TRIAL SOIL NAILS FOR TUNNEL FACE SUPPORT IN LONDON CLAY AND THE DETECTED INFLUENCE OF TENDON STIFFNESS AND BOND LENGTH ON LOAD TRANSFER

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TRIAL SOIL NAILS FOR TUNNEL FACE SUPPORT
IN LONDON CLAY AND THE DETECTED INFLUENCE OF TENDON
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1. INTRODUCTION

Tunnelling in soft ground inevitably leads to ground movement which results in a settlement trough at the surface. In some instances the magnitude of this movement can lead to unacceptable levels of deformation to buildings or buried services. In cohesive soils it is generally assumed that the ground loss per unit length of the tunnel is equal to the settlement trough per unit length.

The method of tunnelling greatly affects the magnitude of such settlement, but essentially the quicker the ground can be supported the lower the settlement will be. Recent contracts have seen the use of sprayed concrete as the primary ground support in a sequence of incremental advances of the face. This is often referred to as the New Austrian Tunnelling Method (NATM). This technique has resulted in volume loss figures typically in the range of 1.0 to 1.3 per cent. However, even at these values, the resulting settlement can still be unacceptable.

The use of compensation grouting to counteract some or all of the settlement, has given rise to some concern in relation to the stability of the advancing tunnel excavation (i.e. when the shotcrete is still in a green state and the ring is incomplete) and also to the stability of the face. Grouting is therefore kept as remote from the fresh tunnelling works as possible whilst still maintaining a suitable distance from any surface or subsurface structures and underground services.

It is well known from observations that about 50 per cent of the volume loss can be attributed to the deformation of the tunnel face and this is equally valid for incremental tunnelling. Therefore, if face deformation can be controlled, surface settlement will be reduced and the need for concurrent compensation grouting limited.

The use of soil nails was adopted to allay concern about the stability and to reduce the deformation of the 80 square metre faces of the Terminal Four platform tunnels which form part of the Heathrow Express Rail Link Project.

Prior to installation in the tunnel, a series of trials was carried out in order to select the optimum combination of soil nail tendons (steel or glass reinforced plastic), borehole diameter, minimum fixed length, and a suitable grout for nails with a maximum mobilised load potential of 200kN to provide short-term face restraint. The maximum installed length was also investigated, since this would determine the number of occasions tunnelling would have to be suspended to allow the next set of nails to be installed to ensure continuous support to the face.
2. SELECTION OF TRIAL NAILS

2.1 Tensile Members

Two main types of material, steel and GRP, are currently available for economic use as soil nail tendons:

Steel tendons have been used extensively for some 25 years, despite their susceptibility to corrosion representing a major potential shortcoming when used for permanent nailing works. Glass reinforced plastic (GRP) tendons were introduced into the rock bolting industry over 10 years ago, albeit generally used in conjunction with resin grouts. GRP tendons have been used in a limited number of permanent soil nailing contracts in the UK with cementitious grout; the main purpose of their usage being to eliminate corrosion of the tendons in the long term. Extensive gun barrel tests have been carried out to determine their pull-out capacity from cement grout (Ref 1), and methods of providing bar gripping systems equal to the bar capacity have been researched (Ref 2).

The use of GRP tendons for temporary soil nails utilised to increase the stability of a tunnel face would provide an advantage over steel tendons both in their flexibility and lightness during installation and their relative ease of destructive removal from the tunnelled spoil. However, it was recognised that the relatively high elastic nature of a GRP tendon (Youngs Modulus - 45,000N/mm²) in relation to that of a steel tendon (Youngs Modulus - 205,000N/mm²) could seriously influence the pull-out capacity of a soil nail. Furthermore it was also acknowledged that the use of a thick steel bar might, due to its even greater stiffness, exhibit higher pull-out capacity than that of a thinner steel tendon and of a GRP tendon. Thus four types of tendon were chosen to be investigated:

i) A 50mm diameter deformed steel bar.
ii) A 20mm diameter deformed steel bar.
iii) A 22mm diameter glass reinforced plastic bar.
iv) A multiple of eight 6mm diameter glass reinforced plastic strands.

2.2 Borehole Diameter

Standard formulae recommended in BS8081 (Ref 3) for the design of tensile members in the ground (ground anchors and soil nails) indicate that load capacity is directly proportional to borehole diameter. The use of an auger drilling system was specified in order that no problems associated with water supply and water flush disposal would be encountered in the tunnel. Augering does not necessarily result in higher pull-out capacity than holes bored with a flushing system, in fact, it is possible that the utilisation of water flush for boring anchor or soil nail holes in stiff clay can result in the presence of a lower degree of smearing than that resulting from an augering system.

Two sizes of augered holes were chosen to be investigated: 100 and 200mm diameter.
2.3 Fixed Length

Although the recommended formulae for the design of anchors (BS8081, Ref 3) and soil nails in cohesive materials indicate that pull-out capacity as proportional to fixed length, as long ago as 1975 Ostermayer indicated (Fig 1) that in fact pull-out capacity (and average bond stress mobilised at failure) generally reduce with increase in fixed length (Ref. 4). For this reason the efficiency and capacity of the following fixed lengths were chosen to be investigated:- 1.0, 3.0, 4.0, 5.0, 7.5, 10.0, 15.0m and a 28m length with GRP strand.

Figure 1 - Bond stress (skin friction) reduces with increase in fixed length (bond length). After Ostermayer 1975.

2.4 Soil Nail Grout

The essential requirement to ensure effective stability of the tunnel face for a minimum period after soil nail installation, demanded investigation of rapid set grouts. The grout must guarantee attainment of early bond strength and be considerably more economic than use of quick-set resins. A number of proprietary rapid setting cement grouts were chosen in addition to neat Ordinary Portland Cement (OPC), and OPC with additives.

2.5 Trial Nail Lengths

Some nail borings were utilized to investigate the drill lengths (19 and 30m) economically attainable with the chosen auger and the available drilling rig, whilst other lengths were drilled to ensure the chosen fixed lengths were remote from the excavation face (3 to 12m). Four long boreholes were augered specifically to establish borehole deviation (27m and 30m). Monitoring was carried out using the maxibor system which had been extensively used on the site for monitoring compensation grouting bores.
Photo 1 - Trial nails installed at base of 24m deep shaft

Photo 2 - Trial nails installed through shotcrete lining between 1 and 3m from shaft base. Tremie pipe being installed.
3.0 TRIAL LOCATION AND GROUND INFORMATION

All trial nails were installed in the vertical shotcreted face near the base of an 11m diameter, 24m deep, shaft sunk into stiff to very stiff London Clay (Photo 1). Levels of the nails from the base of the shaft ranged from 1 to 3m (Photo 2). Undrained triaxial test results from 9 samples taken from the London Clay in the depth range of the nails and within 30m of the fixed length location were 242, 236, 198, 148, 295, 262, 294, 85 and 108kN/m².

Site Investigation reports carried out on the site recommended the use of an undrained shear strength of the London Clay in the 200kN/m² range over the depth range of the tunnel and elastic modulus of the clay of 75N/mm².

4.0 DRILLING AND GROUTING

All nail holes were drilled by augering techniques at up to 5° declination. Tendons were prefabricated complete with centraliser and the longer steel bars were coupled during installing. Grouting, via a tremie installed alongside the tendon, was carried out after tendon installation (Photo 2). All soil nail tendons were sleeved above the intended fixed length to prevent tendon/grout bond and a compressible packer was fitted around the tendons at the top of the fixed length to prevent load transfer into the unbonded length.

Grout strengths during the test period (4 to 19 days after installation) ranged from 30 to 50N/mm². The majority of nails were tested 11 to 14 days after installation.

5.0 NAIL TESTING

Nails were loaded using a calibrated hydraulic powered hollow ram jack bearing on a plate bedded on the shotcrete shaft face. The settlement of the plate was monitored during the test and the jack ram extension value was corrected to establish nett extension of the nail head. The thread capacity of the 22mm GRP bars was found to be inadequate to mobilise bond failure. This necessitated the use of the special Keller Colcrete GRP bar gripping system which would allow, if required, loading to the ultimate capacity of the bar itself. The GRP strand tendons were resin bonded into a threaded steel tube to provide a suitable gripping system to allow testing.

6.0 SOIL NAIL RESULTS

Test results and soil nail parameters are presented in Tables 1 and 2, whilst graphical presentation of average bond stress at the grout/ground interface at failure against fixed length is presented for tendon systems in Figs 2 and 5.

Results of borehole deviation monitoring are presented in Table 3. All boreholes deviated to the right, up to a maximum of 1:42. Deviation in the vertical plane ranged from 1:45 upward to 1:54 downward. No deviations exceeded the tolerable value of 1:30 recommended in BS8081.
### TABLE 1
**GRP TENDONS IN A 100 OR 200MM DIA BORE**

<table>
<thead>
<tr>
<th>Fixed Length</th>
<th>Bore Dia</th>
<th>Total Length of bore</th>
<th>Load</th>
<th>Average Bond Stress</th>
<th>Permanent Displacement after failure</th>
<th>Tendon Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>m</td>
<td>m</td>
<td>kN</td>
<td>kN/mm²</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>3</td>
<td>50 F</td>
<td>159 F</td>
<td>15 F</td>
<td>Bar</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>3</td>
<td>80 F</td>
<td>254 F</td>
<td>15 F</td>
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<tr>
<td>1</td>
<td>100</td>
<td>4</td>
<td>90 F</td>
<td>143 F</td>
<td>15 F</td>
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<td>5</td>
<td>150 F</td>
<td>159 F</td>
<td>25 F</td>
<td>Bar</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>8</td>
<td>140 F</td>
<td>111 F</td>
<td>29 F</td>
<td>Strand</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>10</td>
<td>140 F</td>
<td>89 F</td>
<td>63 F</td>
<td>Bar</td>
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<td>100</td>
<td>7</td>
<td>150 F</td>
<td>95 F</td>
<td>34 F</td>
<td>Bar</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>7</td>
<td>120 F</td>
<td>76 F</td>
<td>&gt;25 F</td>
<td>Bar</td>
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<td>100</td>
<td>7</td>
<td>170 F</td>
<td>108 F</td>
<td>43 F</td>
<td>Strand</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>10</td>
<td>190 F</td>
<td>76 F</td>
<td>49 F</td>
<td>Bar</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>12</td>
<td>190 F</td>
<td>60 F</td>
<td>19 F</td>
<td>Strand</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>12</td>
<td>210 F</td>
<td>67 F</td>
<td>37 F</td>
<td>Strand</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>19</td>
<td>210 F</td>
<td>39 F</td>
<td>19 F</td>
<td>Strand</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>30</td>
<td>210 F</td>
<td>24 F</td>
<td>30 F</td>
<td>Strand</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>6</td>
<td>190 F</td>
<td>76 F</td>
<td>57 F</td>
<td>Bar</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>7</td>
<td>320 F</td>
<td>102 F</td>
<td>&gt;70 F</td>
<td>Bar</td>
</tr>
<tr>
<td>8</td>
<td>200</td>
<td>10</td>
<td>190 F</td>
<td>38 F</td>
<td>64 F</td>
<td>Bar</td>
</tr>
</tbody>
</table>

F - Probable failure at grout/ground interface

Bond stresses shown are at grout/ground interface

* - Tensile failures of strand also observed

### TABLE 2
**20MM AND 50MM DEFORMED STEEL TENDON IN A 100MM AND 200MM DIA BORE**

<table>
<thead>
<tr>
<th>Fixed Length</th>
<th>Bore Dia</th>
<th>Total Length of Bore</th>
<th>Load</th>
<th>Average Bond Stress</th>
<th>Permanent Displacement after failure</th>
<th>Tendon Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>mm</td>
<td>m</td>
<td>kN</td>
<td>kN/mm²</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>7</td>
<td>330 F</td>
<td>105 F</td>
<td>12 F</td>
<td>50</td>
</tr>
<tr>
<td>7.5</td>
<td>200</td>
<td>9.5</td>
<td>450 F</td>
<td>95 F</td>
<td>14 F</td>
<td>50</td>
</tr>
<tr>
<td>15</td>
<td>200</td>
<td>16</td>
<td>600 F</td>
<td>64 F</td>
<td>10 F</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>7</td>
<td>150 F</td>
<td>95 F</td>
<td>32 F</td>
<td>20</td>
</tr>
<tr>
<td>7.5</td>
<td>100</td>
<td>9.5</td>
<td>190 F</td>
<td>81 F</td>
<td>29 F</td>
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<tr>
<td>10</td>
<td>100</td>
<td>12</td>
<td>205 F</td>
<td>65 F</td>
<td>37 F</td>
<td>20</td>
</tr>
</tbody>
</table>

* - Held 600kN for 15 minutes

F - Probable failure at grout/ground interface

Bond stresses shown are at grout/ground interface

### TABLE 3
**DEVIATION OF AUGERED BOREHOLE IN LONDON CLAY**

<table>
<thead>
<tr>
<th>Total Length of Bore</th>
<th>Horizontal Deviation</th>
<th>Vertical Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>Degrees</td>
<td>Proportion</td>
</tr>
<tr>
<td>30 m</td>
<td>0.01 R</td>
<td>0.02</td>
</tr>
<tr>
<td>30 m</td>
<td>0.19 R</td>
<td>0.35</td>
</tr>
<tr>
<td>27 m</td>
<td>0.64 R</td>
<td>1.36</td>
</tr>
<tr>
<td>27 m</td>
<td>0.35 R</td>
<td>1.17</td>
</tr>
</tbody>
</table>
7.0 DISCUSSION OF RESULTS AND DESIGN CONSIDERATIONS

The results of the trial nails are viewed in the light of the requirement for working nails to withstand a short term loading condition of 200kN. This requires a minimum "designed" ultimate capacity of 200kN at the grout/ground interface, based on bond capacity established from on-site trials.

Other aspects of the discussion view the influence of the elasticity of the tendon on the behaviour and exhibited average bond stresses of the tested nails of various lengths.

7.1 GRP Tendons

Initially the data from the strand and the bar system were inspected to investigate the existence of any appreciable difference in load carrying capacity and bond stress variation with fixed length. From the limited data available consistent variation could not be identified. Bearing in mind the relatively minor variation in axial tendon stiffness which is the most likely cause of change in load transfer behaviour, the inability to differentiate is perhaps to be expected.

Axial tendon stiffness (EA)

8 GRP strands - 10 x 10^6 N/mm² x mm²
22mm GRP bar - 17 x 10^6 N/mm² x mm²

Inspection of the results in Table 1 indicates that both of the GRP tendon systems could achieve an ultimate capacity in the order of 200kN when utilising a 10m fixed length in a 100mm diameter bore.

Values of the average bond stress at failure at the grout/ground interface for each fixed length tested are graphically presented in Fig 2. The shape of the curve defining the distribution is highly consistent with that established by Barley (Ref 5) in his investigation in London Clay of distribution of values of average bond stress.

![Graph of Failure Bond Stress at Grout/Ground Interface of GRP Tendon Soil Nails in 100mm Dia. Bore in London Clay](image)
at failure in Single Bore Multiple Anchors, where fixed lengths ranged from 2 to 23m. Both investigations highlight that, when using short bonded tendons (1 to 2.5m), high values of bond stress can be achieved despite the relatively high elasticity of the tendon in relation to the elastic modulus of the clay mass. The exhibited bond stress may equate with the in-situ shear strength of the clay (200 to 250kN/m²). When use is made of longer fixed lengths, then a rapid fall-off in failure bond stress is observed; down to 60kN/m² with 10m fixed length and only 24kN/m² with extreme fixed length of 28m. Based on his research, Barley (Ref 5) proposed a modified design formula for anchors (and nails) which incorporates an efficiency factor, \( f_s \), which relates efficiency in mobilisation of bond to the fixed length:

\[
T_f = \pi \cdot D \cdot L \cdot f_s \cdot \tau_f \quad \text{Equation 1}
\]

where
- \( T_f \) = ultimate load in kN
- \( D \) = bore diameter (m)
- \( L \) = fixed length (m)
- \( \tau_f \) = average failure bond stress at grout/ground interface
- \( f_s \) = average failure bond stress over utilised fixed length

A best fit value of efficiency factor, \( f_s = 1.6L^{-0.57} \), was evaluated for anchors in very stiff clay with a steel axial tendon stiffness value (EA) ranging from 44 x 10⁶ to 221 x 10⁶N/mm² x mm² (Fig 3).

The mean bond stress value mobilised at failure in the two GRP tendons with 1m fixed length (254 and 159kN/m²) was 207kN/m². The value of clay shear strength derived from averaging the nine undrained triaxial test results is also 207kN/m². The latter value is consistent with the clay shear strength value recommended for design considerations at the tunnel depth of 200kN/m². The value of "maximum failure bond stress or Cu value" utilised in evaluation of efficiency factor, \( f_s \), is

**FIGURE 3**

ANCHORS IN STIFF TO VERY STIFF CLAYS
DIAMETER 105 to 190mm

![Graph showing relationship between efficiency factor and anchor fixed length](image-url)
207kN/m². Based on this consideration, a best fit value of efficiency factor, \( fs = 1.19L^{-0.42} \), is derived from these trials on GRP strand soil nails (Fig 4) with axial tendon stiffness value (EA) ranging from 10 to 17 \( \times \) \( 10^6 \)N/mm² x mm², founded in a very stiff London Clay.

Use of design equation 1 incorporating this best fit fs value, a fixed length of 10m and a bore diameter of 100mm, evaluates the ultimate capacity at the grout to ground interface of 186kN. It is interesting to note that the ultimate capacity of a nail with half this fixed length (5m) evaluates to 143kN.

7.2 20mm and 50mm dia Deformed Steel Bar Tendons

It was acknowledged in the planning that the fixed length requirements to mobilise relatively high loads when utilising steel bar tendons would be in excess of 5m. Thus the fixed lengths investigated ranged from 5 to 15m and no data was obtained on failure bond stresses exhibited by short fixed lengths (1 to 5m) to allow direct comparison of behaviour with short GRP tendons. However inspection of Fig 5, which presents average failure bond stress at the grout/ground interface against fixed length, does reveal, as expected, that the gradient of the stiffer steel tendon (50mm dia bar with axial stiffness value of 393 \( \times \) \( 10^6 \)N/mm² x mm²) is less than that of the 20mm dia steel tendon (axial stiffness value of 63 \( \times \) \( 10^6 \)N/mm² x mm²); i.e. the stiffer the tendon, the more uniform the stress distribution along it, and the more efficient is the system in increasing ultimate load with increase in fixed length.

Evaluation of efficiency factor values (fs) is, as with the GRP nails, based on maximum available average bond stress value equating to an average clay shear strength value of 207kN/m². This is presented on Figure 6 and, over the limited
extent of the range investigated, the best fit values of efficiency factor were: \( fs = 0.61 - 0.02L \) for the 50mm bar, and \( fs = 0.61 - 0.03L \) for the 20mm bar.

These best fits represent linear \( fs \) versus fixed length relationships for fixed lengths greater than 5m and, as can be seen from Fig 7, both lie within the envelope defined by those of GRP tendons and the multiple anchors. It may be reasonable to expect that a best fit curves defining the \( fs \) values for fixed lengths less than 5m would also be contained within those envelopes.

Use of design equation 1 incorporating this best fit \( fs \) value for a 20mm bar, with a 10m fixed length in bore of 100mm diameter, evaluates to an ultimate capacity at the grout to ground interface of 202kN, whilst the capacity of half that fixed length (5m) evaluates to 150kN.
8.0 SUMMARY

The results of these extensive trials present a useful demonstration of the behaviour of various soil nail systems in London Clay and the influence of tendon stiffness on the load transfer mechanism. The application of external load to the nail simulates the probable loading mechanism applied to the distal 50% of a working nail which is founded in the "resistant" (passive) section of the soil when used for slope stability. The proximal 50% of the working nail is loaded in reverse direction by the active soil.

Irrespective of the tendon stiffness, when bond length (½ nail length) is short (< 2.5m) the bond mechanism is highly efficient and in bond mobilises a very high proportion of soil strength. As can be seen from Figure 7, when bond length becomes larger, the efficiency of the more elastic tendons (GRP) falls off more rapidly than that of the stiffer tendons (anchors and 50mm diameter steel soil nails). This phenomenon is simply quantified in the design equation by the use of an efficiency factor which relates bond efficiency to bond length. Expressions evaluating this factor have been derived for both GRP and steel tendon bond stresses made available in these trials.

The results suggested that bond lengths of around 10m in a 100mm diameter bore were required in order to attain 200kN capacity nails. Initially production nails were installed utilising GRP bars within 18 to 20m long soil nail bored holes. Nails were installed after every 10m advancement of tunnel face, so that fixed length of the working nail did not fall below 10m and the nail had the capacity to resist a 200kN force applied by the shotcrete face to the nail face plate.
GRP bars were selected in the initial stages, to enable the hydraulic excavators, simply to break off the bar with the bucket. However the presence of GRP fibres in the clay resulted in the material being classified as contaminated, and thus attracted significantly higher tipping charges. In subsequent installations, 20mm diameter steel bars were substituted with little or no effect on the excavation cycle, despite removal, using oxy-acetylene cutting gear or disc cutters, being required.

In total, soil nails were installed to supplement tunnel face retention over a 100m length of tunnel where structures were in particularly close proximity to the tunnel and where specific restrictions were applied to compensation grouting operations.

REFERENCES

Ref 1 Barley, A.D., 1995. "Pull-out tests on 22mm diameter glass reinforced plastic bar from cement grout". Confidential, Keller Colcrete.


Ref 3 Code of Practice For Ground Anchorages BS8081 (1989) BSI Publication.
