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Numerical modelling of the NATM and compensation grouting trials at Redcross Way

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ABSTRACT: The NATM trial at Redcross Way has provided detailed measurements of soil and lining movements and stresses acting on the shotcrete lining, and has allowed the effects of compensation grouting to be quantified. This paper describes the results of comprehensive finite element studies of the effects of compensation grouting on the shotcrete lining and their comparison with the field measurements.

1 INTRODUCTION

The NATM trial at Redcross Way, undertaken as part of the Jubilee Line Extension (JLE), had three main aims. These were to demonstrate that: (a) tunnels and shafts of various diameters can be safely and efficiently constructed in London Clay using shotcrete support, (b) the magnitude of surface settlements caused by this method of tunnelling can be accurately predicted, and (c) surface settlements could be reduced to within specified limits by the use of compensation grouting in the vicinity of the shotcrete tunnels.

In order to achieve these three goals, a number of construction phases were undertaken at the Redcross Way site. The extent, method of construction, sequencing and duration of the shaft, tunnel excavations and compensation grouting in relation to the installed instrumentation is described by Kimmance and Allen (1996). They also summarise information obtained from the comprehensive array of surface and subsurface instrumentation. Figure 1 shows the plan layout of the trial together with positions of the four tunnel sections where instrumentation was installed and the locations of the tube à manchettes (TAMs) used for the grouting. The tunnel excavated diameter was 11.3m, its axis was at a depth of approximately 28m below ground level, and the TAMs were 7-8m above the tunnel crown. The thickness of the completed shotcrete lining was 300mm.

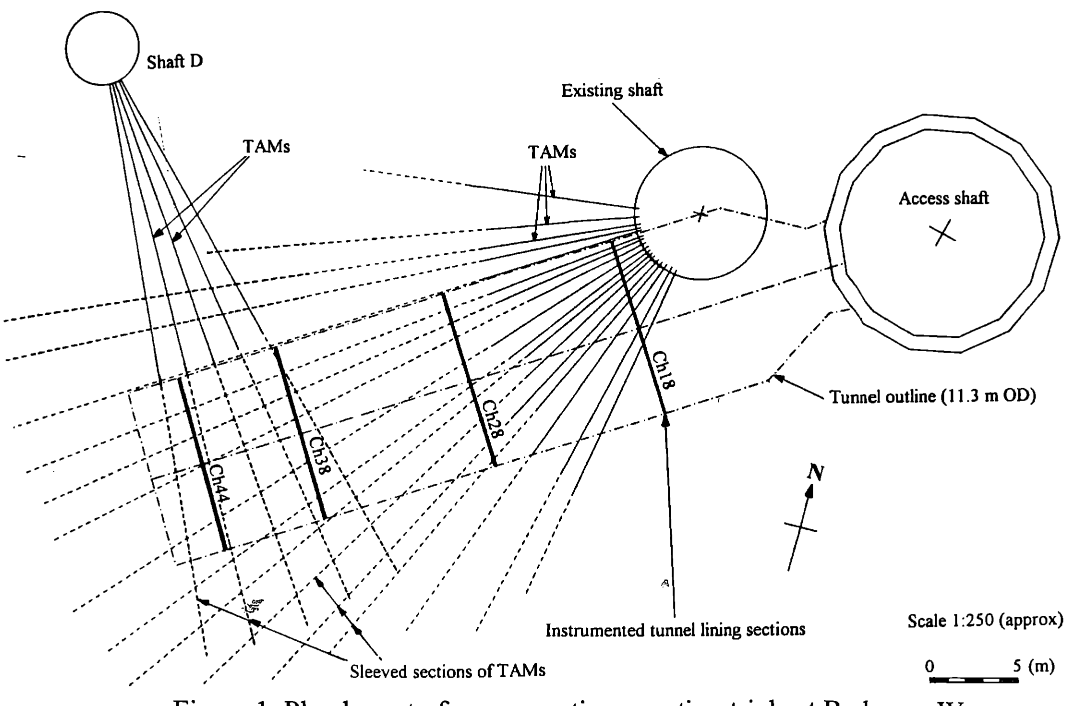

Figure 1. Plan layout of compensation grouting trials at Redcross Way

Tunnel construction was divided into two phases, both approximately 20m in length. Phase 1, from the access shaft to chainage 28, was excavated without any compensation grouting. The tunnel was then extended, in Phase 2, from chainage 28 to chainage 47, but with compensation grouting to reduce the surface settlements. The compensation grouting successfully reduced the settlements to less than 6mm, compared with a maximum settlement of 22mm observed in Phase 1. After completion of the tunnel, an additional grouting trial was carried out from shaft D (see Figure 1) above chainages 38 and 44 with TAMs located only 2-3m above the tunnel lining. This provided information on grouting closer to the tunnel lining than was attempted in the original trial.

2 BASIS OF THE ANALYSES

2.1 Soil profile and material properties

The assumed soil profile upon which the analyses were based is shown in Figure 2. It was deduced from logs of the three closest boreholes to the site that formed part of the investigations along the route of the JLE, and from information obtained during construction of the trial tunnel.

Table 1 summarises the soil properties used for the analyses. These parameters were based on measurements and experience at other central London sites. Made Ground was modelled as being a linear elastic, perfectly plastic material. To model the behaviour of the Thames Gravel, London Clay, Woolwich and Reading Beds (WRB), and Thanet Beds, a non-linear elastic, perfectly plastic constitutive model was used, the non-linear elastic response being described by Jardine *et al* (1986). For these materials soil stiffnesses were dependent on both strains and current mean effective stress, as shown in Figure 3 for London Clay and WRB Clay. A Mohr-Coulomb yield surface and plastic potential were used to model the plastic behaviour of all strata.

In the analyses shotcrete linings were modelled as linear elastic materials with a Young's modulus of 15.0×10^3 MPa and a Poisson's ratio of 0.15.

The adopted pore water pressure distribution is also shown in Figure 2. The distribution of permeability within the ground, given in Table 1, was chosen to be consistent with the pore water pressure distribution.

2.2 Finite element analyses

The finite element code ICFEP (Imperial College Finite Element Program) was used to perform the analyses reported here. Eight noded plane strain isoparametric elements with reduced integration were used to represent the soil. Three noded Mindlin beam elements with selected reduced integration were used to model the tunnel linings (Day and Potts, 1990). An accelerated modified Newton Raphson scheme with a sub-stepping stress point algorithm was employed to solve the non-linear finite element equations (Potts and Ganendra, 1994).

In order to analyse the effects of compensation grouting on a tunnel lining, it is first necessary to simulate realistically the development of ground

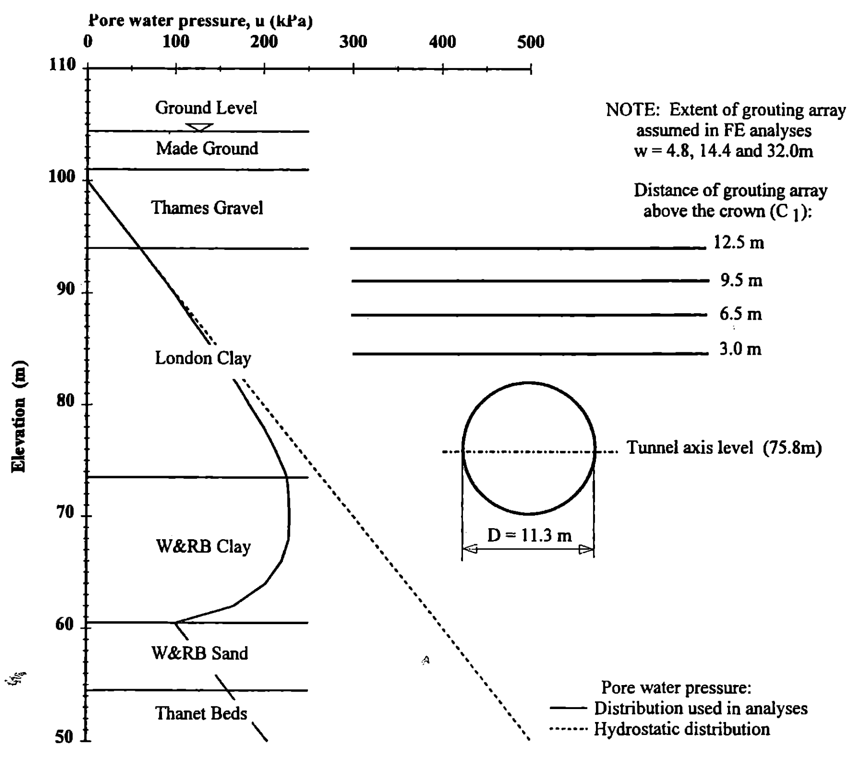

Figure 2. Soil and pore water pressure profiles, and grouting levels assumed

Table 1. Soil properties assumed in the analyses

Strata (Elevation)	Bulk density, γ (kN/m^3)	Effective cohesion, c' (kN/m^2)	Effective angle of shearing resistance ϕ ' (deg)	Angle of dilation, ψ (deg)	Coefficient of earth pressure at rest, K_0	Vertical permeability, k_v (m/s)	Horizontal permeab., k_h (m/s)	Young's modulus, E' (MPa)	Poisson's ratio, ν '
Made Ground (104.5-101.0m)	19.0	0.0	35.0	17.5	0.5	drained	drained	25.0	0.2
Thames Gravel (101.0-94.0m)	20.0	0.0	35.0	17.5	0.5	drained	drained	non-linear	non-linear
London Clay (94.0-73.5m)	20.0	5.0	23.0	11.5	varies 1.4 at 94.0m 1.1 at 73.5m	varies 5.10^{-10} at 94.0m 5.10^{-11} at 73.5m	k_h=2. k_v	non-linear	non-linear
WRB Clay (73.5-60.5m)	20.0	10.0	30.0	15.0	1.1	varies 5.10^{-11} at 73.5m 5.10^{-12} at 60.5m	k_h=2. k_v	non-linear	non-linear
WRB Sand (60.5-54.5m)	20.0	0.0	35.0	17.5	1.0	drained	drained	non-linear	non-linear
Thanet Beds (54.5-44.5m)	20.0	0.0	40.0	20.0	1.0	drained	drained	non-linear	non-linear

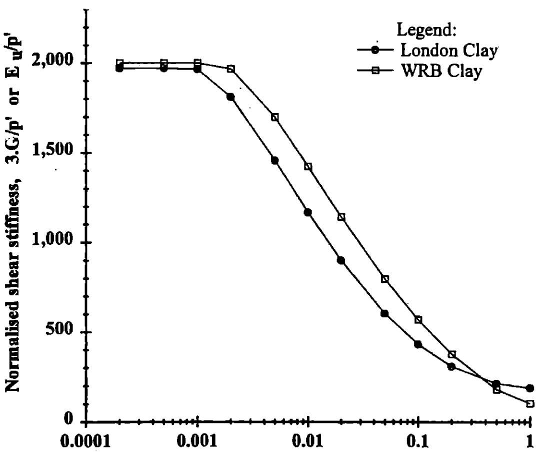

Figure 3. Adopted non-linear elastic small strain stiffness for London Clay and WRB Clay

movements due to tunnel excavation. The tunnel excavation is a complex three-dimensional (3D) problem which has been investigated using a simplified two-dimensional (2D) plane strain FE analysis.

Tunnel excavation was modelled by the incremental removal of the solid elements within the tunnel boundary. The stresses that the soil within the tunnel applied to the tunnel boundary were evaluated and then applied in the reverse direction over several increments. To approximate the 3D effects of an advancing tunnel heading, only a proportion of the initial ground stresses was removed prior to installing the tunnel lining. This is equivalent to the "λ factor" approach (Panet & Guenot, 1982).

As a tunnel is excavated the ground undergoes stress relief, resulting in ground (volume) loss towards the face with associated ground movements at higher levels. Compensation grouting involves the injection of grout between the tunnel and an overlying structure during tunnelling to 'compensate' for these ground movements (Mair & Hight, 1995). Injection of low viscosity grout at sufficiently high pressure will cause hydraulic fracture ('fracture' grouting) of the ground. When applied to a heavily over-consolidated clay (such as London Clay), where the minor principal stress is the vertical stress, fracture will theoretically occur horizontally, resulting in thin sheets or lenses of grout being developed through the ground (Mair, 1994).

In the FE analyses the fracture grouting has been modelled indirectly by including a horizontal 'sheet' of joint (interface) elements (Day & Potts, 1994) in the FE mesh along the side of existing solid elements at the appropriate distance above the tunnel crown (C_1) representing the level of the grouting. Effects of compensation grouting have been modelled by applying a pressure along the boundary of the 'slot' (formed by removing the joint elements from the mesh) until the surface settlement trough due to tunnel excavation was approximately nullified.

Two approaches were considered in the modelling of compensation grouting. In the first, more 'rigorous' approach the settlement trough resulting from each increment of tunnel excavation was 'compensated' immediately in the next increment. However, these analyses had to be controlled from increment to increment, particularly during the compensation stages, in order to determine the appropriate magnitude of pressure to be applied at the grouting level to 'compensate' for the ground loss from the previous excavation increment.

In the second, 'simple' approach, a stress acting at the grouting level was applied at the end of tunnel construction of sufficient magnitude to nullify the settlement trough resulting from complete tunnel excavation. Although the aim of compensation grouting is not to allow an overlying structure to settle during tunnelling and then afterwards to jack it up as a corrective measure, it is considered reasonable to model effects of compensation grouting on tunnel linings using this approach. A comparison of the 'rigorous' and 'simple' approaches showed that the predicted effects on the tunnel lining were similar. Bearing in mind the complexity of the 'rigorous' approach, the 'simple' approach was used for all analyses reported in this paper.

3 PARAMETRIC STUDIES

Once hydraulic fracture occurs during compensation grouting, the grout may penetrate the ground a considerable distance (many metres) from the point of injection, depending on the volume of grout injected. Because the actual lateral extent of compensation grouting is unknown, three values of the extent of compensation grouting array have been assumed for the parametric studies: w = 4.8, 14.4 and 32.0m.

A grouting array closer to the tunnel crown can be expected to produce higher loads on the tunnel lining. As shown in Figure 2, four different grouting levels have been investigated, corresponding to C_1 = 3.0, 6.5, 9.5m (all three in London Clay) and 12.5m (the junction between London Clay and Thames Gravel). For each of these levels, analyses with the above mentioned grouting widths have been performed.

The 'simple' approach of modelling compensation grouting results in a higher level of ground straining, particularly above the tunnel where the settlement trough is concentrated. Also, the stress path in the soil above the grouting level, where heave occurs (see Figure 4), changes its direction when grouting occurs, thereby giving rise to a stiffer soil response. In view of the small strain stiffness soil model used in the analysis, a set of analyses was carried out by re-invoking a low strain stiff response in the soils above the compensation grouting level after completion of tunnel excavation. The effect of this was to increase lining stresses by less than 10%.

4 RESULTS OF THE ANALYSES

4.1 Ground movements

In the 'simple' approach movements due to tunnel excavation and compensation grouting can be easily distinguished, as shown in Figure 4 for the grouting array C_1 = 6.5m above the tunnel crown and w = 32.0m in width. The effects of compensation grouting in reducing the surface settlement profile can be clearly seen.

The predicted surface settlement profile after tunnel excavation unaffected by compensation grouting (see Figure 4.a) is shown in Figure 5. In order to reproduce the observations of ground surface settlement made during Phase 1 construction of the Redcross Way trial, an overall ground loss in the range of 1.0% was targeted. To achieve this, approximately 60% of the initial ground stresses were removed, corresponding to λ = 0.4, where λ is defined by Panet & Guenot (1982). The analysis gave results consistent with measurements, as shown in

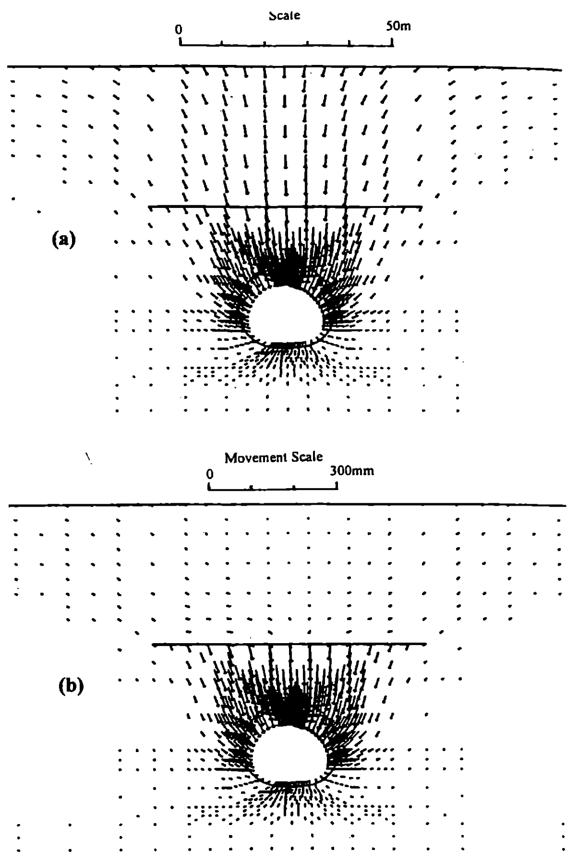

Figure 4. Accumulated displacement vectors after (a) tunnel excavation (without compensation grouting) and (b) compensation grouting

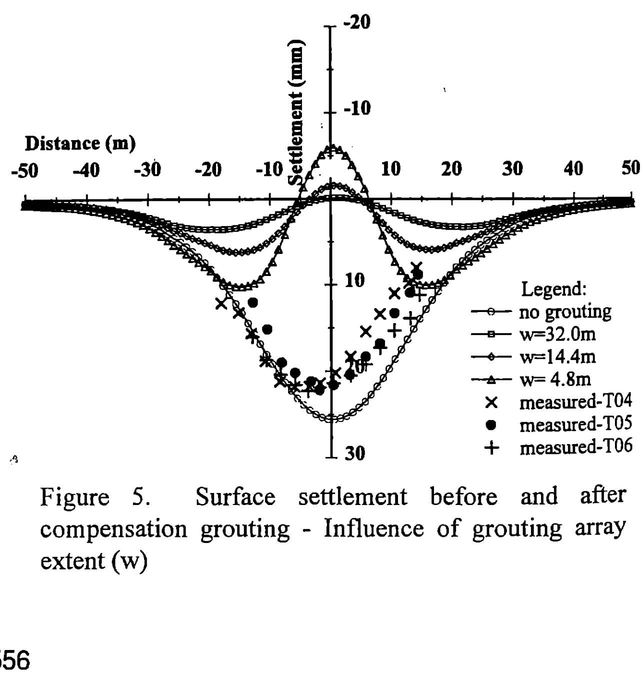

Figure 5. Surface settlement before and after compensation grouting - Influence of grouting array extent (w)

Figure 5, although the maximum settlement was slightly overpredicted.

Figure 5 also shows the predicted final shape of the ground surface after completion of compensation grouting at the level of $C_1 = 6.5$m. It can be seen that the analysis in which the narrowest extent of grouting array (w = 4.8m) was assumed yielded rather concentrated final ground surface movements. The other array widths (w = 14.4 and 32.0m) resulted in predicted final surface settlements of less then 6mm, which is consistent with the observations. This indicates that, as expected, in order to compensate effectively for the surface settlement potentially induced during tunnelling, it is beneficial to grout in a wider array. This will also reduce the loads in the tunnel lining due to compensation grouting.

4.2 Tunnel lining stresses

Figure 6 shows the distribution of hoop stresses in the tunnel lining for four different grouting levels which have been modelled (C_1 = 3.0, 6.5, 9.5 and 12.5m) and the grouting array extent of w = 14.4m. It can be seen that the further away the grouting level from the tunnel crown, the less are the effects of compensation grouting on the tunnel lining, as would be expected.

Figure 7 shows the measured and predicted increases in average hoop stresses in the tunnel lining due to compensation grouting plotted against the ratio C_1/D, where C_1 is the minimum distance between the tunnel lining and the grouting array and D is the tunnel diameter. The averages of all the readings at each chainage are shown by solid symbols, with stars for the original trial and diamonds for the additional trial. The open star symbol represents the average at chainage 38 excluding readings which are considered to be unrepresentative. The increase in maximum hoop stress was typically about 60% greater than the increase in average hoop stress.

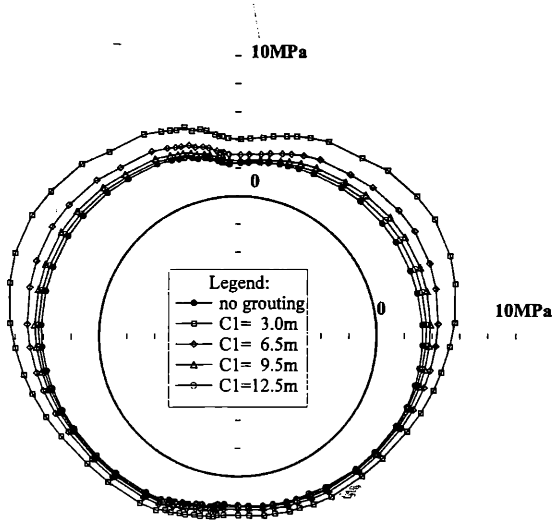

Figure 6. Hoop stresses in tunnel lining - Influence of grouting array level (C_1)

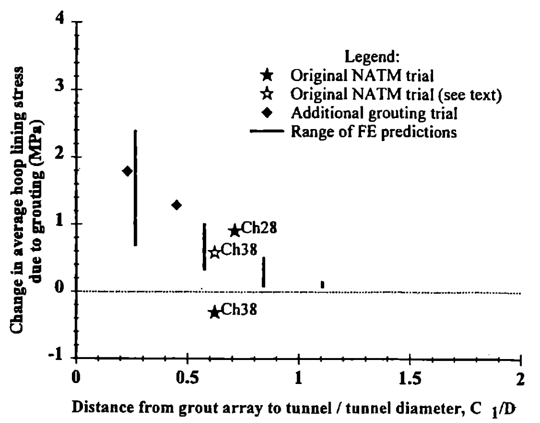

Figure 7. Changes in measured and predicted average hoop lining stresses due to compensation grouting for different values of C_1/D

The range of results from the FE analyses are also indicated in Figure 7. These exclude those for w = 4.8m which was considered to be unrealistic (see Figure 5). It should be noted that the measurements from both of the trials lie towards the higher end of the FE predictions which assumed a grout array width w = 14.4m and reinvoked a stiff soil response at small strains. This width is approximately equal to 1.25 times the tunnel diameter. Also, it can be seen from both the predictions and the measurements that the effect of compensation grouting increases markedly once the grout tubes are within half a tunnel diameter. Conversely, grouting more than one diameter above the tunnel produces little or no effect on the lining in terms of additional hoop stresses.

4.3 Tunnel lining convergence

The lining convergence measured at chainages 18, 28 and 38 for the original trial are compared to the FE predictions for various grout array widths (w) in Table 2.

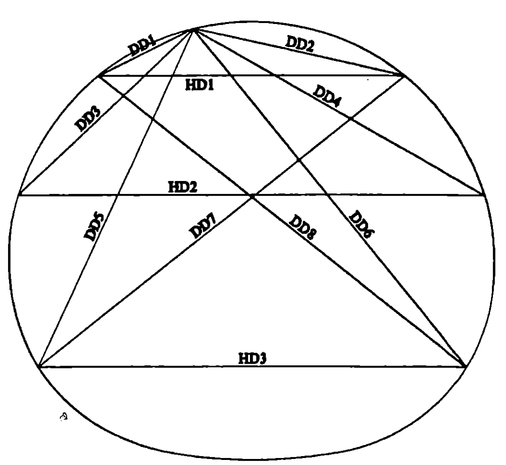

Figure 8. Position of convergence measurements

Table 2. Comparison of measured and predicted tunnel lining convergence with and without compensation grouting

Tunnel section	Measured deformation (mm)			Tunnel section	Deformation predicted by FE analyses (mm)			
	Chainage 18	Chainage 28	Chainage 38		No grouting	w = 32.0m	w = 14.4m	w = 4.8m
HD1	+5.0	Not known	+1.5	**HD1**	+6.0	+7.3	+11.8 (+12.0)	+18.0
HD2	+11.0	+13.0	+9.0	**HD2**	+8.2	+11.0	+22.4 (+25.0)	+31.3
HD3	Not known	+5.5	+3.0	**HD3**	+4.9	+6.5	+7.3 (+8.0)	+8.0
DD1	-0.5	-0.5	-1.0	**DD1**	+0.2	0.0	+1.8 (+2.0)	+4.0
DD2	-0.5	-3.5	-1.5	**DD2**	+2.3	+2.5	+4.0 (+4.0)	+7.0
DD3	0.0	-1.0	-9.0	**DD3**	-2.9	-3.1	-2.9 (-3.0)	-4.0
DD4	-3.5	-2.5	-3.5	**DD4**	+1.5	+2.5	+4.8 (+5.0)	+6.0
DD5	0.0	-15.0	-10.5	**DD5**	-7.0	-9.0	-16.0 (-17.5)	-23.5
DD6	-5.5	-9.0	-5.0	**DD6**	-3.2	-5.0	-10.0 (-11.0)	-16.0
DD7	-1.5	-0.5	Not known	**DD7**	0.0	0.0	-0.3 (-0.5)	+1.7
DD8	+6.0	+1.5	Not known	**DD8**	+5.0	+4.9	+5.6 (+6.0)	+7.6
Positive deformations imply extension, negative shortening; values in brackets refer to FE analysis reinvoking small strain soil stiffness prior to grouting.								

Figure 8 shows the positions of the convergence measurements. The predicted deformations given in the table are all for $C_1 = 6.5$m, which is approximately equal to the actual separation of the tunnel and the grouting tubes in the original trial. No comparison is made for the additional trial because no perceptible convergences resulting from the grouting were measured.

It can be seen that the deformations predicted for the analysis without compensation grouting are broadly comparable to those measured at chainage 18, which was unaffected by compensation grouting.

The convergences measured at chainages 28 and 38, which were affected by compensation grouting, are compared to the results of the three FE analyses which assumed different grouting widths. The measurements from chainage 38 generally show similar movements to those at chainage 18. It is considered that they were probably affected by the fact that the tunnel progressed less than one diameter past the instrumentation section at chainage 38. Chainage 28 is more representative of a 2D tunnel section affected by compensation grouting and is, therefore, more directly comparable to the FE analyses. Comparing the convergence measurements from chainage 28 to the FE predictions indicates that the results from the analysis with w = 32.0m (2.8 times the tunnel diameter) are the closest match to the measurements. The predicted movements are slightly lower than the measured ones, suggesting that assuming a slightly narrower grouting array may produce an improved fit to the measurements. The grout array used for the original trial was somewhat over 2 times the tunnel diameter in width (see Figure 1), i.e. between the 14.4 and 32.0m wide arrays assumed in the FE analyses.

5 CONCLUSIONS

A comprehensive series of parametric studies using finite element analysis incorporating small strain stiffness soil models has been undertaken to predict the effects of compensation grouting on a completed shotcrete lining. The predicted convergences and increases in shotcrete stresses due to compensation grouting are in reasonably good agreement with the measurements from the trial tunnel. The measurements and the finite element predictions indicate a consistent relationship between the stress induced in the shotcrete lining by compensation grouting and the ratio C_1/D, where C_1 is the distance of the grouting above the tunnel crown and D is the tunnel diameter.

In the case of the 11.3m diameter tunnel, which has been the subject of this paper, and for the actual separation $C_1 = 6.5$m between the tunnel and the grouting tubes, the measurements and the analyses indicate that the grouting caused an increase of average hoop stress of less than 1MPa (the corresponding increase in maximum hoop stress being about 1.6MPa). These are only modest increases of hoop stress in terms of the permissible stresses in the shotcrete.

Caution should be exercised in extrapolating the results in this paper to tunnels of different diameter or in different ground conditions.

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