Structural form of tunnel linings

Regular contributor, Dr Benoît Jones, and his colleague Professor Wanda Lewis, from the Tunnelling and Underground Space MSc course at University of Warwick discuss the structural form, or shape, of tunnel linings

THE STRUCTURAL FORM of arches and their three dimensional equivalents, domes or vaults, has been investigated for centuries. In the 20th Century, famous architects, such as Spain's Antonio Gaudi, and engineers, such as Switzerland's Heinz Isler, used physical models to design the shape of arches and shell structures. Gaudi used hanging chains, with bags of sand to represent point loads, to obtain elegant spires for his churches, and Isler used inverted shapes of hanging chains or fabric, as well as inflated membrane models, to generate natural forms of shell/dome structures. In this way, the shape was generated by the loads themselves and this allowed the creation of virtually moment-less arches and shell structures that were perfectly adapted to the loads being applied. These physical models, and the computational models that have followed in recent years[1], allow optimal shapes to be generated through a 'form-finding' process[2].

Structural form of tunnel linings

The design challenge for tunnel linings is always to provide the required internal space envelope, which is usually non-circular, while providing a trade-off between structural efficiency, over-excavation and speed and ease of construction. For instance, in most transportation tunnels a circular or elliptical shape would be the most commonly used structural form, but this would result in a large amount of unused space, particularly in the invert. A flatter invert could be designed, reducing excavation volumes and hence cost. However, this will attract higher bending moments, and this may increase cost by requiring a thicker lining, a more expensive lining material, or more reinforcement

Current methods of designing tunnel linings may be described as 'classic structural optimisation'. The lining is dimensioned, calculations are then performed taking account of soil-structure interaction, and the lining's structural resistance is compared to the factored design loads. If the capacity of the lining is exceeded, it is usually due to excessive bending moments. Then, one of two possibilities are explored.

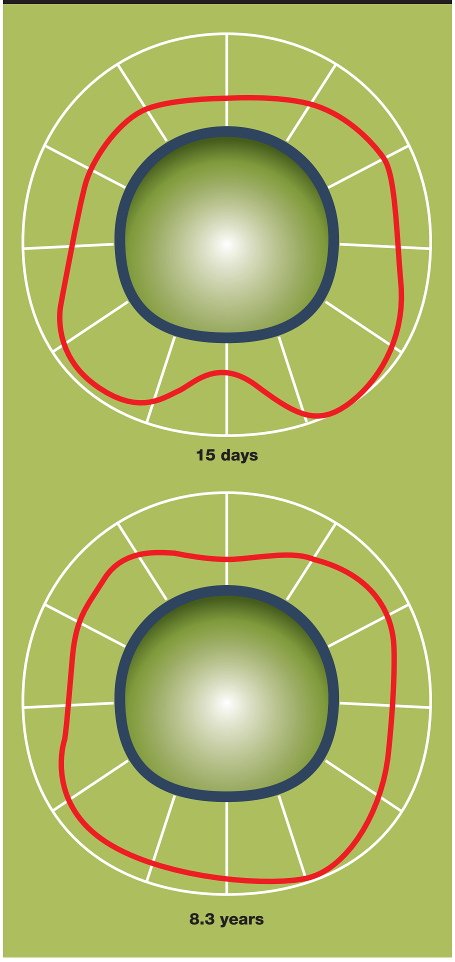
Firstly, either a higher strength material is used, the thickness of the lining is increased, or, for reinforced concrete linings, the amount of reinforcement is increased. If the stiffness of the lining is altered by increasing its thickness or using a different material, then the analysis must be repeated, since this will affect the soil-structure interaction. To make things worse, stiffer linings also attract higher bending moments.

Alternatively, the shape of the tunnel may be adjusted with the aim of reducing bending moments. Again, the analysis will need to be repeated to recalculate the loads for the new shape, taking account of soil-structure interaction. Changing the shape usually means making it 'rounder', which usually makes the tunnel more expensive in terms of excavation volume.

This process is performed in a haphazard manner, commonly making use of significant prior experience to adjust the shape by eye. Analyses involving full soil-structure interaction may be quite sophisticated, and time-consuming to run repeatedly. Therefore, a more rational understanding of how shape affects the forces and moments in tunnel linings would help guide this process.

This understanding may be acquired in two ways. Firstly, by measuring radial pressures acting on tunnel linings, or tangential (hoop) stresses and strains acting within them, and secondly, by attempting to adapt physical and computational form-finding methods to

Figure 1: Radial ground pressure measurements on the Heathrow Terminal 4 Concourse Tunnel lining



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the tunnel lining design problem to allow the loads to determine the optimal shape of the lining.

Stress measurements give us an inkling

Very little is known about the relative performance of underground structures as a function of their structural form. An example of how field measurements can improve our understanding is shown here in Figure 1.

These measurements were made using radial pressure cells installed between the ground and the sprayed concrete tunnel lining. Most of the measurements were taken during construction by the site supervision team, and latterly by Alun Thomas, David Watson and myself. The full interpretation of the data may be found in Jones (2007)[3]. The concourse tunnel shape may be described as a typical soft ground sprayed concrete lining shape, with an excavation area of 49.3m^2, a primary lining thickness of 350mm and the profile defined by 4 circular arc radii. The crown arc was semi-circular and extended to the axis with an internal radius of 3.62m. This was followed by a short bench arc of internal radius 6.32m, a higher curvature arc at the sides of the invert with internal radius 2.27m and finally the flattened invert arc with an internal radius of 5.37m.

The red lines on Figure 1 represent the radial pressures measured by the pressure cells. The white lines represent the hydrostatic full overburden pressure. Figure 1 shows that shortly after construction the shape resulted in a higher ground pressure at the areas of high curvature, where the structural response was stiffer, and lower ground pressures in the centre of the invert, where the curvature was much lower.

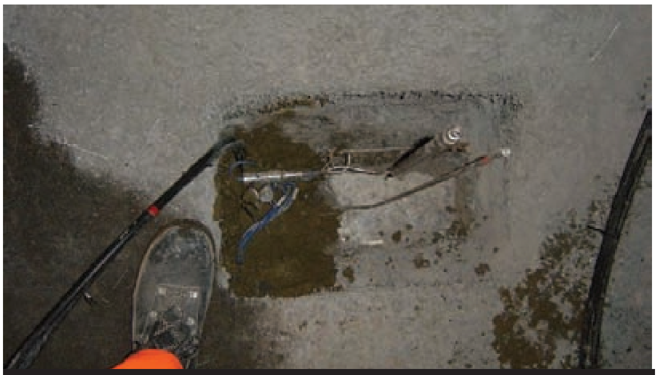
These pressures gradually evened out over several years due to long-term creep and consolidation behaviour of the clay and creep of the sprayed concrete, as is shown in the second diagram at 8.3 years after construction.

Taking the simplest example, we are well used to the idea that bending moments are generated when a uniform pressure is applied to a non-circular tunnel, but a uniform pressure applied to a circular tube results in zero bending moments. Ignoring all loads except the ground load, if the horizontal ground pressure were different to the vertical ground pressure, one would then expect the optimal shape to be elliptical.

However, this simple framework assumes that the ground pressure is a 'following load', like self-weight or snow loading on a building, and as usual what is really happening is a bit more complicated and interesting.

What appears to be shown by Figure 1 is that the shape affects the magnitude of the ground pressure by either providing stiff resistance at the sides of the invert or by deflecting away from the ground at the centre of the invert. This is because the ground, in this case London Clay, is a continuum that can support shear stresses and is not (except at failure) a 'following load'.

It is clear that structural form is crucial to the safe design of efficient, resilient and durable underground structures. But very little is known about the relative performance of underground structures as a function of their structural form and this needs to be addressed.



Radial and tangential pressure cells installed between the ground and the sprayed concrete tunnel lining

In the long-term, it was probably a combination of creep/relaxation and consolidation/swelling of the ground, and creep/relaxation of the sprayed concrete lining that resulted in the balancing out of ground pressures in Figure 1, and this was a gradual process that took several years.

Interestingly, the uneven ground pressures applied in the short term may have been less onerous for the lining than a more uniform pressure would have been, with less pressure applied to the vulnerable long, flat invert span and more pressure applied to its stronger short-span, high-curvature abutments.

Form-finding for tunnels

It is clear that structural form is crucial to the safe design of efficient, resilient and durable underground structures. However, very little is known about the relative performance of underground structures as a function of their structural form and this needs to be addressed.

The direct application of form-finding approaches such as those employed by Gaudi and Isler to tunnels may appear to be problematic, but at the University of Warwick we are planning to build physical models and to adapt modern computational form-finding methods to the tunnel problem. The project will test the hypothesis that optimal shapes of tunnel linings (optimal in terms of safety, cost, functionality, durability and aesthetics) are the ones that emerge from the form-finding process, in which the load shapes the structural form. It is hoped that form-finding may provide a short-cut to a near-optimal solution that will improve the efficiency and quality of tunnel design, and improve understanding of the sensitivity of tunnels to shape.

It is also hoped that obtaining more data from pressure cells and strain gauges used to monitor the ground pressures acting on tunnel linings and the structural response will result in improved understanding of how tunnels interact with the ground.

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