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Load-sharing effect for sprayed concrete lined tunnels in various ground conditions

Effet de répartition de la charge pour les tunnels revêtus de béton projeté dans diverses conditions de sol

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ABSTRACT: This paper explores the load sharing effect through presentation of a series of numerical analyses on a typical shallow SCL tunnel in London Clay and Chalk. Two different lining configurations are investigated for several load cases and compared: permanent primary and secondary linings with bonded and unbonded membrane interfaces. The implication of the results on the suitability of lining configuration in London Clay and Chalk are discussed.

RÉSUMÉ: Cet article explore l’effet de partage de charge en présentant une série d’analyses numériques sur un tunnel SCL peu profond typique de London Clay et Chalk. Deux configurations de garnissage différentes sont étudiées pour les cas de charge en plusieurs portions et comparées: les garnitures primaires et secondaires permanentes avec des interfaces de membrane liées et non liées. Les résultats des analyses sont présentés et comparés. Les implications des résultats sur la pertinence de la configuration de la doublure dans London Clay et Chalk sont discutées.

Keywords: Load sharing; sprayed concrete; tunnels; double shell lining; composite shell lining;

1 INTRODUCTION

The recently completed sprayed concrete lined (SCL) tunnels on the Crossrail project saw significant advances in understanding the behavior of permanent sprayed concrete primary and secondary linings, and spray applied waterproofing membranes (Su and Thomas 2015, John et al. 2016). It is now common practice to treat the SCL primary linings as permanent, which then share the long-term load with the permanent secondary lining via either an unbonded sheet membrane interface in a double shell lining (DSL) configuration or a bonded spray-applied membrane interface in a composite shell lining (CSL) configuration.

The concept of load-sharing realised by these two lining configurations is claimed to be able to reduce the overall lining thickness. However, the recent experiences at Crossrail and other international projects in different ground conditions have raised questions on the design philosophy and optimal configuration of the permanent primary/secondary lining structure considering the bond interface provided by the selected waterproofing system. Indeed, the short- and long-term behaviour of the ground in which the tunnel constructed will significantly affect the design philosophy and load sharing effect. Thus a design configuration adopted in a soft ground such London Clay may not be the optimal configuration in a stiffer medium such as fractured chalk.

A key influence on the optimal deisgn configuration which requires further investigation is the effect of shrinkage and application of groundwater pressure on the lining system, which appears to not have been adequately addressed. This paper presents the results of a numerical study undertaken to assess differences in predicted primary and secondary lining loads for both CSL and DSL configurations in both Clay and Chalk.

2 LOADING CONDITIONS

In order to minimise ongoing maintainence costs, civil engineering tunnels are often specified to be fully tanked in the long term. For design, both short and long-term water pressures are assumed to apply to the extrados of primary lining and waterproofing membrane, respectively. For this reason and to simplify comparison, the analysis in this paper assumes the both CSL and DSL configurations to be fully tanked.

Four load combinations were analysed as listed in Table 1. The load considered for the secondary lining are self weight (SW), shrinkage (SRK), groundwater (GW) and long-term surchare and ground consolidation, if applicable. (LCG). The loading conditions are illustrated in Figure 1.

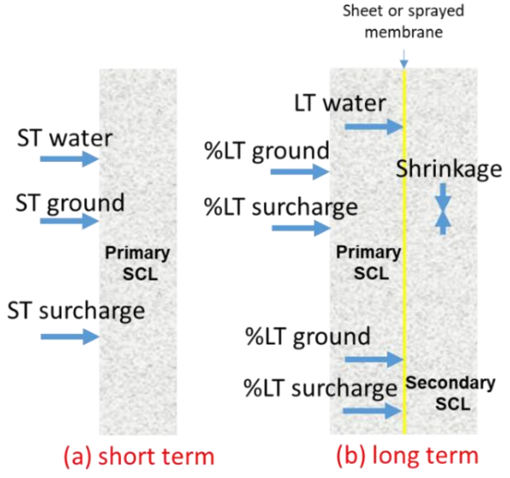

Figure 1 Lining loading conditions

The main difference between London Clay and Chalk is that, during the tunnel excavation, negative pore pressure is generated in London Clay hence only a proportion of the final ground load is applied to the primary lining. In the long term, following the dissipation of excess pore pressure, additional consolidation loads will be shared between the primary and secondary lining. In contrast, for chalk the primary lining carries all the ground loads from the short term, with no further consolidation loads in the long term.

Table 1. Load combinations for the secondary lining

No.	Loads	Stages
1	SW	Short term
2	SW+SHK	Short-term
3	SW+SHK+GW	Short term
4	SW+SRK+GW+LCG	Long term

3 DEVEOPMENT OF MODELS

For this study, plane strain 2D analysis has been carried out using the explicit finite difference program Fast Lagrangian Analysis Continua (FLAC). Two numerical models are developed; Model 1 for London Clay and Model 2 for Chalk.

3.1 Model geometry and boundary conditions

The global model mesh for this study is shown in Figure 2 (a), with a typical SCL tunnel geometry and the corresponding numerical analysis mesh shown in Figure 2 (b) and (c), respectively. The SCL tunnel axis is approximately 20 m below the ground surface. The model is organised into two main areas: fine mesh around the SCL tunnel and coarse mesh for the rest of the model. The model vertical boundaries are fixed horizontally and the bottom boundary is fixed in both vertical and horizontal directions. Overground development is simulated as a 75 kPa surcharge applied at the ground surface in the long term. The dimensions of most lining zones are approximately 0.15m by 0.15m, with slightly bigger zones for the thicker secondary lining invert. Both linings in the model are 300mm thick.

3.2 Numerical analysis assumptions

- The ground water level is assumed to be at the base of the made ground. Short- and long-term water pressure profiles were modelled as hydrostatic.
- For simplicity, the analysis simulated a full face excavation with a stress relaxation of 100-50-0.
- The SCL is assumed to be linear elastic with stiffness of 17GPa for short and long terms.
- London Clay is modelled as an undrained material in the short-term stage. Drained properties of the ground have been assumed for long-term stage.
- The chalk is considered to act as a drained medium for both short and long term stages.
- The effect of shrinkage was simulated by assigning a uniform hoop stress equivalent to 300 microstrain unrestrained shrinkage.
- Groundwater presssure is applied to the waterproofing membrane interface
- For the DSLconfiguration a full-slip interface was assigned witha normal stiffness (4.0GPa/m) (Su & Bloodworth, 2016).
- For CSL tunnels, normal stiffness (4.0GPa/m), tensile strength (0.8MPa), shear stiffness (2.0GPa/m) and shear strength (2.0MPa) were assigned (Su & Bloodworth, 2016).
- For Model 1, both Made Ground and London Clay were modelled with Mohr-Coloumb failure criterion.
- For Model 2, Made Ground was modelled with a Mohr-Coloumb failure criterion whislt the Chalk was modelled using the Hoek-Brown failure criterion.
- Additional long-term ground surface surchage is 75kPa

Table 2. Geological stratigraphy for Models 1 and 2

Top [mATD]	Base [mATD]	Thickness [m]	Model 1 stratugraphy	Model 2 stratugraphy
120.00	115.00	5.00	Made Ground (MG)	Made Ground (MG)
115.00	62.00	53.00	Upper London Clay (ULC)	Chalk (CHK)

Table 3. Geotechnical ground parameters for Model 1

Soil stratum	Made Ground	Upper London Clay
Bulk unit weight [kNm^{-3}]	20	20
Coefficient of earth pressure at rest K_0	0.5	1.2
Undrained shear strength *Cu* [kPa]	-	70+11*z* (*z* from top of LC)
Effective cohesion *c*' [kPa]	0	10
Effective friction angle ϕ' [deg]	25	20
Porosity *n* [%]	35	45
Drained Poiison's ratio ν'	0.3	0.1
Drained elastic modulus *E'* [kPa]	5000	365*Cu*

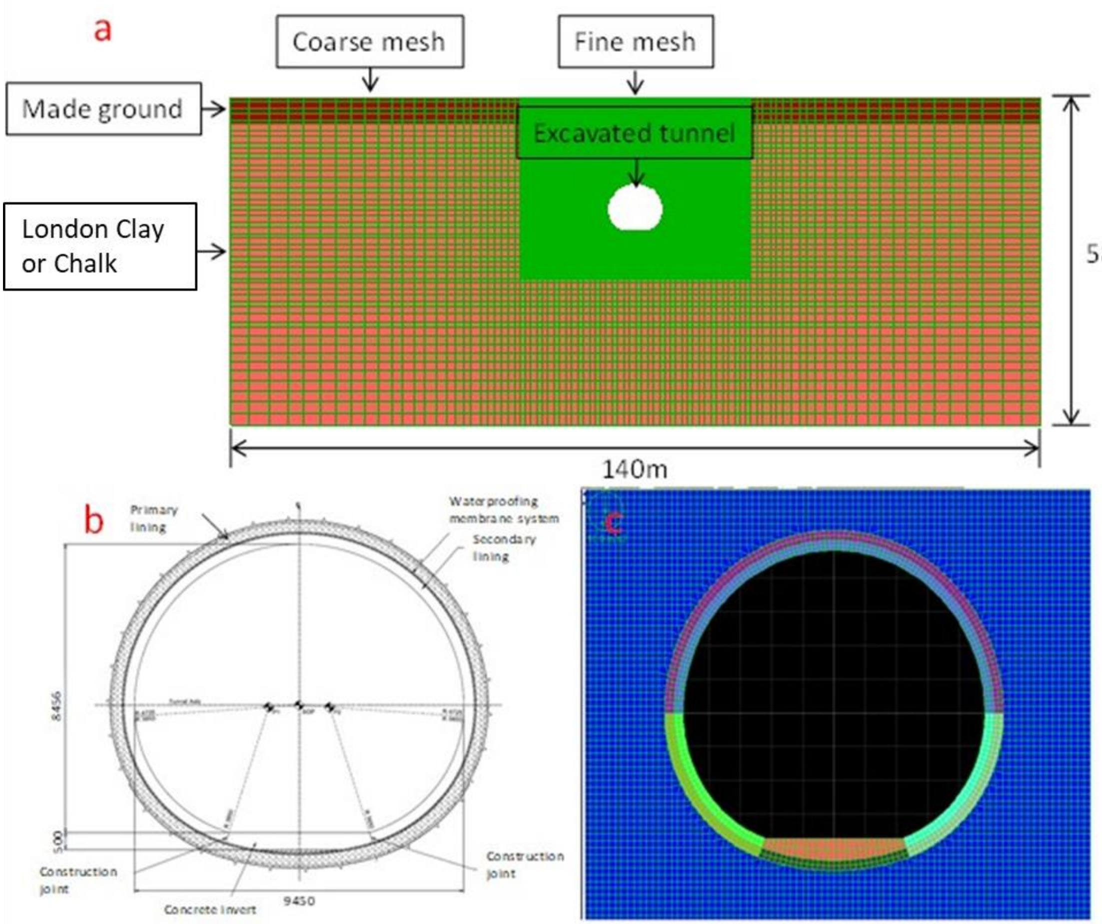

Figure 2 (a) Global model mesh (b) Composite SCL tunnel geometry (c) numerical model mesh

Table 4. Geotechnical ground parameters for Model 2

Soil stratum	**Fractured Chalk**
Bulk unit weight [kNm^{-3}]	20
Geological Strength Index [GSI]	49
Uniaxial Compressive Strength [MPa]	4.87
m_b	1.133
s	0.0035
a	0.506
Drained Poison’s ratio *v’*	0.3
Drained elastic modulus *E’* [GPa]	5.35

4 PRESENTATION OF NUMERICAL MODELLING RESULTS

This section presents the resultant axial force and – figures (a) and (c) for primary and secondary lining, respectively – and bending moment plots – figures (b) and (d) for primary and secondary lining, respectively – for each of the four load cases defined in Table 1.

The Figure 3 (a) and (b) represents the short-term forces in the primary SCL at the end of its construction and immediately after the secondary lining is constructed. The notable difference between the clay and chalk analyses are the significantly larger bending moments in the invert for the chalk for both CSL and DSL. This is due to the fractured chalk mass acting in a drained manner in the short term, and so the primary lining is required to resist the full hydrostatic pressure due to the tanked nature of the tunnel.

At this stage, the secondary lining is only lightly loaded under self weight, and behaves similarly in both clay and chalk analyses, as shown in Figure 3 (c) and (d). Of note, as a result of tensile and shear bond between the primary and secondary lining in the CSL configuration, tensile loads develop in the crown and haunch of the secondary lining for the CSL configuration while the DSL lining remains in net compression.

Figure 4 shows that subsequent shrinkage of the secondary lining leads to an increase in primary lining axial forces for the CSL but minimal change of axial force in the DSL (Figure 4(a)). There is little change in bending moment between LC1 and LC2 (Figure 4(b)). In contrast, there is a significant reduction in axial load in the secondary lining for the both the CSL and DSL, with considerable tensile loads materialising in the CSL (Figure 4(c)); the DSL lining remains in net compression. Both CSL and DSL show an increase in bending moment (Figure 4 (d)). The increase in secondary lining bending moment is more pronounced in the DSL.

As the groundwater pressure is applied to the secondary lining in LC3, a significant reduction of axial load is noted in the primary lining for the DSL, with a less pronounced increase in axial force for the CSL Figure 5(a). The former is due to the water pressure in the DSL lining applying an equal and opposite pressure to both primary and secondary lining as it is assumed to spread across the membrane, which can separate from the secondary as a result. In contrast, the bond between the membrane and linings in the CSL means that water pressures are shared between primary and secondary lining, and so result in an increase in axial force in both primary and secondary linings, as can be seen in Figure 5(c). Another consequence of the difference in tensile bond conditon between DSL and CSL is that bending moments are increased in both primary and secondary lining for the DSL case as the primary lining separates from the secondary (Figure 5(b) and (d)).

In the long term case, application of the 75kPa long term surcharge results in an increase in axial force in the primary lining for all analysed cases (Figure 6 (a)). Compared to the chalk, consolidation of the clay in the long term imparts a significant increase in axial force in both the DSL and CSL (Figure 6 (a) and (c)). In terms of bending moments, a significant increase is noted in the invert for both ground conditions in the DSL configuration, with a much smaller change for the CSL (Figure 6(b)). For the secondary lining, while there is an increase in axial load in the secondary, areas in the crown and invert remain in net tension for the CSL while the DSL remains in compression. Bending moments in the secondary lining are significantly increased for the DSL, with little increase for the CSL Figure 6(d)).

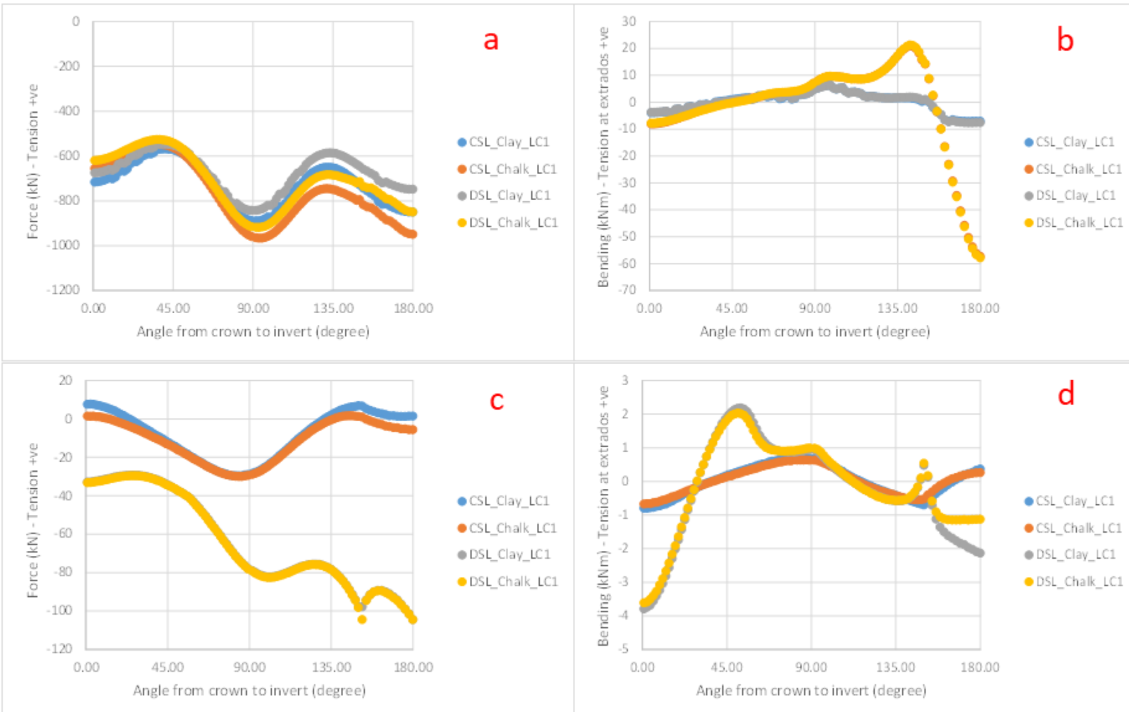

Figure 3 Load Case 1 – Self weight

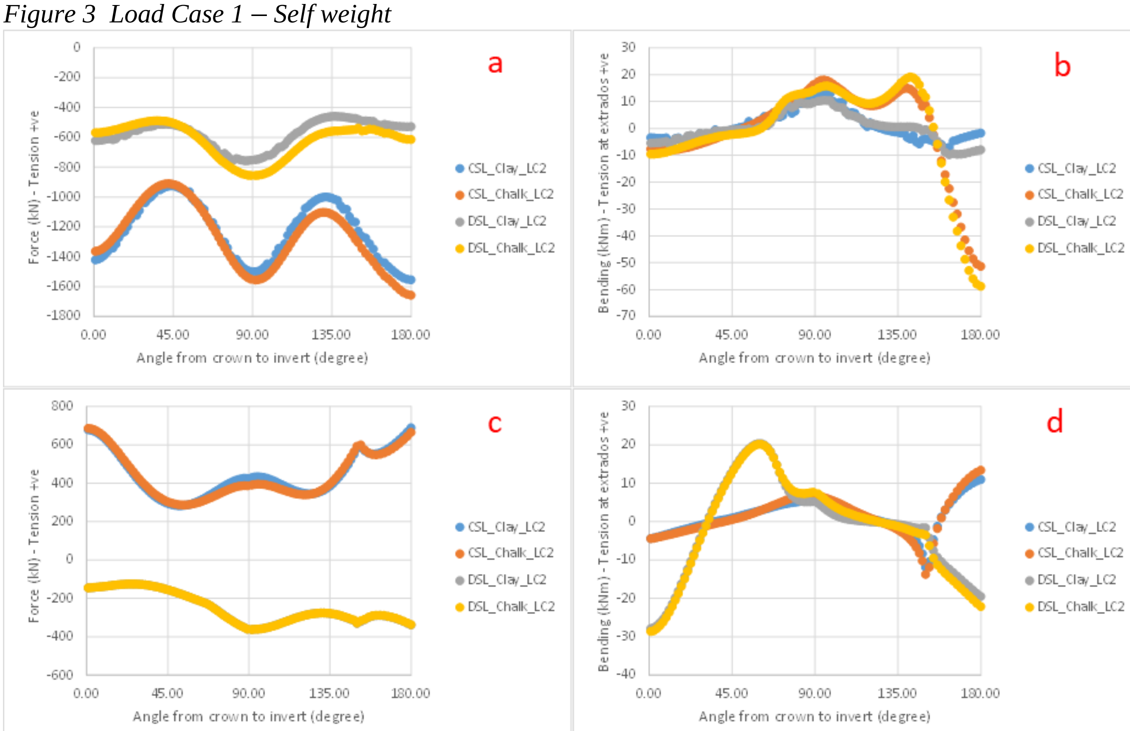

Figure 4 Load Case 2 – Self weight + Shrinkage

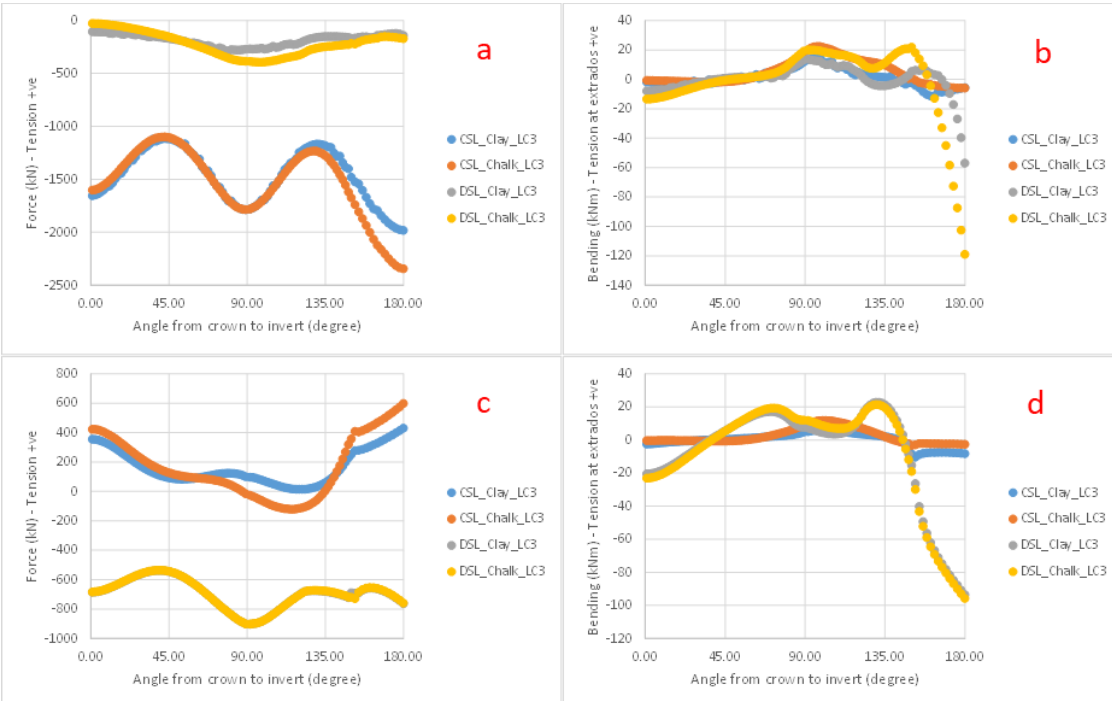

Figure 5 Load Case 3 – Self weight + Shrinkage + Ground Water

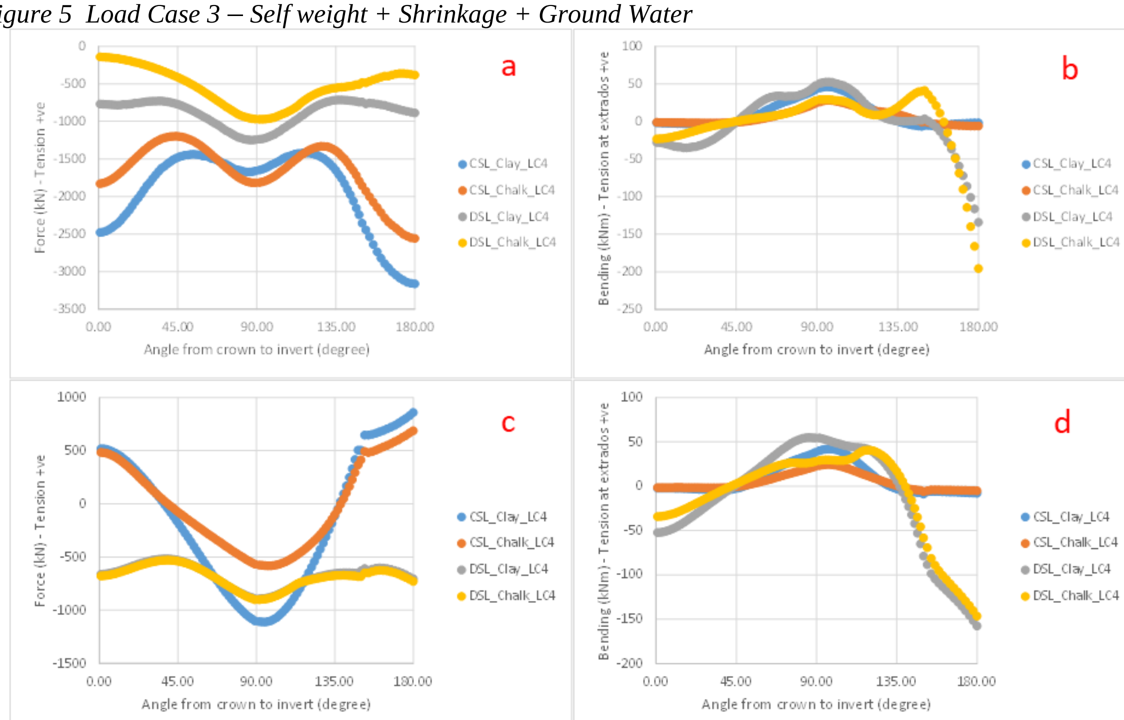

Figure 6 Load Case 4 – Long term loading

5 DISCUSSION

For the CSL configuration, shirnkage of the secondary lining leads to tensile forces in the secondary lining. This is attributed mainly to the restraint provided by the bonded sprayed memrbane inteface. As a result, same amount of compression is introduced to the primary lining. When groundwater pressure is applied to the bonded sprayed membrane interface in the CSL, it causes an increase in compressive force for both primary and secondary linings. As both linings have the same thickness and stiffness, the amount of increased compression force in each lining is same. In the long term load case for the clay load cases, application of the 75kPa surface surchage and consolidation of the ground results in incresaed compressive forces in both the primary and secondary linings. A similar effect is noted within the chalk model, however the magnitude of axial forces increase is less. Of note, the crown and invert of the secondary lining remain in net tension; however, due to the interface bond of the CSL, the bending moment increase in the long term is negligible. This shows that in the CSL there is a clear load-sharing between the primary and secondary linings, which leads to reduced bending moments in both linings, but may cause net tensions in parts of the the secondary lining in both the short and long term cases.

For the DSL tunnel, slip and lack of bond between the primary and secondary linings means that shirnkage of the secondary lining does not induce tensions in it as it is free to move away from the primary (Figure 7). However, this lack of bond also leads to larger bending moments in the DSL secondary linings. For the clay tunnels, the bending moments in the primary lining are small due it undrained nature in the short term. In contrast, the drained nature of the fractured chalk requires the primary lining to resist hydrostatic pressures in the short term leading to high bending moments in the invert.

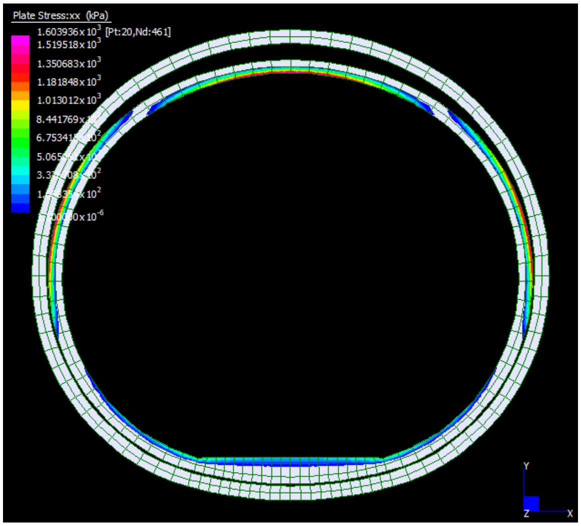

Figure 7 Separation of primary and secondary lining for DSL (LC2 – SW + SHK) shown)

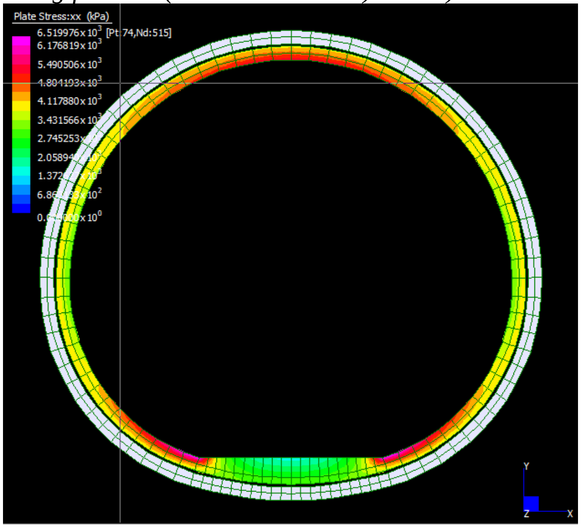

Figure 8 Bonding of the primary and secondary lining and tensile stresses in secondary for CSL (LC2 – SW + SHK) shown)

The bending moments in the secondary lining continue to increase as the groundwater pressure is applied to the back of the secondary lining in the DSL configuration. The axial forces in the primary lining also reduce over time. In the long term, the long-term consolidation load is all taken by the primary lining for the clay case with little load shed on to the secondary lining, which is largely due to the unbonded interface and the gap induced between the primary and secondary linings due to shrinkage.

For full composite case (Figure 8), the whole secondary lining is in tension in the short term when the seocndary lining is loaded only by its self weight and shrinkage is complete. Provided the bond strength of the sprayed membrane is not exceeded, this tension in the secondary lining due to shrinkage will induce the same magnitude of compression in the primary lining. On the contrary, the non-composite lining is able to slip and contract away from the primary lining, leading to very low levels of tensile stress and avoidance of net tension in the secondary lining. It should be noted that in these models an unrestrained shrinkage of 300 microstrain is applied, which causes significant levels of net tension in the full composite lining. For the example shown the level of tensile stress at the crown and knees of the secondary lining may exceed the peak tensile strength of the fibre reinforced lining

6 CONCLUSIONS

As a relatively new and innovative lining configuration, the CSL has been promoted as an optimal solution which could lead to reduced overall lining thickness when compared with traditional DSL in all ground conditions. However, the authors have not been able to find sufficient and detailed support in the literature to substantiate this claim. This study fills this knowledge gap by presenting a series of numerical analyses results for CSL and DSL in in two different ground conditions, namely, clay and chalk. The study identified key factors affecting the lining behaviour and design.

The results presented above suggest that the CSL may be a preferrable solution in tanked tunnels where full hydrostatic pressure is required to be resisted by the secondary lining. This is especially applicable to ground which exhibits strong long-term consolidation effect, such as London Clay. The bonded waterproofing interface would lead to load sharing in the long term between the primary and secondary lininig, potentially reducing the secondary lining thickness. However, shrinkage strains induced by the secondary lining may lead to axial forces and potential cracks in the secondary lining of the bonded CSL lining in the short term. This critical load case needs to be checked and designed against for the prevailing ground conditions.

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