Design and construction of dry soil mix ground treatment in soft estuarine clays for a road embankment

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ABSTRACT
Dry soil mix (DSM) columns have been used to improve soft estuarine clay for construction of a bridge approach embankment. The geotechnical design aimed to minimise the number of columns required to achieve technical requirements and assumed uniform column shear strength and stiffness. Constructed DSM columns are highly non-uniform and the approach used in the construction specification to ensure construction met design requirements is discussed. Field trials are a vital component of the specification and results of the field trials are presented. Field and production QA testing was primarily performed using the pullout resistance test (PORT). The strengths and limitations of this test are discussed. Field and production QA test data are presented. Monitoring data during construction and subsequent settlement is presented and discussed with reference to design requirements and QA testing.

RÉSUMÉ
Des colonnes constituées d'un mélange de sol sec (Dry soil mix - DSM) ont été utilisées pour améliorer en place l'argile molle estuariennes, pour la construction d'un remblai d'accès à un pont .La conception géotechnique vise à optimiser le nombre de colonnes nécessaires pour atteindre les exigences techniques (réduire les tassements attendus). Il s'agit de conférer une homogénéité à un sol en terme de résistanceau cisaillement et de rigidité. En partant du principe que les colonnes DSM soient hautement non-uniformes, l'approche détaillée dans le cahier des charges de construction pour garantir la faisabilité et répondre aux exigences de conception mérite d'être détaillée. Les essais in-situ sont une composante essentielle du cahier des charges. Les résultats de ces essais sont présentés. Sur le terrain, la production QA tests résulte principalement du test de résistance retrait (PORT). Les avantages et les limites de ce test sont discutés. Le résultat de tous les essays (in situ et production d'AQ) est présenté. Les données de surveillance pendant et aprés la construction sont présentées et discutées en référence aux exigences de conception et de tests d'assurance qualité.

1 INTRODUCTION

Dry soil mix (DSM) columns are a form of semi-rigid ground inclusion constructed by mixing dry cement powder or other binders into a soil mass using a specialised mixing tool attached to the Kelly bar of an excavator.

DSM columns have been used to improve soft estuarine clay for construction of the southern approach embankment to the Cumbalum Flood Plain bridge near Ballina on the east coast of Australia. The soil at this location is an estuarine clay composed of 75% clay particles of which 63% is smectite and 12% is kaolinite. The organic content lies between 2% and 5%. Moisture contents are as high as 140%, the liquid limit ranges between 70% and 140%. The plastic limit ranges between 30% and 40%. The depth of the estuarine soil was about 13.5m at the abutment and increasing in depth away from the abutment. The embankment height varied from 4.5m to 5m from west to east. The design settlement criteria was a 50mm in 40 years at the abutment to control differential settlement from the bridge to the embankment as well as limiting lateral soil movements acting on the bridge piles, along with a differential settlement of the embankment no greater than 0.5% to accommodate flexible pavement.

Potential ground treatments at this location included surcharge with wick drains, dry soil mixing, wet soil mixing, stone columns, displacement auger piles and a piled embankment. Selection of the type of ground treatment balanced cost, construction time, flood constraints and long term performance. DSM was favoured after a multi-criteria assessment was performed.

Design of DSM aimed to be cost effective. No load factors were used in the design although a resistance factor was used on the strength of the DSM columns. Due to the lack of margin in the design high quality construction of the DSM columns was required to achieve the design intent. The construction was controlled via the project specification. A description of this process along with measured data is presented in the following sections.

2 GROUND TREATMENT DESIGN

Design of DSM adopted the philosophy that closely spaced columns improve the mass behaviour of the soil and the soil mass can be assigned weighted average parameters and be analysed as a homogeneous equivalent block. The design methodology was developed based on the Swedish Geotechnical Society report SGF 495E (1997).

DSM columns were installed in panels and grids beneath the batters to maintain stability. Single columns were placed beneath the crest of the embankment and act to control settlement. The geotechnical design aimed to minimise the number and length of columns required to achieve the technical design criteria. The design adopted full depth single columns around the bridge abutment and incorporated a transition zone comprising tapered DSM columns was installed behind the full depth zone to provide a smooth change in settlement from the bridge abutment to the general embankment. The tapered zone was adopted to control the differential settlement of the embankment and to reduce construction costs. An elevation drawing of the embankment and ground treatment is shown in Figure 1.

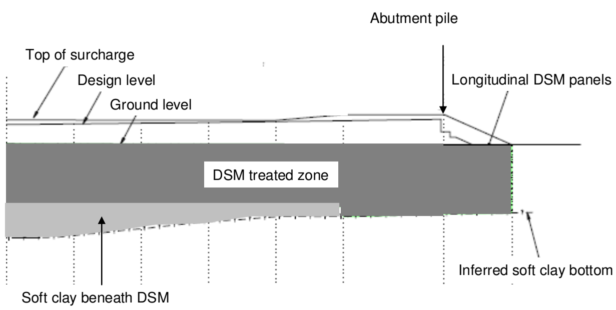

Figure 1 Elevation drawing of ground treatment

The design method assumes equal strain in the DSM columns and soil at all depths. The method assumes that the DSM columns have uniform strength and stiffness. The method limits the load carried by the columns to a maximum of 75% of their ultimate capacity and this limit was adopted for the design. The equivalent block approach was validated through comparison with results of 3D finite element analyses. The computed settlements were found to be similar using both methods and the finite element analyses demonstrated that the DSM-soil mass deformed substantially as a block.

Design parameters adopted were column diameter of 0.8m, column shear strength of 150kPa and the constrained modulus of the column was assumed to be 200 times the shear strength. The design adopted a bulk unit weight of fill of 21kN/m^3 and resulted in single columns spaced at 1.4m centres in a square pattern. This is equivalent to an area replacement ratio of 0.256. The constrained modulus of the soil was assumed to be 150 times the undrained shear strength of the soil. The settlement due to primary consolidation was assessed to be about 120mm. Panels were constructed at 3m centres on the sides of the embankment and 2.5m centres at the end of the embankment. Grids of columns were constructed at the corners of the embankment where the side and end panel arrangements intersected.

3 SPECIFICATION

Prior to construction it is not clear what mixing parameters and binder contents are required to successfully construct the columns. The specification was designed as a multi-stage process to develop the required parameters and then prove that construction was successful via QA testing. The specification required the following stages to be followed:

1. Perform laboratory mix trials varying the quantity of the binder in order to provide a first pass estimate of the required binder content and to develop a relationship between strength and time;
2. Perform field trials varying mix parameters and binder contents prior to production; and
3. Adopt the parameters determined in the field trials and confirm via QA testing on production columns.

The acceptance criteria aimed to strike a balance between achieving the design strength criteria and cost effective construction. The acceptance criteria were based on 28 day test results although earlier test results (e.g. 7 day or 14 day results) may be used for indicative purposes. To allow for variations inevitably associated with DSM (e.g. Filz, 2009) the acceptance criteria for DSM allowed for 10% of the test results falling below the target strength criteria provided these test results are equal to or greater than 75% of the target strength.

The column shear strength was measured using the pull out resistance test (PORT) and unconfined compressive strength (UCS) tests on samples taken using triple tube NMLC coring located approximately 200mm from the centre of the columns. UCS data were divided by 2 to convert to shear strength. Both measures of shear strength had to meet the acceptance criteria. In the case of the PORT results the strength profile in the column with depth also had to meet the design criteria. If the average strength measured by the PORT test was in excess of the design column strength but more than 10% of the length of the column was below 75% of the design strength then the test was not accepted.

The PORT test is described in SGF 495E (1997) and comprises a steel blade that is pulled through a column and the force required to pull the blade through the column is measured. The force is converted to a column shear strength using an empirical factor, N, in a similar way to other types of conventional soil penetrometers. The measured force is corrected for shear mobilised along the cable during extraction. SGF 495E (1997) assigns a value of 10 to N. This value does not appear to be substantiated in the literature. Larsson (2005) discussed that other recommendations exist for the N factor such as 11 (Broms, 1984) for normal soils and 20 for peat (Wiggers & Perzon, 2005). Porbaha (2002) reports that a value of 15 is specified for interpretation of the tests in Finland. Attempts to calibrate the PORT test to unconfined compression strengths (UCS) from samples recovered from DSM columns are reported by

Axellson and Rehnmann (1999). They suggest that N could be greater than 10 but do not specify a value for N. Calibrating the PORT to UCS test data or other measures of strength is difficult because of the variability within the DSM columns and the consequent uncertainty whether the small scale UCS samples are representative of the overall column behaviour. For this project, the UCS tests were performed on samples successfully recovered using triple tube coring. These samples represent the higher strength part of the columns as the lower strength material was either not able to be cored or was too fractures for UCS testing. Attempting to calibrate PORT to UCS would have resulted in skewing the calibration towards the high strength end of the range. The specification required both PORT and UCS data to meet the acceptance criteria as a means of addressing the uncertainty in both measurement methods.

4 TEST RESULTS

4.1 Laboratory mix trials

Laboratory mix trials were performed on samples obtained from test pits dug within the upper 2m to 3m of the soil. The trials were performed using binder contents of 140kg/m^3, 160kg/m^3 and 180kg/m^3. Results of the trials are shown in Figure 2. Following SGF 495E (1997), a reduction factor of 2.5 was used to assess the potential field strength of the columns from the laboratory mix trials. The reduction factor is applied because laboratory samples are mixed more thoroughly than the in-situ soil. The results indicated that a binder content of 140kg/m^3 achieved an unconfined compressive strength of 973kPa at 28 days which is greater than the required value of 750kPa.

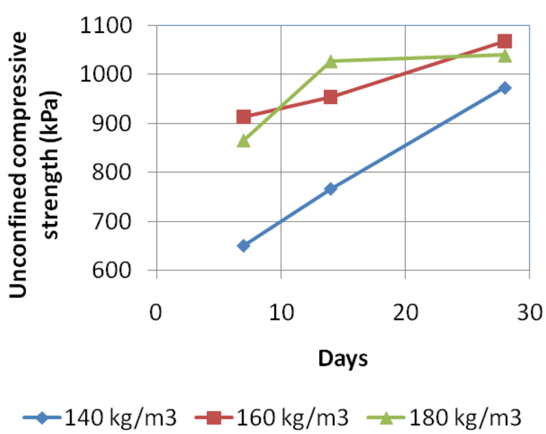

Figure 2 Results of laboratory trials

The variation of soil moisture content with depth is shown in Figure 3. The moisture content increases with depth and is greater at 5m to 8m depth than at 2m to 3m depth. Later field trial results showed that more cement was required for successful column construction than indicated by the laboratory mix trial and it is possible that this is because the laboratory trials were performed on samples with relatively low moisture content. A lower moisture content results in a lower water:cement ratio and lower water:cement ratio can lead to stronger samples.

4.2 Field Trials

Field trials were performed at 6 locations within the footprint of the works in order to cover a reasonably representative proportion of the site. Soil samples were taken at these locations to assess moisture content, plasticity index and organic content with depth. The scope of the field trials is summarised in Table 1. In Table1 RPM is revolutions of the tool per minute and BRN is blade rotation number as defined in SGF 495E (1997).

Table 1 Scope of field trials

No. of cols	Dia. (m)	Cement (kg/m^3)	No. of blades	RPM	BRN
12	0.6	160	6	135	430
12	0.6	180	6	135	530
12	0.6	220	6	133	580
45	0.8	160	8	130	830
10	0.8	180	8	132	830

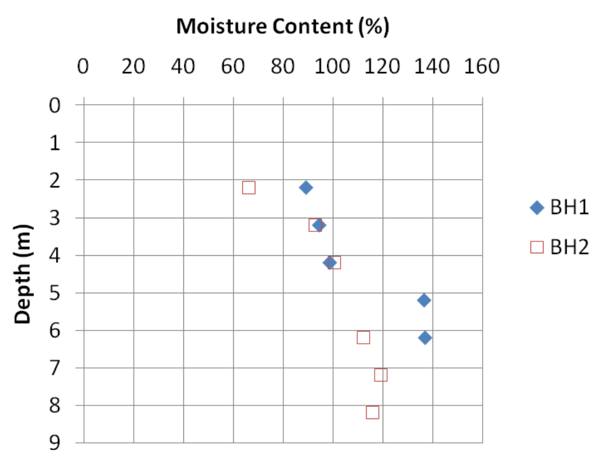

Figure 3 Moisture content variation with depth

PORT tests were performed in 52 of the columns and 11 columns were sampled by triple tube coring with 57 UCS tests performed. The remaining columns were installed to assess construction methodology and some had wire strands pulled through them to facilitate correction of PORT tests for wire friction.

The results of the PORT tests are summarised in Table 2. The mean strength represents the average of all PORT tests. Each PORT test is characterised by an average column shear strength. The standard deviation refers to deviation from the average column strength rather than deviation within each column. Results of the

UCS tests are summarised in Table 3. Although the mean strength measured in PORT tests was generally greater than 150kPa, the standard deviation was large enough to result in the average strength of some columns failing the criteria.

In addition, sections within the length of columns constructed with cement contents of 160kg/m^3 were often less than 150kPa, although the mean strength of the entire column was adequate. Results of the UCS tests also show variability in columns strength when a binder content of 160kg/m^3 was used.

Based on the results of these tests the following parameters were adopted for production:

- 800mm diameter columns
- 8 blade mixing tool
- Binder content of 180kg/m^3
- Minimum RPM of 100
- Extraction rate in the range of 1.1m/min to 1.4m/min
- Cement feed rate between 100kg/min and 150kg/min
- Average BRN >750

A ratio of 28 day to 7 day strength of 1.2 was adopted.

Adopting a cement content of 180kg/m^3 rather than 160kg/m^3 had two benefits. First the amount of cement was increased which decreased the water:cement ratio with the probably effect of increasing the column strength. Second the time required to pump the increased volume of cement into the ground increased and this results in a greater quantum of mixing. Increased mixing is likely to result in columns with more uniform and higher strength (e.g. Larsson and Nilsson, 2005).

Table 2 Summary of PORT tests performed for field trial

No. blades	Dia. (m)	Cement (kg/m^3)	Ave. Age (days)	Mean strength (kPa)	Std Dev (kPa)
6	0.6	160	4.9	139	52
6	0.6	180	4.8	200	81
6	0.6	220	4.3	313	125
8	0.8	160	3.0	340	171
8	0.8	160	10.3	393	205
8	0.8	180	6.3	311	119

Table 3 Summary of UCS test data for field trial

No. blades	Dia. (m)	Cement (kg/m^3)	No. of samples UCS > 300kPa	No. of samples UCS < 300kPa
6	0.6	160	0	2
8	0.8	160	24	21
8	0.8	180	8	1

4.3 Production QA tests and data

A total of 33 columns were subject to QA testing. Of these, 30 PORT tests were performed and 44 UCS tests were performed in 3 columns. Seven of the PORT tests could not be completed due to the inability to mobilise the PORT vane due to high column strength. The total number of columns in this area was approximately 2,600. About 1% of columns were subject to completed QA tests.

The results of the QA PORT tests are summarised in Table 4. None of the UCS tests had compressive strengths less than 300kPa. These results demonstrate that the columns were constructed in accordance with the specification.

The distribution of field trial and production average column shear strengths interpreted from PORT tests taken from columns constructed with the accepted mixing parameters is shown in Figure 4. There are a total of 26 tests, the average columns shear strength was 416kPa and the standard deviation was 175kPa. These data demonstrate that DSM columns are highly non uniform in strength and because of this the average column shear strength needs to be much greater than the design strength of 150kPa to meet the requirements of the specification.

Table 4 Production QA PORT tests

Ave. age (days)	No. of tests	Mean strength (kPa)	Std Dev (kPa)
3.4	12	500	175
6.5	8	368	166
11.0	3	610	127

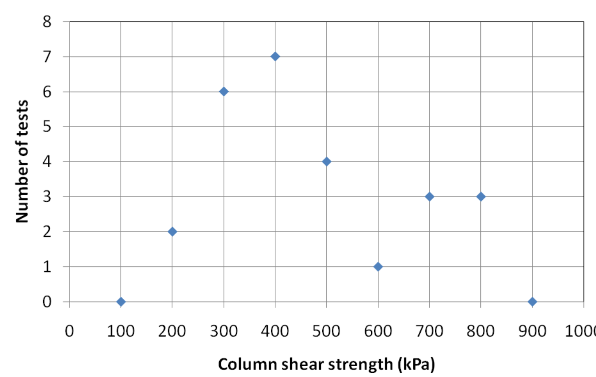

Figure 4 Distribution of column shear strengths from PORT tests.

The elastic modulus of the DSM columns was assessed from the results of unconfined compression tests (UCS) where the axial displacement was measured during compression. The load-displacement curves were often non-linear with higher initial stiffness then decreasing in stiffness with increasing load. The columns were designed to be loaded to 75% of their

UCS. Tangent stiffnesses at 75% of UCS are shown in Figure 5.

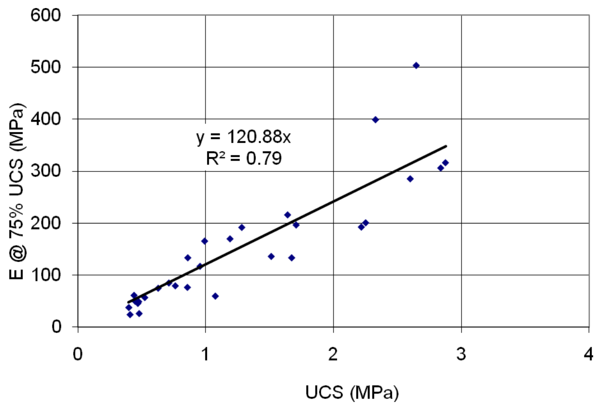

Figure 5 Elastic modulus and UCS test data

The elastic modulus correlates to about 120 times the UCS or 240 times the column shear strength. The secant modulus to 75% UCS starting from zero strain gives a correlation between the stiffness and UCS of 102. Filz (2009) reports that Poisson's ratio for cement mixed soil is generally considered to range between 0.25 to 0.5. The constrained modulus therefore ranges between 300 times the column shear strength and infinity. This value is greater than that assumed in design and confirms that the design assumption was reasonable.

5 MONITORING DATA

Settlement and fill height with time data from settlement plates installed at the abutment and in the transition zone are shown in Figure 6. The settlement plates were installed on top of the 1m thick construction platform after the DSM columns were installed but prior to filling. Settlement at the abutment location was 84mm and appears to have finished primary consolidation within a 3 month period. This is less than the predicted value of 120mm. Settlement in the transition areas is ongoing. Settlement with distance from the abutment is shown in Figure 7. The trend of settlement in the transition zone shows increasing settlement with distance away from the abutment which conforms with the design intent. Surcharging in the transition zone had not been completed at the current time.

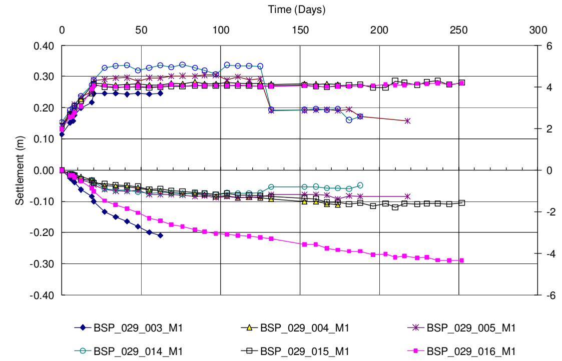

Figure 6 Settlement with time

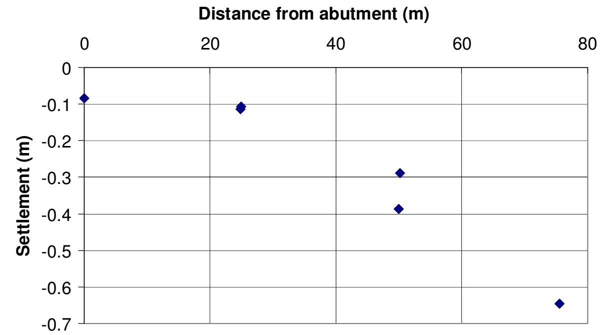

Figure 7 Settlement during construction with distance from the abutment

6 CONCLUDING REMARKS

DSM ground treatment to support a bridge approach embankment has been successfully designed and constructed. The following remarks are made based on this experience:

Laboratory mix trials indicated that the cement content required to achieve the design column strength was 40kg/m^3 less than that adopted after field trials. This is considered to be due to near surface samples being used for the mix trial where the moisture content would have been lower than at greater depth. If the in-situ moisture content is higher then the cement content needs to be increased to achieve the same water:cement ratio. It is also possible that the factor of 2.5 converting laboratory to field strength should be greater;

Field trials are a vital component of the works. In other areas of the project where thorough field trials were not performed an increased proportion of columns with strengths lower than the design limit were encountered during production. However, the scale of the field trials probably does not have to be as extensive as at this particular location in order to achieve satisfactory production performance;

DSM strengths are variable between columns and within columns. Design assumes that the columns have uniform strength and stiffness. The specification must be written to account for this variability;

Measurement of column shear strength using PORT tests or UCS tests does not necessarily provide definitive values. From a consultant's perspective the PORT must either be calibrated or an independent measure of strength used. In principle the PORT is considered by the authors to be an appropriate test because it penetrates the greatest area of column of the available test methods, providing that it can be calibrated. It is not clear that the value of calibration factor N =10 accurately represents the shear strength of the columns. Despite this, the mixture of PORT and UCS test data used to accept the field trial and production test data for this project achieved the design intent. This may have been due in part to the acceptance criteria forcing up the average column shear strength and in part to construction of relatively strong columns allowing successful recovery of core for UCS testing;

The proportion of columns tested during production was 1% of all columns. This quantum of testing developed a reasonable level of confidence in the quality of the constructed DSM columns. The authors consider testing 1% of columns was probably more than required. Other areas of the project tested between 0.5% and 1% of columns and achieved acceptable measures of quality and post construction settlement performance. The authors consider 0.5% to be the lower bound for the proportion of columns being subjected to QA testing.

Acceptance criteria in the specification need to balance column variability with cost effective production. The acceptance criteria on this project achieved the desired result but forced the average column shear strength to be significantly higher than the design strength. The cost of the additional cement per column was considered to be less than the cost of installing more columns and assuming a design strength less than 150kPa. However, there might be other criteria or a greater percentage of columns with strength below the design strength that can be adopted to optimise DSM construction. There appears to be no guidance in the literature for what an acceptable distribution of strength might be.

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