Geotechnical aspects of the Strood and Higham railway tunnel relining and refurbishment

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Abstract: The Strood and Higham Railway Tunnel is some 3.7km in length and was originally built as a canal tunnel enabling boats to pass freely between the river Medway and the river Thames. The tunnel was excavated between 1819 and 1824 through reasonably competent Seaford Chalk such that many sections were left unlined. In 1830, a 100m long section was opened out in cutting as a passing basin for the canal boats before in 1844 a single track railway was added to the tunnel. Finally in 1846, the canal was infilled to permit a double railway track to be built. Over the years, the operating railway has suffered disruption because of flooding, problems associated with old shafts and from chalk falls in unlined sections of the tunnel, one of which in December 1999 caused derailment of four railway carriages. Six months later one of the original construction shafts collapsed and the tunnel was closed for four weeks, re-opening only after a 30km/hour speed restriction was applied. This was clearly not a viable long-term solution and following option studies, in January 2004 a 12 month blockade began, to allow the tunnel to be fully refurbished. This paper summarises various geological and geotechnical aspects associated with the relining and refurbishment works.

Résumé: Le tunnel ferroviaire 'Strood et Higham' est d'environ de 3,7km de longeur. A l'origine, Il était construit en tant que tunnel de canal pour donner aux bateaux la possibilité de passer librement entre les fleuves Medway et Thames. Les travaux d'excavation se sont déroulés entre 1818 et 1824 à travers la Craie de Seaford, qui était assez competente laissant plusieurs sections sans envoutement. En 1830, une section de 100m était ouverte créant une tranchée pour permettre aux bateaux de canal de passer. En 1844 un chemin de fer á seule voie était ajouté au tunnel. Finalement, en 1846, le canal était élargi afin de permettre la construction d'une voie supplémentaire. Au cours des années, l'exploitation du chemin de fer a été perturbée par des inondations, des problèmes associées aux vieux puits et des chutes de craie dans les sections du tunnel sans envoutement, dont l'une était derrière déraillement de quatre wagons en decembre 1999. Six mois plus tard, l'un des puits de construction original s'etait écroulé et le tunnel était fermé pendant quatre semaines, puis re-ouvert seulement après l'introduction d'une limite de vitesse de 30km à l'heure. Manifestement, cela n'était pas une solution viable à long terme. A la suite des analyses d'options, en janvier 2004, le tunnel a été suspendu pour 12 mois dans l'objectif de rénover le tunnel. La présente étude reprend un nombre d'aspects géologiques et géotechniques des travaux de renforcement et de renovation.

Keywords: chalk, collapse, concrete, geophysics, grouting, tunnels.

HISTORY OF THE TUNNEL

General

Strood and Higham Railway Tunnel is located on the North Kent Line between Higham Station and Strood Station. The tunnel runs in a south-easterly direction (Figure 1) and was originally constructed as a canal tunnel as part of the Thames and Medway Canal which ran from Gravesend on the River Thames to Strood on the River Medway. The canal was first conceived by Ralph Dodd so as to allow sailing barges to pass between the two rivers thereby avoiding the longer sea journey around the Isle of Grain. Construction of the tunnel commenced in April 1819 and was completed in May 1824 being open to traffic on 14th October 1824.

The original single tunnel was 4012 yards (3668m) in length and at the time was the second longest in Britain and the largest in terms of volume of excavation. The tunnel had a 5 foot (1.5m) towpath on its northern side with the base of the canal some 11 feet (3.5m) below towpath level lying at about 2.4m AOD. Towpath level is now about 1.8m below track level (Figure 2). The tunnel was designed to take 60 ton sailing barges up to 100 feet (30.5m) long and 18 feet (5.5m) high. The canal was closed for 10 weeks in 1830 so that a 139m long section of tunnel could be opened out in cutting (up to 30m deep) to allow a passing basin to be built. This open section, known as the "Bombhole", split the tunnel into two sections, the Higham Tunnel being 1529 yards (1400m) long and the Strood Tunnel 1 mile 572 yards (2129m) long.

Geological maps for the area typically show Upper Chalk overlain on occasion by Thanet Beds, the tunnel having been constructed wholly through the Seaford Chalk unit. Cover over the top of the tunnel varies up to 50m. The geological memoir describes the Upper Chalk as being soft, featureless white chalk with bands of thalassinid flints at 1m to 3m separation. Marl beds are practically absent and hard bands only occur locally. The strata dips at a few degrees to the north-northeast and major faulting is absent.

Tunnel construction: period 1819 to 1824

Information on tunnel construction is provided by Varley (1996). The tunnel was built by first dropping several working shafts, believed to be twelve in number, from ground level to tunnel level along a surface line of sight. These working shafts were typically 9 to10 feet (2.7m to 3m) in diameter and were generally left unlined within the chalk. It was common practice to construct narrow climbing shafts adjacent to the working shafts in order that miners could enter the tunnel without interrupting the removal of rock up the working shafts, but whether these actually exist is uncertain. From the base of each construction shaft irregularly profiled pilot headings, 7 feet (2.1m) square, were driven outwards in both directions just below the level of the proposed crown.

Figure 1. Tunnel location plan

On completion of the pilot heading from portal to portal, a manual tramway was installed and the roof was then cut out to form an elliptical arch, since "an ellipse is found in practice to sustain the greatest super-incumbent weight, and to prevent the loose and crumbling portions from separating from the roof or arch" (Varley, 1996). The springing line for the foot of the arch commenced at about 1.8m above towpath level. The stability of the roof was assessed when the floor of the tunnel was at this level. Where "weak and crumbling" rock was evident a brick arch was formed; its thickness being varied to suit the ground conditions.

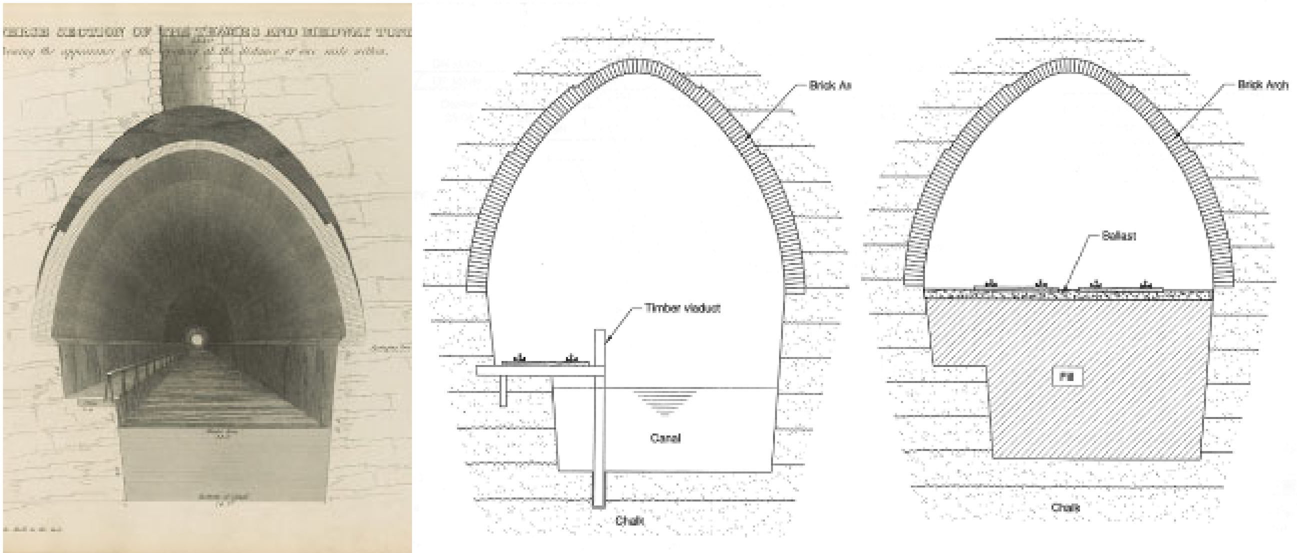
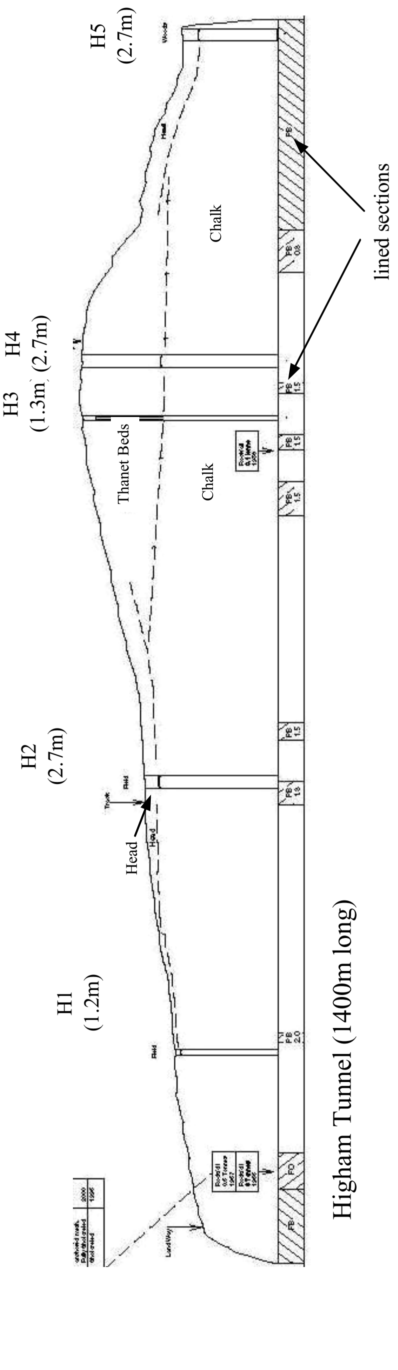


Figure 2. Tunnel sections illustrating the historical development of the tunnel



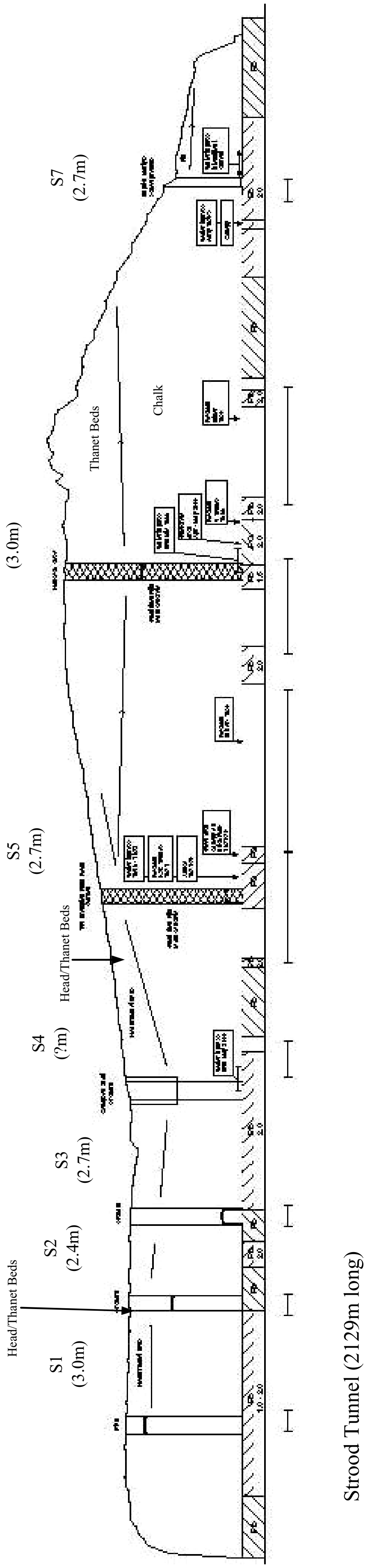


Figure 3. Tunnel longitudinal section, indicating shaft locations/diameters

The chalk rock was described as being generally hard and massive, such that a considerable portion of the tunnel could be left unlined. Most of the excavation was undertaken by miners with hand picks but it is reported that gunpowder was used on occasion were the rock was hard. The original pick marks are still visible over most of the remaining unlined sections of tunnel. There were, however, "numerous and appalling difficulties" (Varley, 1996) in some sections due to the presence of flint veins and loose joints. "Many of the workmen were killed by the falling in of large masses occasioned by vents which were imperceptible, in the most solid and apparently compact parts of the work, and where no precautions had been taken, or deemed necessary" (Varley, 1996). Excavation within "loose and shaken ground" was first achieved by cutting parallel galleries to connect the roof headings and the working level at springing line elevation. Vertical timbers on wide foot blocks were erected at 6 to 10 foot (1.8m to 3m) centres between the remaining chalk pillars, with horizontal head beams to support the roof. The pillars were then cut out and the brick arch built on a temporary timber frame arch.

The quantity of water found during shaft sinking was apparently much less than anticipated. The bottom and sides of the canal were lined with puddle clay to prevent water loss in areas of "soft and crumbling rock".

Operational history: period 1824 to 2003

The canal operation ran into difficulties almost as soon as it opened, despite increasing the throughput of traffic by introducing the passing basin in the central section by excavating out the 30m deep central "Bombhole" section in 1830. In particular the canal suffered from excessive water loss and pumps had to be installed to maintain the water level. As a result the proprietors formed the Gravesend and Rochester Railway and Canal Company and in 1844 added a single track railway over the length of the canal, one rail being sited on the towpath and the other supported over the water by wooden piles. A report produced at this time stated that the original shafts had been covered over and partly filled in. There were also rumours at this time that the tunnel was unsafe, and a stability trial was undertaken which consisted of firing a cannon several times in the tunnel but no rock falls occurred. General Paisley also made an inspection in 1845 which similarly included the firing of blank mortars in the tunnels. He ordered the addition of a small amount of brick lining.

The tunnel opened to rail traffic on 10th February 1845 and was an immediate success, so much so that in December 1845 the company was bought out by the South Eastern Railway Company. Robert Stephenson inspected the tunnel in 1846 and advised that the canal be infilled with chalk rubble to permit a double track railway to be built. The tunnel walls were trimmed back to increase their width, and to permit the installation of further brick arches, supported on chalk benches. A double track railway was subsequently installed and the tunnels were re-opened to railway traffic in 1847. In 1904, a 21m deep well with adits driven out from three levels was constructed in the "Bombhole" to provide a water supply for the steam trains. The well was used until the 1960's when the line was electrified.

Both tunnels contain lined and unlined sections. The width of the tunnel at rail level varies between 8.1m and 9.6m depending on whether it is unlined or lined and the type of lining. Where brick lining springs from haunch level (commonly at about 2m height above the rail level) the tunnel width at springing level is 9.3m. The tunnel height from rail level to crown varies from 5.5m to 6m although increases to 8m locally because of overbreak or due to over-excavation of the crown area ("cathedral areas") because of local chalk stability problems at the time of its construction. The typical tunnel profile is shown in Figure 2. A longitudinal section, showing location of shafts and various types of lining (prior to refurbishment works) is given in Figure 3.

Although most of the lined sections were formed of brickwork, because of ongoing problems with chalk falls throughout its recent history, a variety of other support measures had been installed since the 1970's, including Armco lining, shotcrete and steel arch canopies with supporting brick arches. Prior to start of the refurbishment works, some 871m, representing 62% of the 1400m long Higham Tunnel remained unlined, a further 40m being lined with Armco or shotcrete. In comparison, in the Strood Tunnel, some 529m, representing 25% of the 2129m tunnel length, remained unlined, a further 130m being lined with Armco, steel arches or shotcrete. This 130m length comprised a 70m length adjacent to shaft S6 (lining formed of 17m steel arch canopy on brickwork followed by 53m of Armco installed in 1973 to 1976 when the shaft was grouted) and a 60m shotcrete length installed in May 2000 following large chalk falls that occurred in the area over the period December 1999 to early May 2000 (refer to Table 1).

NEED FOR TUNNEL RELINING AND REFURBISHMENT

Since the railway tunnel has been operational, a number of ongoing ground-related problems have been encountered. These include:

- flooding of the tunnel after sustained periods of heavy rainfall
- chalk falls from the unlined sections of tunnel
- problems associated with the unlined shafts and in particular surface collapse of ground into unlined shaft S4

Flooding of tunnel

The first reported incident of flooding due to high groundwater table in the chalk was in January 1988, which short-circuited the rail's electrical system. This led to new pumps being installed in the well in the "bombhole" with the aim of controlling the surrounding chalk water levels by pumping, automatic switches being installed to ensure that pumping starts when the water is 2.5m below track level (+1.7m AOD) and stops when the water is 7.3m below track level (-3.1m AOD). The pumped water (typical abstraction 0.7 Ml/day) is discharged via a hose which pipes the water through the Higham Tunnel before feeding into a ditch near Higham Portal which feeds a remnant of the Thames to Medway Canal. However, flooding problems have continued, most notably in the early months of 2001 following a sustained period of heavy rainfall and consequently, a new drainage system was installed as part of the tunnel refurbishment works.

Chalk falls from the unlined sections of tunnel

Table 1 summarises the information related to known chalk falls that have occurred in the tunnels since 1957 up to 2004 based on records held by Network Rail. Since this time there have been 46 reported chalk falls, of which 12 could be considered large (i.e. falls above 0.2 tonne; equivalent to one event every 4 to 5 years). The greatest frequency of logged falls was during the period 1990 to 1999 (18 falls; equivalent to approximately 2 events per year). Information from a Spacetec survey of the existing tunnel profile undertaken at 1m intervals along the entire unlined length of the Strood and Higham Tunnel indicates that falls of 4 to 7 tonnes have been common in the past, failures being typically confined to the unstable shoulder and haunch areas, block detachment being along subhorizontal bedding surfaces forming the crown and adversely disposed joint sets aligned at about 30 degrees to the tunnel alignment and dipping in both directions at angles varying from 40 to 80 degrees (see Figures 4 and 5). Falls are particularly common immediately adjacent to brick lined sections, where there is increased tendency for joints within the chalk to "daylight" because of over excavation of the tunnel profile to allow the brick lining to be built.

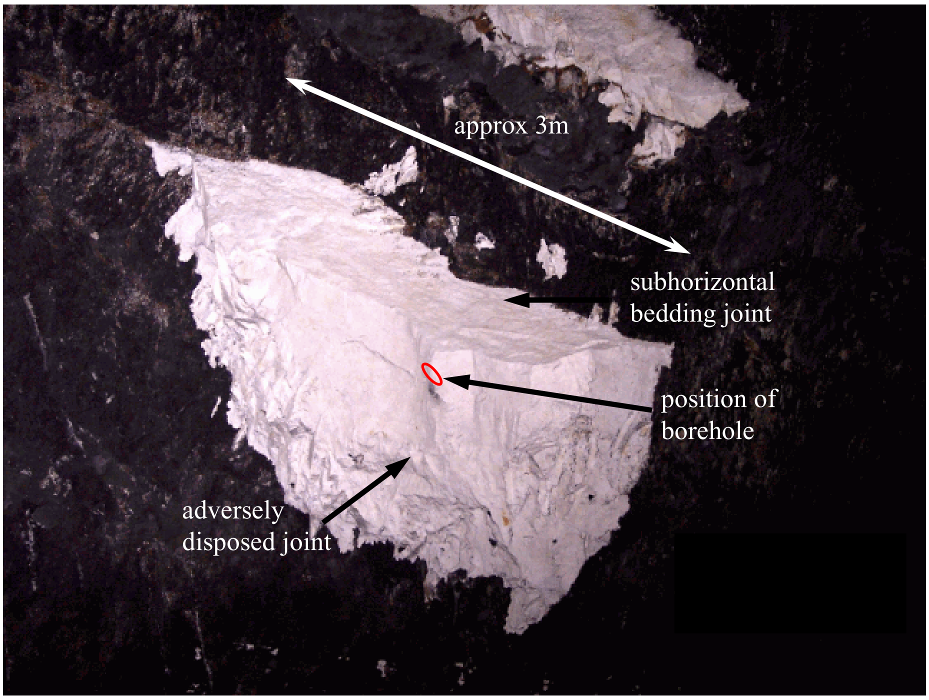


Figure 4. Chalk fall in Higham tunnel triggered by borehole coring in 2001 (see Table 1)

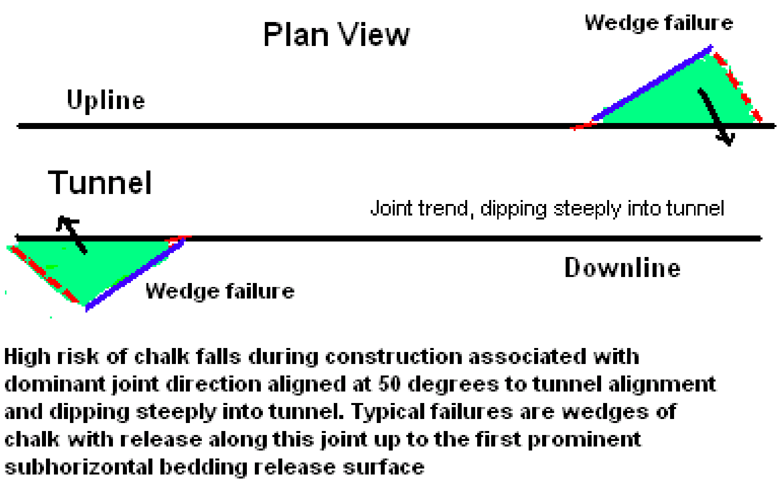


Figure 5. Schematic of typical chalk failure mechanism

Based on the evidence there was a risk that a passenger train could be derailed within the tunnel in future due to ongoing chalk falls which could be initiated by several differing reasons or combinations of causes. There is little doubt that most of the previous falls relate to the presence of adversely disposed jointing within the chalk which produced a metastable condition especially in the shoulder and haunch area, with falls being triggered by such factors as water ingress, vibration from passing trains, temperature and moisture changes, minor falls of soot from the roof and walls and changes in the above ground land use.

Table 1. History of known rock falls in Strood & Higham Tunnel

Date	Tunnel	Approx weight (kg)	Comment
22/3/1957	Strood	12000	
25/9/1966	Higham	3000	near Higham Portal
1967	Higham	500	water ingress from broken water main
1971	Strood	750	water ingress swimming pool leakage
1973 (4/7, 7/8 & 13/9)	Higham	< 7	3 small falls
1974 (11/7 & 30/8)	Higham	< 15	2 small falls
16/10/1976	Higham	14	
26/6/1980	Strood	27	
17/9/1980	Strood	1	
23/10/1980	Strood	150	damp area
28/5/1982	Higham	14	
4/2/1983	Higham	220	
6/6/1985	Higham	3	
4/3/1986	Higham	200	10000 kg removed during maintenance
16/9/1988	Higham	not known	brickwork fall
30/12/1989	Strood	140	
19/4/1990	Strood	140	
15/8/1990	Strood	140	
1990 - 1999	Both	< 8	18 falls; downline blocked in 1996
16/12/1999	Strood	6000	derailed train; water ingress noted
2000	Strood	6500	close to 16/12 fall; wet area
2001	Higham	2000	failed during coring a borehole (see Fig 4)
3/10/2003	Strood	3000	minor water ingress; slickensided joint
24/1/2004	Strood	600	
30/2/2004	Higham	25	
4/3/2004	Higham	300	at commencement of relining works

Figure 6. Surface void produced by collapse of shaft S4

Problems associated with unlined shafts (collapse of shaft S4)

Of the twelve shafts present along the alignment (with diameters ranging from 1.2m to 3m), five are in the Higham section and seven in the Strood section. Eight shafts were clearly visible in the crown of the tunnel and the positions of a further three were indicated by the pattern of brickwork lining the crown. The position of the remaining shaft, S4, was confirmed when, on 12th June 2000, a large hole (Figure 6) opened up in the orchard over the centreline of Strood Tunnel in the vicinity of a shaft position previously reported by the Kent Underground Research Group.

Although there was no distress to the tunnel, both tunnels were closed to rail traffic. Following inspections, Railtrack (now Network Rail) decided to keep the line closed and to inform immediately any landowners who had shafts beneath their land. It was also decided to carry out remedial works to any shaft considered to pose a significant risk either to the railway beneath or to the people or property near the shaft tops. Following a series of investigations, including historical searches, ground investigations in and around shafts and CCTV surveys up from the shaft base from inside the tunnels, many of the shafts were infilled with grout or foamed concrete. This work was carried out from the date of the collapse until when the line was reopened on 31st July 2000. Further investigations, however, were continued at shaft S4, with eight boreholes being drilled from the surface around the perimeter of the shaft to a depth of some 40m (i.e. 10m below the bottom of the shaft) to allow cross hole seismic tomography to be carried out.

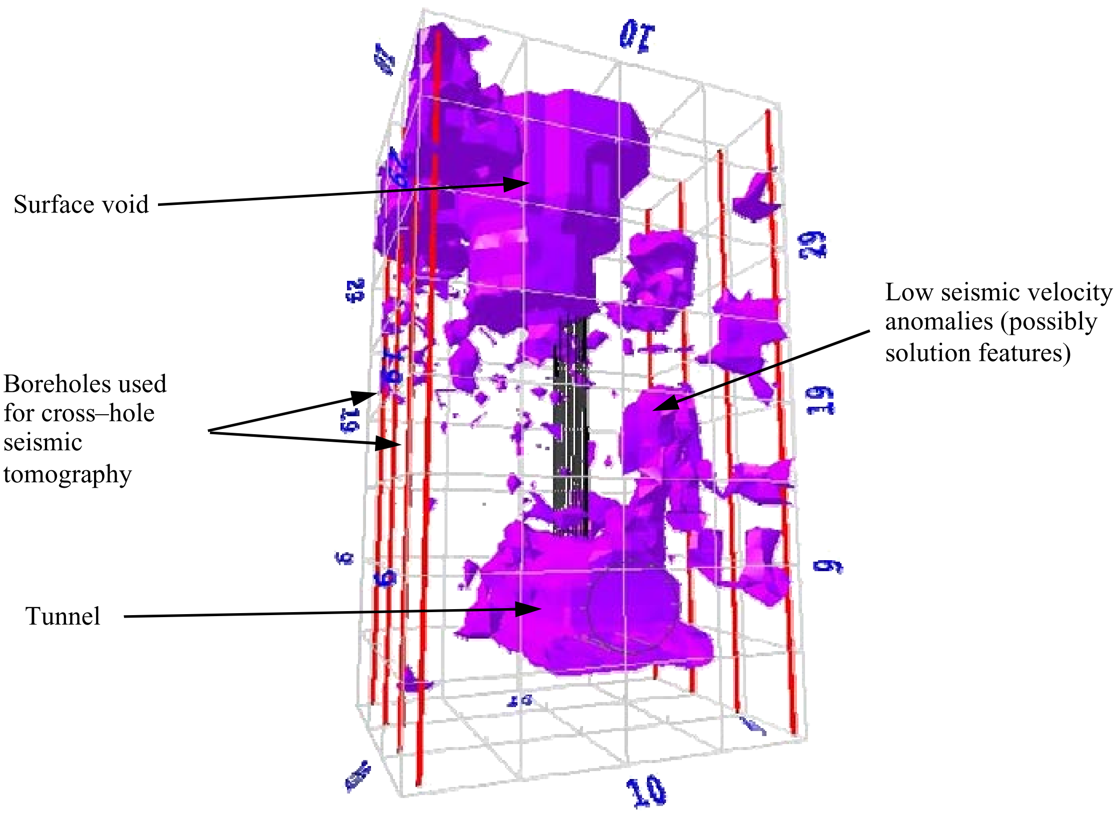


Figure 7. Tomogram in the region of shaft S4

This method involved the measurement of the travel times of seismic waves between pairs of boreholes in order to derive an image of seismic velocity, or tomogram, for the intervening ground. Figure 7 shows a tomogram for the region around the shaft, which indicates an anomalously low velocity region believed to represent the shaft into which the ground collapsed on 12th June 2000. Confirmation of this was provided by exploratory drilling in the tunnel in 2004. In the light of these results, the collapsed shaft and hole at the surface were subjected to various forms of ground treatment, details of which are given in the next section.

REFURBISHMENT AND RELINING WORKS

Relining and refurbishment of the Strood and Higham Tunnel was carried out during a 12 month blockade period starting in January 2004 and comprised the following work:

- lining the remaining unlined sections of tunnel (including those sections covered and/or supported by Armco, shotcrete or a steel canopy arrangement)
- construction of refuges typically 1.4m wide and 0.7m deep at 20m centres along the full length of tunnel
- stabilisation and infilling the remaining shafts including collapsed shaft S4
- brickworks repairs where required

- installation of a new drainage system between and beneath the tracks
- complete renewal of the track

Use was made of as much of the existing rail track as possible. The works were carried out 24 hours a day for 5 days a week, with maintenance and movement of materials being undertaken on Saturday and Sunday. The lining work involved a number of operations, principally:

- piling and capping beam works ahead of the main protective canopy
- rock bolting, chalk trimming and arch/mesh erection from beneath the canopy
- concrete lining works using a steel shutter behind the canopy

Those areas where Armco, steel arches and shotcrete lining had been installed since the early 1970's were typically rock bolted and meshed upon removal of the lining.

Figure 8. Tunnel lining works

The work was progressed simultaneously on two fronts, commencing at each tunnel portal with materials being supplied from the Bombhole area centrally placed between the two tunnels (Sims et al., 2005). Transport logistics formed an important part of the project to ensure that materials arrived at the required working area at the right time thus avoiding costly delays to the work. The two protective canopies, designed and fabricated specifically for the works, included 6m long crash decks at the rear to protect the live railway track and tunnel invert during chalk trimming operations (see Figure 8). The two steel shutters for casting the structural lining were manufactured by CIFA of Italy. The lining work can be broken down into three main construction stages, each of which are detailed below:

(a) Work undertaken ahead of the main protection canopy

- *Casting a 0.6m wide by 0.3m deep first stage capping beam* along both sides of the unlined section of tunnel with inserts at 2m centres for positioning the raking minipiles.
- *Installation of 300mm diameter concrete minipiles*, some 7.5m long drilled outwards at 2m centres at about 17° to vertical, so as to extend through the canal fill and into the chalk sidewall. Each minipile was reinforced to its full depth by the installation of a 112mm diameter steel tube centrally placed in the hole, the tube acting as a tremie pipe during concrete placement. The piles were bored by three small auger rigs fitted with canopies to protect personnel from chalk falls (see Figure 9)
- *Casting a 0.6m wide 0.5m deep reinforced second stage capping beam* above the first stage capping beam and installed minipiles.

(b) Work undertaken from beneath the main canopy

- *Installation of 100mm square 4mm thick steel mesh* held by four 4m long steel rock bolts over the central crown area above and outside the sidewall areas where additional trimming of the chalk was required. The drilling was carried out from the front end of the canopy by miners using air-leg drilling machines, the 24mm diameter bolts being installed in 27mm diameter holes and grouted using fast-setting Celtite 2 component grout resin to obtain the required bond strength (minimum 150 kN per bolt, trials having being undertaken prior to construction to confirm this strength). The bolts were installed at 1m centres along the entire length of the unlined tunnel. The installed mesh and bolts stabilised the chalk in this area and provided protection for the plant and workforce operating at the back of the canopy.

- *Trimming the chalk sidewall to achieve the required profile*. This was undertaken by a small roadheader which sat on the crash deck at the rear of the canopy, any falling chalk hitting the protective steel crash deck. The depth of trim varied along the length of the tunnel but was typically 100mm to 200mm thick (occasionally up to 500mm) and the trimming was carried out over a length of about 2 to 3m such that a new steel arch could be set. On occasion, wedges of chalk fell out of the sidewall immediately above the trim zone.
- *Installation and erection of steel arches* at 2m centres, lateral steel tie bars being used to connect adjacent arches and a timber prop installed to the chalk in the crown. Grouted bags and later timber packing was used to support the arches against the chalk at shoulder level as necessary (see Figure 10).

Figure 9. Auger rig used for piling operations

(c) Work undertaken from behind the main canopy

- *Drilling, installation and cement grouting of horizontal 7m long Fibregrip GRP 31/15 hollow anchors* through the capping beam at 2m centres on both sides of the tunnel into the chalk.
- *Casting of the structural concrete arch* to a minimum 150mm above the crown of the steel arches and to the inside of the steel arch such that it was exposed. A specially designed self compacting concrete was used to minimise vibration so as to reduce the potential for chalk falls. Plastic fibres were added to the concrete (8kg per m^3) to minimise shrinkage and the volume of concrete for each 10m pour was of the order of 60 to $70m^3$.
- *Grouting of the void above the crown* using an expanding, non-structural lightweight foam (Carbotech Fosroc Wilkit Foam T) following the initial curing of the concrete.
- *Installation of a new central drain* along the complete length of Higham Tunnel and the 100m northern end of Strood Tunnel and replacement and renewal of the old track and ballast in both tunnels.

For shaft stabilisation, apart from collapsed shaft S4, Wilkit lightweight foam was also used, a steel cover plate being rock-bolted into the chalk using resin-grouted fibre-glass bolts at the base of each shaft in the unlined section. At shaft S4, core drilling was initially undertaken from within the tunnel to establish the location of the shaft and this was followed by treatment works carried out both from within the tunnel and from the ground surface (Wall et al., 2005). A summary of the treatment successfully carried out at shaft S4 is given in Table 2 and illustrated in Figure 11.

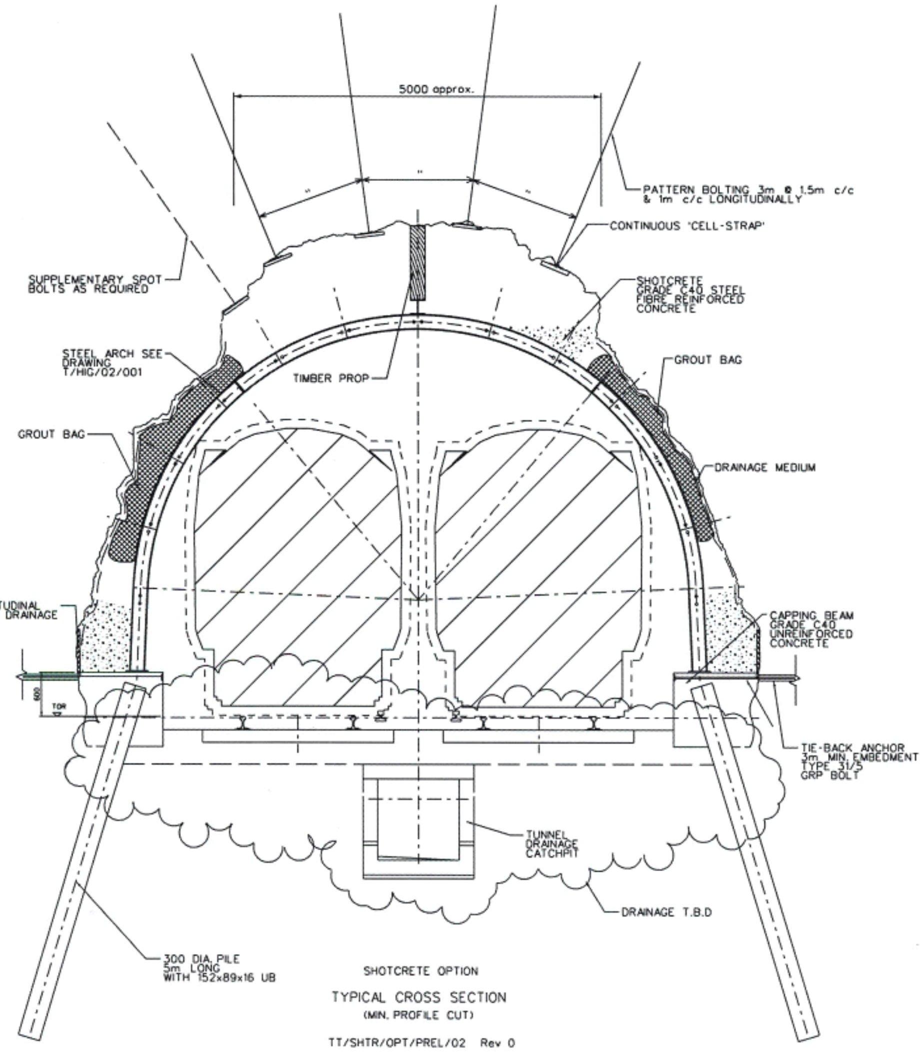


Figure 10. Typical cross section showing various aspects of the tunnel refurbishment works

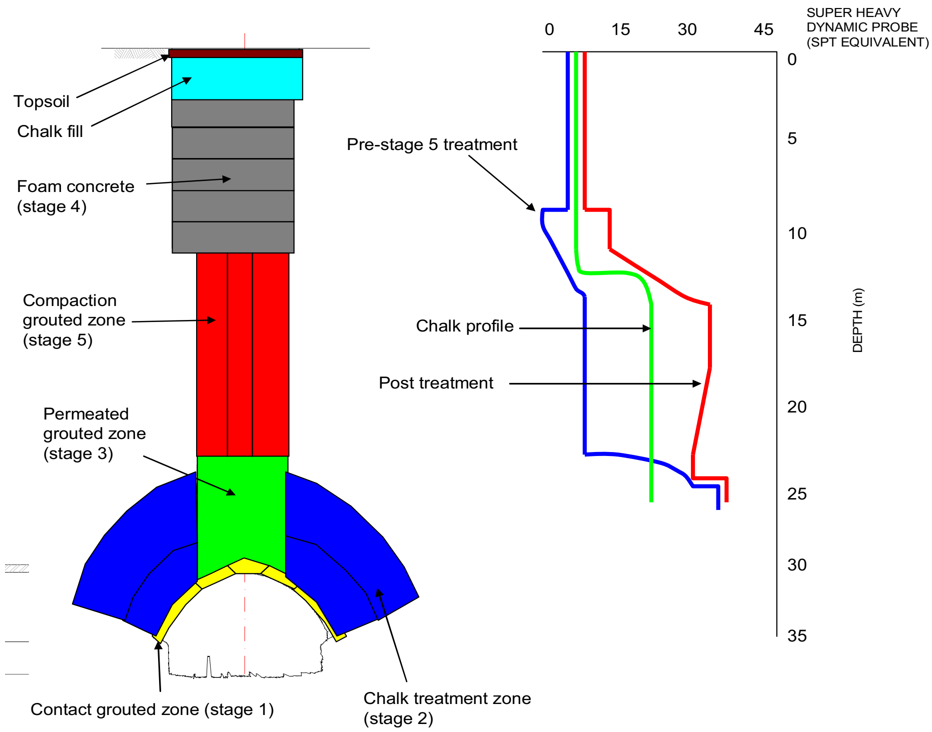


Figure 11. Treatment of shaft S4

Table 2. Summary of treatment works at collapsed shaft S4

	Stage and zone of treatment	Form of treatment
Treatment from within tunnel	*Stage 1* Brick lining/chalk interface (0 to 1m from crown/haunch)	Contact grout injection into 87 number 42mm diameter boreholes using 2 : 1 water to bentonite-cement (ratio 1:10) or conbex-cement (ratio 1:10) mix by wt. Injection pressure up to 0.5bar. Grout take was 40m^3 i.e. 19% of rock volume
	Stage 2 Crown/haunch area surrounding central shaft area (1to 6m from crown/haunch)	Chalk permeation grouting into 87 number 27mm diameter boreholes & 4 number 68mm diameter tube-a-manchette boreholes using 2 : 1 water to bentonite-microfine cement (ratio 1:10) by wt. Injection pressure up to 12bar. Grout take was 3.8m^3 i.e. 0.4% of rock volume
	Stage 3 Central shaft area (0 to 7m from crown/haunch)	Permeation grouting into 22 number 68mm diameter tube-a-manchette boreholes using 2 : 1 water to bentonite-cement mix (ratio 1:10) by wt for first pass and 2 : 1 water to bentonite microfine cement (ratio 1:10) by wt. for subsequent passes. Injection pressure up to 12 bar. Grout take was 17.4m^3 comprising 12.6m^3 on 1st pass, 2.6m^3 on 2nd pass & 2.2m^3 on 3rd pass i.e.17% of rock volume.
Treatment from ground surface	*Stage 4* Infilling of surface collapse/void 11.5m deep & 12.6m diameter	Hole infilled up from base using 36 m^3 of high strength foam concrete followed by 460 m^3 of lower strength foam concrete followed by chalk infill and then topsoil at surface
	Stage 5 Grout injection into boreholes drilled down 24.5m inside/around perimeter of 3m collapsed shaft i.e. extending to zone treated from within tunnel	Compaction grouting into 7 number 114mm diameter boreholes (3 primary , 3 secondary & 1 central tertiary test hole) using 2:1 water to grout with solids comprising 6 parts sharp sand (minor addition bentonite):1 part cement:1 part PFA by wt). Grout pressure in primary and secondary holes 0.5 bar/m depth and 1bar/m depth respectively. Grout take was 285m^3, equivalent to 17% of rock volume assuming 5m diameter zone of treatment

RISK ASSESSMENTS

So as to better define the risk associated with chalk falls occurring during the tunnel refurbishment works, a detailed survey was undertaken in each unlined section of tunnel before commencing the main construction activities. The unlined tunnel was initially zoned into various risk categories based on a number of factors, including:

- The prevailing tunnel profile (e.g. regular, irregular),
- Evidence of past and more “recent” falls (“recent” evidenced by clean, non-sooted joint surfaces),
- Evidence of minor water ingress, and
- The nature of discontinuities (dip, dip direction, degrees of freedom, openness, planarity, coating, etc.).

Areas or sections of concern were colour-coded so as to forewarn the miners working in or accessing the tunnel. Each individual pile location was similarly marked up, categorised as a low, medium or high risk so as to inform the personnel of the risk of chalk falls occurring during the capping beam and piling operations. Walking in the unlined sections of tunnel ahead of the main protective canopy was prohibited for anyone apart from essential personnel; and even then, only via the central 6 foot section which typically had a low risk categorisation, having had only 4 “recent” falls, all less than $0.3m^3$, out of a total of 30 in both tunnels. The assessment was constantly updated during the progress of the works and a record kept of any falls occurring during the roof bolting, sidewall trimming operations or before the secondary lining was installed.

CONCLUSIONS

Despite the sometimes hazardous and difficult ground conditions prevailing in the unlined sections of the Strood and Higham Tunnel, the lining works were successfully completed on time, enabling the tunnels to be re-opened to traffic in early January 2005. Most of this achievement was the result of the vigilance and experience of the skilled miners and associated workforce undertaking the work.

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