The secret life of a sprayed concrete tunnel

What is different about sprayed concrete? Sprayed concrete is different to in-situ concrete only in that it has evolved to meet particular requirements driven by structural performance and the placement method. Benoît Jones reports.

The life of a typical wet mix sprayed concrete could be described in the following way:

- As a 1m advance of the tunnel is excavated, the concrete is batched and transported to the pump.
- The concrete is pumped, sometimes 200m or more down a shaft and along a tunnel.
- At the end of the pipeline a flexible hose takes the concrete to the nozzle of the spraying robot where compressed air is introduced containing a fine mist of accelerator.
- The compressed air propels the concrete at high velocity against the excavated ground. The impact drives out the air so that the final air content is similar to that of normal concrete.
- The concrete needs to set immediately in order to adhere to itself and the ground and not to fall down in lumps from the crown of the tunnel. Layers 300–500mm thick can be sprayed overhead in one layer with the right set-up.
- When the next advance of the tunnel is excavated, the newly sprayed concrete ring will begin to take on load; the exposed ground supports itself by arching over from in front of the face back onto the sprayed concrete lining. As the tunnel advances still further, more and more load will come on to the lining in smaller and smaller increments. At the same time, the strength and stiffness of the sprayed concrete is increasing with age.
- In the medium- to long-term, the sprayed concrete will experience shrinkage, creep and thermal effects just like an in-situ concrete. Loads may change due to long-term pore pressure changes in the ground. A permanent sprayed concrete lining will need to be durable, with a specified design life of 120 or 150 years.

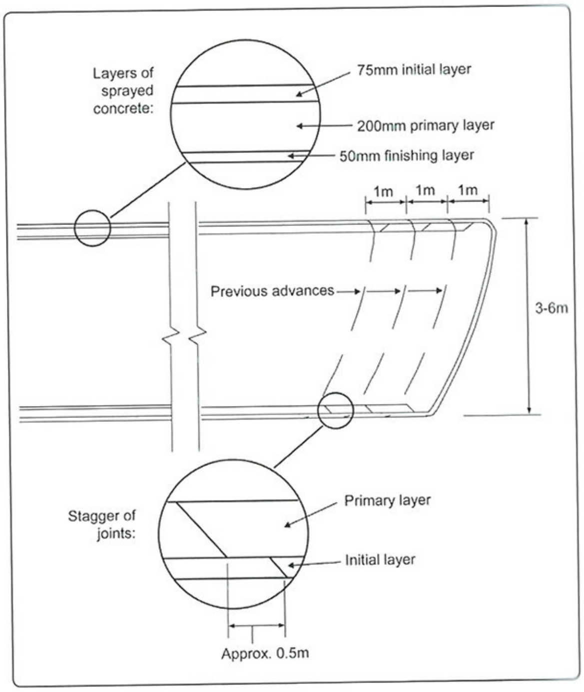

Figure 1: The LaserShell method.

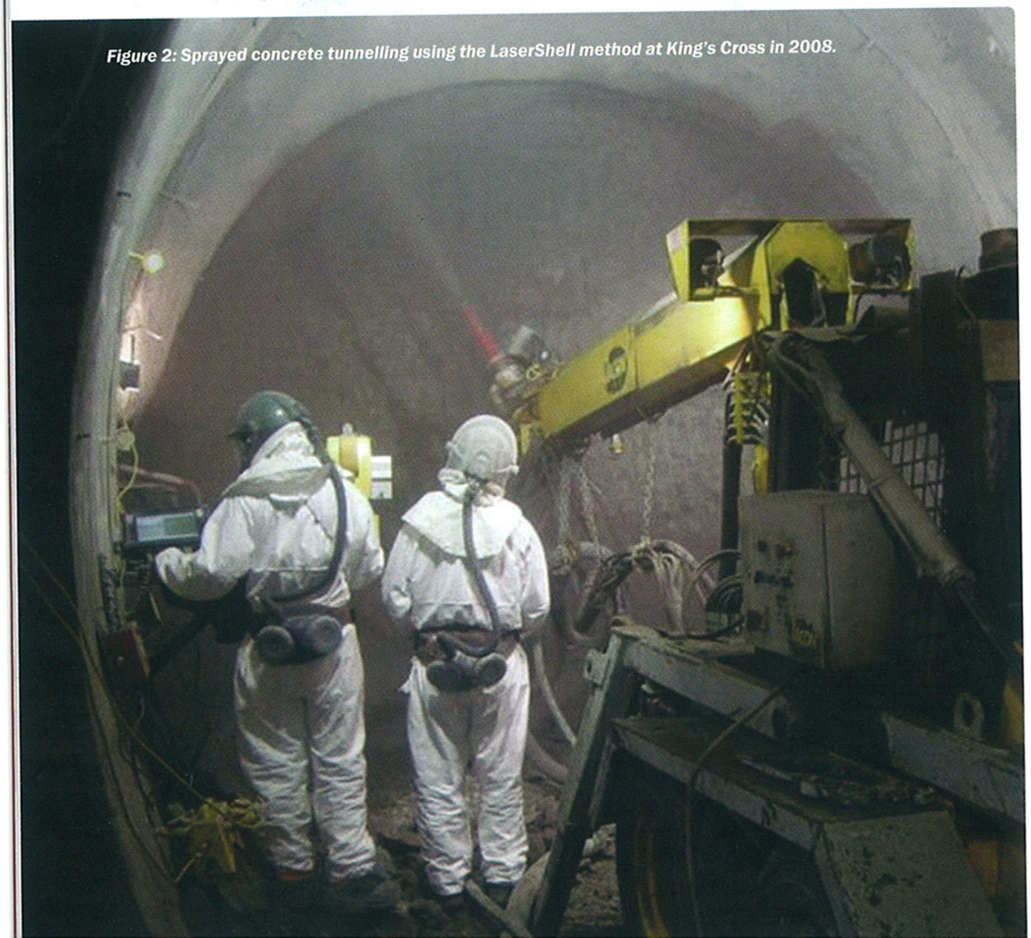

Figure 2: Sprayed concrete tunnelling using the LaserShell method at King's Cross in 2008.

To meet these requirements, sprayed concrete will contain more sand and less aggregate than a typical in-situ concrete and the aggregate will be limited to a maximum size of 6 or 8mm. The sprayed concrete will have a higher cement and total binder content, and will often contain retarder to extend pot life, superplasticiser to enhance workability and hydration efficiency, and accelerator to achieve a fast initial set and kick-start hydration. Table 1 shows a typical sprayed concrete mix.

The high fines content and small aggregate size aid pumpability and prevent segregation in the pipeline, as well as improving adhesion and reducing rebound. Rebound is the name given to the material that bounces back off the wall during spraying and consists mainly

Table 1 – Typical sprayed concrete mix proportions

Aggregate (usually <6–8mm to aid pumpability)	315kg/m³
Sand, or rock dust	1255kg/m³
Cement	450kg/m³
Silica fume	50kg/m³
Water	203kg/m³ (0.4 w/c)
Steel fibres	30kg/m³
Polypropylene fibres	1.5kg/m³
Superplasticiser	5.4 litres/m³
Retarder	1.1 litres/m³
Accelerator	25 litres/m³

of aggregate and steel fibres. In particular the addition of silica fume has been found to lubricate the pipeline, improve adhesion and reduce rebound and is now nearly always included in a sprayed concrete mix design.

The high cement content, the accelerator and the superplasticiser improve early-age strength gain. The sprayed concrete goes off very quickly, setting immediately, and within a few minutes it is impossible to indent with a thumbnail. These few minutes, when the sprayed concrete has set but has an almost spongy quality, are beneficial as they minimise rebound and enable a homogeneous lining to be built up with each nozzle pass blending seamlessly with the last.

Sprayed concrete lining design

Traditionally, lattice girders were used to control the shape and thickness of the lining, and steel fabric was used as reinforcement. However, rebound may be trapped in 'shadow zones' behind the bars, affecting the durability, permeability and strength of the lining. This can be prevented up to a point by careful spraying and minimising the use of reinforcement. Lattice girders and fabric need to be installed by the miners, which entails them entering the face of the tunnel and either being exposed to open ground, or to ground covered by a thin initial layer of young sprayed concrete, both of which can fall causing serious injury. Alternatively, laser or camera surveying of excavation profile and sprayed concrete thickness can avoid the need for lattice girders and adding steel fibres to the mix can remove the need for fabric to resist punching shear and light bending moments.

> **The monitoring also showed that tunnel linings are living, breathing structures that are not in a single constant equilibrium.**

A sprayed concrete tunnel lining is loaded at early age, both by its own weight and by ground load coming on to the lining. The magnitude of the ground load will in part be dependent on the stiffness of the sprayed concrete. A stiffer tunnel lining will attract more load. A tunnel lining that has a low stiffness at early age would induce the ground to arch further back onto the stiffer lining behind it and to mobilise arching in the ground in the circumferential direction as well. However, this would result in larger overall ground movements and potentially cause damage to existing infrastructure. There is also some evidence to suggest that in soft ground (ie, soil rather than rock) very little deformation is required to mobilise arching in the ground and allowing more ground deformation to occur may also result in higher long-term lining loads due to a loosening effect that reduces the ground's ability to support itself. In soft ground it has long been generally accepted as good practice to minimise ground movements to preserve the ground mass.

Sprayed concrete linings at Heathrow's Terminal 5

Taking all the aforementioned considerations into account, the best approach to sprayed concrete tunnelling in soft ground would be:

- Remove the need for lattice girders and fabric reinforcement by using laser surveying methods and steel fibre reinforcement, thereby improving safety and quality.
- Optimise the design by using a durable, permanent one-pass sprayed concrete lining, removing the need for a sprayed or in-situ concrete secondary lining.
- Minimise ground movements by installing a relatively stiff lining as early as possible in the process.
- Angle the face of the tunnel to provide a protective canopy over operatives near the face, removing the risk of injury due to falls of ground or fresh sprayed concrete.

This approach was the one developed by a

Table 2 – Sprayed concrete design strength development

Age of sprayed concrete lining	Sprayed concrete design strength (MPa)
0	0.0
0.1 hour	0.2
1 h	0.5
3 h	1.0
6 h	3.0
12 h	8.0
1 day	15.0
3 days	25.0
7 days	30.0
15 days	33.0
28 days	35.0

partnership of Morgan Est and the Austrian contractor Beton- und Monierbau, and it was given the name 'LaserShell'. A section through a tunnel constructed using the LaserShell method is shown in Figure 1 and the construction method is shown in action in Figure 2.

The first use of this tunnelling method was at the SWOT (Stormwater Outfall Tunnel) frontshunt tunnel at Heathrow Terminal 5 in 2003 (many other sprayed concrete tunnels were to follow at T5). The tunnel external diameter was 4.8m and the depth to tunnel axis was 12.28m. The water table was 1m below the surface. The advance rate was on average 3.3m/day. This first tunnel was subjected to careful analysis, both during the design phase by using sophisticated 3D numerical modelling, and during construction by extensive monitoring. This evaluation of the method was done by Mott MacDonald on behalf of the client, BAA.

The instrumentation used for monitoring the ground and lining behaviour during construction is shown in plan in Figure 3. Surface settlement was monitored using 97 levelling points arranged in transverse arrays, and subsurface ground movements were monitored using inclinometers and extensometers grouted into boreholes. Tunnel lining displacements were monitored by 3D optical surveying of prisms mounted inside the tunnel. Ground pressure on the tunnel lining was measured using radial pressure cells, and stresses in the sprayed concrete lining were measured using tangential pressure cells. The numerical model is shown in Figure 4.

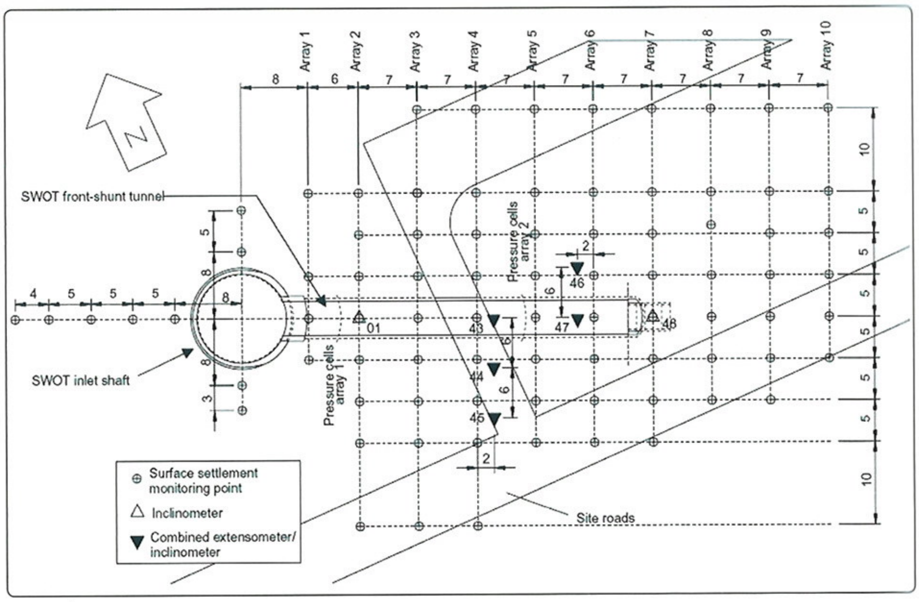

Figure 3: Location of instrumentation (dimensions in m).

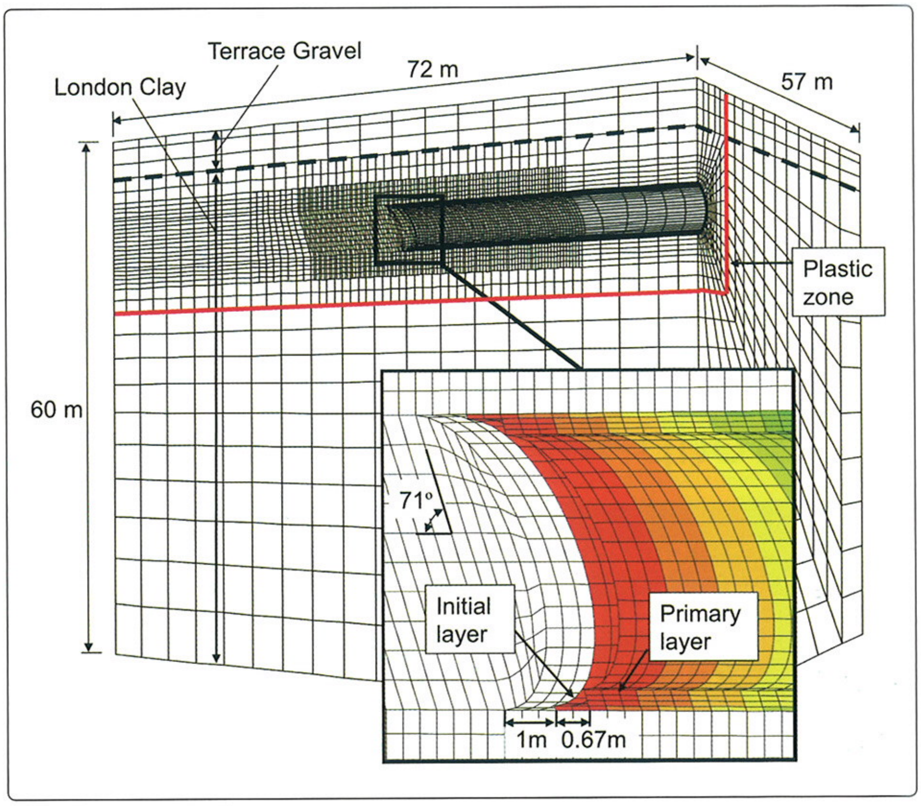

Figure 4: FLAC3D mesh used for numerical analysis of the SWOT frontshunt tunnel.

Laboratory tests were carried out on the sprayed concrete to determine its full stress–strain curve. As the sprayed concrete aged in the model, the compressive strength increased; selected values are shown in Table 2.

Initial tangent Young's modulus and strain at peak strength were also obtained from the laboratory test data.

In general, the model predicted the stresses and displacements of the ground and the sprayed concrete lining very well.

Concluding remarks

The LaserShell method represented a significant advance in the state of the art of tunnelling. The evaluation of the method at Heathrow's SWOT frontshunt tunnel using sophisticated numerical modelling and extensive monitoring during construction showed that the method was successful structurally and successful in terms of controlling ground deformations. Sprayed concrete may be used to provide permanent tunnel linings as durable as precast or in-situ concrete linings.

The monitoring also showed that tunnel linings are living, breathing structures that are not in a single constant equilibrium. Thermal effects, as well as time-dependent effects such as creep and shrinkage of the concrete and pore pressure changes in the ground, will cause changes in the soil–structure interaction, altering the way that load is shared between the ground and the tunnel lining. ●

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