items required to fully automate the tunnelling process are listed in Table 2. It is interesting to note that the only technology that has not been implemented successfully is the offloading of TBM consumables, and even this appears straightforward when compared to systems employed in other industries. Automation requires a lot of up-front investment, but saves in the cost of operatives, so the cost-benefit is likely to be most apparent in long tunnels in locations where wages are high. However, the system must have a high degree of reliability. Downtime will increase if the operatives required to rectify the problem are not already on site, so the incidence of failures must be minimised if an automated system is to achieve performance that is as good as or better than current practice.

In addition to the tunnel, there are also potential benefits to automating other parts of the segment manufacture and supply process. Automation at pit top could easily tie in with the automatic trains operating in the tunnel. Meanwhile there are many aspects of the manufacturing plant that can be automated such as reinforcement welding, automatic batching, segment turning, marking, and cranelage. In this area automation is already developing in a piecemeal way as automation of various aspects becomes cost-effective, and this process is likely to continue.

**Quality control**

The automation of segment manufacture, transport and erection can also bring benefits to quality control/quality assurance. In normal practice each segment is equipped with a unique identifier, often simply a number sprayed onto a segment. This number is usually manually entered into a database, and then tied to data such as date cast, batch number, etc. However with an automated system this information could be automatically entered. A bar code could be affixed to the segment immediately upon demoulding. Alternatively, a barcode or other binary system could be cast into the segment.

If all handling steps could record the specific item that they were handling then a database could be created which linked records of all inspection and test steps. If such steps were recorded electronically in wireless devices (such as tablets) then paper entry could be almost eliminated and fail safes used that prevent unchecked segments proceeding to the next stage. Much of this technology already exists and has been applied to a few projects. However, tying the quality control system into an automated segment delivery and erection system could allow the full history of the segment to be recorded, from mould cleaning and preparation through to the time, location, and orientation of placement. This could free up time for the actual quality control activities that require human inspection, improving quality and freeing up staff for more productive activities.

**Intelligent segments**

Another area that may see significant changes over the coming years is intelligent segments: segments that monitor their activities. If all handling steps could record the specific item that they were handling then a database could be created which linked records of all inspection and test steps. If such steps were recorded electronically in wireless devices (such as tablets) then paper entry could be almost eliminated and fail safes used that prevent unchecked segments proceeding to the next stage. Much of this technology already exists and has been applied to a few projects. However, tying the quality control system into an automated segment delivery and erection system could allow the full history of the segment to be recorded, from mould cleaning and preparation through to the time, location, and orientation of placement. This could free up time for the actual quality control activities that require human inspection, improving quality and freeing up staff for more productive activities.

**Table 2: Components of tunnelling automation.**

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Excavation and advance</td>
<td>Either from a TBM operator’s cabin located at the surface or completely automated</td>
</tr>
<tr>
<td>Segment erection</td>
<td>Robotic controlled erecter arm. All segment connectors are pre-installed push fit type.</td>
</tr>
<tr>
<td>Segment identification</td>
<td>Bar code or more durable cast in system to uniquely identify each segment.</td>
</tr>
<tr>
<td>Grouting</td>
<td>Automated two component type grout fed by pipes on self-extending system.</td>
</tr>
<tr>
<td>TBM consumables supply</td>
<td>Either by robotic processing of cars delivered by automated train or by self-extending supply lines</td>
</tr>
<tr>
<td>Segment supply</td>
<td>Automated trains with robotically controlled transfer station to place segments on segment feeder.</td>
</tr>
<tr>
<td>Muck handling</td>
<td>Self-extending conveyors.</td>
</tr>
<tr>
<td>Survey for TBM guidance</td>
<td>Access for survey could be targeted mainly at routine maintenance.</td>
</tr>
<tr>
<td>Routine maintenance</td>
<td>Systems designed for lower levels of routine maintenance to limit personnel entry into tunnel</td>
</tr>
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**Automation requires a lot of up-front investment, but saves in the cost of operatives, so the cost-benefit is likely to be most apparent in long tunnels in locations where wages are high.**
been deployed successfully in an underground context. Paired with the development of other technologies such as distributed glass fibre monitoring, it is entirely feasible that at least some segments in the tunnel may be "intelligent," able to assess their performance against what they were designed for. Over the next decade, it is reasonable to assume that the cost of such systems will come down significantly. The potential benefits would be many, but one that the authors consider most significant is for critical infrastructure where creating downtime for inspection and maintenance is problematic, as the additional cost of the system could be many times less than the cost of just a single inspection.

Special circumstances
As well as more routine segment designs, there will continue to be "one-off" designs that fulfill a particular need. These have the potential to provide new technologies that push the industry in different directions. A few such circumstances are discussed below.

One-pass pressurised tunnels
The traditional approach to pressurised tunnels is to use the segmental lining to provide a primary lining that resists external ground and water loads during construction, and then to provide a secondary lining (of reinforced concrete, steel or other material) that provides the resistance to the tensile hoop forces generated by the internal pressure. If this can be achieved in a one-pass system, then the cost and schedule benefits are self-evident.

One solution is to thread post-tensioning cables through ducts specially cast into the segments, and then use the cables to compress the entire ring, as used in recent projects in both Switzerland and Japan. This solution has much merit insofar as it keeps the concrete and the gaskets between the segments in compression under tensile service loads, thereby enhancing durability (by minimising cracking) and minimising leakage. However, the cable is hard to assure for the 100 year design life often required, and it can be difficult to install. However, if a robust and cost-effective solution to these issues can be found, then it is likely that such solutions will proliferate.

A second solution is to design the lining to take the tension. This can be achieved by systems that span the longitudinal joint, such as bolts, or across the circumferential joint by dowels (Figure 5). A system has also been developed in Japan where a profiled circumferential joint interlocks with the segments in the adjacent ring, allowing the tension to be transferred between rings in the same manner as dowels.

Heat recovery
Another area that is likely to receive increased attention is to enhance return on the capital investment by utilising the tunnel for a secondary use. One such idea that has been proposed is to recover energy through a series of pipes cast into the tunnel lining. These are interconnected to form a continuous circuit through each ring of the lining which are then in turn fed into a main to circulate water to a surface heat exchanger. This can be used as a very effective heat sink or source of heat, providing a very economic source of energy for heating and cooling. The energy that is able to be captured can be quite staggering.

The authors are convinced that there
Conclusions
Precast concrete segmental tunnel linings may appear to be a mature technology that has changed little over the years. However, in their previous article[1] the authors showed how the technology has changed significantly over the last 20 years. In this article the authors have shown how there is plenty of scope for the technology to continue to develop over the next decade and beyond. In some areas, such as geopolymer concrete and non-ferrous linings, the authors have been able to pinpoint what the solutions might look like.

In others the authors have merely been able to highlight the problems and the benefits of solving them. However, if the authors were asked what the ideal lining might look like in ten years’ time they would offer the following:

• Geopolymer concrete lining with macro-synthetic fibre reinforcement.
• Non-ferrous connections on longitudinal and radial joints
• Hexagonal segments to allow continuous mining
• Ability to resist internal tension loading
• Intelligent segments monitor tunnel performance remotely, reducing the requirement for inspection and maintenance
• Void filling assured by an expanding material cast into the outside face of the segment that actuates on exit from the tail shield
• Database that allows the QC and as-built records of every segment on the job to be easily called up.

This may appear to be a mature technology that may appear to be a mature technology that could be other beneficial applications that could be applied if entrepreneurs/inventors were given the challenge.

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