Papers

Ground treatment to improve tunnel progress on the Channel tunnel marine drives

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Synopsis

To optimise progress through water bearing fissured chalk 5km out from the English coast, TML and Stent Soletanche carried out a controlled programme of tube à manchette grouting to both marine running tunnels, ahead of the tunnel boring machines. The grout used was a crystalline hydrated lime silicate – Silacsol T. Treatment allowed tunnelling of both the marine running tunnels to accelerate through difficult ground conditions.

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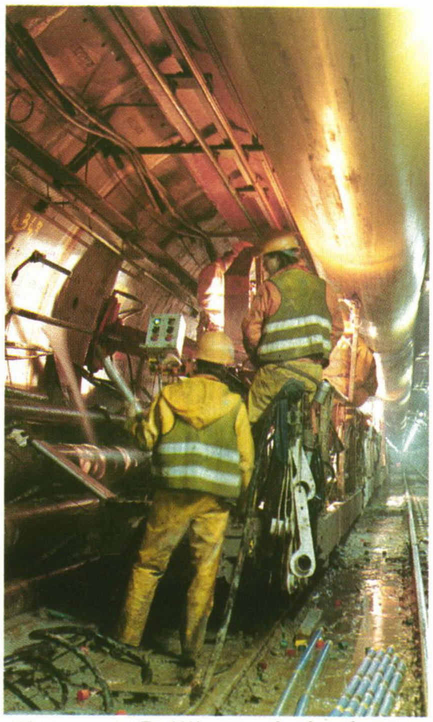


Picture 1: Drilling train in the service tunnel.

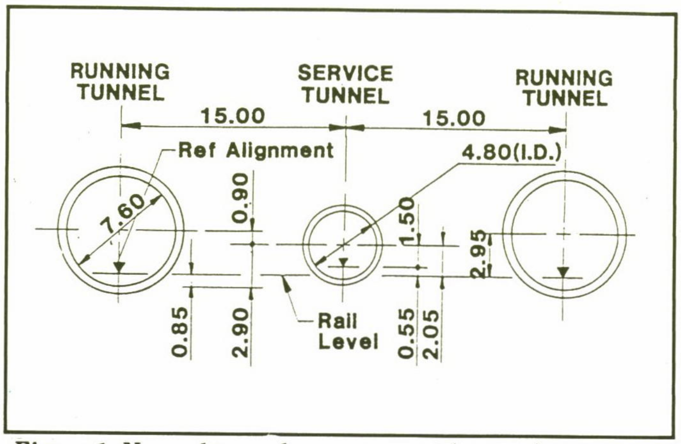


Figure 1: Normal tunnel arrangement (metres).

Introduction

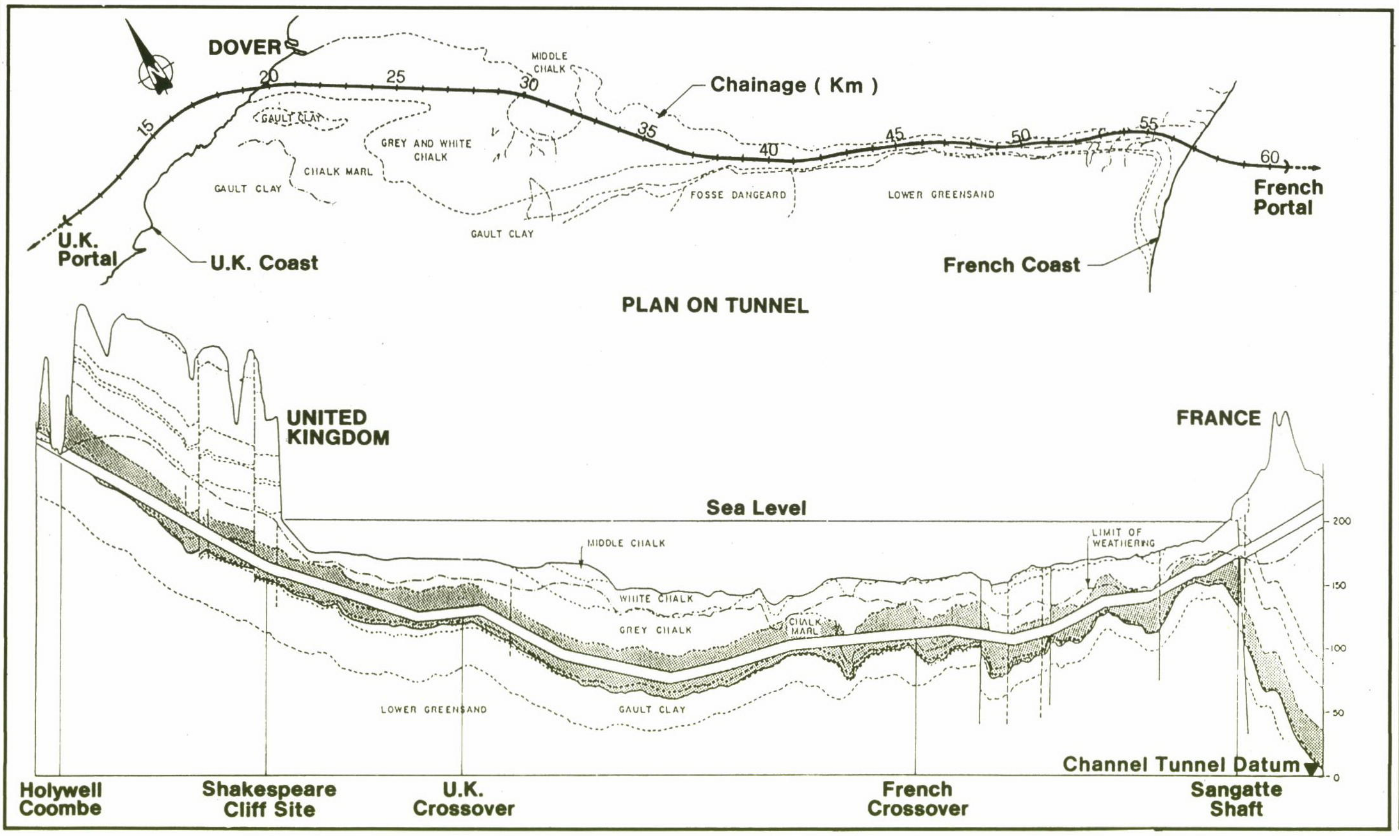
The Channel tunnel is in fact three parallel tunnels – a service tunnel of 4.8m nominal internal diameter with two running tunnels of 7.6m nominal internal diameter spaced at 15m centres on either side (**Figure 1**). This configuration is maintained in all areas except the crossovers, pump stations and Shakespeare Cliff access area where other constraints change the distances between the three tunnels.

The tunnel alignment is designed to accommodate a high speed railway with maximum gradients of 1% and horizontal radii of 6000m. At the same time it follows the geologically favoured tunnelling horizon of the Lower Chalk Marl, see **Figure 2.**

The geology of the Straits of Dover has been examined and explored for the purposes of a tunnel over many years. However, the cost of marine boreholes and seismic surveys is extremely high and particularly difficult in the world's busiest shipping lanes. The net result is that the boreholes are on average 1km apart and in some cases over 2km from the tunnel alignment; seismic survey lines are typically 1km apart.

In order to provide more detailed geotechnical information the service tunnel was to act as a pilot tunnel and was to be driven 10km

Figure 2: Geological plan and cross section.



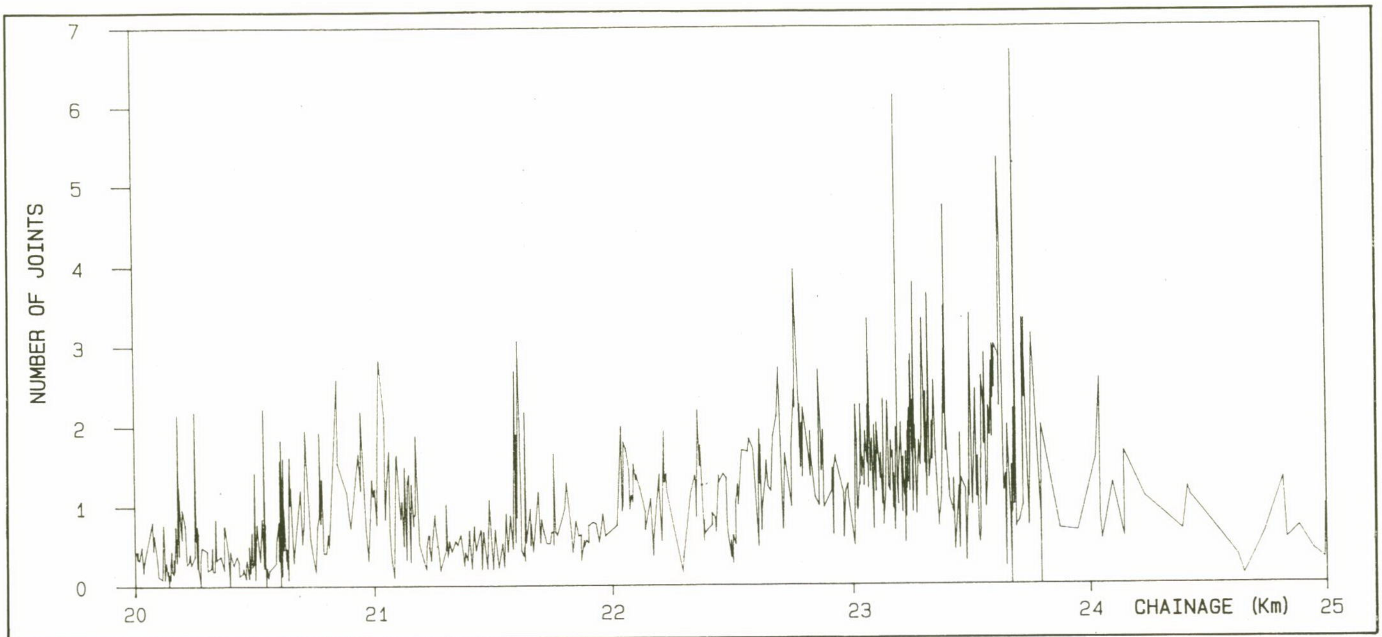


Figure 3: Number of joints observed per square metre in face and and sidewall exposures in the marine service tunnel – chainage 20 to 25km.

to 15km ahead of the running tunnels.

Service tunnel drive

This tunnel was driven by an open face TBM which incorporated provisions to seal the face in the event that it encountered large inflows which could not be controlled by the pump system. The pump system was designed to cater for seepage flows and the anticipated flow from encountering an ungrouted borehole.

Probe holes were drilled ahead of the face to detect unfavourable conditions. Initially these were in pairs 100m long and overlapped 20m. As tunnelling progressed this was reduced to one hole 250m long with a 20m overlap. Micropaleontological examination of the drill washings was used to determine that the longer borehole trajectory was within the projected line of the tunnel bore.

Cored vertical probes were used to determine the position of the glauconitic marl marker bed to check 'actual' against 'predicted' geology.

The tunnel was lined with an expanded precast concrete segmental lining. The design life of the lining is 120 years and segments are reinforced and cast from 60N concrete. Random drilling through these segments could not be permitted and so specific locations, marked with dimples in the concrete surface, were designed into the segment to allow the drilling of a pattern of holes from service tunnel to the running tunnel. This pattern allowed holes at about 1m spacing across the running tunnel face.

Ground conditions in the marine service tunnel

The marine service tunnel drive started from Shakespeare Cliff at chainage 19 823m in December 1987. At chainage 20 140m and some three months into the drive, the increased frequency of jointing and water ingress, accompanied by considerable overbreak, made tunnelling advance difficult in spite of modifications to the TBM.

This continued until chainage 23 802m where conditions improved and tunnelling reached programmed outputs. The records of jointing, water ingress and overbreak in the face and ringbuild areas are shown in **Figures 3, 4** and **5.**

Ground treatment trial

After the experience with the service tunnel, modifications were made to the running tunnel boring machines to enable them to cope with these ground conditions. However, it was realised that with the larger diameter and the fact that the tunnel crown was higher in the succession – and thus nearer the sea bed – it would be necessary to examine the possibility of treating the relatively tightly jointed chalk marl, from the service tunnel, prior to the arrival of the running tunnel boring machines.

A programme of sideways probes was instituted to examine permeabilities at the higher level of the running tunnel crown. These ranged from 1 to 29 Lugeons[3]. On the basis of these results it was decided to carry out a ground treatment trial. The service tunnel drive could not be delayed and also due to the limited room in the service tunnel the location for the trial had to be from a cross passage.

The plan for the trial was to inject an area of ground in the crown zone of the running tunnel and to excavate a heading into the treated ground to examine the effectiveness of the grouting. Lugeon tests were to be carried out before and after treatment, prior to excavation work.

Six major ground treatment specialists were asked to provide proposals and budgets for carrying out a trial to prove the effectiveness of their proposed treatment. All returned full technical proposals which ranged from cementitious grouting, to resin grouting and other specialist systems.

[3]The lugeon is a unit for measuring watertightness in boreholes. 1 lugeon = 1 litre/min/metre of hole at an effective pressure of 1000kN/m^2 (10 bars).

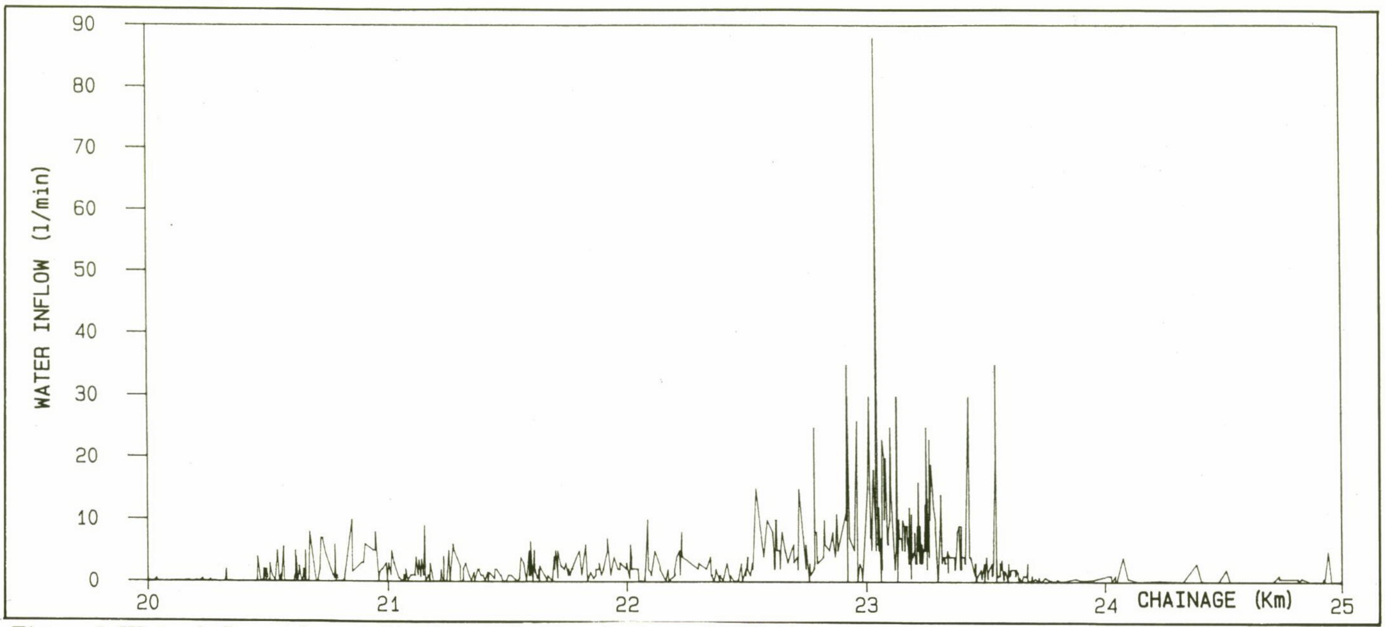


Figure 4: Water inflows observed in the marine service tunnel – Ch 20 to 25km.

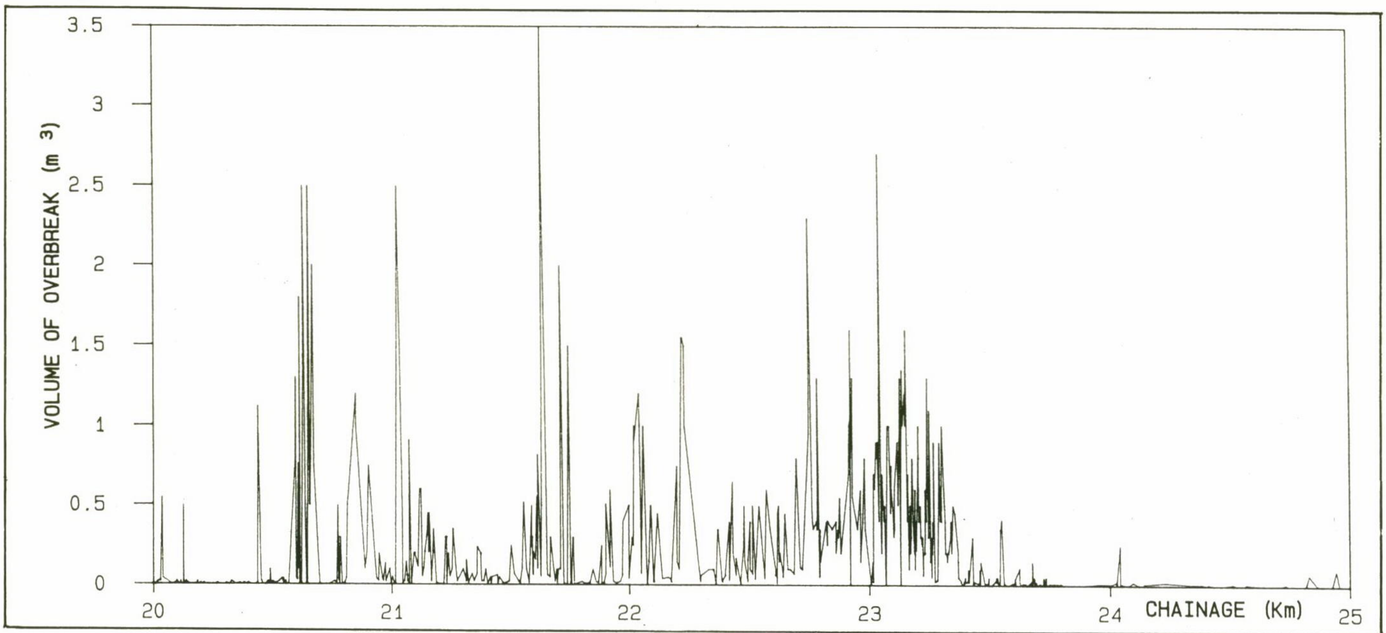


Figure 5: Volume of overbreak observed in the marine service tunnel – Ch 20 to 25km.

Stent Soletanche was chosen to carry out the trial. It had successfully completed grouting in similar conditions on the French side of the project, the material it proposed to inject appeared to be very suitable for the small fissures involved, and its proven control and recording system was ideally suited to a trial situation.

The trial was carried out during September 1988. Some 30 holes were drilled and grouted in stages up to hole depths of 15m. The reduction in permeability achieved was from a range of 4.7-14.5 lugeons before treatment to 0-3.9 lugeons after treatment.

The results of the trial can be summarised as follows:

a) Permeability of the ground could be substantially reduced by injection of the proposed grout – Silacsol T.
b) Controlled hydrofracture was required to enable effective injection.
c) Injection using tube à manchette gave a much better degree of locational control than open hole grouting.
d) While permeability was reduced there was no resulting inherent improvement in joint adhesion.
e) Hole centres at 3m were suitable for treatment purposes.

Running tunnel drives

The driving of marine running tunnel north commenced in February 1989 at chainage 19 300m. It first encountered the more adverse ground at about chainage 20 200m. Despite the modifications to the boring machine, carried out as a result of the service tunnel experience, the conditions were bad enough to require that cast iron linings were used in place of concrete segments. Thus the rate of progress was reduced, and with the resulting longer standup times required, the situation deteriorated further.

The geotechnical records showed that the water inflow had a salinity approaching that of seawater, and the inflows were larger than those recorded in the service tunnel.

The service tunnel records clearly indicated that the worst zone was yet to come. After considerable discussion between TML and Eurotunnel it was jointly agreed that a 700m length of both running tunnels should be treated. It was accepted that the main effect would be to reduce permeability with no guarantee of an improvement in the stability of the excavated hole.

However, it was considered that a reduction in water inflow would have a very positive benefit on the morale of the mining crews and would considerably reduce plant maintenance requirements, which had been dramatically increased by the saline water ingress. It was also possible that the stability of the excavations would be improved by reducing lubrication along the joint surfaces.

Following exploratory discussions with Stent Soletanche on 3 November 1989, an instruction to proceed was given on 28

November 1989 with an on-site start date of 18 December 1989 and a completion date of 25 March 1990. The treatment had to be completed before the arrival of the tunnel boring machines at the treated section.

Scope of the ground treatment works

Analysis of the effect of groundwater on the tunnelling operations in general indicated that grouting to reduce the permeability in the ground surrounding the upper half of the marine running tunnels would provide the most cost effective method of treatment.

Two treatment options were investigated:

a) a 2m wide grouted annulus over the upper half of the tunnel;

b) a similar 3m wide annulus.

After review, the 3m annulus was adopted to maximise the effectiveness of the grouting programme in the time available.

In order to assess the success of the ground treatment during the work a relatively simple and relevant method of testing the treated ground was required. The primary performance specification was therefore defined as the requirement to achieve a maximum insitu permeability of 3 lugeons in the ground after treatment.

Ground treatment principles

The means of achieving the specified performance requirements were based on the following principal points:

a) Ground treatment was to be achieved through a programme of drilling and grouting, utilising the tube à manchette system. The TàM technique allowed for individual grouting of short (500mm) lengths of the drill holes, and for the re-grouting of any 500mm length if required. It also had the additional advantage of providing flexibility in working procedures, the drilling and grouting phases of the works could be programmed and executed independently of each other.

b) The grout holes were to be drilled from the marine service tunnel (MST), perpendicular to the tunnel so as to intersect the line of the north and south marine running tunnels (MRTN and MRTS). The location of the grout holes was designed to provide the most efficient coverage of the treatment zone, bearing in mind the limited available locations for drilling through the tunnel lining. A fan shaped row of three grouting holes, spaced at 3m intervals (ie alternate tunnel rings) was drilled perpendicular to the MST over the 700m length, for both MRTN and MRTS. Grouting holes were 17.8m to 20.5m in length, see **Figure 6.**

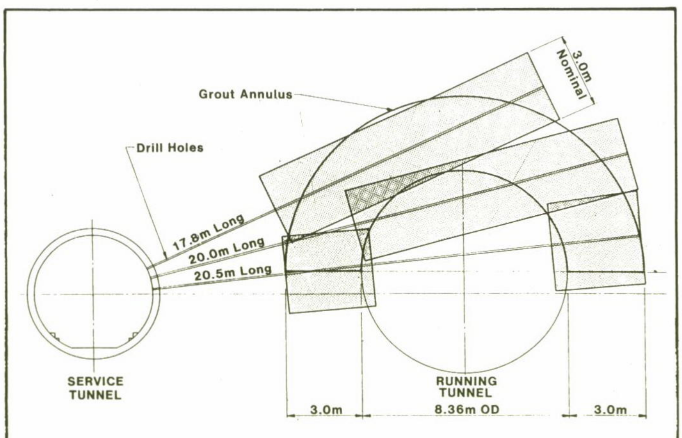


Figure 6: Grout treatment – schematic cross section.

c) Based on the experience of the ground treatment trial and work in France, Silacsol T grout, a proprietary silicate-based low viscosity grout, was used to achieve the necessary penetration of the joints in the chalk.

Silacsol T grout

Silacsol T is a silica-based grout incorporating a calcium reagent, and a fine grained inert filler. It is specifically designed for good penetration in the treatment of sands and fissured rocks, with small particle size characteristics. The reaction of the calcium with the silica causes the formation of an hydrated calcium silicate crystalline grout. This crystalline characteristic, rather than the gel of the more standard silica grouts, provide greater strength, reduced permeability, and greater permanence (ie less deterioration with time).

Drilling and grouting requirement

Materials storage and workshop facilities were located at the surface on the Shakespeare Cliff lower site.

In the 4.8m id service tunnel, space was at a premium. One of the fundamental tenets of the treatment was that there should be minimum disruption to the other activities in the MST. At the time these activities were the main TBM drive and the crossover, cross passage and pump station construction works. To allow rail access to these other activities the drilling and grouting operations were restricted to one side of the MST only.

All operations were contained on three specially designed trains:

a) Drilling train – four track mounted rotary drilling rigs, TàM sleeve grouting station and TàM materials storage.

b) Grouting train – six grouting pumps and recorders, TàM packer winders, Silacsol proportioning mixer and materials storage. Control drilling rig for post-treatment permeability testing.

c) Supply train – tanks and pallets for replenishing TàM and Silacsol materials and spare parts.

Mobilisation

The task required the assembly of a large team of drillers and grouters together with supervisory and maintenance staff, totalling some 92 in number.

Before working in the tunnel, each person attended a two day induction course for instruction in tunnel safety and general and specific procedures.

A large number of personnel were French, and care was taken to ensure that each shift had sufficient bilingual staff.

The drilling and grouting plant had to be adapted to fit on the TML flat bed rolling stock and keep within the operating structure gauge. This was carried out by Stent Soletanche at Shakespeare Cliff following initial preparation off site.

The mobilisation was substantially completed within 30 days of the instruction to proceed.

Drilling and grouting operations

One side of the tunnel was maintained open, unimpeded, throughout the works. Control of trains in the single line working zone was strictly in accordance with TML procedures and controllers and flagmen were provided by TML for this purpose.

Drilling and TàM installation commenced on the north side (for MRTN), working towards France, followed by grouting (approximately one week behind), and finally control hole drilling and testing.

At the mid point of the operation the works switched to the south

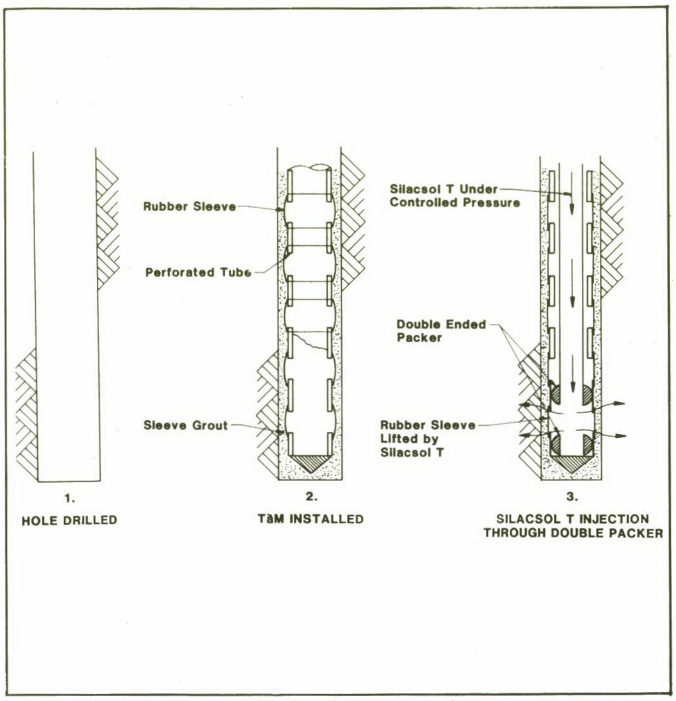


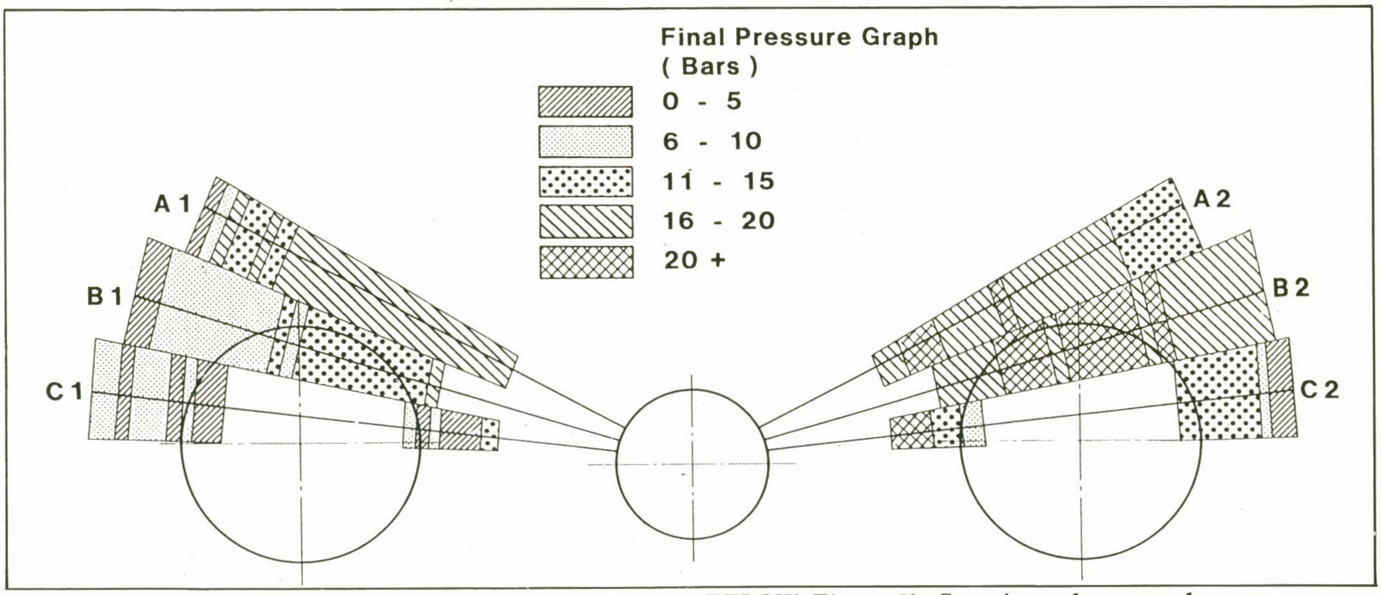
Figure 7: Tube à manchette injection system.

side – (for MRTS) again working towards France.

Production was good, with work continuing 24 hours/day, 6 days a week, and the treatment was completed in approximately 10.5 weeks, 1.5 weeks ahead of programme.

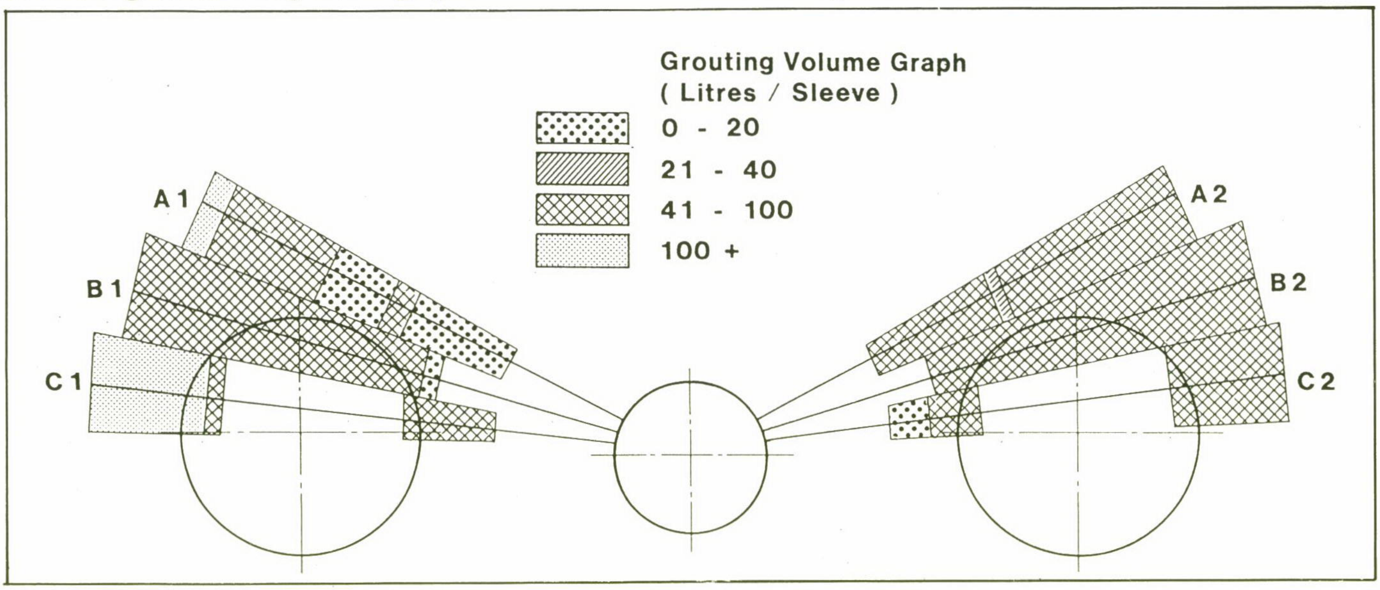
Coring through the MST tunnel lining had to be carried out with great care to ensure that the 120 year design life of the lining was not jeopardised. Open hole drilling through the chalk, followed by TàM installation – placing of the TàM pipe and grouting of the annulus around it – followed conventional lines. TàM sleeves were located at 500mm centres in the treatment zone and the sleeve grout was a cement-bentonite mix, see **Figure 7.**

The grout programme was designed for the treatment of a total volume of some 80 000m^3 of fissured chalk. Based on experience gained from treatment trials and work carried out on the French side of the Channel, an optimum injection of 65 litres/sleeve (ie 65 litre/500mm length of drillhole) was proposed and adopted. A



***ABOVE:** Figure 8a: Final pressure graph.*

***BELOW:** Figure 8b: Grouting volume graph.*



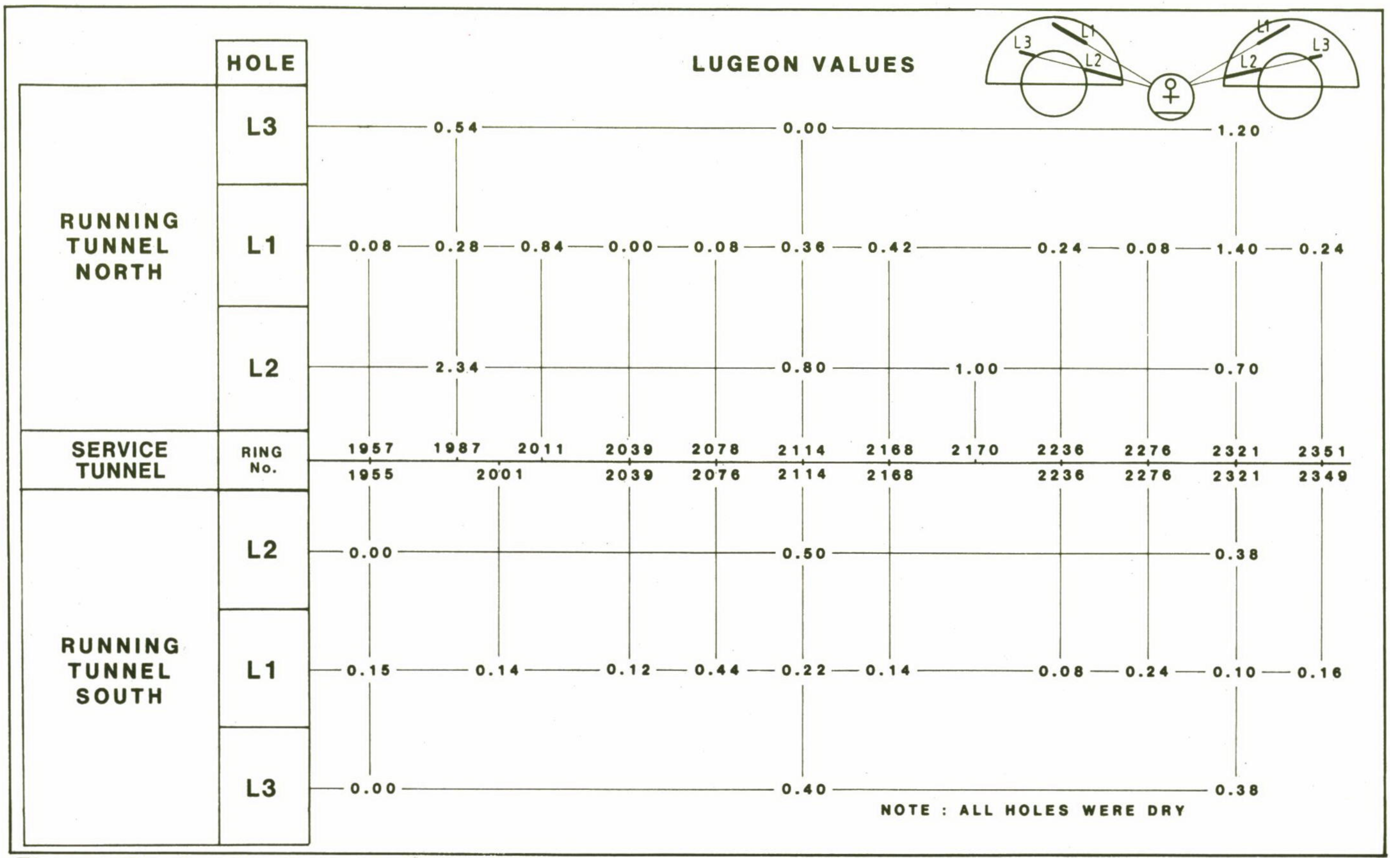


Figure 9: Results of performance control tests.

maximum pressure of 2500kN/m^2 (25 bars) was specified.

The setting time of the Silacsol T grout can be varied; to optimise the overall programme a rapid set of between 30 minutes and 40 minutes was used. Consequently it was necessary to hold the grout, components – silica liquor, hydrated lime, filler, water – separately underground, prior to mixing in a Soletanche Silacsol proportioning mixer. This mixer draws the correct proportion from the holding tanks of each constituent, and after mixing discharges to the array of pumps via a 'ring main'. Thus the quantity of mixed grout held in the system is minimised.

Each of the pumps operated independently, discharging through a double-ended packer located with one packer above and one below the sleeve to be injected, see **Figure 7.** Injections were made systematically commencing at the further sleeve and progressing towards the mouth of the hole (**Picture 2**).

Picture 2: Inserting a tube à manchette PCC lined section.

Quality control

The Channel tunnel project has a firm commitment to quality assurance. Quality plans and quality control systems were set up to provide suitable quality management.

At an average progress of 40 holes a day grouted – ie injection at 800 sleeve positions – there was an obvious requirement for careful and contemporaneous monitoring of the ground treatment. This was provided automatically by using Kent flow meters (recording injection pressures and quantities at each of the sleeves) monitored through the SINNUS 2 proprietary computer system. Not only did this system monitor the grout treatment, but it also provided automatic control of maximum injection volumes and/or pressures. As soon as either parameter was exceeded at a sleeve, the pumping was automatically stopped; the required parameters were 'punched' in at the key pad of the control panel prior to commencing injection which then proceeded automatically.

A record of the injection was printed out at the work place and this was retained as a primary quality record. Additionally the same information was stored by SINNUS 2 on cassette(s). These cassettes were brought to surface daily and entered into the office-based computer to produce the comprehensive set of quality records, as well as generating graphic interpretation of the grouting data, see **Figures 8a** and **8b.**

The quality control system employed for the works automatically generated seven quality records (QR 101-107) allowing subsequent checking of any phase of the works. The quality assurance plan formulated for the works was fully implemented.

Performance control

As already indicated, the primary performance control was based on tests of the insitu permeability of the chalk marl after treatment, measured in control holes drilled following completion of the grouting; the maximum limiting acceptance value being 3 lugeons.

Water testing was carried out a minimum of four days after treatment. The results, recorded as equivalent lugeon values, ranged from 0.08 to 1.4 lugeons – with a single 'high' value of 2.34 lugeons, see **Figure 9.** These rates can be compared with values of 3 lugeons to 30 lugeons prior to treatment, see **Figure 10.**

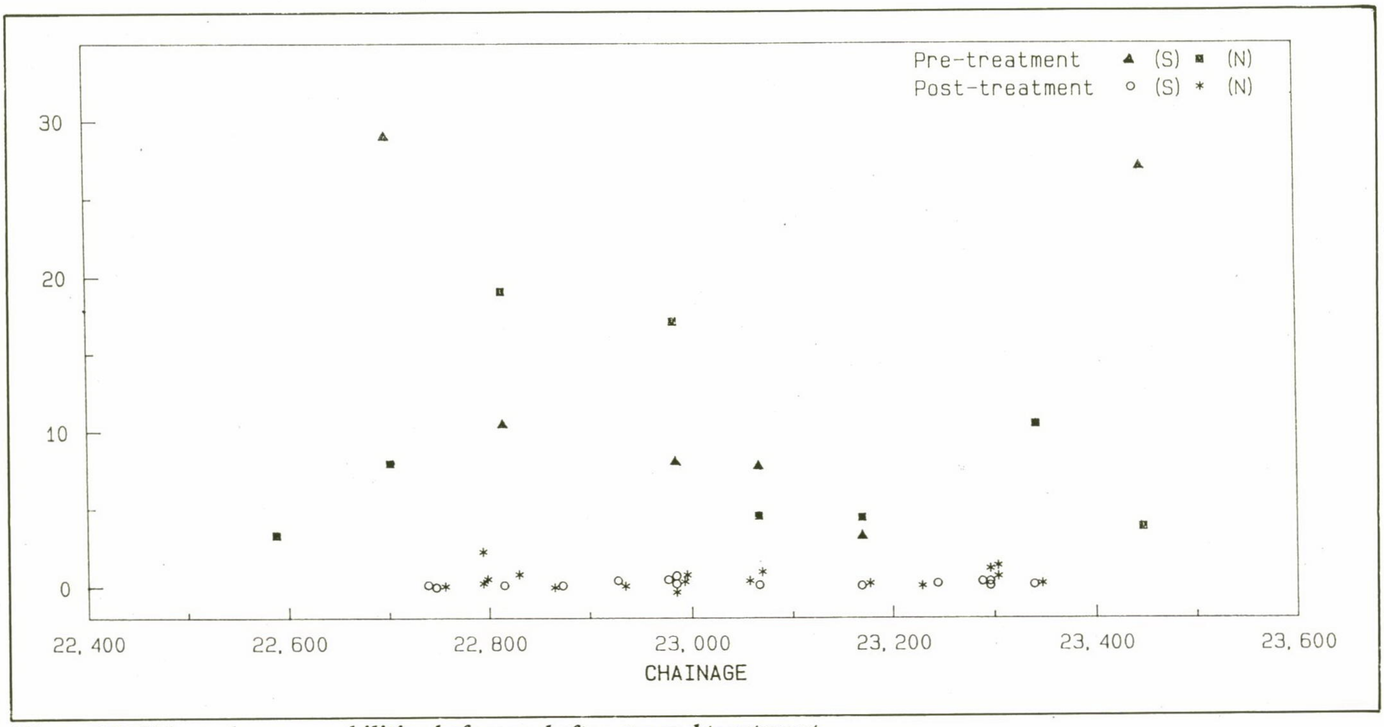


Figure 10: Side probe permeabilities before and after ground treatment.

Additional parameters were monitored during construction of the running tunnels through the treatment zone between chainages 22 700m and 23 400m;

a) Water inflow was significantly reduced to a value approaching nil, with the exception of a single high inflow between chainage 22 950m and 23 000m in MRTN. (In this context it must be remembered that treatment was deliberately targeted at the upper portion of the tunnels only).

b) Logging of the exposed excavation in the face showed that treatment had been carried out in the upper half of the tunnel, with Silacsol T grout visible in joints at and above axis level.

c) Despite the evidence of no improvement in joint adhesion in the earlier trials, the decrease in permeability and consequent reduction in water inflow gave a marked improvement to the general ground stability in the treated zone.

Running tunnel progress

The progress of both running tunnels through the treatment zone is, of course, the most critical measure of the value of the ground treatment. The north and south TBMs both entered the treated areas shortly after grouting had been completed, MRTN some six weeks ahead of MRTS.

While there are many factors to take into account, it is clear from the progress graphs that there was a very positive improvement in both the north and south running tunnel progress – instead of the anticipated greatly reduced production through the area of poor ground between chainage 22 700m and 23 400m, see **Figure 11.**

Conclusion

The ground treatment was completely successful in lowering the insitu permeability of the chalk in the treated zone. The two running tunnels were not only able to record improved rates of progress through this treated zone but they also avoided the major delays which were considered a possibility had no treatment been undertaken.

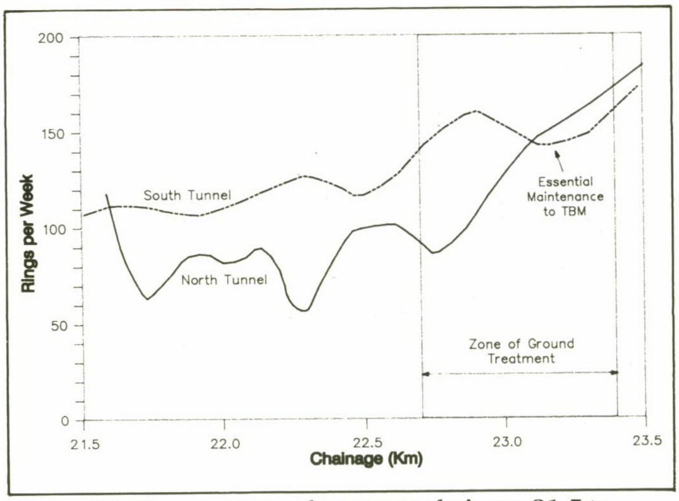


Figure 11: Running tunnel progress chainage 21.5 to 25.5.

Acknowledgments

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They also acknowledge the valuable contributions to the work by the TML on-site geotechnical team and the invaluable co-operation of the TML construction staff.

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