GROUTING OF ANCHORS TO RESIST HYDROSTATIC UPLIFT
AT BURNLEY TUNNEL, MELBOURNE, AUSTRALIA

Devon Mothersille and Stuart Littlejohn

1Managing Director, Geoserve Global Ltd & Single Bore Multiple Anchor Ltd, 51 Inchmery Road, London, England, SE62NA; devon.mothersille@sbmasystems.com

2Emeritus Professor of Civil Engineering, University of Bradford, Bradford, England BD71DP; gslittlejohn@ntlworld.com

ABSTRACT: Failure of the unreinforced concrete invert of the Burnley Tunnel during a field pressure test to 600kPa required the installation of some 5200 permanent ground anchors for structural remediation. The paper describes grout simulation gun barrel tests, carried out under factory controlled conditions, to investigate and demonstrate the effectiveness of the anchor components when grouted and subjected to tensile loading. In addition, the techniques to ensure satisfactory in situ grouting of the anchors under hydrostatic pressures of up to 600kPa are described. The associated testing and quality control systems employed for the grouting are detailed as they were considered essential in order to ensure that the highest quality product was constructed and fit for its intended purpose over the 120-year designed service life of the tunnel.

INTRODUCTION

The Burnley Tunnel, forming part of the Melbourne City Link project, was constructed between 1996 and 2000. The three lane east-bound tunnel is 3.4km long comprising 2.9km of driven tunnel, part of which runs 60m beneath the River Yarra. The tunnel section, a modified ellipsoid shape 16m wide x 9m high, was driven using the New Austrian Tunnelling Method. The tunnel walls had a 300-450mm thick concrete lining and to seal the tunnel against groundwater pressures an additional 1.8m thick unreinforced concrete slab was placed over 2.6km of tunnel floor.

In late 1999 following a ten-month period of grouting to seal construction joints in the tanking membrane (waterproofing grout curtain around tunnel periphery), concerns were raised about the ability of the tunnel to withstand the 60m head of water. During subsequent water injection tests at pressures up to 600kPa, several invert slab panels (typically 12m long and 12.7m wide) heaved up to 200mm and cracking was observed in others.

In order to facilitate structural remediation of the invert, some 5200 permanent ground anchors were installed in the underlying Melbourne mudstone to tie down 160 panels over a 2km length of the concrete invert, the anchor lengths varying from 7m to 13m with working loads of 700kN and 1000kN. In the middle section of the tunnel, where the hydrostatic head was greatest, the ground anchors were installed in downward inclined arrays at 1.1m centres along the length of the tunnel, the actual geometry depending on the tunnel location and geological conditions encountered (Figure 1). At either side of this section, towards the west and the east where there was a reduced hydrostatic head, vertical twin anchors were installed at centres varying from 1.1-1.3m along the length of tunnel (Figure 2). Bearing in mind the
location of the tunnel relative to the water levels, the control of groundwater represented a significant challenge during the anchor construction process.

Gun barrel tests were carried out under factory controlled conditions followed by full-scale grout simulation tests to ascertain the effectiveness of grouting with respect to the design and location of the ground anchor components, e.g. tendon, spacers, corrosion protection and packers. Such testing proved vital in identifying anomalies in ground anchor fabrication which could have affected adversely the durability of the anchors and would not have been discovered through the routine application of on-site proof load – tendon displacement acceptance tests. This work was complemented by the production of a detailed material specification for every component used in the construction of the anchors, such as component type and name, place of manufacture, material composition, material standard, dimensions/tolerances and relevant test certificates.

Figure 1 Layout of inclined bar anchors in the invert of Burnley Tunnel

Figure 2 Layout of vertical bar anchors in the invert of Burnley Tunnel showing also the position of grout tubes for the application of the primary anchor grout
In advance of production anchor works, techniques were developed to water test and pre-grout anchor boreholes. Water tests were also carried out on the tendon’s corrosion protection system which comprised a HDPE corrugated duct. Testing and quality control systems employed for the grouting were detailed, as they were essential to ensure that the highest quality product was constructed, and fit for its intended purpose over the 120-year designed service life of the tunnel.

SITE GEOLOGY

The tunnel was constructed through inter-bedded marine sediments of Silurian age known as the Melbourne mudstone. This formation consists of inclined beds of hard, fresh siltstone, interrelated with beds of very hard, fresh, fine grained sandstone, which have been extensively folded locally and occasionally intruded by igneous rocks.

The deep section of the tunnel, where the anchors were installed, lay within the Melbourne mudstone formation that was generally competent and moderately fractured, the fracture and bedding plane spacing typically varying between 100mm and 300mm. A number of shear zones were also present and these varied up to several metres thick comprising thin seams of intensely fractured and sheared material with clay coated surfaces typically 500mm thick. Benson et al (2005) record that for the tunnel length involved, material UCS values ranged from 30MPa to 60MPa.

GROUND ANCHOR BOND

The ground anchor design was carried out in accordance with BS8081:1989 and the RTA QA Specification B114 (1998). An ultimate rock/grout interfacial bond stress of 3MPa was derived initially from field testing undertaken by Haberfield and Baycan (1997). Reference was also made to BS8081:1989 which recommends that, in the absence of results from pullout tests, ultimate skin friction may be taken as 10% UCS of the rock up to a maximum value of 4MPa, given the design 28-day grout strength for neat cement grout (w/c = 0.45 by weight) of 40MPa. Based on the rock material UCS values of 30 to 60MPa an ultimate rock/grout bond of 3MPa was confirmed.

PRELIMINARY GROUND ANCHOR TESTS

Two specialist anchor contractors were used during the anchor installation programme; these were Austress-Freyssinet and National/VSL in collaboration with Geotech Pty who were primarily responsible for the drilling and pre-grouting of the boreholes. Bearing in mind that the substantial ground anchoring programme was remedial work (i.e. not part of the original tunnel design), it was essential that the highest quality product was designed and installed to ensure fitness for purpose throughout the service life of the anchored structure. As a consequence, the specialist anchor contractors were required to carry out a series of preliminary tests to verify the integrity of the corrosion protection system when subjected to proof loading and to demonstrate that the grouting of the anchors would be effective and satisfactory given the location of the various tendon components.
Gun barrel tests

The concept of placing anchor tendons in grout confined by steel tube to simulate a rock mass is well established and has been used by researchers, e.g. Littlejohn and Weerasinghe (1997). Known as gun barrel tests, these methods permit inspection of the tendon and its corrosion protection system after it has been subjected to test loading. At Burnley Tunnel the overall objective was to demonstrate absolute confidence in the performance of the corrosion protection system.

*Gun barrel tests carried out on Macalloy ‘PT’ bar and strand tendons by Austress Freyssinet*

Austress Freyssinet used two types of tendon; a 1295kN characteristic tensile capacity, 40mm diameter threaded Macalloy ‘PT’ bar for working loads of 700kN and a 7No. 15.2mm diameter strand tendon with a capacity of 1750kN for working loads of 1000kN.

Two gun barrel tests were carried out using 40mm diameter bar. Each bar with a 1m bond length was located centrally in corrugated plastic duct, with a sinusoidal shaped profile, to meet the requirements of the RTA Specification B114 (1998). The ducting had a nominal ID of 67mm and OD of 86mm with a minimum wall thickness of 2.1mm, amplitude of 7.5mm and wavelength of 21mm. The bars were fitted with plastic spacers to ensure centralisation within the duct.

The assembly was then placed in the gun barrel comprising a 1.2m long, 330mm OD steel pipe with the bar and duct seated on the temporary base plate welded to the pipe. External to the corrugated duct, aluminium circular ducting was located centrally within the pipe to facilitate spacing of the arrangement and spiral anti-burst reinforcement was utilised over the entire length of the gun barrel (Figure 3). The steel base and internal diameter of the pipe was coated with oil to ensure easy stripping from the grout after curing. The outer annulus was completely filled with grout and the inner encapsulation grout column was terminated approximately 100mm lower to allow movement in the event of failure during stressing. The grout mix comprised 80kg OPC, 15kg Meyco FC 100, 100mL RheoBuild 1000 and 36 litres of water.

*Figure 3 Schematic representation of gun barrel test with top plate and stressing assembly removed (dimensions in mm)*
The initial quality control tests indicated a 14.3-14.5 second ASTM flow cone reading, a specific gravity of 1.80 to 1.88 using a Baroid mud balance, 0-0.4% bleed at 4 hours and 100mm grout cubes achieved 44-45MPa at 5 days and 54-63MPa at 28 days.

Using a 1500kN annular hydraulic jack, a series of loading cycles were applied to the bar with increasing peak loads in increments of 10% UTS until 80% UTS was reached. Load was held constant at each peak load for a minimum of 5 minutes to check for creep.

Post stressing inspections, following complete dissection of the grouted bar and corrosion protection system, revealed that the encapsulation duct sustained no damage or distress and confirmed satisfactory performance. Maximum test bond stresses of 7.28MPa and 7.43MPa were exhibited at the grout/bar interface and the outer corrugated duct sustained bond stresses of 3.83MPa and 3.91MPa.

A similar procedure was undertaken for a 7No. 15.2mm diameter low relaxation strand tendon using a 4m long gun barrel and an identical grout mix design. Consistent with normal usage in the ground anchor industry the 15.2mm diameter low relaxation strand was generally noded to form three closure points within a 4m tendon bond length.

Two tests were undertaken; the first test failed at the grout/steel interface, providing an ultimate bond of 3.66MPa and test bond of 4.53MPa at the grout/duct interface. The second test did not fail confirming maximum test bond values of 3.78MPa and 4.67MPa at the grout/steel and grout/duct interfaces, respectively. Post test inspections confirmed that in both cases the corrosion protection system showed no signs of distress.

_Gun barrel tests carried out on Stressbar by National/VSL_

VSL carried out similar gun barrel tests on 38mm diameter (UTS = 1080MPa) and 46mm diameter (UTS = 1710MPa) threaded Stressbar for working loads of 700kN and 1000kN, respectively. In order to assess the load transfer mechanism at failure these tests were designed with 1m and 1.5m bond lengths, respectively, and tested in load cycles up to 82.5% UTS. The outer annulus within the gun barrel comprised 50MPa reinforced concrete and the inner grout was OPC with a w/c ratio of 0.45 by weight and anti-bleed Methocel at 0.1% by weight of cement.

The initial gun barrel test confirmed rupturing of the corrosion protection system at the transition point between plastic corrugated duct in the fixed anchor length and smooth plastic duct in the free anchor length (Figures 4 and 5). This observation necessitated the implementation of higher levels of quality control during tendon fabrication with particular emphasis on adequate 200mm lap lengths between the two types of duct and correct application of the heatshrink bonding sleeve (i.e. ensuring that the adhesive element within the heatshrink was completely extruded and visible before insertion in the borehole).
Figure 4 (left) Rupture of corrugated ducting and distortion of heatshrink wrap after initial gun barrel testing

Figure 5 (right) Damaged sample of corrugated ducting

The 38mm diameter Stressbar exhibited an ultimate bond stress of 6.5MPa at the grout/bar interface where post stressing inspections revealed evidence of shear failure. The grout/duct interface exhibited a test bond stress of 4.9MPa without showing any signs of distress in the corrugated duct or cracking of the surrounding grout.

Similar results were achieved for the 46mm diameter Stressbar with shear failure at the grout/bar interface established with an ultimate bond stress of 6.02MPa and a test bond stress of 4.6MPa at the grout/duct interface.

Grout simulation tests

Preliminary grouting trials were carried out to demonstrate the effectiveness of the grouting operations by the execution of a standard grouting procedure with the tendon installed in a vertical rigid plastic pipe to simulate a vertical anchor borehole. The completed grouted tubes were dissected after grout curing to inspect the integrity of the grouting particularly in the vicinity of the main tendon components, e.g. centraliser/spacer, compressible packer and coupler.

Grout simulation tests undertaken by Austress Freyssinet

Austress Freyssinet grouted two types of tendon (bar and multi-strand) into 7m long plastic pipes with 125mm ID and sealed bases to simulate boreholes. These were secured to a vertical scaffold tower with access platforms. Initially the encapsulations were water tested, after insertion of the tendon, using a 2m excess head over 30 minutes with observations taken every 5 minutes. After confirmation of no discernible loss of water the corrugated duct was grouted by gravity displacement along with the annulus between the encapsulation and the simulated borehole. After a minimum of three days and a grout UCS of 20MPa the pipes were laid horizontally for dissection and examination.

The cured grouted tendons were cut transversely, at approximately 500mm centres, with a disc cutter. Inspection of the transverse sectional cuts, through the bonded and de-bonded lengths of both the bar and strand anchor tendons, revealed good quality grout and efficient
void filling inside and outside the corrugated duct. The strand tendons were not fully centralised but adequately spaced to ensure efficient grout penetration. The curvature of the strand tendon and protective duct within the bond length between centralisers was clearly evident and led to the recommendation that external centraliser spacing in the bond length be reduced from the proposed 2.5m to not greater than 1.5m. In the case of the bar tendon, the restricted annulus around the taped bar coupler, albeit small, had allowed the full passage of grout in the duct and effective grouting of the annulus between bar and encapsulation duct. Based on the test results, a minimum outer grout cover of 15mm was specified for the corrugated duct over the tendon bond length and 10mm cover for the smooth plastic duct over the tendon free length. Inspections of longitudinal cut sections revealed satisfactory grouting for both bar and strand tendons with no indication of voids due to air bubbles or bleed.

*Grout simulation tests undertaken by National/VSL*

Bearing in mind that the majority of the VSL anchors were designed at a downward inclination of 2V:1H, along sections of the tunnel, it was important that the grout simulation accurately represented this layout. In order to prevent transfer of compressive stresses from the fixed length into the free length grout column, a compressible packer comprising plastic foam material was introduced at the top of the fixed length. This additional component was included in the tendon fabrication for the grout simulation exercise. During the first test, the dissection of the cured grout simulation identified a 400mm long, 80mm wide zone of poor grout, including a void underneath the compressible packer. This unsatisfactory feature necessitated the introduction of a grout vent tube which allowed the passage of grout through the packer and into the free anchor length (Figure 6).

*Figure 6* Exposure of compressible packer showing position of vent tube in a tendon comprising 7 x 15.2mm diameter steel strand
During initial water tests, carried out on the bar anchors, observations confirmed failure due to a significant loss of head which could not have reasonably been accounted for by the escape of air bubbles within the system. It was also noted that the outer protective duct showed no signs of leakage, bearing in mind that previous test work had confirmed that leakage from a pin hole could be identified by water loss at a differential head of 2m. Further investigation confirmed that the water loss occurred at a small annulus between the bar coupler and the surrounding greased sheathing. The measured water loss generated from a differential head of 2m could have falsely indicated that the outer duct was damaged resulting in unnecessary delays during the production anchor works. This observation led to the introduction of a grease impregnated tape and a heatshrink protected special foam wrap at each end of the coupler location. Such measures proved essential to ensure watertightness within the internal system (Figure 7).

![Image of bar coupler with grease impregnated tape and foam wrap]

**Figure 7** Sealing the ends of the bar coupler with grease impregnated tape and foam wrap to allow uninhibited movement during stressing and prevent water ingress

**GROUTING**

**Field proving tests**

Following the preliminary gun barrel and grout simulation tests, field proving tests at the tunnel with 1m fixed anchor lengths confirmed a rock/grout bond value of 2.29MPa without any sign of failure for the OPC grout (w/c = 0.45).

**Production anchor grouting**

Production fixed anchor lengths ranged from 3.5m to 4.0m and overall lengths from 7m to 13m with working loads of 700kN and 1000kN. The tendons were installed in boreholes of 115mm diameter (38mm diameter Stressbar) and 125mm diameter (46mm diameter Stressbar, 40mm diameter Macalloy PT bar and strand tendons).
To isolate highly permeable features immediately beneath the concrete invert panel, the hole was drilled through the problematic area and a plastic lining tube was inserted and sealed into the underlying sound rock. Thereafter, the hole was drilled to the required depth.

On completion of borehole drilling, a water test was carried out to assess the permeability. Specifications for borehole watertightness acceptance required each borehole to attain a field permeability value of less than 1.0 Lugeon. A packer was inflated inside the borehole, water was then pumped into the borehole at an excess pressure of 100kPa over the confirmed ambient water pressure of 550kPa measured over a 10 minute period, during which time the volume of water injected was recorded. Pre-grouting was required if the boreholes failed to meet the acceptance criterion. In such circumstances, cement/bentonite grout was injected and thickened in the sequence w/c = 2.1, 1.4 and 0.7, each with 3% bentonite by weight of cement, until refusal at 650kPa or a maximum of 200 litres had been injected. The injection hole packer was kept in place for 6 hours and re-drilling was permitted after 10 hours, following which the hole was water tested again. This process was repeated until the water test result was approved, the majority of the boreholes being accepted within five attempts and typically the grout volume absorbed per attempt ranged from 40 to 80 litres.

Thereafter, the protective corrugated duct and tendon were inserted into the borehole. In order to confirm the integrity of the corrosion protection the corrugated duct was filled with water by tremie and injection continued for 5 minutes to remove air bubbles. In situ water testing of the duct was then carried out using a 2 metre excess head within the duct encapsulation with measurements at 0, 15 and 30 minutes. The acceptance criterion was no discernible loss of water, after which the anchor tendon was tremie grouted within the encapsulation for load transfer at the grout/steel interface and within the annulus between encapsulation and borehole for load transfer at the grout/duct and rock/grout interfaces.

As a grout quality control, three Baroid mud balance density tests and two samples of two 100mm grout cubes were taken per mixer per shift. When the grout UCS had attained 30MPa, each anchor installed on the site was acceptance tested to 150% of its working load in accordance with RTA QA Specification B114 before being certified satisfactory for service. On-site acceptance testing provided confirmation of the effectiveness of the in situ grouting process.

IMPROVEMENTS TO STANDARD

The RTA Specification B114 (1998) was the principal document governing the design, construction, stressing and testing of the anchors. As a direct result of work undertaken during the preliminary trials, improvements were made to the RTA Specification which have subsequently been implemented in the 2007 version of the document. Specifically, these include the recommended use of split (re-usable) gun barrels for proof loading and subsequently examining the integrity of the corrosion protection system and clarification of the corrosion protection methods to satisfy extended design service life (e.g. 120 years). Amendments were also made to the terminology associated with various aspects of the
anchor components and the pregrouting procedure to reduce the likelihood of grout loss during the placement of primary grout.

CONCLUSIONS

The circumstances associated with the decision to apply remedial stabilisation to the Burnley Tunnel were unusual and called for the design and installation of a large number of ground anchors. The project specification demanded high levels of scrutiny over every aspect of the tendon fabrication, installation and testing, and this necessitated the implementation of a preliminary test programme, a detailed material specification for all system components and quality control procedures for the installation of the ground anchors. Gun barrel and grout simulation tests were vital in identifying anomalies in tendon fabrication that would not have been identified in routine acceptance testing and that could have affected adversely the long-term durability of the anchor. Bearing in mind that 5200No anchors were installed the costs of the test programme were very small in comparison to the production anchor works.

It is also significant that all production anchors were routinely subjected to on-site tests with rigorous acceptance criteria relating to proof loading to ensure a margin of safety, load-displacement to ensure efficient load transfer to the tendon bond length and a stable load in service before they were judged suitable for the permanent works. This is a unique feature of ground anchor practice in geotechnical engineering. The technical rigour applied to the ground anchor work and the lessons learned led to the development of improved standards of practice, e.g. Australian RTA QA Specification B114 (2007).

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REFERENCES


