FORMIDABLY FORMED: cutting edge segments

Moulds and segments are checked for dimesional accuracy using VMT's 3-D laser tracking system

Amanda Foley, takes a look at various factors in the design and production of pre-cast concrete segments and their impact on the overall cost and performance of the lining

AS TUNNELLING methods have developed, so have tunnel linings. Demands on the performance of modern precast concrete lining designs are more stringent than ever. Be it a large diameter mega-project with massive segments that need to be manufactured to extremely tight tolerances – or a smaller diameter utility tunnel where ring design and ease of segment installation are the key to successful production rates and quality ring build – a copious number of issues have to be taken into consideration when setting out to produce a durable tunnel lining that will minimise direct and indirect costs and handle all anticipated conditions throughout the design-life of the structure.

Factors such as static and dynamic ground loading, water control, internal or external corrosion, internal impact and/or fire in transport tunnels, concrete mix design (including curing times, and a balance between early age and long-term strength),

An increasing number of large-scale soft ground tunnelling projects involve facilites for the local production of precast linings. Here manufacturers Herrenknecht Formwork (left) and CBE (below) undertake a series of checks during the fabrication of segment moulds

type of reinforcement, design and fabrication of concrete moulds and set-up of casting facilities, the logistical interaction between the segment plant and the tunnel, as well as ever more demanding segment tolerance specifications and cost and time-schedule constraints, all need to be considered.

As we move forward into a new era of accountability for sustainable solutions, it is also important that clients are educated in and encouraged to encompass technologies and methods of precast production that are as environmentally responsible as possible.

Evolving designs

First introduced in the UK in the 1930's, and in North America in the 1960's, by the 1980's precast concrete segmental linings had become the preferred lining method for tunnels in soft ground worldwide. The primary reason for their widespread adoption was cost. Today precast concrete segments are roughly a quarter of the price of comparable cast iron segments. Of course, construction efficiency and superior long-term performance were also key factors and indeed have remained critical drivers in the development of precast linings to-date.

With the rapid evolution of TBMs in the 1970's and 1980's came the introduction of mechanical, and then vacuum, segment erectors, which removed previous constraints on segment weights and allowed the design of thicker one-pass precast concrete lining rings; eliminating the need for secondary cast in-situ linings. Segment widths could also be increased and, as a result, rings of around 1m in width soon became the industry standard.

Driven by the need to improve water-tightness, designers and contractors then began to experiment with trapezoidal keys and segments. "A disadvantage of early trapezoidal designs was building the ring," says Steve Skelhorn, Project Manager with McNally Construction, in Toronto. "Starting with a counter key segment, the build sequence required a 'key' segment to be built on either side of the key before installing the other two counter keys." This resulted in difficulty compressing all the gaskets and ensuring water tightness.

Designs advanced over the course of time, with tapered rings introduced in order to reduce the need for packing of joints when negotiating curves. This evolution culminated in the Universal tapered ring commonly employed on projects today. A number of different variations of the Universal ring are now in use, with differences in segment geometry often resulting from project specific demands or contractor preference.

"The optimum ring width is also the subject of much debate," says Skelhorn. "It follows that the wider each ring is, the more production can be achieved for a set number of rings in a shift." This can be an important factor, especially as tunnel lengths increase. Also, by increasing the width, the total number of rings required for the tunnel is reduced – a bonus if the joints and bolt pockets need to be patched prior to the tunnel going into operation.

The ring width also affects the design of the TBM and its backup system, particularly on smaller diameter tunnels. The length of the tail shield, width clearance through the trailing backup, as well as muck handling and grout quantities, all need to be considered. The segment width also directly affects the amount of taper required to navigate curves.

"As a rule of thumb, it is preferable to incorporate twice the amount of taper required to negotiate the tightest curve on the project to allow for steering adjustments," says Skelhorn. "But if you have too much taper it can create build problems within the tailshield and cause adjacent rings to move sideways as TBM thrust is imposed resulting in lipping between rings." One possible solution to this problem is to provide standard tapers with shorter rings for the curve.

Tolerating excellence

In an effort to eliminate such ring build issues designers are now specifying tighter and tighter tolerances for the dimensional accuracy of segments. But there is still some debate between contractors about what level of tolerance is actually required – with some stating a couple of millimetres is adequate and others wanting much tighter limits – and whether the level of required accuracy should vary depending upon tunnel diameter and depth.

Despite generally available recommendations – for example the British Tunnelling Society's Lining Design Guide and the German Tunnelling Committee's (DAUB) Recommendations for Concrete Lining of Tunnels) – there remains little guidance on how dimensional accuracy should be linked with the ongoing quality control on a project. One problem with this is that few design specifications state at what point in time and at what temperature segment tolerances should be reached, and therefore measured, during production.

Another issue in the past has been the reliability of results when undertaking such precise measurements. Traditionally, dimensional checks on moulds and segments were carried out using micrometers, which even when undertaken by a skilled technician did not provide uniform results. "This is what got people interested in 3-D measurement," explains Nod Clarke-Hackston, International Sales Manager for VMT. "Not just a linear measurement between two points, but 3-D measurement of the object's planes."

Initial attempts to achieve 3-D measurement in the late 1990's involved photogrammetry. But, as with micrometers, repeatability of the results was often not forthcoming. "Then we started to get into laser interferom-

etry," says Clarke-Hackston. "With photogrammetry we could measure about 180 points on a mould or a segment and from that we were getting a reasonable interpretation of the dimensional accuracy. But with a laser tracker system you're measuring many thousands of points on each plane. When using a good system this provides you with very fast and reliable method for determining accurate dimensional tolerances."

Quality production

Another key precast design consideration is the type of steel reinforcement used. Concrete segments have traditionally been reinforced using steel rebar cages. However, for the large majority of utility and transportation tunnels, the use of steel fibres offers the potential for deletion of this cage; greatly reducing manufacturing costs, improving durability and crack resistance, and mitigating the potential for damage during handling. With numerous tunnels built over the last 15 years having used steel fibres, there is now a vast quantity of project data now available on both the short- and long-term benefits of adopting steel fibres in precast linings, and popularity is growing.

Fibres also represent a significant reduction in the overall amount of steel used on a project. A traditional rebar reinforced lining segment will incorporate anywhere between 80kg to 120kg of steel rebar, whereas an equivalent steel fibre segment is likely to contain 30kg to 35kg of steel. This offers huge savings – not just in terms of cost, but also in terms of reduction in labour and the project's impact upon CO_2 emissions.

The location and logistics of segment manufacture is an important factor in overall project costs. When making the decision of whether or not to build project-specific facilities careful consideration is required to balance the additional capital expenditure against benefits obtained from the dedicated resources of an on-site plant. Project specific facilities can certainly offer the ability to better control quality during production and in many cases the cost can be offset against reduced transportation costs and the elimination of potential risk affecting timely segment delivery.

The wise contractor will usually seek the assistance of specialist engineers or plant manufacturers when establishing facilities. However, leading segment mould manufacturers possess a vast amount of project experience and their advice should also be sought at an early stage of the procurement process. In addition to moulds, most of the industry's leading tunnel lining manufacturers supply a wide range of equipment from fully automated carousels to concrete feeds and compaction devices.

Top: Segments are removed from their moulds using a CBE vacuum beam
Above: Casting underway for Mexico City's Emisor Oriente Sewer Project

Careful handling of segments also needs to be considered and the devices chosen – from demoulding to ring erection at the TBM – are likely to have a substantial effect upon the design of the concrete mix and the segment itself. In addition to any deficiencies in segment composition, poor handling is the greatest potential source of segment damage. As careful sequencing of segment delivery is usually practised, especially in curved drives, any loss of a segment due to damage can affect progress disproportionally due to delays in the tunnel advance. Correct handling is particularly important after casting when the segments are not yet at full strength. Various devices have been developed for steady lifting and turning of the segments, sometimes combining more than one function.

Perfect build

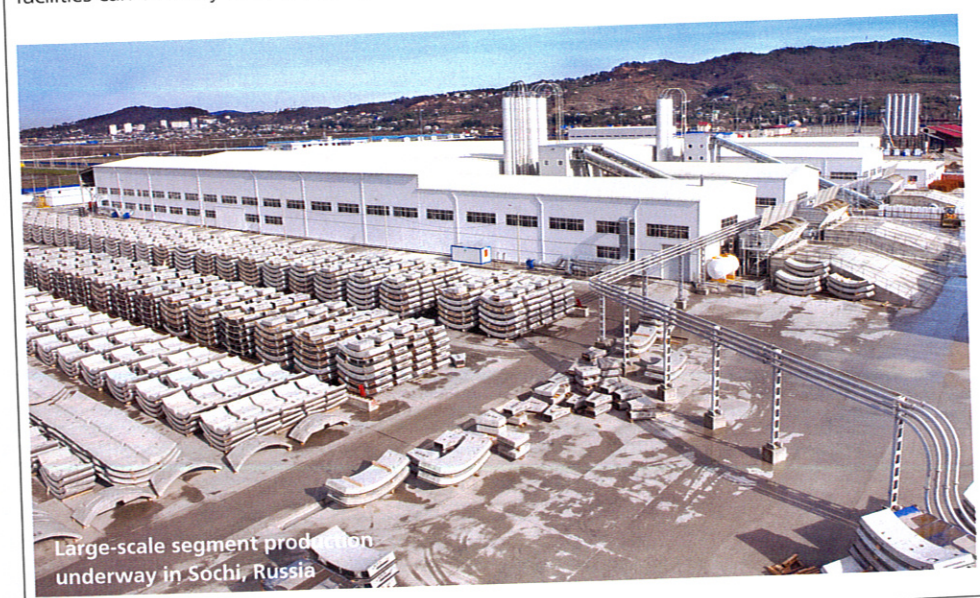
Calculating the correct installation sequence of segments to achieve planned curves in the alignment, or to correct drift, is a laborious process if carried out manually and often prone to error. VMT's Ring Management Program (RMP) is one of a number of tools available on the market to assist in this process. Using the RMP the parameters of influence are considered in each calculation, including TBM thrust ram extensions, tailskin clearance, specific ring design, joint positioning and the position of the TBM relative to the tunnel axis.

Conclusions

There are no hard and fast conclusions when it comes to optimum ring design, reinforcement and segment production techniques. Precast tunnel linings have prove their worth many times over, but trying to reach a balance between capital costs, environmental costs and logistical requirements can be a tricky business.

Current thinking is advancing at such a ra that developments in TBM design, concrete materials, casting techniques and automate build systems will inevitably progress even further in the next few years. Advances suc as laser guided erectors and polymer concr segments are also on the horizon.

However, in order to actually make best of this technology, it is important that clien are willing to accept advances and see the employed on their projects. In this regard, i key for owners, engineers, consultants and contractors to come together – as each gr will have varying agendas – and provide resolved guidance and recommendations where current ambiguity lies.



Large-scale segment production underway in Sochi, Russia