Numerical modelling of sprayed concrete tunnel linings

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ABSTRACT: In addition to the complications normally associated with designing tunnels, the designers of sprayed concrete lined (SCL) tunnels have to contend with the lining's complex material behaviour and construction sequences. The modelling of the lining is critical to the assessment of the safety of the tunnel during and after construction. The paper will consider the material behaviour of sprayed concrete, the common simplifications in current design analyses and the merits of performing more sophisticated numerical modelling. The initial results from 3D numerical analyses will be compared with field data from the Heathrow Express project in London.

1 INTRODUCTION

Tunnel construction using sprayed concrete linings arguably offers a freedom in choice of geometry and a versatility, which is superior to that offered by traditional segmental linings. Hence it is particularly suitable for complex arrangements of tunnels, such as those found in metro stations. However, this additional freedom demands a higher degree of sophistication in design and construction supervision than would be required if traditional tunnelling methods were used to construct the same structures. One reason for this is that the sprayed concrete is subjected to loads from the moment it is sprayed on to the exposed ground. The need for extensive instrumentation and rigorous monitoring procedures has been well documented (eg: HSE 2000). This paper will explore whether the design methods which are commonly used for SCL tunnels are as sophisticated as they should be.

Specifically, having reviewed the material behaviour of sprayed concrete, the common design methods for SCL tunnels in soft ground will be outlined. Numerical modelling will be discussed in more detail. Finally some results from ongoing research into the influences on the stress and strain distribution in sprayed concrete tunnel linings will be presented.

This research, which is being conducted at the University of Southampton, involves the modelling two sets of case studies. Firstly, large-scale laboratory tests on sprayed concrete rings, which were performed as part of a recent EC-funded BRITE EURAM research programme. More details of this part of the work can be found in Thomas et al (2000) and (Norris & Powell 1999). The second case study is the platform tunnels at Heathrow Express (HEX) Terminal 4 station.

2 SPRAYED CONCRETE

2.1 *Introduction*

A detailed discussion of SCL tunnel construction can be found in the ICE design guide (ICE 1996). This section will focus on sprayed concrete as a material rather than the SCL tunnelling method. While the behaviour of sprayed concrete is essentially the same as conventionally placed concrete, the method of placement of sprayed concrete requires and imparts different properties.

2.2 *Material properties*

The composition of sprayed concrete is tailored so that: it can be conveyed to the nozzle and sprayed with a minimum of effort; it will adhere to the substrate, support its own weight and the ground loading as it develops; it attains the strength and durability requirements for its purpose in the medium to long-term. In general this leads to a mix (in the wet or dry process), which has more sand, a higher cement content, smaller sized aggregate and more additives compared with conventionally cast concrete (see Table 1). Also the water-cement ratio is relatively high. In general the consequences of this are: a faster growth in strength and other properties with age; a lower ultimate strength and more pronounced creep and shrinkage. Table 2 contains typical values of these properties. More detailed discussions of the composition of sprayed concrete can be found in Malmberg (1993) and Brooks (1999).

Table 1. Typical mix

Material / Property	High quality wet-mix shotcrete *	Cast insitu concrete (Neville 1995)
Grade	C40	C40
Water/cement ratio	0.43	0.40
Cement inc. PFA, etc	430 kg/m^3	375 kg/m^3
Accelerator	4 %	-
Plasticiser	1.6 %	1.5%
Stabiliser	0.7 %	-
Micro-silica	60 kg/m^3	-
Max aggregate size	10 mm	30 mm
Aggregate < 0.6 mm	30 - 55 %	32 %

* Data from the Heathrow Express project (Darby & Leggett 1997).

Table 2. Typical properties

	High quality sprayed concrete*	Cast insitu concrete (Neville 1995)
Uniaxial compressive strength after 1 day	20 MPa	6 MPa (est.)
Uniaxial compressive strength after 28 days	59 MPa	44 MPa
Elastic modulus after 28 days	34 GPa	31 GPa (est.)
Shrinkage after 100 days	0.1 – 0.12 %	0.03 – 0.08 %
Specific creep after 160 days	0.01 - 0.06 % / MPa	0.008 % / MPa
Density kg/m^3	2140 – 2235	2200 – 2600
Total porosity	15 – 20 %	15 – 19 %
Permeability m/s	10^{-12} to 10^{-14}	10^{-11} to 10^{-12}

* Data from the Heathrow Express project (Darby & Leggett 1997).

2.3 *Material behaviour*

Like ordinary concrete, up to about 30% of its uniaxial strength, sprayed concrete behaves as a linear elastic material. Beyond that point, the stress-strain behaviour becomes increasingly nonlinear due to microcracking (see Figure 1). Under uniaxial compression at an early age, the creep of sprayed concrete consists of a rapid short-term component, which tends to a finite value of creep strain increment, and long-term component, which leads to the increase in creep strains at a constant but low strain rate. The magnitude and rate of creep decrease with age and increase with stress, particularly above 0.5 f_{cu} (Aldrian 1991). Hence the elastic component of the strain in a sample of sprayed concrete may only represent a small fraction of the total strain (see Figure 2).

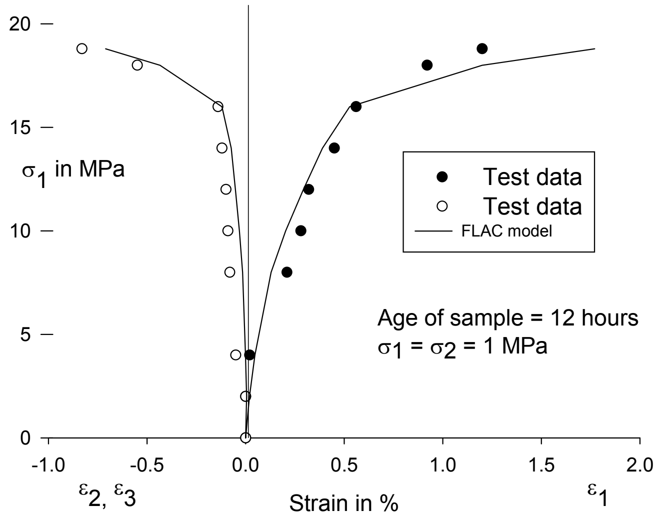

Figure 1. Behaviour of spray concrete under triaxial compression (Brite Euram 1997) with predictions using Kotsovos & Newman nonlinear elastic model in FLAC3D.

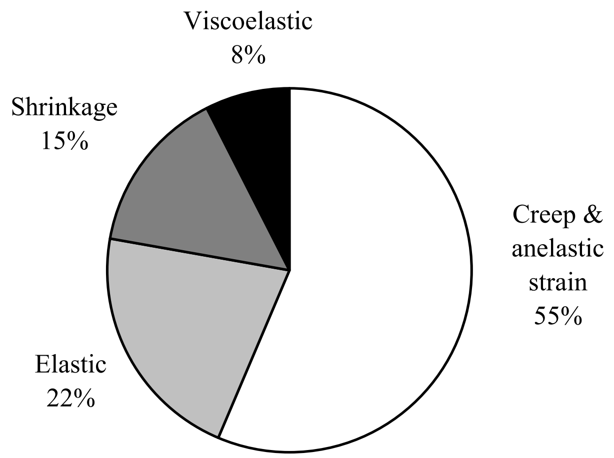

Figure 2. Composition of strains after 240 hours for SFRS under uniaxial compression (after Ding 1998)

2.4 *The influence of spraying*

The influence of the spraying process depends on whether the dry or wet mix is used, since increasingly more automated equipment is used with the wet mix and so the nozzleman has less influence. However, in both methods, there is evidence to suggest that it may be mildly anisotropic, with 10 to 25 % higher strengths in the plane perpendicular to the direction of spraying (eg: Huber 1991, Aldrian 1991). One possible explanation for this is that the sprayed concrete is less well compacted and dense at the interfaces between the layers (Aldrian 1991).

The addition of reinforcement (either in the form of mesh or fibres) leads to further anisotropy.

2.5 *The influence of construction sequence*

A sequential construction method is normally used for SCL tunnels, in which a top heading or side-gallery is driven ahead of the tunnel. Considering, the top heading and invert sequence, this suggests that the mode of action of the lining changes with time (from a cantilever / arch in the top-heading to a completed ring, mainly in compression). In any case, the lining, which is usually considered as a monolithic shell, actually consists of a series of sections. There may be a considerable difference in age between adjacent sections, which may lead to differential strains due to shrinkage.

2.6 *The influence of construction defects*

Traditionally sprayed concrete has been regarded as inferior in quality, compared to conventionally cast concrete, because of the lack of curing, poor workmanship at the numerous construction joints, the influence of spraying, "shadowing" around and intermittent bond to bar reinforcement and the variation in lining thickness and shape. Typically the standard deviation in compressive strengths at 28 days is 5 MPa for 25 MPa primary lining wet mix (Bonapace 1997), which is poor by normal concrete's standards. That said, the recent technological advances in spraying equipment and mix design are continuing to reduce the effect of these detrimental influences.

3 THE DESIGN OF SCL TUNNELS

3.1 *Design methods*

The context for following discussion is that of SCL tunnels in soft ground. It is recognized that the role of sprayed concrete linings is different in rock tunnels, where questions of block stability or large tectonic stresses predominate (Rabcewicz 1969).

Broadly speaking there are three categories of design methods – empirical, analytical and numerical. Since most empirical methods, such as the Q-system, have been developed for rock tunnels, analytical and numerical methods are generally used for the design of SCL tunnels. Analytical methods include continuum "closed-form solution" models (eg: Curtis & Muir Wood) and Panet's convergence-confinement method (CCM) (Watson 1997). Bedded Beam Models are rarely used these days, not least because of their limited ability to model the soil-structure interaction. The continuum analytical methods are relatively simple and provide information on stresses in the lining and its deformation. Some of them may be extended to include features such as plasticity in the ground or the timing of placement of the lining.

However, they share several fundamental limitations: they assume plane strain or axisymmetry and the solutions are almost invariably developed only for circular tunnels, constructed in full-face excavation in homogeneous ground.

The modelling of soil-structure interaction is limited yet this is fundamental to all tunnels. The closed form solutions in their basic forms make no allowance for stress redistribution ahead of the face. The CCM assumes that K_0 equals 1.0 and that the stress in the lining independently increases as a function of the ground's convergence until the lining stress matches the radial stress in the ground.

To overcome these limitations (and others), one must turn to numerical methods, such as the finite element and finite difference methods.

Table 3: Sources of errors in modelling

Aspect of the model	Example
Geometry	2D analyses instead of 3D
Construction method	"Wished in place" analyses
Constitutive modelling & parameter selection	Assuming linear elasticity for the lining
Theoretical basis of solution	Modelling discontinuous ground as a continuum
Interpretation	-
Human error	Errors in input data

3.2 *Numerical modelling of SCL tunnels*

Despite their advantages, numerical models are still merely approximations of reality. Table 3 lists the six main areas of simplifications and sources of errors in modelling (after Woods & Clayton 1993), together with examples from the design of SCL tunnels.

It seems reasonable to assume that, if one or other half of the ground-structure interaction problem is inadequately modelled, this will compromise the results from the analysis as a whole. Considerable effort has been expended in recent years in improving the modelling of the ground. Taking London Clay as an example, the spatial variation of material properties, the initial stress state, nonlinear elastic stress-strain behaviour, plasticity and anisotropy have been shown to be significant influences on the predictions of ground movements (eg: Lee & Rowe 1989, Gunn 1993, van der Berg 1999) and these features are routinely included in numerical models.

In contrast, relatively simple models are used for the sprayed concrete lining. The norm is to assume an homogeneous, isotropic, linear elastic constitutive model, albeit including some variation in elastic modulus with age. It is usually assumed that the lining has been constructed to the exact (nominal) geometry specified by the designer. However, as has been shown earlier, the behaviour of sprayed concrete and the properties of a sprayed concrete lining differ substantially from these assumptions.

3.3 *Modelling of the sprayed concrete lining*

Before reviewing current practice, it is worth noting that it is often the limitations of available computing power as much as deficiencies in knowledge, which have dictated the simplifying assumptions in numerical modelling.

3.3.1 *Constitutive models*

Linear elastic models are the most commonly used because of their simplicity and computational efficiency. The effects of ageing are incorporated by increasing the stiffness of the sprayed concrete with time. Numerous relationships have been proposed for predicting this (eg: Chang & Stille 1993 - see Figure 3). In a ground-structure interaction problem, the stiffer the elements are the more load they tend to attract, so it is unsurprising that incorporating the gradual growth in stiffness of the sprayed concrete into the model, results in considerable reductions in the predicted bending moments together with smaller increases in deformation and reductions in axial forces, compared to analyses using a constant (high) stiffness (Soliman et al. 1994).

The **Hypothetical Modulus of Elasticity** (HME) approach uses a reduced value of the elastic modulus to account for factors such as creep, shrinkage and the effect of stress redistribution ahead of the face in 2D analyses (Pottler 1985). This “short-cut” is widely used but the choice of HME values is usually based on engineering judgement and experience.

Nonlinear elastic models have often been used in numerical modelling of concrete structures but rarely in the modelling of SCL tunnels. A modified version of the Kotsovos and Newman tangent modulus model has been found to agree well with data from laboratory experiments on sprayed concrete (see Brite Euram 1997 & Figure 2).

A more common way of accounting for the nonlinear behaviour is to use strain-hardening **elastoplastic models** (eg: Meschke 1996, Hellmich et al. 1999, Hafez 1995). If limited yielding occurs, the additional deformation permits more stress redistribution, which leads to lower stresses in the lining as a whole. Compared with elastic analyses, the bending moments tend to be reduced more than the axial forces (Haugeneder et al. 1990).

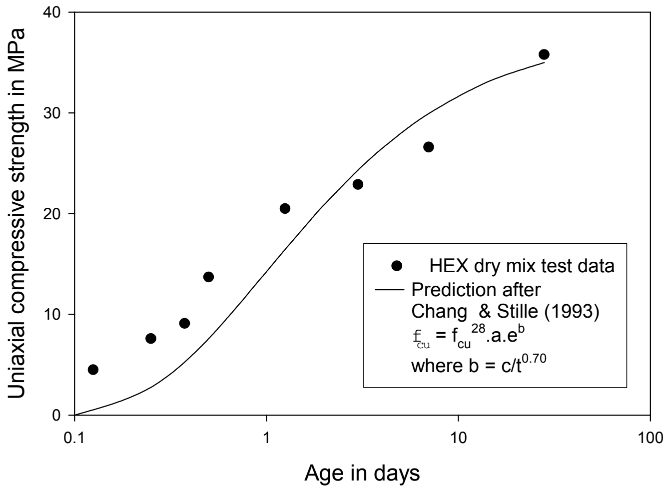

Figure 3: Strength gain of sprayed concrete, with data from Heathrow Express Project

Considering individual plasticity models, the Drucker-Prager model is often favoured because it is easier handle numerically since the yield surface has no corners. However, the shape of the yield surface of the Mohr Coulomb model agrees better with experimental data for concrete at low hydrostatic stresses (Chen 1982).

Creep is widely believed to be responsible for reducing stress concentrations and bending moments in linings (eg: Rabcewicz 1969, Golser et al. 1989, Rokahr & Zachow 1997) and many different creep models have been proposed for sprayed concrete (see Table 4). However, designers remain hesitant about including creep because of the uncertainty over its actual effects. In the case of the most recent SCL tunnel in the UK, an Hypothetical Modulus of Elasticity was used with an elastic-perfectly plastic model for the sprayed concrete in the structural design, while a viscoelastic model was used to estimate creep strains for the purposes of deformation monitoring trigger limits only (Watson et al. 1999).

Table 4: Creep models for sprayed concrete

Type	Example
Viscoelastic	Rokahr & Lux 1987, Yin 1996, Sercombe et al. 2000, Eisenstein et al. 1991
Viscoplastic	Meschke 1996, Hellmich et al. 1999
Power law	Probst 1999, Alkhiami 1995
Rate of Flow method	Golser et al. 1989, Aldrian 1991

Most of the models have clear strengths and limitations. Viscoelastic models cannot account for any inelastic strains. However, considering the behaviour of sprayed concrete, the generalised Kelvin or Burgers viscoelastic models appear to be the most suitable models, since they predict an initial immediate elastic response, followed by a viscous response which progresses at an ever decreasing rate, tending to an ultimate value or a constant strain rate in the long-term respectively.

Considering other models, in its basic form the commonly used viscoplastic model has a constant viscosity, which implies unlimited creep strains, progressing at a constant strain rate. Power law models are simple but they do not simulate the elastic behaviour of the lining. The Rate of Flow method attempts to account for all the major influences on stresses and strains, namely, time-dependent elasticity, nonlinear elasticity, creep, shrinkage and temperature changes. However, while it has been used to examine strain gauges data from tunnel linings and uniaxial compression tests in the laboratory, it has not been possible to apply it in 3D numerical models (Rathmair 1997).

It is difficult to generalize but typical results show that the inclusion of creep behaviour in the lining can lead to significant reductions in stress and bending moments (eg: 20 – 30 %, Golser 1999 & 30 to 60 %, Alkhiami 1995). However, this depends on the behaviour of the surrounding ground.

Shrinkage and heat from the rapid hydration of the sprayed concrete can lead to differential strains, which may cause cracking. This is of particular concern when the primary sprayed concrete lining forms part of the permanent lining. With the exception of the thermo-chemomechnical model (Sercombe et al. 2000) and the Rate of Flow method, current models ignore this aspect. The assumption that loading due to the ground is more important than shrinkage or temperature effects is not always valid (Hellmich et al. 1999).

The behaviour in **tension** should be considered where tensile stresses due to bending or shrinkage are expected to be important. Most current models assume a linear elastic behaviour in tension up to the tensile strength, followed by brittle failure. Post crack behaviour has been modelled as linear, bilinear or exponential softening (Lackner 1995) but the response in numerical models is strongly dependent on the mesh density (Meschke 1996). Although almost all sprayed concrete tunnel linings contain some sort of steel reinforcement, this is not normally included in numerical models. Reinforcement produces tension stiffening after the first crack occurs (Haugeneder et al. 1990, Chen 1982).

Construction defects, such as variations in thickness and the shape of the lining, are rarely considered in published reports of SCL designs. Yet sprayed concrete is known to be inherently more variable than ordinary concrete and construction defects have been highlighted as an important factor in SCL tunnel collapses (HSE 2000). In contrast, the effects of ovalisation of the lining and possible localised crushing at joints are often considered in the design of segmental linings.

3.3.2 *Behaviour of the lining*

A tunnel lining may behave in many different ways, depending on its material characteristics and the ground loading (Rokahr & Zachow 1997, Pottler 1990, Alkhiami 1995). For example, the additional deformation of a lining due to plasticity or creep causes additional deformation in the surrounding ground. This will only lead to the ground carrying more of the load if the ground can sustain it. Otherwise the load on the lining will increase. It is incorrect to assume that creep in a tunnel lining will automatically lead to a "relaxation" of stresses.

It is important to consider the behaviour of the lining as a whole and how this develops over time. High utilization factors during the early life of the lining may decrease with time due to the strength gain and creep (Rokahr & Zachow 1997, Golser et al. 1989). Evidence suggests that, so long as the stress does not exceed 70% of the ultimate strength, the spray concrete's long-term strength will not be adversely affected (Moussa 1993).

On a more optimistic note, one simplifying assumption, which can reasonably be made, is that the stress state in the lining is biaxial rather than triaxial. This permits simpler formulations of some constitutive models to be used (Meschke 1996). Also the behaviour of sprayed concrete during unloading can be overlooked, since most tunnel linings only experience loading. This is not a valid assumption in more complex construction sequences and at junctions.

4 NUMERICAL MODELLING OF A SINGLE TUNNEL HEADING

4.1 *Introduction & project background*

As part of the Heathrow Express (HEX) project in London more than 150,000 m^3 of tunnels and underground works were constructed using sprayed concrete linings. Extensive monitoring of the tunnels and the ground was performed, particularly when SCL tunnelling restarted after the collapse in 1994. This has yielded a detailed picture of the behaviour of shallow SCL tunnels in soft ground. Further information on the HEX project and the monitoring can be found in Powell et al. (1997) and van der Berg (1999).

The construction of one of the platform tunnels at HEX Terminal 4 station has been taken as a case study, with a view to examining the influence of the constitutive model for sprayed concrete on the predictions of lining stresses and displacements.

4.2 *Programme of analyses*

In order to achieve this, the numerical model of the platform tunnel will be run repeatedly, with different constitutive models for the tunnel lining and different advance lengths. The constitutive model for the ground will also be varied. However, for the first runs in this programme, a simple anisotropic linear elastic model has been used for the ground, in order to reduce the runtime for each analysis.

Table 5: Construction sequence for platform tunnels

Step	Numerical model	HEX
1	Top heading & bench	Top heading
2	Top heading & bench	Bench
3	2 sections of invert	Top heading
4		Bench
5		2 sections of the invert

All analyses will be performed using the FLAC3D finite difference program. A series of 2D and 3D analyses were performed to assess the effect mesh discretization and boundary positions, before the main programme of analyses was commenced. Each 3D model contains about 23000 zones and takes between 1.5 to 3.0 days to run, depending on the constitutive models used.

4.3 *Details of the model*

With Table 3 in mind, it has been attempted to create a numerical model, which is as close to the real case as is possible, given the limitations of computing power and the analysis programme. For example, the profile of the top heading, bench and invert excavation sequence has been replicated and the ring is closed within 5 advance lengths from the face. However, a 3-step construction cycle was used rather than the 5-step one, which was used on site (see Table 5). Figure 4 shows the mesh for the model. The ground is entirely London Clay, with the overlying 2 m of Terrace Gravels modelled by applying a surcharge load to the top of the mesh. The external diameter of the tunnel is 8.30 m.

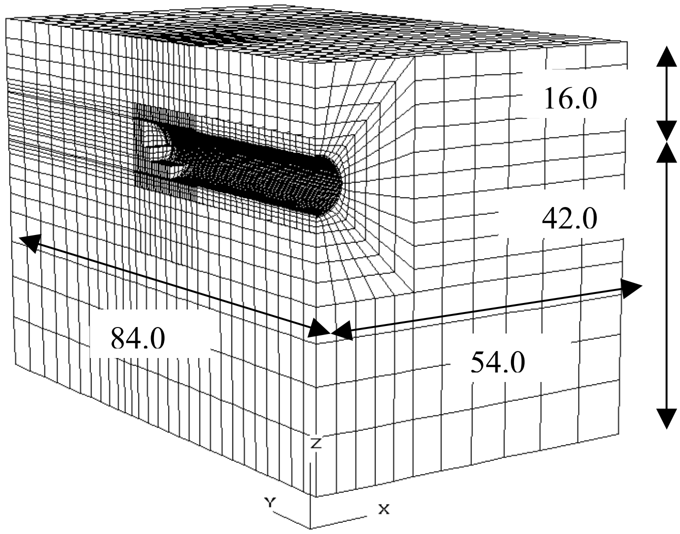

Figure 4: FLAC3D model for HEX platform tunnel

After the initial stresses have been established, the displacement is fixed on the boundaries - in all 3 directions at the base, in the longitudinal (Y) direction at both ends and laterally (X) on both sides. The tunnel is then advanced according to the sequence in Table 5.

The properties of geotechnical constitutive model are contained in Table 6, along with the details of the models for the sprayed concrete. A K_0 value of 1.50 has been used, which is consistent with site investigation data from HEX (Powell et al. 1997).

The base case uses an age dependent linear elastic model for the lining (ID code = Et) with an advance length of 1.5 m. The other advance lengths, which will be used, are 0.5 m and 3.0 m.

4.4 *Sprayed concrete lining*

The sprayed concrete used in the HEX primary linings was of a lower specification that the one quoted in Tables 1 & 2, with a specified 28 day strength of 25 MPa. Higher strengths were attained on site and these have been used in the numerical model (see Figure 3). The lining was 300 mm thick, reinforced with 2 layers of 8 mm steel mesh (150 mm c/c).

As far as possible, the parameters for the sprayed concrete were taken from HEX project records. However, since routine testing of sprayed concrete is limited to strength development and elastic modulus, parameters for other aspects of the behaviour had to be chosen after a review of published data.

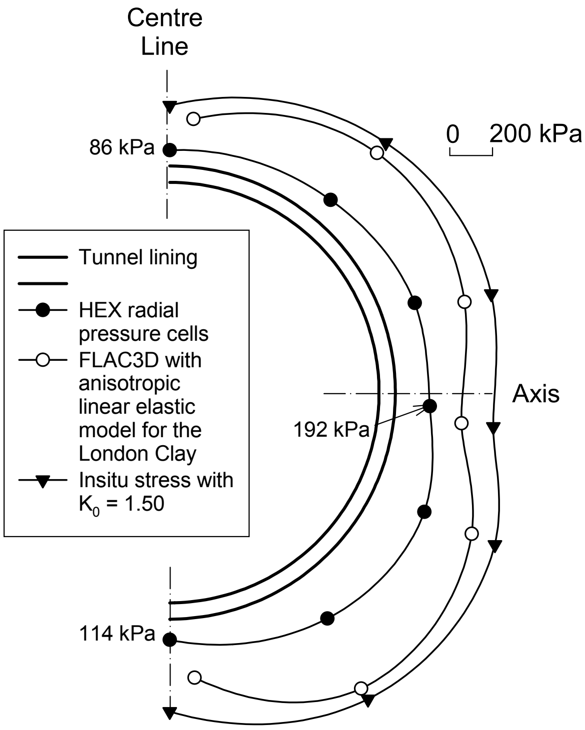

Figure 5: Radial stresses acting on tunnel lining

4.5 *Results*

As one would expect, the use of a linear elastic model for the ground underestimates the amount of stress redistribution in it. Figure 5 shows the radial stress in the ground acting on the lining. While these values are about 3 times greater than those recorded by the radial pressure cells at HEX (on average 75% of full overburden pressure), the pattern is essentially the same and therefore the results are presented here as an indication of the influence of constitutive model on the behaviour of the lining. A more complete report of this work, including analyses using an elastoplastic strain-hardening model for the ground, will be presented in a future paper (Thomas et al. 2001).

5 RESULTS & DISCUSSION

Although they relate mostly to the crown of the tunnel, the results presented below are typical of the behaviour in the rest of the ring.

Figure 6 shows the variation of axial force in crown of the lining with distance from the tunnel face. The constitutive model of the sprayed concrete is a major influence on this. Incorporating the nonlinearity of the stress-strain behaviour reduces the forces by about 40 %, compared to the age dependent linear elastic model.

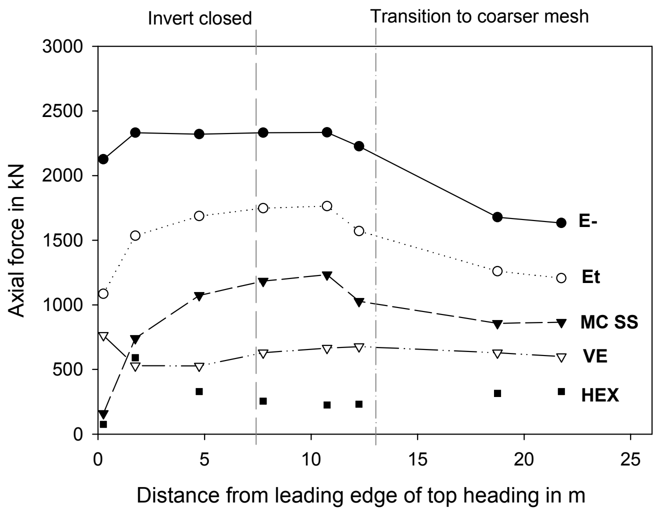

Figure 6: Axial forces in tunnel lining at crown

Table 6. Constitutive models for FLAC3D runs

ID	Description	Parameters
	London Clay	
-	Anisotropic linear elastic (undrained)	$E_v = 400*(50 + 8z)$; $E_h = 1.6*E_v$; $G_{vh} = 0.433*E_v$; $v_{hh} = 0.2$; $v_{vh} = 0.48$ (after van der Berg (1999) & Lee & Rowe (1989))
	Sprayed concrete	
E-	Elastic constant modulus	E = 25 GPa, ν = 0.2
Et	Elastic age-dependent modulus	E = 27 GPa after 28 days, ν = 0.2, according to Sezaki et al. (1992)
NLE	Non-linear elastic Et model	According to Kotsovos & Newman (Brite Euram 1997) with ν = 0.2 **(NOT RUN YET)**
MC SS	Et model with age-dependent plasticity	Strain hardening post-yield behaviour with strain at peak strength estimated from published data and strength using Chang's formula (Chang & Stille 1993)
VE	Et model with visco-elasticity	An ageing Kelvin model , with parameters from published data

The results from pressure cells in linings at HEX are significantly lower than the results of the numerical modelling, even if one allows for the excess loads in the model. Pressure cells are generally believed to underpredict the stresses (Golser et al. 1989, Rokahr & Lux).

Figure 7 shows that the bending moments are influenced by the SCL model to an even greater extent than axial forces. The magnitude of the moments raises the question of whether any reinforcement is required in the lining. "Shadowing" around reinforcement bars can lead to voids in the sprayed concrete, which adversely affect the impermeability of the lining.

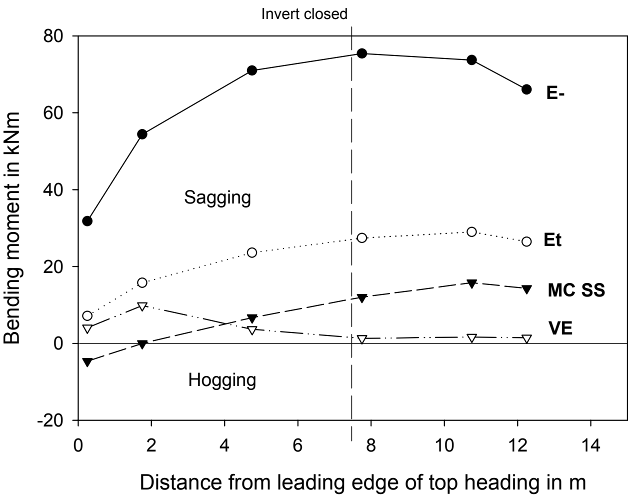

Figure 7: Bending moments in circumferential direction at crown

Figure 8 shows how the utilization factor, which is a measure of the factor of safety, varies through the lining. The utilization factor, α, is defined as the current deviatoric stress divided by the size of the yield surface, allowing for age and the beneficial effect of the hydrostatic stress. As suggested by other research (eg Golser et al. 1989, Rokahr & Zachow 1997), α decreases with increasing distance from the face to between 0.2 and 0.3 at about 2 or 3 diameters from the face. Given the high ground loading in these numerical analyses, one would expect the utilization values to be lower in the real case. Furthermore the equation used to predict the strength gain appears to underestimate the strength of the sprayed concrete in the first 48 hours (see Figure 3). However, these analyses make no allowance for construction variability or defects.

One hypothesis behind this research is that more sophisticated analyses of SCL tunnels will reveal important aspects of behaviour, which have gone unnoticed to date. Figure 9 shows one such aspect, namely, the fact that the stress varies considerably within each advance length of the lining. Stresses tend to be higher at the leading edge of one ring, than the trailing edge of the ring ahead. This difference in stresses occurs at the joints, which themselves may be weaker than the rest of the lining due to poor workmanship.

6 CONCLUSIONS

The importance of modelling the behaviour of sprayed concrete in more detail has been recognised for a long time (eg: Rokahr & Lux 1987) but the complexity of the problem has defied engineers' efforts to analyse it.

Analytical design methods are inadequate for SCL tunnels because of their inherent simplifications. However, they remain useful in the initial stages of design and as independent checks on the results from numerical modelling.

The initial results of the numerical analyses support the view that the sprayed concrete's constitutive model is major influence on the stresses in the lining. Incorporating the nonlinear stress-strain behaviour of the sprayed concrete and creep into the numerical model leads to considerable reductions in the predicted axial forces and bending moments in both cases.

With the increase in knowledge of how sprayed concrete behaves as a material and the advances in computing power, there is the real prospect that engineers will soon be able to design sprayed concrete tunnel linings with the same degree of certainty as is currently achievable for segmental tunnel linings.

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SYMBOLS AND ABBREVIATIONS

α	utilization factor
E	elastic modulus
E_v	elastic modulus in the vertical plane
E_h	elastic modulus in the horizontal plane
Est.	estimated
f_{cu}	uniaxial compressive strength
G_{vh}	independent shear modulus
HEX	Heathrow Express project
HME	Hypothetical Modulus of Elasticity
PFA	Pulverised Flue Ash
SCL	sprayed concrete lined
SFRS	steel fibre reinforced shotcrete
ν	Poisson's ratio
v_{hh}	Poisson's ratio for effect of horizontal stress on horizontal strain
v_{vh}	Poisson's ratio for effect of vertical stress on horizontal strain

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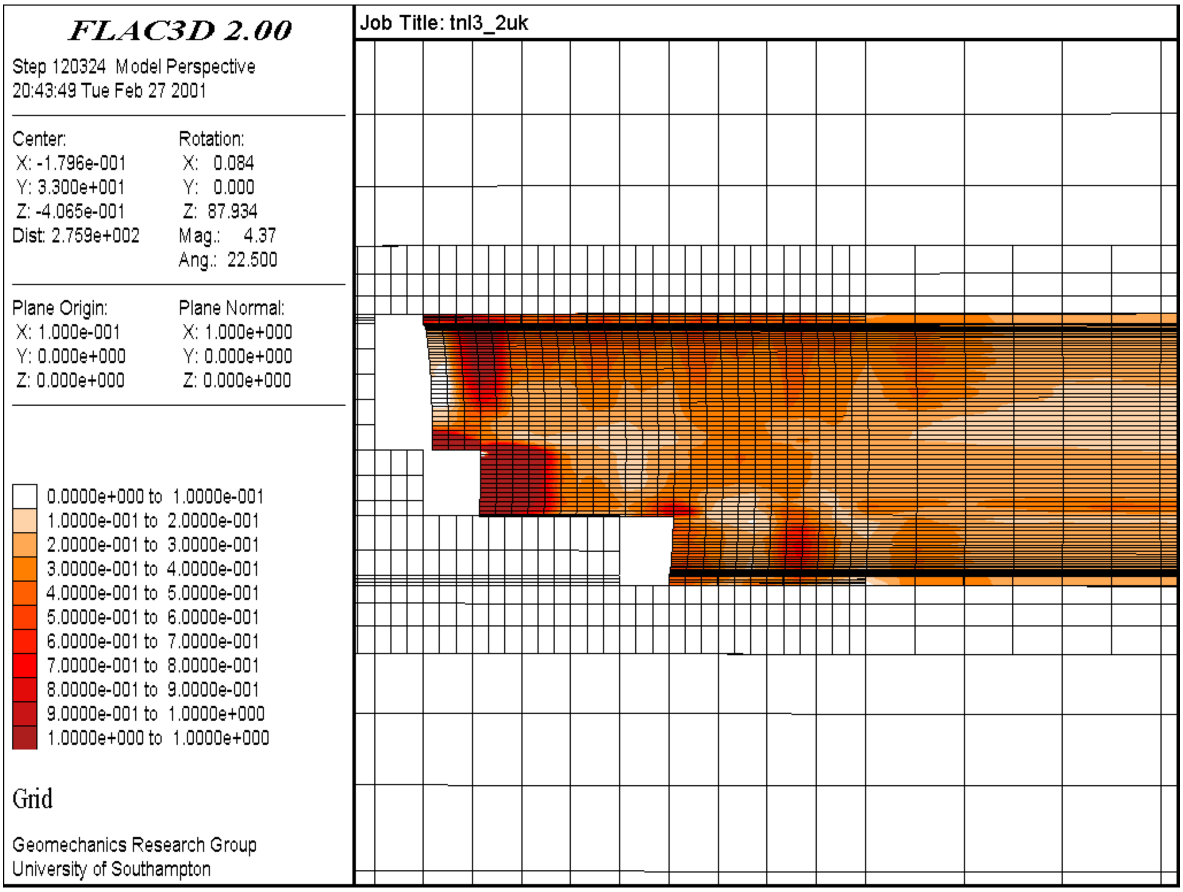

Figure 8: Utilization factors for elastoplastic SCL model (MCSS).

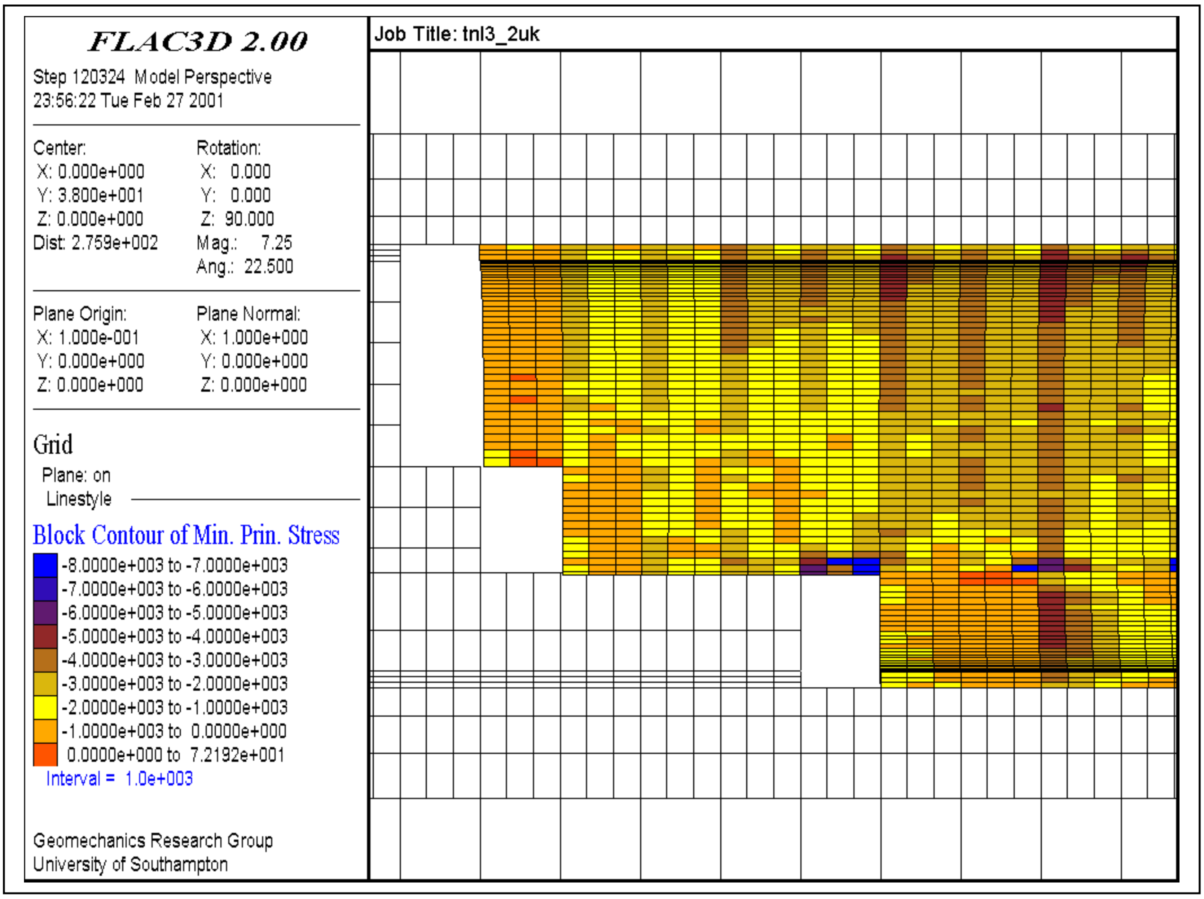

Figure 9: Circumferential stress in the tunnel lining for the elastoplastic SCL model (MCSS).