CASE STUDY: JET GROUTED MASS GRAVITY WALL TO STABILISE BRIDGE ABUTMENT UPGRADE

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ABSTRACT

The Southern Expressway Duplication project involved the construction of a new roadway alongside the existing Southern Expressway, the extension of existing road and bridges and the duplication of existing interchanges in order to provide a two-way 18.5 km road from Darlington to Old Noarlunga in Adelaide, South Australia.

As part of the Southern Expressway Duplication project, a modification to the eastern abutment of Elizabeth Road Bridge was required. The proposed modification involved demolition of the existing underbridge Reinforced Earth (RE) wall, which was supporting the bridge abutment foundation, to accommodate a new southbound off-ramp. Menard Bachy’s scope of work included the design and construction of a jet grouted mass gravity block in order to stabilise the abutment prior to the staged removal of the existing RE wall.

The jet grouted block wall concept was proposed by Menard Bachy and detailed design carried out by Coffey Geotechnics. The design required detailed consideration of the interaction of construction of jet grouted block and bridge loading on the existing RE wall and bridge abutment foundation. This paper describes the design and construction process and advantages of this form of construction to allow for extension and modifications to existing Reinforced Earth walls.

1. INTRODUCTION

1.1. PROJECT OVERVIEW

The existing expressway exclusively facilitates a reversible one-way traffic movement stretching from Darlington to Noarlunga. The $407.5 million southern expressway duplication project includes the design and construction of 18.5kms of roadway alongside the existing expressway carriageway to convert the one way road into a multi-lane, two-way road from Darlington to Old Noarlunga to the south of Adelaide. The project also includes the extension and duplication of bridges, pedestrian walkways and interchanges located along the existing expressway, and construction of new ramps.

Construction started in December 2011 and is scheduled for completion by mid-2014. The Southern Expressway Duplication project is being delivered by Lend Lease.

1.2. GEOTEchnICAL REQUIREMENTS

The original Elizabeth Road Bridge was a 20 m long single span structure crossing the original one-way traffic Southern Expressway.

For duplication of the Southern Expressway towards the west, the existing western abutment was replaced with a central pier and a new spill through abutment was constructed at the western end of the carriageway. This bridge upgrade provides an extension of the original bridge to span approximately 30.8 m over the duplicated Southern Expressway.

Reconfiguration of the eastern abutment of Elizabeth Road Bridge was also required to allow for widening of the Southern Expressway. The proposed modification involved stabilisation of the bridge abutment prior to the demolition of the lower reinforced earth wall (RE wall) between the level of the
expressway and the level of the shared path. The soil behind this reinforced earth wall was to be cut back to the face of the upper RE wall to allow space for the construction of a new southbound off-ramp. Arrangement of the bridge is shown on Figure 1.

Figure 1: Extract of drawing BAJV-DRG-1-6066-16103 - Elizabeth Road Bridge - General Arrangement

In order to safely accommodate a new southbound off-ramp, it was necessary to identify and implement geotechnical solutions to:

- provide underpinning to the footing of the upper RE wall sufficient to allow excavation in front of this wall to a vertical cut at the front toe of the wall with a freestanding face of approx. 4m
- stabilise the block of soil behind the upper RE wall to strengthen the block and reduce the earth pressure on the back of the upper RE wall
- stabilise the block of soil behind the lower RE wall to strengthen the block and negate all soil pressure on the back of the lower RE wall, allowing the lower RE wall to be removed and the soil block to be self-supporting while at the same time taking the surcharge of the upper RE wall the block of soil retained by the upper RE wall and the bridge structure
  - Allow for design consideration in regards to lateral extent of the jet grouting, parallel to the expressway, to be sufficient to adequately support the spread of loading from the bridge and the cemented soil blocks so that during ramp excavation unsupported face excavation can be carried out without affecting the stability of the bridge
  - Allow for all necessary steps to provide adequate grout coverage with due consideration of the RE wall straps and existing structures (deck, headstock, diaphragm, wing-walls, approach slab etc.) in place
  - Allow for adequate Protection from damage of RE wall panels to be left in place as part of the new structure
  - Allow for demonstration of the effectiveness of the jet grouting through an agreed program of testing.
1.3. GROUND CONDITIONS

Based on the available geotechnical information in the area of eastern abutment, the subsurface stratigraphy along the proposed road re-alignment was inferred to be reasonably consistent.

The ground condition can be described as follow:
- Medium dense selected backfill within the Reinforced Earth (RE) block.
- Dense to very dense in-situ clayed sand below the RE block structure: fine to coarse grained orange to light brown, fines of medium plasticity.

Groundwater was expected to be encountered at depths greater than 10m and not considered as likely to affect the design and construction of the retention wall.

2. PROPOSED SOLUTION USING JET GROUTING

In order to perform the works, ground treatment option using jet-grouting has been proposed by Menard Bachy and has been accepted by the project main contractor and the South Australia’s Department of Transport and Infrastructure (DPTI) as the preferred method to stabilise the eastern abutment of Elizabeth Road Bridge.

![Figure 2: View of proposed extent of jet grouting in elevation at the Eastern abutment of Elizabeth Rd Bridge](image)

2.1. PRINCIPLES

Jet grout columns are installed by initially drilling a small hole, typically 100 mm in diameter to the required depth. Then the soil is eroded by a high pressure jet of grout, water, or air-enshrouded grout or water, and the simultaneous injection of cement suspension grout into the disturbed soil by means of a nozzle. The injection pressure can be up to 60 MPa. The drill stem and nozzle are simultaneously raised and rotated so as to combine the grout with a portion of the original soil to form a solidified soil mixed mass resulting in a cementitious round column. Repeating this process at close centres (depending on the diameter of the columns) results in a stabilised block as shown in Figure 3.
There are three major systems for jet grouting; i.e. the single, double and triple fluid systems. In the single fluid system a special hollow drill rod which is equipped with a monitor containing a horizontal jet nozzle at the tip is lowered into the hole. Cement suspension grout is pumped down the drill rod at a very high pressure of up to 60 MPa while the drill rod and monitor are simultaneously rotated and withdrawn. The grout that exits the jet nozzles at high velocity disintegrates the soil and mixes with it to form soilcrete. In the double fluid system the grout is encased within a shroud of compressed air. The air acts as a buffer between the groundwater and the grout, greatly increasing the cutting efficiency. It also creates turbulence in the waste spoil, improving the efficiency of its removal. In this method a special coaxial drill string and jet monitor are used. The triple fluid system requires a triaxial drill stem and monitor with appropriate nozzles. In this system an air-enshrouded jet of water erodes the soil while the grout is simultaneously injected through separate nozzles. The cutting jets are located above the grout supply, which allows a nearly complete replacement of the soil with grout as the monitor is withdrawn. The three grouting systems are shown schematically in Figure 4.

Jet grout columns can be constructed in all soils; however the effective radius and strength depends on the properties of the soil and the jet grouting parameters used. In granular soils jet grout columns can have a strength of about 10 to 15 MPa or more; however the strength of jet grouted columns in clay can be quite less and as low as 1 MPa. Jet grout strength is primarily determined by the soil type; however the amount of cement used per unit volume and the water cement ratio also have an effect. Typical water-cement grouts have a water-cement ratio in the range of about 0.6 to 1.2 by weight. For single fluid system jet grouted columns, typically diameters are on the order of 0.4 to 0.6 m in cohesive soils and up to about 1.2 m in granular materials. In two-fluid system column diameters are
on the order of 0.8 to 1.2 m in cohesive soils and up to about 2.5 m in granular soils. Implementation of the triple fluid system allows the construction of larger diameter columns whereas in cohesive and granular soils the diameters can be respectively up to 1.5 m and 3.6 m.

Typical injection parameters for different jet grouting systems are shown in Table 2.

<table>
<thead>
<tr>
<th>Jet Grouting System</th>
<th>Single fluid</th>
<th>Double fluid</th>
<th>Triple fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grout injection rate (l/min)</td>
<td>40-360</td>
<td>70-360</td>
<td>70-360</td>
</tr>
<tr>
<td>Grout pressure (MPa)</td>
<td>20-60</td>
<td>30-60</td>
<td>3-17</td>
</tr>
<tr>
<td>Air flow (l/min)</td>
<td>-</td>
<td>3700-6000</td>
<td>2700-6000</td>
</tr>
<tr>
<td>Air pressure (MPa)</td>
<td>-</td>
<td>0.6-1.2</td>
<td>0.6-1.2</td>
</tr>
<tr>
<td>Water flow (l/min)</td>
<td>-</td>
<td>-</td>
<td>70-150</td>
</tr>
<tr>
<td>Water pressure (MPa)</td>
<td>-</td>
<td>-</td>
<td>20-50</td>
</tr>
<tr>
<td>Rotation (RPM)</td>
<td>4-25</td>
<td>4-15</td>
<td>2-15</td>
</tr>
<tr>
<td>Withdrawal rate (cm/min)</td>
<td>10-50</td>
<td>7-50</td>
<td>5-40</td>
</tr>
</tbody>
</table>

Table 2: Typical injection parameters for different jet grouting systems

2.2. DESIGN

2.2.1 DESIGN PRINCIPLES / APPROACH

In the detailed design of the jet-grouted wall, the following construction sequence was considered:
- Construct jet grouted wall.
- Excavate part of the existing reinforced soil wall (RE wall portion in front of the jet-grouted wall) and the batter slopes on either sides of the Elizabeth Road Bridge.

Limit state design methodology, which is generally in accordance with AS 5100 – 2004, was adopted in the design of the jet-grouted wall strength and stability. The following failure mechanisms were considered in the limit state design of the jet grouted wall:
- Sliding within or at the base of the wall.
- Rotation of the wall around wall toe.
- Bearing failure of the wall base footing.
- Deep-seated failure of the wall.
- Wall internal integrity.

2.2.2 ADOPTED DESIGN PARAMETERS

The design geotechnical strength was calculated as the appropriate ultimate strength (Ru) multiplied by the appropriate strength reduction factor (φ). Geotechnical strength reduction factors applied to this JG wall design are provided in Table 3 below.

<table>
<thead>
<tr>
<th>Failure mechanism</th>
<th>Strength reduction factor φg subject to static loads</th>
<th>Strength reduction factor φg subject to seismic loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing</td>
<td>0.40</td>
<td>0.77</td>
</tr>
<tr>
<td>Sliding</td>
<td>0.50</td>
<td>0.77</td>
</tr>
<tr>
<td>Overturning</td>
<td>0.50</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Table 3: Adopted geotechnical strength reduction factors

The appropriate ultimate geotechnical strength was calculated from the representative soil parameters summarised in Table 4 below.
Table 4: Summary of the adopted geotechnical design parameters

<table>
<thead>
<tr>
<th>Soil name</th>
<th>Location</th>
<th>( \gamma ) kN/m(^3)</th>
<th>( E ) MPa</th>
<th>( K_0 ) (-)</th>
<th>( \varphi' ) deg.</th>
<th>( c' ) kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>General fill</td>
<td>Above and behind jet-grouted wall</td>
<td>20</td>
<td>15</td>
<td>0.5</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Select fill</td>
<td>Existing reinforced soil wall</td>
<td>20</td>
<td>30</td>
<td>0.5</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>Tertiary Sand</td>
<td>Embedment and base of the jet-grouted wall</td>
<td>20</td>
<td>100</td>
<td>0.5</td>
<td>35</td>
<td>0</td>
</tr>
</tbody>
</table>

The jet grouted block is formed by jet-grouted columns with an overlap of 0.2m to 0.6m between columns. The designed mechanical properties of the jet-grouted material are as follows:
- Bulk unit weight = 21kN/m\(^3\).
- Unconfined compressive strength UCS = 3.5MPa.
- Ultimate average shear stress (\( \nu_u0 \)) along a critical jet-grouted wall section: 0.227MPa (\( \nu_u0=0.15 \times UCS^{1/3} \)).
- Maximum tensile stress (\( f_{tu} \)): 0.673MPa (\( f_{tu}=0.36 \times UCS^{0.5} \)).
- Approximate elastic Young’s modulus: \( E = 910 \)MPa.

A horizontal seismic action factor \( a_{kh} \) equivalent to half of the seismic acceleration coefficient and a vertical seismic action factor \( a_{kv} \) of zero has been considered in the design of the jet-grouted wall in accordance with AS4678-2002.

2.2.3 GEOMETRY

The approximate level of the Southern Expressway grade line is RL 76.5m AHD and underside of the existing eastern abutment is estimated as RL 81.1 m AHD. The jet-grouted depth on Elizabeth Road Bridge varies from RL 73.9 m AHD to RL 81.1 m AHD. A typical section of the jet grouted wall is shown in Figure 5 below:

![Figure 5: Typical Cross Section through Jet Grouted Wall](image)

2.2.4 EXTERNAL STABILITY

The design of jet-grouted wall against external instability (sliding, rotation, and bearing failure modes) involved calculations using analytical method. Coulomb’s earth pressure theory has been used to design the retaining wall against external stability (sliding, overturning, and bearing failures). Rankine’s earth pressure theory has been used to estimate passive resistance from the front embedment of the wall. The passive resistance from the first 0.5m wall embedment has been ignored.
To allow for the future excavation of the proposed 450 mm diameter drainage pipe in front of the wall, only a third of the passive resistance has been considered in the external stability assessments. In addition, the jet grouted wall base was also founded below the invert level of the pipe so that stress of wall will not transfer to the pipe.

### 2.2.5 DEEP SEATED FAILURE

Limit equilibrium method has been used to design the wall against deep-seated failure. This involved analyses using SLOPE/W software package developed by Geo-slope International Ltd. Drained soil parameters have been used in the global stability analysis for the jet-grouted retaining wall.

### 2.2.6 INTERNAL INTEGRITY

The internal stress developed within the jet grouted wall at critical wall sections was analysed using finite element analysis for internal stability assessment. This involved analyses using PLAXIS 2D software package (developed by Plaxis BV). In this internal stress analysis, the jet grouted wall was modelled as elastic material and the computed stresses were then checked against the values of limiting stresses (the ultimate average shear stress and the maximum tensile stress) indicated in the design parameters section above.

Under the footing of Elizabeth Road Bridge, due to access constraint, two rows of the jet-grouted columns will have a separation gap to approximately 3.5 m depth below the underside of the bridge footing. In the global stability analyses, this gap has not been considered as it does not have impact on the overall stability of the wall. However, in the internal integrity check of the jet-grouted using PLAXIS 2D, interface with negligible shear capacity between two jet-grouted columns has been used to simulate the free sliding capability of this gap subject to external loads.

Figures 6 and 7 show a typical analysed stresses in the jet grouted wall using PLAXIS 2D. The PLAXIS analysis results are generally consistent with hand calculation results. Some development of tension in the columns as a result of local stress concentration was found, but this was limited to very small area of the wall.

### 2.2.7 POTENTIAL EFFECT OF CUTTING RE STRIPS

Reinforced Earth Company’s in house wall design program was used to assess the potential effect of the grouting cutting some of the existing reinforcing strips. The jet grouting was installed using a 100 mm diameter drill bit and hence not more than one strip at any one level of reinforcement could be damaged. The analysis indicated that under the proposed short term conditions the cutting of one strip at each level would not compromise short term stability or endanger the wall. After the grouting has been completed the section of wall will behave as a cemented mass gravity structure. The reinforced earth wall strips will then become redundant for the purpose of long term stability.

### 2.3. INSTALLATION OF JET GROUTING COLUMNS
A complex system of jet grout columns were designed with different diameters, inclination, lengths and geometry to satisfy the project requirements from the necessity to avoid wing walls, bridge abutment, services and beams.

The first row of columns at the underside of the bridge abutment had to be installed from the bridge deck and reach the 200mm gap between the back of the upper RE wall and the bridge abutment. Lend Lease had to break back the deck to expose the reinforcement to allow the 89 mm diameter drill rod to pass through. This technique provided a minimum of a 150mm square hole between existing reinforcement. The services was disconnected and removed, the precast barrier temporarily removed and the eastern approach slab demolished prior to our arrival so it did not affect our column arrangement at the back of the abutment.

The final jet grouted wall consisted of 90 no 1800mm columns, 14 no. 2200mm inclined columns and 12 no. 2200mm inclined half columns. The construction drawing of the jet grout columns at the eastern abutment is shown in Figure 8.

Due to the sensitivity of the project, variations in ground levels, and head and toe elevations of jet grout columns it was necessary to implement a very stringent surveying method on site that would minimize errors. Thus, the installation point of each JG column and actual ground levels was identified using a GPS system that was capable of reporting all three coordinates of each setup location.

Pre-excavation of the first 500 mm was required to expose and locate the first row of strips in order to avoid hitting obstruction and / or having the strips wrapped around the rods during drilling operation.

Special sequences were applied during column installation to allow sufficient setting time of the grout as needed. Adjacent columns were not installed during the same shift. In addition, columns adjacent to the RE panels were also installed in a hit one-miss one fashion.

Visual observation of the spoil flow and features of the spoil return at the surface have been maintained at all times to mitigate the risk of ground heave and lateral displacement of the RE wall. In order to ensure minimum pressure of jet grouting apply on the existing reinforcement wall, a distance of 800 mm between the centre of the first row of column and the external face of the RE wall was
considered. Prior to commencement of the grouting operation, the RE joints was sealed to avoid grout leakage on the adjacent live traffic lane.

2.4. SELECTION OF TRIAL JET GROUTING OPERATIONAL PARAMETERS

The initial selection of operational parameters for the jet grouting was based on past experience in similar ground conditions. To assist the selection of trial jet grouting parameters, Menard Bachy have developed charts based on fluid energy dissipation approach and soil erodibility classification.

These charts which consists in relating column diameter with treatment energy and with some simple soil properties such as N-SPT and CPT $q_c$ cone resistance are still highly empirical. However, this method still provides relevant first parameters approximation.

The treatment energy is calculated at the pump ($E_p$) by the following formula:

$$E_p = \frac{P[MPa] \times Q[m^3/s]}{v[m/s]}$$

Where $P$ is the grout pressure, $Q$ the grout flow rate and $v$ the lifting rate.

In order to account for the losses along the high pressure hoses and through the nozzles, the treatment energy is calculated at the nozzles ($E_n$) rather than at the pump by the following formula:

$$E_n = \frac{8\rho Q^3}{\pi^2 n^2 d^4 v}$$

Where $\rho$ is the grout density, $Q$ is the grout flow rate, $n$ is the number of nozzles, $d$ the diameter of nozzles and $v$ the monitor lifting rate.

Relying on the large amount of field data accumulated over the last few years, Menard Bachy can estimate for trial purpose the range of the required energy for a given column diameter and soil type.

For this specific project, a treatment energy of up to 200MJ/m for 1800mm diameter column was required to break down the cohesion between the soil grain in the stiff natural material below the RE backfill. In light of the above required energy, pre-cutting which consist of cutting the in situ material with high pressure water jet prior to the grouting phase was introduced in order to optimise cement consumption. In this case, the total erosive energy is equal to the energy of the pre-cut and grout phase.
2.5. QUALITY ASSURANCE & QUALITY CONTROL

2.5.1 TRIAL TESTING
Prior to the commencement of the jet grouting works, an extensive trial campaign was performed onsite to ensure that anticipated production jet grouting parameters met or exceeded the design requirement.

A total of seven numbers of jet grout columns of different diameter and shape were installed as trial columns. After a minimum curing period of 12 hours, the top of Jet grout columns were exposed by excavation to measure the actual diameter of the column within the RE select fill material. Coring, with triple core barrel, was performed in the overlap of 1800mm diameter columns to confirm column diameter and integrity of the overlap throughout the RE backfill and the natural material below. Figure 9, on the right, show an example of the cored columns and samples. The jet grouting parameters had to be adjusted across the site in order to achieve design requirements.

Figure 9: Half Column and full column with 2.2m diameter top exposed and core box

2.5.2 PRODUCTION TESTING
Both drilling and jetting were monitored by digital recording hardware. During drilling, depth, advance speed, rotary speed and thrust pressure were recorded. Grout pressure, grout flow, grout volume, stationary time, air pressure, air flow, uplift speed and rotation speed were monitored during the jetting phase. The start and stop time for each columns was also recorded. Furthermore, the grout density and viscosity were measured during each working shift. Jet grouted test columns were subjected to UCS testing on wet grab samples taken from spoil material. The tests demonstrated that the minimum required UCS of 3.5MPa had been achieved as shown on Figure 10.

Figure 10: Summarised Results of UCS testing against time on wet grab samples

2.6. MONITORING
The JG wall was constructed and completed during August and September 2012. Excavation of the existing reinforced soil wall in front of the JG wall commenced early 2013. The reinforced soil wall excavation reached final excavation level in April 2013. Movement monitoring points were established on the JG wall and were monitored during the JG wall construction and during the excavation of the exiting reinforced soil wall. The monitored relative movements of JG wall from the end of JG wall construction to after the full excavation of the existing reinforced soil wall were generally less than 2mm lateral and 4mm vertical. There were consistent 3mm to 4mm upward movements of the JG wall along the wall.
alignment. It is considered that the monitored upward movements of the JG wall were due to unloading effect from excavation of the existing reinforced soil wall.

The monitored lateral movements of the JG wall were relatively small compared to the size of the wall. The monitored relative wall lateral movements to date representing less than 0.1% strain. Therefore, the JG wall and the founding materials are still behaving in the elastic range. The monitored relative movements of the JG wall indicate that the JG wall generally performed in accordance with the wall design.

![Figure 11: Photos of Elizabeth Rd Bridge: (a) Prior to jet grouting (b)&(c) During staged excavation (d) After excavation with jet grouted wall exposed](image)

3. CONCLUSION

The innovative solution of stabilisation and strengthening of an existing reinforced earth wall abutment using jet grouting has proven to be an effective solution at the Southern Expressway Duplication project. The solution minimised disruptions on existing traffic for both Elizabeth Road and Southern Expressway whilst also providing significant program benefits and cost savings.

The engineered solution allowed taking advantage of all existing structural components of the existing bridge whilst minimising requirements for removal and replacement of existing structures.

Finally the implementation of a careful regime of testing, quality control and monitoring allowed successful control of the execution process throughout the entire construction life to achieve performance requirements whilst validating the design throughout the respective stages of works.
REFERENCES


