A CASE STUDY OF GROUND IMPROVEMENT USING SEMI-RIGID INCLUSIONS FOR BREAKWATER ROAD BRIDGE

Nelson Fok[1,a], Tony Qiu[1,b], Philippe Vincent[2,c] and Michal Kreminsky[2]

[1] *Technical Consulting Department, VicRoads, 12 Lakeside Drive Burwood East VIC, Australia. E-mail: [a] nelson.fok@roads.vic.gov.au, [b] tony.qiu@roads.vic.gov.au*

[2] *Menard Bachy, Level 3, 13-15 Lyonpark Road Macquarie Park NSW Australia. E-mail: [c] pvincent@menardbachy.com.au*

The Breakwater Road Realignment project involves construction of a 640 m long multi-span bridge over the Barwon River and is expected to be completed in mid 2012. The western bridge approach consisting of a bank of culverts and an earth fill embankment is to be constructed over a floodplain, which is underlain by soft and compressible alluvial swamp deposits of up to 6 m thickness. This stratum if untreated was predicted to undergo large time-dependent settlements that would not satisfy the serviceability requirements. Various ground improvement techniques were investigated to alleviate the effect of long term settlement and the “Controlled Modulus Column (CMC)” as a type of semi-rigid inclusion solution was adopted for the site.

This paper details the development of the CMC ground improvement from initial investigation through to construction with particular emphasis on the design and construction quality control of the ground improvement works. Typical quality control measures include slump tests on trial/production grout mix, Uniaxial Compressive Strength (UCS) testing on the design grout mix and formed columns, static load testing, full-depth coring of trial columns and pile integrity testing. The post-construction performance of the improved ground is being assessed by a settlement monitoring system consisting of hydraulic settlement gauges, in-situ pressure cells and a remotely accessible data logger. The actual total and differential settlements have been monitored during construction and will be continuous for two years following completion of the construction. So far, the current field testing and monitoring results have indicated that the required performance of the CMC is achievable.

Keywords: Controlled modulus column, Static load testing, Pile integrity testing, Settlement monitoring.

1. INTRODUCTION

Breakwater Road forms part of a major east-west connection across the Barwon River and is a vital freight link between Geelong and the Bellarine Peninsula in Victoria, Australia. The existing two-lane single carriageway bridge over the river is carrying around 20,000

Proceedings of the International Conference on Ground Improvement and Ground Control
Edited by Buddhima Indraratna, Cholachat Rujikiatkamjorn and Jayan S. Vinod

ISBN: 978-981-07-3559-3 :: doi:10.3850/978-981-07-3559-3_02-0028

vehicles each day but is subject to periodic closures due to flood inundation in winters. To reduce the flood impacts on road users, VicRoads, the state road and traffic authority proposed to realign a 1.3 km section of the Breakwater Road and construct a new 640 m bridge over the Barwon River. The 19-span structure commences at a distance of approximately 180 m from the west bank of the Barwon River to the eastern end connection. Approach to the western end of the structure is via a 170 m long earth fill embankment and a bank of culverts of 130 m long to allow passage of flood water. The earth fill embankment together with the culverts is to be constructed over a floodplain immediately west of the Barwon River where soft and compressible alluvial deposit is expected.

Due to the need to complete the project within the nominated timeframe, conventional ground improvement techniques such as surcharging were considered unviable. As a result, other types of ground improvement techniques were investigated. Deep soil mixing (DSM) and semi-rigid inclusion were both considered suitable options by VicRoads. Controlled Modulus Column (CMC) as one of the semi-rigid inclusion techniques was finally adopted by the Contractor. Project construction has commenced in late 2010 and expected to complete in mid 2012.

2. GEOTECHNICAL CONDITIONS

A comprehensive geotechnical investigation was carried out for the proposed realignment between 2007 and 2009. The extent of the soft ground was investigated by closely spaced boreholes, CPTs and test pits. Both bulk and undisturbed soil samples were collected and subsequently divided into representative groups for laboratory testing for determinations of Atterberg limits, particle size distribution, compressibility and shear strength.

The investigation results indicated the upper soil strata of the entire western fill embankment and box culvert footprint is predominated by Quaternary and Tertiary river alluvial deposits comprising clay, sand and gravel to approximately 22 m below ground surface. Typically, a layer of very soft/loose clayey/sandy swamp deposits was found between 1.5 m and 7.5 m below the ground surface, overlying a medium dense to dense High-Level Alluvium sand layer of 2 to 3 metres, which is in turn underlain by the stiff High-Level alluvium clay layer of 8 metres. The Waurn Ponds formation consisting of RS-DW limestone is overlaid by the alluviums and commonly known as the bedrock unit of the Geelong region.

The investigation indicated the groundwater level was approximately 1 m (RL +0.5 m) below ground surface. It is known that the groundwater level fluctuates with the river water level, which could have risen to very close to the grounds surface during periods of heavy rainfalls.

A summary of the subsurface conditions encountered at the western approach embankment is presented in Table 1. A generalized subsurface condition of the west bank of the Barwon River is illustrated in Figure 1.

3. TECHNICAL REQUIREMENTS

VicRoads was responsible for assessment of the potential impacts of the untreated soft ground and provision of appropriate geotechnical designs to ensure that the long term performance of the structures meets its serviceability requirements. The investigation results

Table 1. Subsurface conditions at west bank of the river.

Typical Elevation (m AHD)	Unit Name	Soil Description	Geotechnical Test Results
+1.5 to 0	FILL & ALLUVIAL CRUST	firm-stiff sandy CLAY or loose clay SAND	SPT $N = 7$ to 11 $q_c = 1$ to 5 MPa
0 to −6.0	RIVER ALLUVIUM (SWAMP DEPOSIT)	very soft to soft sandy/silty CLAY	SPT $N = < 1$ to 3 $q_c = 0.2$ to 1 MPa $Su = < 35$ kPa
−6.0 to −9.0	HIGH-LEVEL ALLUVIUM	medium dense to dense gravelly SAND	SPT $N = 23$ to 50 $q_c = > 25$ MPa
−9.0 to −22.0	FYANSFORD CLAY	firm-stiff silty CLAY; CLAY	SPT $N = 7$ to 27 $q_c = 1$ to 4 MPa
−22.0 and below	WAURN PONDS LIMESTONE	XW-DW Limestone	SPT $N = > 50$

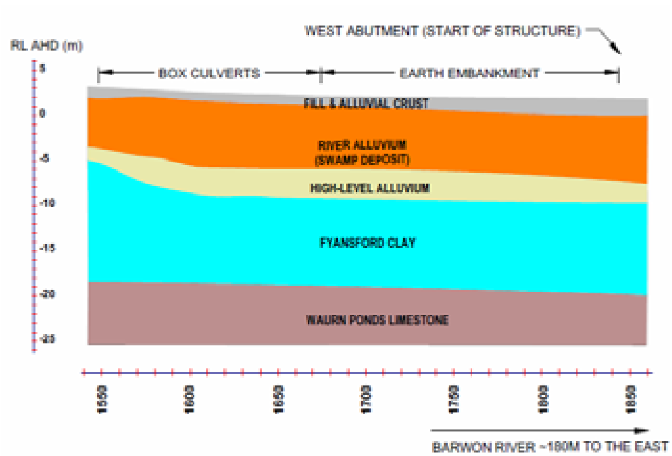

Figure 1. Generalized subsurface condition the west bank (longitudinal).

were used as inputs to the computer program PLAXIS (2D), which predicted long term settlements of up to 200 mm and 120 mm for the fill embankment and box culverts, respectively. In addition, risks of potential immediate foundation bearing failure due to placement of fill were also anticipated. After assessing various ground improvement techniques, Cutter Soil Mixing (CSM) was initially adopted as a means to minimize the construction risks and limit the long term differential settlement. Contract document prepared by VicRoads offered a CSM ground improvement design solution but also called for alternative solutions using other DSM or semi-rigid inclusion techniques.

To achieve the project performance and serviceability, VicRoads stipulated the following design criteria and settlement monitoring requirement for the ground improvement work:

- The area where ground improvement work is required
- Total settlement of any road pavement to be limited to 50 mm from the date of practical completion

- Differential settlement of any road pavement to be limited to no greater than 1/200
- A design serviceability life of 100 years
- A comprehensive ground settlement monitoring regime covering both construction and post construction stages

McConnell Dowell was awarded the contract of the Breakwater Road Realignment project in mid 2010. Due to the need to relocate the west abutment further away from the Barwon River at the time of project execution, the length of the western embankment was reduced from approximately 490 m to 300 m. Upon review of the project requirements, the head Contractor's geotechnical specialist, Menard Bachy, proposed an alternative ground improvement scheme relying on the use of Controlled Modulus Columns (CMC). As well as presenting program benefits, this was considered cost effective and was accepted by VicRoads. A comparison between the use of CMCs and the use of CSMs indicated an approximately 10–15% cost savings could be achieved. The CMC design, construction and settlement monitoring will be discussed in this Paper.

4. GROUND IMPROVEMENT DESIGN & CONSTRUCTION

4.1. *CMC Design*

CMCs were firstly developed in Europe and the design concept relies on the modelisation of the interface between vertical semi-rigid inclusions made of weak mortar and the in-situ treated ground to exploit the properties of the resulting composite material (Combarieu, 1988). The columns distribute overburden/loads throughout the soil mass to surrounding soils and competent founding substrata to limit deformability of soft compressible ground. Unlike conventional rigid structural elements (e.g. piles) which transfer the entire structure load down to a competent rock layer as bridging elements, CMCs are designed to transfer a proportion only of the structure load. This given level of deformation in accordance with the structure acceptable range of deformations. The resulting product is an improved "soil mass system" with increased equivalent defomability to reduce total and differential settlements caused by the loads imposed. The principles of the CMC ground improvement were discussed in detail by Liausu and Pezot (2001), Plomteux and Porbaha (2004) and Masse *et al*. (2008).

On breakwater road, the design load in Ultimate Limit State (ULS) to be imposed on the footprint of the fill embankment and the box culverts were 95 kPa and 88 kPa, respectively. The CMC system developed in this project comprised two major components: (1) a Load Transfer Platform (LTP) and (2) vertical CMC elements between the LTP and the supporting substratum.

The LTP has been designed to transfer the loads uniformly to the CMC improved soil mass by soil "arching effect" (Halvordson, 2007). It consists of a layer of 600 mm thick crushed rocks (Class 2) with 3 layers of bi-axial geogrid reinforcements. Two woven geotextile layers of very robust (G>2000) classification were used beneath and over the LTP to function as separation and filtration purposes.

Static calculation methods were adopted to determine the depth of the CMC columns, anchorage length into the founding stratum and grout properties to be used, mainly based on the soil parameters derived from SPT, CPT and shear test results. The CMCs used in this

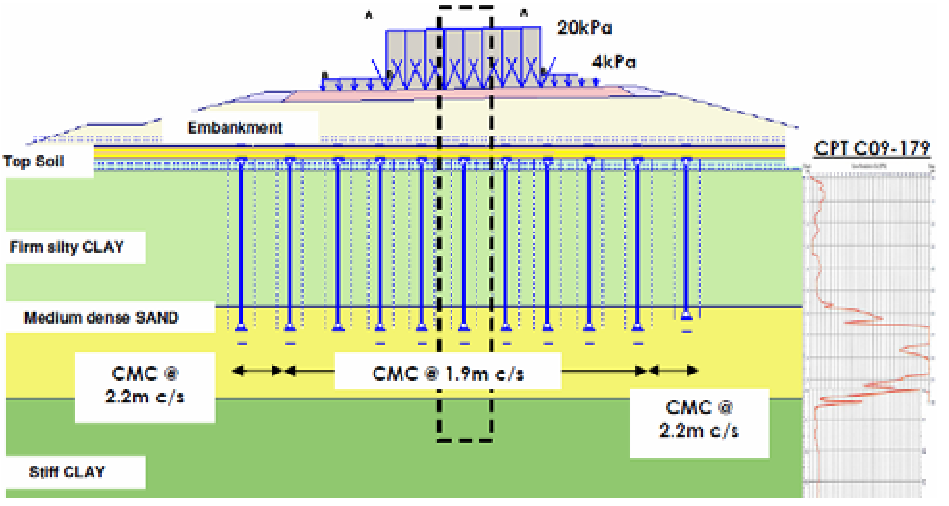

Figure 2. Adopted Plaxis model.

project had a nominal diameter of 450 mm and were designed to extend approximate 6–9 m below the ground surface to obtain an anchorage of at least 1.0 m into the medium dense to dense gravelly sand layer. Since the dense founding layer only has a limited thickness of 3 m, the 1.0 m embedment depth was carefully selected to allow at least 2 m of bearing stratum for the load transfer so that the columns would not punch through the dense layer and sit on the underlying weaker clay layer. The CMCs were generally spaced at 1.9 m on a square grid (refer Figure 2 for Plaxis modelisation).

As a design check it is verified that CMC's geotechnical capacity are capable of supporting the entirety of the design loads. During checking of individual CMC's performance, skins frictions above the founding strata were ignored in the design. Based on the spacing of the CMCs and the design loads, each of the CMCs was designed to achieve a geotechnical strength of 350 kN of which 270 kN and 80 kN were to be developed respectively through end bearing and side friction in the founding substratum. Structurally, the columns were designed assuming a Uniaxial Compressive Strength (UCS) of 10 MP and a Young's modulus (E_y) of 5 GPa at 28-day. A total of about 1100 CMC columns were proposed underneath the footprint of the western fill embankment and the box culvert section. Figure 3 and Figures 4a-b demonstrate the ground improvement layout and the two types of column spacing designed under various loading conditions, respectively. The total area to be improved was approximately 8,500 m^2. The area replacement ratio for the CMC system was approximately 4.5% (and higher in transition zones).

4.2. *Numerical Analysis*

A series of two-dimensional finite element modelling using Plaxis was carried out to assess the effectiveness of the proposed CMC ground improvement design with respect to total settlement of the soft compressible material, differential settlement across and along the road and bearing capacity of the bearing stratum. The FEM analysis was made in short-term and long-term conditions to assess the time dependent behaviour of the improved

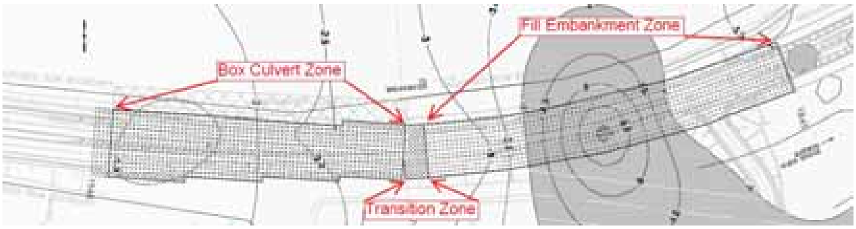

Figure 3. CMC ground improvede layout.

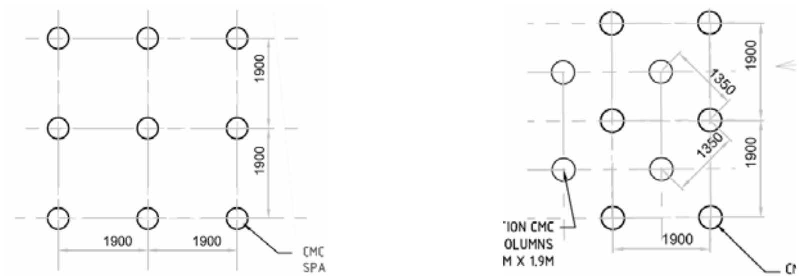

Figure 4. a. CMC spacing for the box culverts and fill embankment section; b. CMC spacing for the transitional section between the box culverts and fill embankment section.

Table 2. Summary of Calculated Settlements Using FEM.

Stage	**Vertical Displacement (mm)**		**Residual Settlement (mm)**
	Immediate	Drained	
Embankment Construction	28	50	22
Service Load	9	12	12
		Total	34

ground subjected to loading. The modelling approach was similar to that of many published literature and consistent with Pearlman and Porbaha (2007). A summary of the predicted total settlements under the drained (long term) and undrained (short term) is summarized in Table 2. The maximum differential settlement at the top of the fill embankment and box culvert sections were also calculated using FEM and a 14 mm over 9.17 m giving a gradient value of 0.3/200 was calculated. The FEM analysis results indicated the design criteria required by VicRoads were achievable.

4.3. *CMC Installation*

The CMC installation system uses a displacement auger powered by a multi-purpose foundation rig with high torque capacity and high static downward thrust. The specifically designed reverse-flight displacement auger pushes the soil laterally during penetration whilst generating minimal spoil, noise and no vibration. The low impact profile of the technique was a key benefit for the Breakwater project as ground improvement was to be installed within close proximity of live road traffic (refer Figure 6).

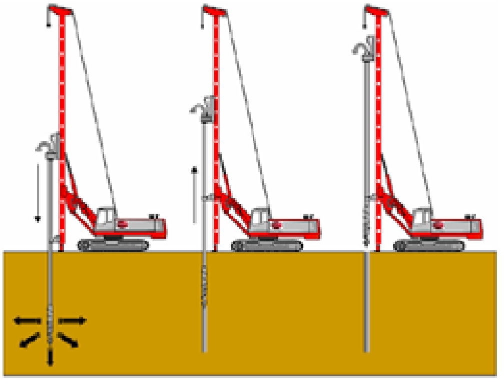

Figure 5. Construction process for CMCs.

Figure 6. CMC installation at the field.

The CMC displacement auger is hollow in order to permit pumping of the grout during withdrawal of the auger. Injection pressures used range between 1 and 5 bars and are higher than conventional piling techniques and more akin to pressures used in shallow compaction grouting applications. In addition the CMC rig is equipped with computerised quality control systems in order to automatically record date and time of the installation of each column as well as essential construction parameters such as depth, torque and down-thrust during drilling, grout volume and installation pressures.

The elimination of spoils allows for a cleaner site with less traffic required for the evacuation of the unwanted material but also mitigate the risk of having to handle contaminated in-situ material. This point proved useful during the construction phase as initial investigation by VicRoads and the head Contractor highlighted the presence of localised superficial pockets of rubbish (including Car/Motorbike tyres, Steel Wire Rope approx 25–30 mm diameter in large bundle, bricks, bottles, shells, concrete blocks). Upon review of the nature and size of the obstructions encountered, it was decided that CMC works could be carried out through the rubbish fill without requiring expensive and lengthy works to excavate and replace. Further the very nature of the ground improvement philosophy would have allowed the relocation of a number of CMC on the field should large obstructions prevent the formation of any column. During production, the presence of the obstructions identified proved to be manageable and induced only minor slowdown in productivity thanks to the displacement technique which laterally displaced the contamination.

Overall, the project totalled in excess of 15,000 l m of CMCs which were installed between March and May 2011 over a period of 12 weeks using one rig. Typical industrial productivities achieved on site of 300–350 l m per shift where in line with expectations.

Figure 5 illustrates the construction process of the CMCs and Figure 6 shows the installation rig in operation within the box culvert section of the site.

5. QUALITY CONTROL

Since CMC ground improvement was used for the first time in Victorian roads, VicRoads has placed a stringent set of quality control measures throughout the construction and post-construction stages. The quality control was mainly a three fold process consisting of:

- VicRoads stipulated construction control measures such as field trial requirements, UCS testing on grout samples, pile integrity testing, coring of trial columns and static load testing
- Menard Bachy's field installation control measures such as column profile, depth and mortar quality
- McConnell Dowell settlement monitoring during and after construction

5.1. *Grout Trials*

Grout mixes typically vary depending on the location of the project, distance of batching facility to the site and local availability of materials (fly ash, sand, cement, etc). As a results and prior to any field trial, UCS, grout slump and fluidity testing on several trial grout mix were performed by Menard Bachy. The proposed mixes were composed of a blend of cement/fly ash (200–250 kg/m^3), a homogeneous mixture of sands between 2 and 7 mm (1750–1900 kg/m^3) and additives as required for workability and fluidity.

Due to the close proximity of the batching facility within 30 minute's drive of the site, a workability of 3 hours was targeted with a slump of 200–300 mm. UCS test results of the CMC mortar showed that strength was readily achievable within a 7-day curing period and results at 28-day curing all exceeded 15 MPa, well over the required strength of 10 MPa. Upon selection of a compliant mortar, pumping tests were organised on site to verify the dynamic behaviour of the mixes during the grouting process and bring the final adjustments required to the mix.

5.2. *CMC Field Trials*

An extensive field trial program was stipulated by VicRoads and executed by Menard Bachy two months prior to installation of production columns. The purpose of the field trials was to (1) determine whether the field performance of the CMCs would fulfil the design intentions and (2) formulate a set of site specific installation criteria for the installation rig. The methods and equipment used in the field trials were those would be used for production works. The trial program comprised the following:

- Installation of ten trial CMCs in the vicinity of existing borehole or CPT sites for verification of drilling parameters
- Grout testing and sampling for slump and UCS
- ten pile integrity tests
- Coring of five trial columns and samples at 2 m, 4 m, 6 m and 8 m depth to be UCS tested

Following the installation of the trial columns, the geotechnical data was correlated with the drilling parameters to assess the column depths and refusal criterion for production columns. Figures 7 and 8 showed the field installation record and the correlation between CPT data and drilling resistance parameters for a typical trial column. Based on the correlations of all ten trials, the gravelly sand founding stratum for the CMC was identified as developing a typical torque of 75–100 kNm. The production CMCs would be terminated when 1.0 m penetration was achieved into material with this typical torque range.

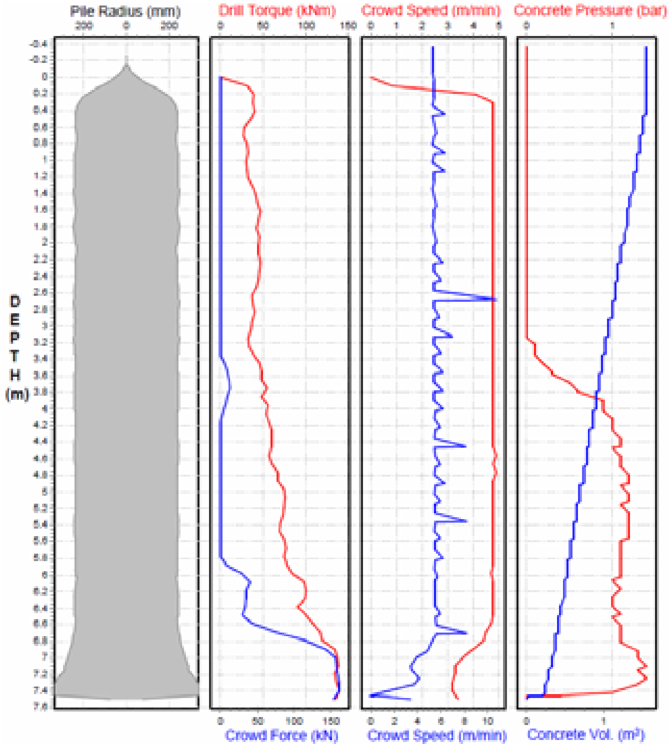

Figure 7. Field Installation Record of TrialColumn TC5.

Pile integrity testing was carried out on the trial columns using the transient dynamic response (TDR) method. Integrity testing was proposed to identify eventual neckings associated with the "auger and grout pumping" type of column installation process. The testing assumed an average wave velocity of the concrete lies within the range of 3500 m/s to 4000 m/sec, which reasonably correlated to the grade and strength of mortar used for these columns. The testing generally indicated satisfactory results (i.e. no major necking detected) and increased impedance corresponding to the dense founding stratum. An exception was found in the Test Column No. 1 where a slight decrease of impedance at approximately 4 m was noted. This minor defect was later verified by coring of column, where a clay lump at approximately 4.4 m depth was identified (discussed later under this section). As the integrity testing was carried out using the TDR method, pile head stiffness E' of the columns were able to be determined. Values of E' for the trial columns generally varied from 0.25 MN/mm to 0.44 MN/mm and were reasonably consistent across the site. Based on Davis and Dunn (1974), this benchmark range of E' was used at the later production stage to assess column integrity by comparing the E' values of the production columns to the benchmark values.

Coring of five trial columns was undertaken as part of the field trial program. The trial columns were cored using a geotechnical coring rig equipped with HQ sizing coring to give a core diameter of approximately 60 mm. All cored columns showed a full and continuous except the above mentioned clay lump inclusion in the Trial Column No. 1 at 4.4 m depth,

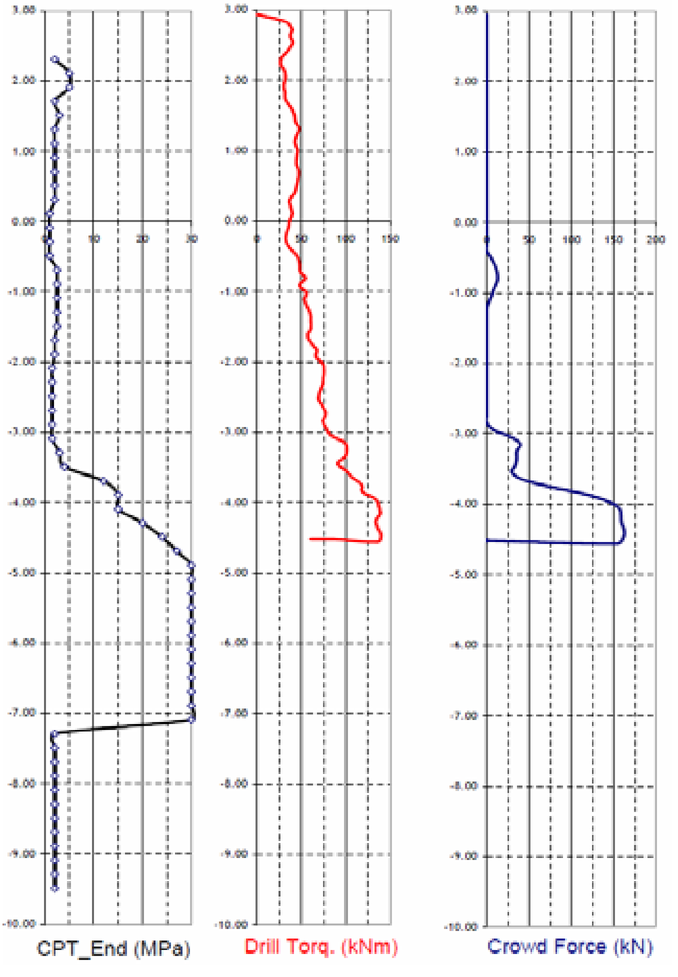

Figure 8. CPT Correlation Graph of TrialColumn TC5.

which was suspected to be a small soil intrusion due to the unbalanced grout pressure and the active (K_a) soil pressure at a horizon between the soft and stiffer materials. Representative samples were taken from the cored samples for UCS testing and the average of UCS strength was 14.6 MPa. Out of the 16 samples tested, only one sample displayed strength of 9 MPa that was lower the required 10 MPa at 28 days. This anomaly was however considered acceptable on the basis that (1) the single anomalous result was 10% less than the required strength, (2) the overall average strength of 14.6 MPa was 46% above the required strength, (3) the CMCs work on a systematic manner rather than relying on an individual discrete columns.

5.3. *Static Load Testing*

The performance of the CMCs was confirmed by static load testing on two selected trial columns, namely TC9 and TC10. The purpose of the static load tests were to check that the

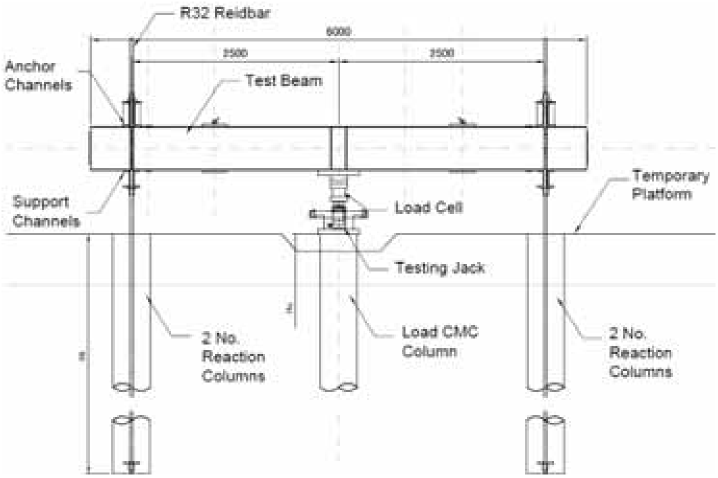

Figure 9. Design of the static load testing load transfer system.

Figure 10. Site photo of the static load testing setup.

columns are capable of bearing the loads imposed on them and to assess any "creep settlement" under the maximum loading. The reaction system consisted of four CMCs installed at a distance of 2.5 m from the test pile. The reaction piles were located at a distance to minimise any interference to the test pile through interaction of soil resistances. Transfer of the test forces was carried out by a series of beams and bars as shown in Figure 9. A hydraulic jack and load cell was set on the test element directly beneath the reaction beam. Pile top displacements were monitored with three analogue dial gauges with load cell reading and jack hydraulic pressure being recorded at the same time. The system setup in the field is demonstrated in Figure 10.

A three-stage testing regime was formulated and adopted:

1. First loading stage: 50 kN pre-load; 20% Design Load (DL) for 20 minutes; further load increment of 10%DL to 100%DL at a 20-minute interval, 100%DL held for 60 minutes;

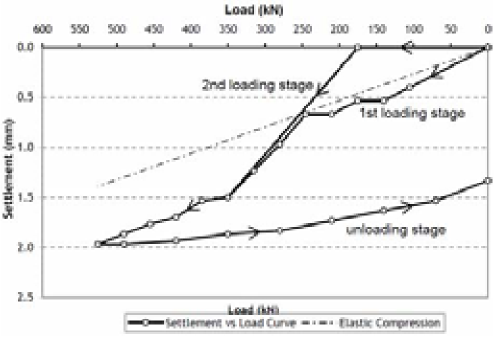

Figure 11. Load-settlement graph of TC9.

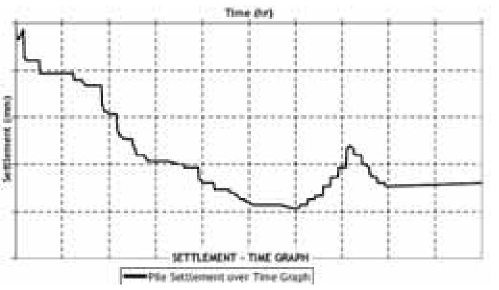

Figure 12. Settlement-time graph of TC9.

further load increment of 10%DL to 150%DL at 20-minute interval, 150%DL held for 60 minutes.

2. Unloading stage: load decrement from 150% to 140%, held for 10 minutes; further load decrements to 20%DL at a 10-minute interval, 20% held for 10 minutes.
3. Second loading stage: load increment of 20%DL to 100% at a 10-minute interval; 100%DL held for three days.

The acceptance criteria of the test columns were established as (1) no failure of test piles during any incremental load stages and (2) “creep settlement” on any columns was to be limited to less than 1 mm per day for a minimum duration of three consecutive days. The results of the static load testing are graphically illustrated in Figure 11 and Figure 12. The results of the incremental loading showed a mix of elastic behaviour of the test columns and some nominal permanent movement of less than 1.5 mm. The “creep settlements” on both tested columns showed zero reading in three consecutive days, virtually showing no continued displacement under the design load.

5.4. *Production Quality Control*

The grout quality is one of the most essential elements in the success of the CMC productions as other installation procedures and/or criteria were pre-determined in the field trial. To ensure the grout quality meets the design criteria, it was required that a slump test is performed for each truck mixer delivered on site and for each 100 m^3 of grout, six cylinder samples were taken for UCS testing at 7 and 28 days.

Following the installation of CMCs, 10% of the production columns were selected for integrity testing at 28 day. Out of the 110 columns tested, five were detected to have abnormal pile head stiffness and decreased impedance at shallow depths, for which soil inclusions to the columns were suspected. Excavations around these columns to the designated depth however did not encounter the detected defects. It was considered that these anomalies were most likely to be caused by the inhomogeneous nature of the thin fill layer at near the column heads, which affected the wave propagation and reflection along the column. In general, the slump tests, UCS tests and integrity testing indicated satisfactory results throughout the production stage.

6. MONITORING

Immediately following the completion of the CMC production works in August 2011, a settlement monitoring system consisting of settlement monitoring gauges, earth pressure cells and automated data logger was installed at two locations over the treated area of the western fill embankment section to assess potential settlements during and after embankment construction. To avoid constructional disturbances/damages to the conventional monitoring gauges (e.g. settlement plates and survey pegs) as experienced in many construction projects, a differential settlement monitoring (DSM) type of gauges based on the principle of hydraulic pressure variation was used. The monitoring gauges and earth pressure cells were installed directly above the LTP to provide real-time readings of the settlement of the improved ground and the actual loads being applied to the ground. A schematic plan showing the monitoring system is shown in Figure 13.

Up to the time of this paper writing, the construction of the western fill embankment has been on-going. Under the current fill height of approximately 1.5 m, the earth pressure gauges recorded a pressure range between 25–32 kPa, equivalent to 90–115 kN force on

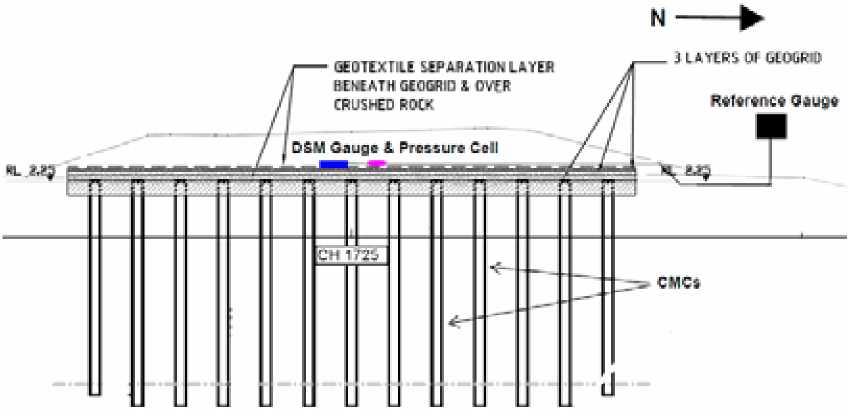

Figure 13. A schematic plan of the settlement monitoring system used for the ground improvement.

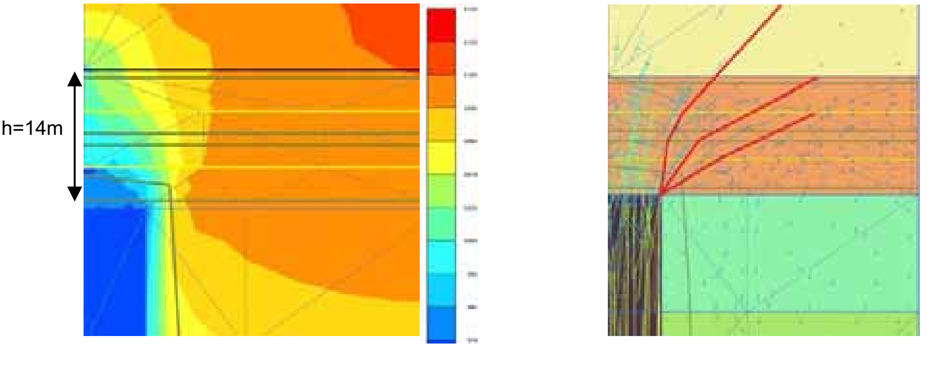

Figure 14. Total displacement and Principal effective stress direction.

each column (i.e. one third of the maximum design load). The average settlement measured under the currently recorded load is approximately 5 mm. This magnitude of settlement is higher than that recorded during the static load testing on isolated columns. This difference is explained as the load is applied on the composite material rather than directly on top of the CMC inclusion. As the clay between CMC inclusion starts to settle under the increased applied stress an arching effect progressively develops above the CMC column heads. This arching effect is fully developed when equilibrium is achieved between soil consolidation (negative soil friction) and CMC punching within the transition layer has occurred. As a result, deformation on top of the transition layer is always greater than that experienced at the top of the column head as illustrated in Figure 14.

Settlement monitoring will continue during the construction period and beyond for an additional two years following the completion of the project. Based on the measured results to date, it is anticipated the actual total settlements and differential settlements will be within the design criteria and predicted numerical analysis estimates.

7. CONCLUDING REMARKS

The soft and compressible ground on the proposed Breakwater Road Bridge site in Geelong, Victoria was successfully improved using CMCs. The case study of the project demonstrates the effectiveness of the CMC system to allow a tight construction program whilst meeting the serviceability requirements of the structure. During the design and construction of CMC, the following project specific features were noted:

- The design method incorporating both static soil mechanics methods and numerical analysis was proved to be effective by the well correlated results between predicated settlement values and the actual measured results of the static load testing and settlement monitoring.
- The use of CMC system significantly shortened the construction time than other conventional ground improvement methods such as pre-loading. The CMC installation was completed within three months for an area over 8500 m^2, which then enabled consequent construction of box culverts and fill embankment to proceed without delay.
- CMC ground improvement solution is advantageous in cost to deep soil mixing methods. A 10–15% cost saving was achieved by the utilisation of CMC in this project compared to the deep soil mixing based CSM technique.

Further to the design and construction, a well structured construction quality control regime consisting of quantitative and qualitative assessments using slump tests, visual inspection by coring, UCS tests and pile integrity testing was stipulated by VicRoads and executed professionally by the Specialist Contractor. In general, results obtained from the quality control measures suggested satisfactory results and minor issues identified were explainable by cross-verifications. The purposely designed static load testing proved that the installed columns had sufficient load bearing capacity whilst developing minimal "creep settlement". The project is currently under construction, preliminary results from the monitoring system provide a high level of confidence that the specified settlement criteria will be met in the long term.

ACKNOWLEDGEMENT

The authors would like to thank the Executive Director, Mr Steve Brown of Regional Services of VicRoads for providing permission to publish this paper and opportunities to participate in this project. In addition, the authors express their appreciation to Mr Nathan Kamalan, Breakwater Road Realignment Project Manager of VicRoads South Western Region, Mr Brendon Davey of the head Contractor McConnell Dowell, Mr Greg Taylor (Project Manager) of Menard Bachy and Mr Stephen Darmawan of Geotesta for their collaboration to execute the monitoring program and make the results available.

REFERENCES

1. Combarieu, O. Amélioration des sols par inclusions rigides verticales. Application à l'édification de remblais sur sols médiocres. *Revue Française de Géotechnique*, 1988, vol. 44, pp. 57–79.
2. Davis, A.G. and Dunn, C.S. (1974). From Theory to Field Experience with the Non-destructive Vibration Testing of Piles. *Proceedings of the Institution of Civil Engineers.* Part 2, 57, December, 571–593.
3. Halvordson, K. A. (2007). Three-Dimensional Analysis of Geogrid Reinforcement Used in Pile-Supported Embankments. Virginia Polytechnic Institute and State University.
4. Liausu, Ph and Pezot, B. (2001). Reinforcement of soft soils by means of controlled modulus columns. XVth International Conference of Soil Mechanics and Geotechnical Engineering– Instanbul, Turkey-September 2001.
5. Masse, F., Pearlman, S. amd Bloomfield, R.A. (2008). Support of MSE walls and reinforced embankments using ground improvement. Otani, Miyata & Munkunoki (ed.) Taylor and Francis Group, London.
6. Pearlman, S.L and Porbaha, A. (2007). Design and monitoring of an embankment on controlled modulus columns. TRB paper #06-1743 – Transportation Research Board, Washington DC.
7. Plomteux, C. and Porbaha, A. (2004). CMC Foundation System for Embankment Support – A Case History. ASCE Conference 2004.