

JET GROUTING FOR LISAROW RAIL BRIDGE RENEWAL

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ABSTRACT

This paper describes the design and installation of a jet grouted deep foundation system to support a rail bridge on the Main North Line, just north of Lisarow in New South Wales, as part of a bridge renewal. The adopted method of jet grouting is a replacement/mixing technology that uses a high pressure jet to erode and hydraulically excavate soils, to form a grouted soil mass. This is understood to be the first application of the jet grouting technique to support a rail bridge in Australia.

Parsons Brinckerhoff provided a specification, reference design, construction surveillance and certification for the works. Following consideration of alternatives, including driven piles, compaction grouting and mini-piles, Austress Menard was selected to construct the works on a design and construct basis, using jet grouting.

The project was completed on schedule, during limited track possession time, under low headroom conditions. The specification requirements, design, installation, monitoring and post-construction performance of the successful footing system are outlined in this paper.

1 INTRODUCTION

A railway bridge built in 1911 on one of Australia's major railways has been given a new life through the first application of jet grouting to support a rail bridge in Australia. Jet grouting technology is growing in popularity in various parts of the world due to its cost-effectiveness and proven performance, but it had never before been used by an Australian transportation authority to support a bridge.

The bridge spans about 19 m across Cut Rock Creek, 90 km north of Sydney between Gosford and Wyong. It was originally built of masonry piers on timber piled foundations, with about 2.3 m clearance between the steel superstructure and the creek. Originally designed for steam-powered trains, the aging foundations needed to be upgraded to support today's heavier rail traffic and to reduce ongoing maintenance costs. For the Rail Corporation of New South Wales (RailCorp), the choice was between shifting the existing structure to new piers at a higher cost and significant disruption to train traffic, or finding a way to strengthen the existing foundations to support a new bridge.

After evaluating a number of options, Parsons Brinckerhoff and RailCorp concluded that ground treatment would be the preferred solution. Following consideration of alternatives including piles, compaction (displacement) grouting and minipiles, jet grouting was adopted. A load transfer slab and culverts support the bridge loads applied to the 23 metre deep foundations.

2 SITE DESCRIPTION

The site is located at Cut Rock Creek, just north of Lisarow, which is 88.815 km north of Sydney on the Main North Railway Line (see Figure 1).

The previous bridge structure was a two span, transom topped bridge supported on a brick pier and abutments (see Figure 2). The creek bed reduced level is 19.7 m AHD at CPT2 (see Figure 3), and the 100-year flood level is 22.7 m AHD.

2.1 SITE INVESTIGATION

Site investigations were carried out by RailCorp and Austress Menard. Fieldwork included borehole drilling and sampling, cone penetration testing (CPT) and pressuremeter testing. The exploration locations are shown in Figure 3.

The boreholes were drilled with truck-mounted drilling rigs using open hole augering and concrete coring techniques, and air track drilling. Standard penetration testing (SPT) and U50 (50 mm) tube sampling were carried out. The CPT probes were performed using an electric 100 kN truck-mounted rig, without pore pressure measurement. The pressuremeter testing used a Menard GA pressuremeter.

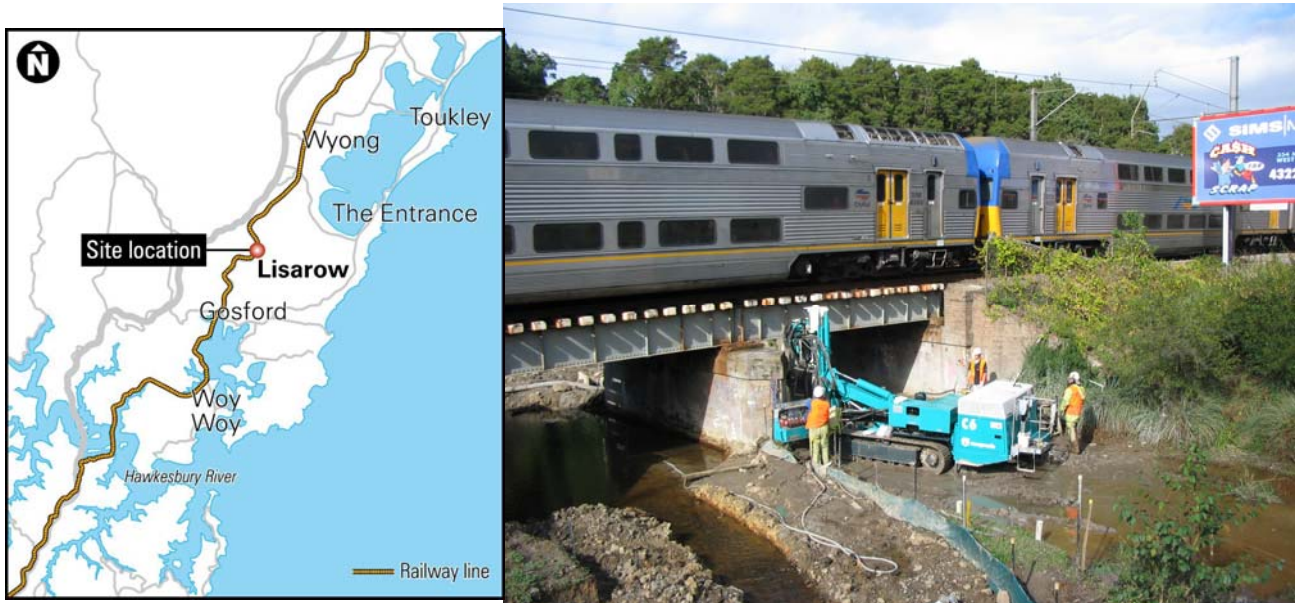


Figure 1: Site location plan.

Figure 2: Previous bridge showing jet grout installation.

2.2 SUBSURFACE CONDITIONS

Subsurface conditions at the site comprised compressible sand and clay alluvium to depths of about 17 m to 20 m, overlying siltstone. The alluvium was highly variable and comprised an upper, very loose to loose clayey sand layer to about 5 m to 6 m depth, over a stiffer, soft to firm, silty clay layer. The CPT probes indicated that the alluvium contained sandy and clayey layers. Soft to firm, silty clay existed from about 5.5 m to the limit of the auger boreholes at 16 m depth. The pressuremeter tests showed that the soil elastic modulus from the first unload-reload cycle ranged from 13 MPa to 20 MPa.

Figure 4 shows a simplified, inferred ground profile, showing the cone resistance (q_c) and friction ratio (F) in the creek bed at CPT2, and an envelope of the cone penetration resistance against reduced level.

The CPT and pressuremeter test results indicate that the subsurface conditions comprised, in descending order:

- 3 m to 4 m of loose silty sand that provides little resistance and has a very low limit pressure (P_l) typically in the range of 100 to 200 kPa; defined as, the point where the Menard pressuremeter tests become asymptotic on a pressure versus volume curve.
- a layer of firm to stiff clay/silty clay from RL 16.5 m to 8.5 m with higher cone resistance (between 0.5 MPa and 2 MPa) and higher limit pressure (600 kPa to 800 kPa).
- interbedded thin layers (about 1 m thick or less) of hard clay/dense sand or gravel from RL 8.5 m to 12 m
- a layer of firm to stiff clay from RL 7.5 m to 1.5 m with limit pressure of 600 kPa to 800 kPa
- a competent founding stratum at a depth of about 17 m to 19.5 m.

CPT3 gave a refusal depth of 16 m. The two air track holes, which penetrated 4 m into siltstone, confirmed weathered rock levels of RL 1.3 m and RL 0.9 m on the western and eastern side of the bridge respectively. The characteristics of the rock improved with depth. The drill rig experienced refusal at RL -4m in both holes in material identified on site as “blue shale”, which was inferred to be representative of the regional siltstone bedrock.

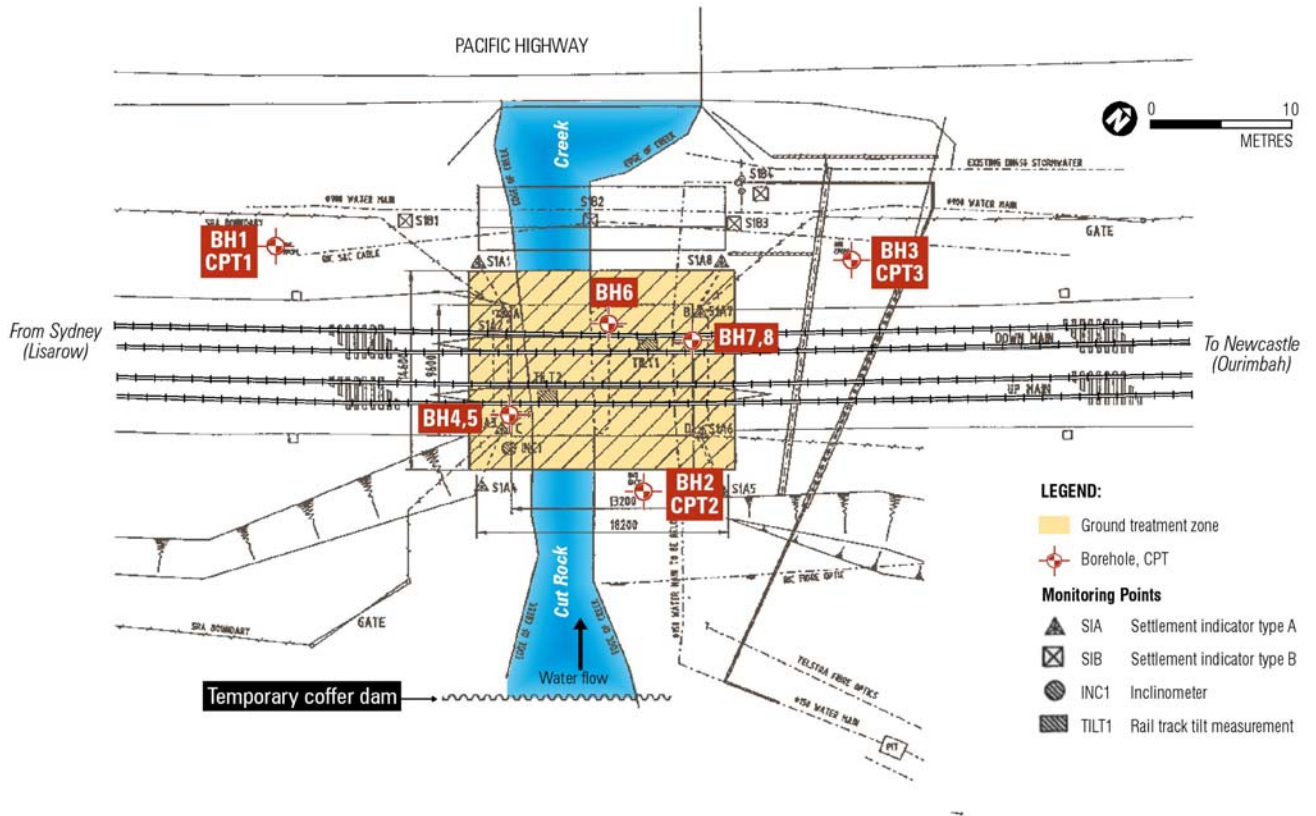


Figure 3: Exploration and monitoring location plan.

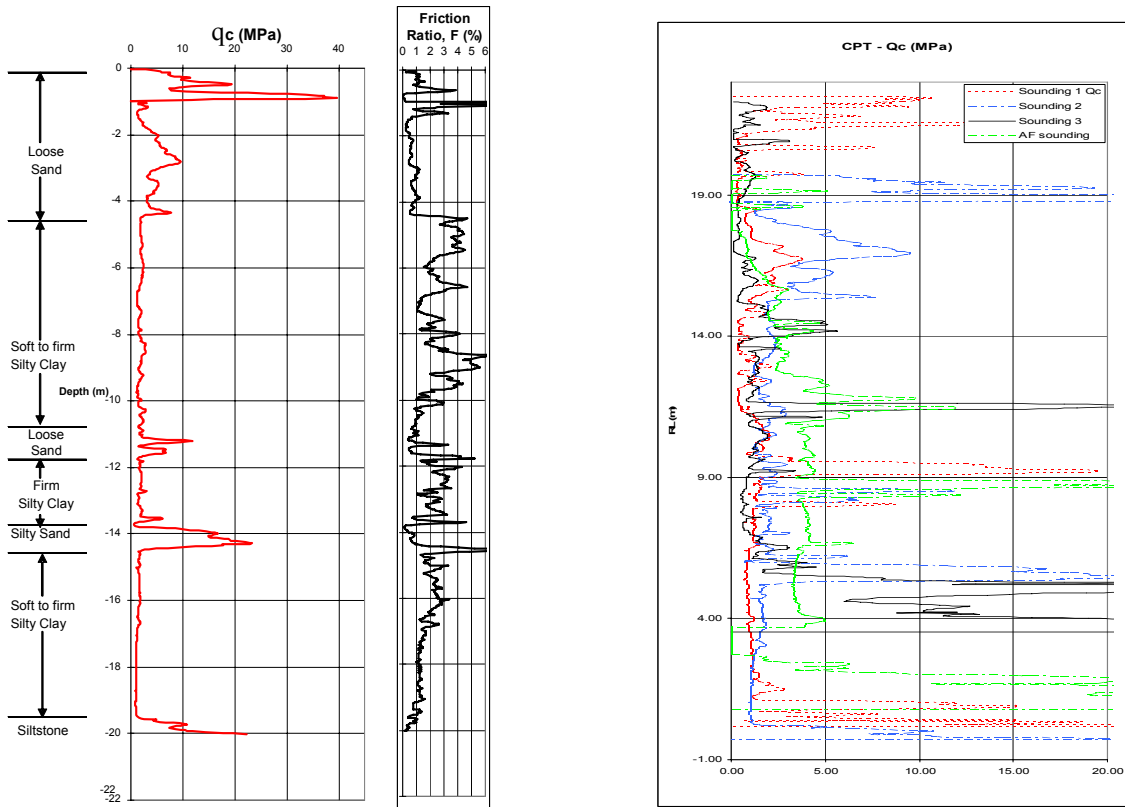


Figure 4: Inferred ground profile and CPT data.

3 FOUNDATION SELECTION

RailCorp’s preferred option for replacement of the existing bridge was a concrete box culvert (see Figure 5). However, due to poor ground conditions, the site offered a very low bearing capacity and the prospect of unacceptable settlement, hence the use of conventional culvert foundations was not possible without piling or ground treatment.

Without ground treatment or deep foundations (piles), the bridge was predicted to settle up to 200 mm under a serviceability load of 100 kPa. Piles were not considered suitable due to the existence of adjacent, vibration and settlement-sensitive utilities, including fibre-optic cables, rail communications, a water main and limited clearance of 2.3m beneath the existing bridge.

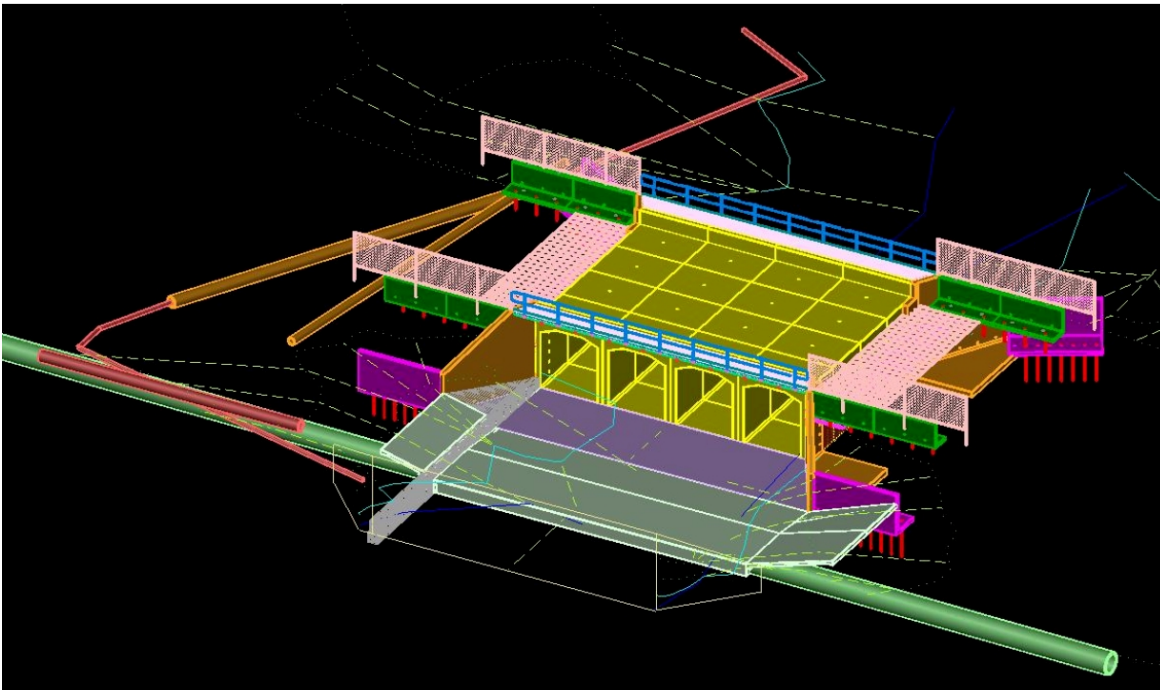


Figure 5: Bridge replacement concept.

Alternative foundation solutions considered by RailCorp at tender stage included:

- piles to transfer loads to stiffer ground at depth
- a large rigid slab to distribute the pressure to acceptable levels
- soil improvement of the compressible soils to support the bridge loads and control settlement.

Tender documents were targeted at achieving the required performance, based on a minimum volume of ground treatment, assessed to comply with design criteria.

4 OPTIONS CONSIDERED

Since a conventional deep foundation system was not considered practical, specialist ground treatment contractors were selected to tender for the works on a design and construct basis, based on tender documents prepared by RailCorp and Parsons Brinckerhoff. Six tenders were received from three tenderers. Details of the proposed methods submitted by the tenderers are summarised in Table 1 and described further in the following sections.

Table 1: Ground treatment methods submitted by tenderers.

| Method | Schedule | Tender Details | Relative cost | Comments |
|------------------------------------|-----------|--|---------------|---|
| Jet grouting | 4-5 weeks | 18, 1100mm diameter jet grout columns to about 20 m depth. Replacement ratio 6% on 3.3 m x 3.6 m grid – see Figure 9. | 1.0 -1.2 | Jet grout columns to rock using a mono-fluid system. Predicted settlement complies with design criteria. |
| Compacting (displacement) grouting | 10 weeks | Compaction grouting to the surface of the stiffer soils at about 6 m depth. Involves controlled injection of mortar as an expanding bulb, to displace and compact loose soils, without causing hydrofractures, using low-slump mortar injected under pressure. | 1.1 -1.4 | Addresses substantial expected settlement in top 6 m. Risk of differential settlement below ground treatment zone. About 160 mm settlement predicted with no ground treatment. Treatment of upper 6m reduces predicted bridge settlement to 25-30 mm. |
| Minipiles | - | Grout injected minipiles – 150 mm diameter to 20 m depth at 1m centres. | 2.0 -2.3 | Long construction program and comparatively expensive. |

4.1 JET GROUTING

Jet grouting is a partial replacement/mixing technology that uses a tool equipped with one or more high pressure jets to erode and hydraulically excavate soils, while mixing cement grout with the insitu soils, creating soil-cement columns or soil-cement panels (Bruce, 2005). The soil-cement columns are designed to carry loads to the siltstone at between 17m and 20m depth, thereby mitigating the risk of settlement in the alluvium (see Figure 6).

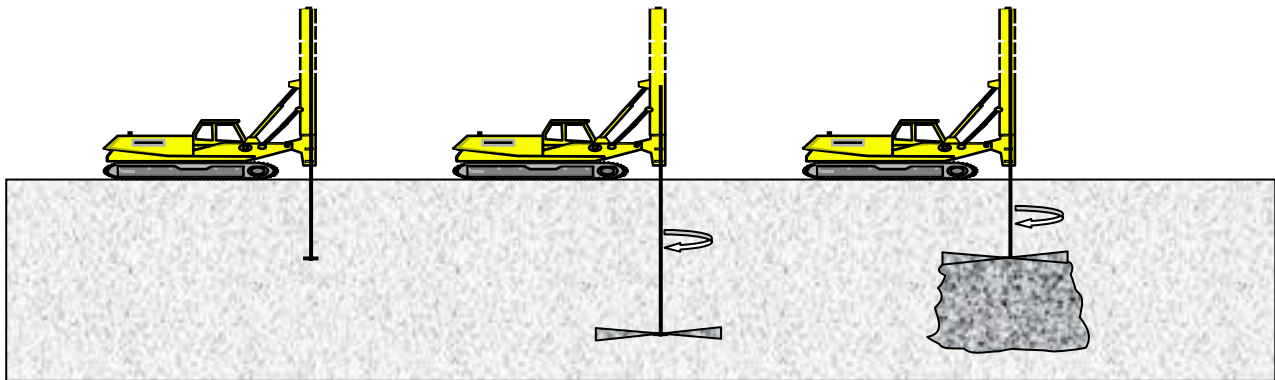


Figure 6: Schematic of jet grouting construction procedure.

4.2 COMPACTION GROUTING

Compaction or displacement grouting is a technique of injecting very low slump grout under high pressure to densify or controllably displace mostly granular soils (see Figure 7). Because the grout is thick, it is unable to enter the pore space of the soil allowing displacement to compact the surrounding soil. This process can be used to minimise the effects of subsidence and settlement caused by underground construction; to arrest sinkhole development; and for large scale site improvements in which loose soil strata preclude the use of alternative methods of support. Bruce (2005) defined compaction grout as grout injected with less than 25 mm slump. The compaction grouting alternative was designed to take foundation loads to the surface of the stiffer silty clay at about 6m depth but carried some additional risk, as it might not meet the stringent settlement performance criteria.

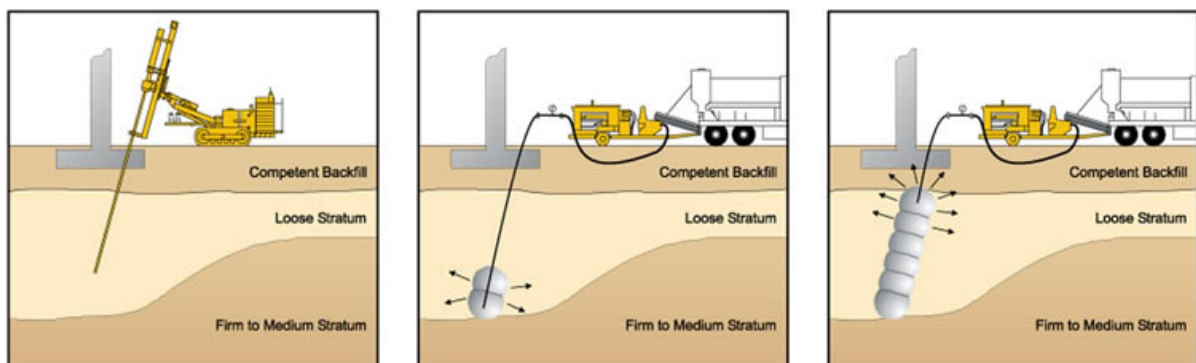


Figure 7: Schematic of compaction grouting (Hayward Baker, 2004).

4.3 MINI-PILES

A solution comprising the use of 150 mm diameter mini-piles, capable of being installed in the low headroom conditions to the underlying siltstone, was also considered. However, this option was rejected on the basis of the likely extended installation time, the lack of sufficient design information on which to assess the tender and cost.

4.4 SELECTION OF THE PREFERRED OPTION

Following a rigorous tender evaluation process, Austress Menard was selected from a group of three competitors and awarded the performance criteria based, design-construct ground treatment contract using jet grouting. Advantages of the jet grouting scheme were as follows:

- All soil types were groutable
- Ability to work around buried active utilities
- Can be performed in limited workspace/ headroom
- Specific in situ replacement possible
- Treatment to specific subsurface locations
- Designable strength and stiffness
- Only inert components
- No harmful vibrations
- Maintenance-free
- Faster than alternative methods and
- Design addressed performance criteria.

5 JET GROUTING DESIGN

The jet grouting construction process employed a high kinetic energy jet of fluid to break down the soil formation, wash the fine particles into suspension, and combine the coarser *in situ* soils with a fluid grout. This process of hydrodynamic washing of the soil and mixing the residual material with grout forms an *in situ* soil-grout mix (Hewitt, 1994). Therefore jet grouting reworks the soils in three distinct physical processes:

- breaking down the soil formation using a very high-velocity (energy) jet
- removing spoil to the surface via the return flow
- introducing and incorporating a binder in the form of a grout.

5.1 DESIGN CRITERIA

Performance criteria for evaluating the method of preferred treatment, including compliance with RailCorp track maintenance specification and British Standard BS EN 12716:2001, “Execution of special geotechnical works – Jet grouting”, were:

- immediate settlement of less than 20 mm
- residual settlement limited to a maximum of 50 mm over a 10-year maintenance period
- maximum settlement of 15mm over any 12 month period following construction completion
- differential settlement (change in grade) of : $\leq 0.3\%$ longitudinally
 $<0.1\%$ transversely
- compliance with RailCorp track maintenance limits.

5.2 DESIGN METHOD

A realistic design of a jet column network can only be developed with a calculation that takes into account both stress and deformation. This calculation should include laws for the behaviour of the soil, the jet column and ground and ground/ grout interaction. In particular, computer programs using simple failure analysis, which are commonly used for routine geotechnical calculations, are not appropriate.

The design process involved determining for a given diameter, the centre-to-centre spacing and anchorage (bond) length of the column, the distribution of stresses between the soil and columns and the corresponding settlement of the structure. The calculation was based on the French Laboratoire Central des Ponts et Chaussées (LCPC) design method for a mixed shallow/deep foundation (Combarieu, 1990). This involved the use of:

- the Combarieu (LCPC) method to evaluate the negative skin friction and neutral point effect (negative skin friction limited to the upper part of the column length)
- the Frank and Zhao (1982) method to evaluate the settlement of the columns in the surrounding soil.
- Hooke’s law for the column material (elastic behaviour).

Checks were made to establish whether the calculated values of the stresses were acceptable for the slab-on-grade and were compatible with the material of the jet column and if the settlements were acceptable for the structures.

An important initial assumption was that of the distribution of load between the soil and the columns. From there, the settlements of the soil and of the columns were calculated separately. An iterative calculation was then conducted until an equal deflection of the soil and of the columns was obtained.

The steps of the calculation were as follows:

- The knowledge of the stresses at the toes of the columns allowed the calculation of the settlement, $w_t(H)$, of the toe of the columns.
- The settlement of the shallow footing, $w_s(0)$, could be calculated, if the linear compression of the jet was neglected, by $w_s(0)=w_t(H)$.
- The stress distribution under the shallow footing and the settlement, $w_{soil}(z)$, at depth, z , within the soil could be deduced from $w_s(0)$.
- At any levels of the column, the relationship between the relative settlement soil/jet, $w_r(z) = w_{soil}(z) - w_t(z)$, and the mobilised skin friction, $q_s(z)$, allowed the calculation of $q_s(z)$.
- The linear compression of the jet columns created, over the whole length of the columns, additional settlements Δw_t , to the settlement of the footing. This total settlement, $w_s(0)=w_t(H)+\Delta w_t$, allowed definition of the stress distribution under the shallow footing.

The iterative calculation was undertaken for the relationship between the tip resistance of the jet column, the distribution and transmission of shear over the length of the column and the stress modified under the footing. The combination of these three components represented the total loading of the mixed foundation. The corresponding settlements at the tops of the columns were calculated as $w_s(0)=w_t(H)+\Delta w_t$ and the settlements at the toes of the jet columns were calculated as $w_t(H)$.

An explanation of some of the terms used is given in Figure 8 (Combarieu, 1990).

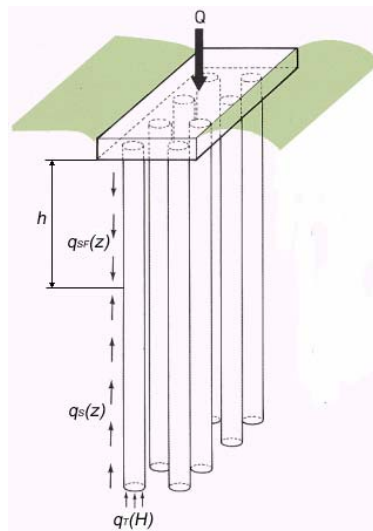


Figure 8: Stress distribution and negative skin friction.

5.3 SETTLEMENT CALCULATION (JET GROUTING COLUMN)

Due to the layout of the columns (see Figure 9), and the transfer of load through the culvert walls, the area of soil and load per column varied across the area to be treated. The information is summarised in Table 2 based on a compression service load of 495 kN at each column, as supplied by RailCorp. The total predicted settlement at the top of the piles was less than 20 mm, with a peak service stress in the column of 2.3 MPa.

Table 2: Jet column layout and calculated settlement.

| Row | | 1 | 2 | 3 | 4 | 5 | 6 |
|-----|-----------------|-------------|-------------|-------------|-------------|-------------|-------------|
| A | Area (m) | 3 m*1.9 m | 3 m*2.6 m | 3 m*2.2 m | 3 m*2.2 m | 3 m*2.6 m | 3 m*1.9 m |
| | Settlement (mm) | 4.8 | 10.6 | 5.6 | 5.6 | 10.6 | 4.8 |
| B | Area (m) | 3.6 m*1.9 m | 3.6 m*2.6 m | 3.6 m*2.2 m | 3.6 m*2.2 m | 3.6 m*2.6 m | 3.6 m*1.9 m |
| | Settlement (mm) | 5.9 | 13.1 | 6.9 | 6.9 | 13.1 | 5.9 |
| C | Area (m) | 3 m*1.9 m | 3 m*2.6 m | 3 m*2.2 m | 3 m*2.2 m | 3 m*2.6 m | 3 m*1.9 m |
| | Settlement (mm) | 4.8 | 10.6 | 6.9 | 6.9 | 10.6 | 4.8 |

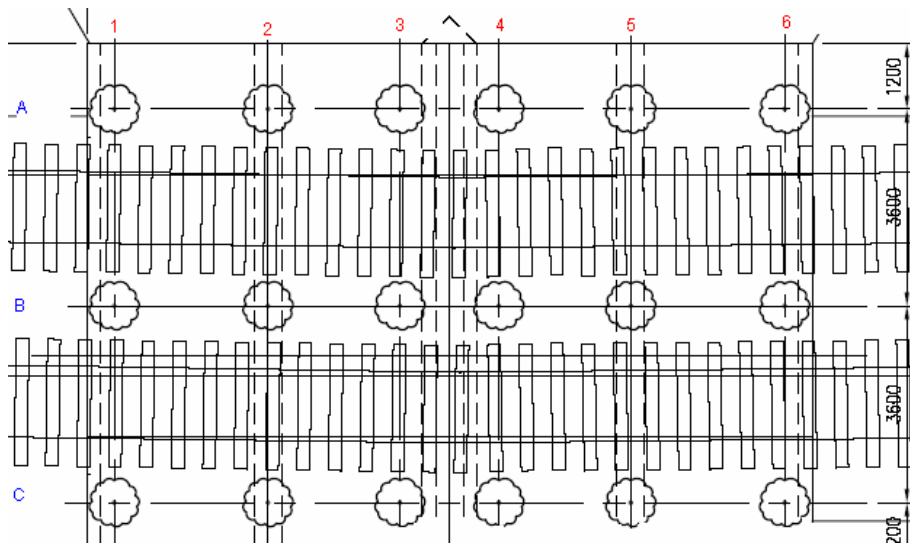


Figure 9: Jet column layout.

5.4 SEQUENCE OF OPERATIONS

Following construction of a coffer dam, to protect the site against inundation, and a working platform, the treatment was performed as follows:

- a small diameter drill hole (90 mm to 150 mm) was drilled to the depth to be treated (see Figure 6).
- a high speed jet of fluid propelled by a high pressure pump was introduced through one or several small diameter nozzles positioned on a 'monitor' at the foot of a series of rods of 70 mm to 120 mm diameter. The jet grouting pump delivery rate was typically 250 L/min.
- the rods were extracted whilst they were slowly rotated, to form a column of soil-grout mix (or "soilcrete") with the grout evenly distributed throughout the treated volume.
- during the jetting process, the excess of the soil-cement mix (referred to as 'spoil') exited freely to the top of the borehole and was removed as work proceeded.

The result (diameter, composition and strength of the columns) depended on the:

- treatment parameters (i.e. the speed of extraction of the monitor, the pressure generating the flow of the fluid grout)
- ground characteristics (nature, density, composition and grain size distribution)
- grout composition
- jetting method used.

The cement used was a low shrinkage portland cement. The resulting composition of the soil cement mix related to the jetting parameters (flow and grout lifting speed) and to the degree of displacement of soil by grout, in order to obtain the target strength of 4.5 MPa specified for the soil-cement mix columns. The grout dosage typically ranged between a water/cement ratio of 0.8 and 1.0.

The soil improvement works were performed using a mini jet grouting rig with a hydraulic 3.0 m height mast to execute the works from underneath the bridge apron (see Figure 2). A total of 18, 1100 mm-diameter columns were constructed between 16 June and 15 July 2005, to a maximum depth of 27.5 m at column B4. The adopted layout is given in Figure 9. The columns' average depth was 23 m, not 19 m as envisaged in the original design. This greater depth allowed for variability of the depth at which suitable weathered rock for founding was encountered.

The jet grouting parameters as well as the work sequence had to be adjusted almost daily to minimise any impact on the live railway structure, particularly in terms of movement, especially ground heave.

Changes in work method involved pre-cutting from top-down or bottom-up using water or cement grout and at medium to high pressure (25 MPa to 45 MPa typically), with a particular emphasis on monitoring the spoil returns to prevent any pressure build-up in the ground. Loss of spoil meant interrupting the column or the pre-cut and repeating the pre-cutting of the column, top down.

Management of the spoil generated by pre-cutting and jet grouting sought to prevent any contamination of the groundwater. Temporary platforms on each side of the bridge central pier were used to divert the flow away from the platform. The spoil was then funnelled away from the working area using a system of clay bunding and a 4 inch pump, before dredged into a stockpile area.

6 OBSERVATIONS, MONITORING AND TESTING

6.1 EFFECTS ON ADJACENT GROUND

Effects on adjacent structures were closely monitored during the jet column installation, because of risks associated with the presence of soft clay combined with the use of high-flow injection techniques. At one stage, the centre pier was lifted 38 mm which disrupted train running.

As a result of the monitoring, the jet grouting column installation was progressively refined using an observational approach, until "zero movement" was observed at the monitoring points.

6.2 STRUCTURE AND GROUND MONITORING

An instrumentation and monitoring program was specified to monitor ground and structure movement in the vicinity of the works to measure:

- ground movements
- angular distortion of the track
- settlement of structures
- settlement of utilities.

The following points were monitored:

- settlement points situated on the bridge piers and abutment (monitored against a local benchmark)
- reference points on the abutments and piers (to monitor possible rotation of the bridge supports)
- settlement points at rail levels (to check against RailCorp criteria).

Monitoring included settlement indicators, inclinometers and rail track tilt measurements.

6.3 COLUMN TESTING

Testing of the soil-cement columns was essential, because accurate design and prediction methods for column properties and load-deformation characteristics are currently limited. Before the final columns were constructed, one short (3 m) sacrificial demonstration column was installed at a point where relatively soft/loose alluvium existed. Compressive strength tests on sample cubes of the injected grout revealed strengths ranging from 10.5 MPa to 30.0 MPa, after 17 to 23 days curing, and strengths of between 5 MPa and 8 MPa in samples obtained from the soilcrete in completed jet columns B2 and B5.

7 PERFORMANCE

Monitored instruments confirmed that soil-cement columns were effectively supporting the bridge. The data showed:

- less than 5 mm horizontal movement of the brick pier and abutment during jet grout installation
- less than 5 mm settlement following construction completion
- movement at the bridge (six points): controlled heave of between 3 mm and 44 mm
- relative movement of pier/abutments (rotation): less than 5 mm (precision of instrument)
- heave at rail level: less than 5 mm measured on a weekly basis between 27 June and 12 July 2005.

The bridge remained open during the soil improvement works and the new section was opened to traffic in November 2005. The completed bridge is shown in Figure 10.



Figure 10: Completed rail bridge.

8 CONCLUSIONS

Although jet grouted foundations have a history of being relatively expensive, the total cost of the jet grouting was significantly less than the cost of constructing new bridge foundations and piers, and less disruptive to train operations and adjacent utilities. Other benefits included that, unlike other types of piles installed by pile-driving techniques, jet grouted pile installation did not endanger the existing bridge structure through vibration, nor did it affect nearby fibre-optic cable installations. It could also be done in the tight workspace and low headroom conditions present beneath the underbridge.

The rail bridge renewal was done with minimal disruption to train traffic and minimal environmental impact, demonstrating the viability of this technology and its suitability as a solution for this situation. Successful construction and performance of the jet grouted deep foundation is proof of the success of the adopted solution.

The innovative use of jet grouting enabled the project team to:

- avoid disruption of the railway operations
- reduce construction costs and
- advance the state-of-the-art.

9 ACKNOWLEDGEMENTS

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