Ground improvement for a large above ground storage tank using cutter soil mix columns

L'amélioration du sol pour installer un grand réservoir de stockageen utilisant des colonnes de coupe et de mélange du sol

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ABSTRACT

Deep soil mixing (DSM) has been used in European and Asian countries for a few years but was introduced only recently in Australia. DSM is frequently used to improve soft compressible clays where traditional methods such as surcharging and wick drains are not feasible due to either stability reasons or time and/or space constraints. Bridge abutments and road embankments are classic examples where DSM is traditionally used. This paper presents a case study where deep soil mixing was carried out using Cutter Soil Mixing (CSM) equipment. CSM columns were used to support a 53.5m diameter, 20m high, large storage tank instead of founding on deep piles. Analyses using analytical and numerical methods provided confidence that the settlement criteria imposed by the client could be achieved. Numerical analyses were simplified by adopting 2-D axi-symmetric conditions and converting CSM columns into equivalent "doughnuts". Although laboratory tests were carried out to assess the strength of the mix for different cement volumes, sensitivity studies were carried out numerically to assess the effects due to variations in column strength before finalising the design. Further strength testing was carried out during and following installation to confirm actual strength gain. To improve the stress transfer to the CSM columns, "pile caps" were formed during the installation process. These caps were formed by pre-excavating one metre deep at each column location and using the overflow of cementitious/soil materials to form the cap. This environmentally friendly innovation avoided the removal of excess cementitious material from CSM operations. Settlements were monitored during water testing and results indicated the successful completion of the project.

RÉSUMÉ

Le mélange du sol en profondeur (Deep Soil Mixing - DSM) a été utilisé en Europe et en Asie pendant quelques années mais a été introduit seulement récemment en Australie. DSM est utilisé fréquemment afin d'améliorer des argiles douces et compressibles lorsque des méthodes traditionnelles telles que des drains avec mèche pour surcharge n'étant pas faisables dû à des raisons de stabilité du sol ou des contraintes de temps et/ou d'espace. Les contreforts de ponts et les remblais routiers sont des exemples classiques d'utilisation traditionelle de DSM. Ce document présente une etude de cas dans laquelle le mélange du sol en profondeur a été mené a bien en utilisant un equipement pour mélanger et couper le sol (Cutter Soil Mixing – CSM). Les colonnes CSM sont utilisées pour soutenir un grand réservoir de 53.5m de diamètre et de 20m de hauteur plutôt que de le baser sur des piles profondes. Les analyses utilisant des méthodes analytiques et numériques confirment que le critère d'établissement imposé par le client pourrait être suivi. Les analyses numériques étaient simplifiées en adoptant les conditions d'axe symétrique 2-D par la conversion des colonnes CSM en "doughnuts" (forme de beignets) equivalents. Tandis que les tests étaient menés en laboratoire afin d'évaluer la force de mélange pour différents volumes de ciment, des études de sensibilité ont été numériquement exécutées pour évaluer les effets en raison des variations dans la force de la colonne avant de finaliser sa conception. D'autres essais ont été exécutés pour tester sa force pendant et après l'installation pour confirmer le véritable gain de force. Afin d'améliorer le transfert de tension sur les colonnes CSM, « des bouchons de pile » ont été formés pendant le processus d'installation. Ces bouchons ont été contitués en creusant dans un premier temps un mètre en profondeur à chaque emplacement de colonne et en utilisant le surplus de matériels crée avec le ciment et le sol afin de former ce bouchon. Cette innovation écologique a évité l'enlèvement du matériel de ciment supplémentaire lors des opérations CSM. Les installations ont été contrôlées pendant le remplissage d'eau et les résultats ont indiqué une réussite dans l'achèvement du projet

Keywords : ground improvement, deep soil mixing, cutter soil mix, soft clay

1 INTRODUCTION

Deep soil mixing (DSM), has been used in European and Asian countries for a few years but was introduced only recently in Australia. DSM is frequently used in these countries to improve soft compressible clays where traditional methods such as surcharging and wick drains are not feasible due to either stability reasons or time and/or space constraints. Bridge abutments and road embankments are classic examples where DSM is traditionally used. This paper presents a case study where deep soil mixing was carried out using Cutter Soil Mixing (CSM) equipment.

A large storage tank, having a diameter of 53.5m and 20m high, was to be located at a site in Townsville where subsurface conditions were not competent enough to carry the heavy imposed load with shallow foundations. In addition, strict settlement criteria were associated with the performance of the storage tank. Due to time limitations associated with the project the initial proposal was to construct the tank on driven piles to weathered rock, generally of the order of 15m deep or improve the soils using stone column foundations. Pile foundation required the construction of a reinforced concrete raft slab in order to transfer all load to the piles and therefore the overall cost estimate was high. Ground improvement by stone columns with conventional equipment was not considered because of the

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depth of the compressible clay and the difficulty in achieving the strict settlement criteria for the tank. The Client was open to an alternative scheme proposed by the Contractor using DSM technology with CSM columns to improve subsurface conditions. The CSM technique provides versatile solutions for various types of temporary and permanent walls, retaining structures and shafts as well as structural foundation piles. The alternate proposal using CSM was accepted by the Client due to many advantages it offered for the project, including the following:

- Cost effectiveness of the method.
- CSM construction does not generate significant vibrations, thus eliminating the potential for damaging the surrounding structures (existing tanks).
- The modified method proposed eliminates off-site disposal.
- Advantage of increasing the strength of sandy materials in the profiles and thereby controlling potential soil liquefaction issues.

2 PROJECT DESCRIPTION

The site is located at the south-eastern extremity of an existing fuel storage terminal in South Townsville. Increased production required the expansion of the existing facility and the Client decided to construct an additional above-ground steel fuel storage tank of 53.5m diameter. The proposed tank height was 20m with the roof supported by a central column and eight internal columns. The tank base was an inverted cone, supported on a pad of compacted soil, contained within a reinforced concrete ring beam, approximately 1.2m above adjacent ground level. Under water testing, the surface pressure expected on the subgrade was greater than 220 kPa without taking into account the structural loads. Under operating conditions, loadings would be slightly lower, as the unit weight of the fuel was of the order of $9kN/m^3$.

3 SUBSURFACE CONDITIONS

A geotechnical investigation for the site conducted by the Client included three boreholes to bed rock and associated insitu testing and sampling. Only limited laboratory tests had been conducted at the initial stage. Based on the engineering logs of the boreholes drilled at the site, the assessed subsurface profile was as follows.

Unit 1: Fill - generally described as loose to medium dense sand of variable thickness, typically ranging from 1.5m to 3.3m thick, underlain by

Unit 2: Sand -generally described as loose to medium dense sand with a trace of shell fragments, underlain by

Unit 3: Estuarine Clay - compressible natural estuarine clay, typically described as soft to firm silty clay, varying in thickness from 0m to a maximum of 1.9m, underlain by

Unit 4: Alluvial - a thin layer of Alluvial Deposit typically described as medium dense sand or hard silty clay, and underlain by

Unit 5: Bedrock - weathered granite, which was encountered below 15m to 16m from the existing ground surface

Subsequent Cone Penetrometer testing confirmed this general model and provided further data to assist in parameter selection.

The geotechnical design model was developed based on parameters assessed from the results of the investigations carried out at the site. Table 1 presents the material properties for the various units adopted in the PLAXIS analyses.

4 DESIGN SETTLEMENT CRITERIA

In addition to the bearing capacity of the subgrade, the tank performance was governed by tight settlement criteria. The criteria provided by the Client were as follows:

- Maximum differential settlement between any two points at 10m intervals on the circumference shall not exceed 100mm (1%)
- Maximum differential settlement between any two points along the circumference shall not exceed 300mm
- Maximum centre to edge settlement shall not exceed 300mm.

Table 1: Adopted material properties

Unit	1	2	3	4 Clay	4 Sand	5
t (m)	3.0	2.5	1.9	4.5	6.0	
γ_b (kN/m$^{3)}$	18	18	16	19	19	24
c′ (kPa)	0	0	0	2	5	10
ϕ' (deg)	30	30	25	25	35	35
E (MPa)	20	24	3	18	80	500

Note: t- Thickness, γ_b- Bulk unit weight, c′-Effective cohesion, ϕ'-Effective friction angle, E - Drained elastic modulus

5 DESIGN OF CSM COLUMNS

Deep soil mixing (DSM) is carried out to improve the soil characteristics, e.g to increase shear strength and to reduce the compressibility by mixing the soil with some additives. Deep mixing is classified with methods of mixing and additives used. From a design viewpoint, if DSM columns are to be used in a regular pattern over a relatively large area, the reinforced soil can be defined by equivalent strength and deformation properties. Most methods of assessing these equivalent properties consider the behaviour of a "unit cell" of the system.

The design of the proposed foundation treatment involved the following steps:

1) Estimate likely strength of soil mix, given site subsurface materials. and assume all load is carried by the CSM columns to founding strata.
2) Make initial estimate of total number of CSM columns required and check using the area-ratio method.
3) Design the layout of CSM columns on a plan to provide a good coverage and to maintain the influence area of each column to the same order.
4) Carry out numerical analyses to assess settlements and induced stresses for the adopted design parameters.
5) Carry out sensitivity analyses for parameter variation
6) Increase or decrease the number of columns and repeat steps 2 to 4 above until the results indicate that the design criteria could be met.
7) Install instrumentation and monitor during construction to implement remedial measures if the observed behavior is different from that expected.

In the current project, a cementitious material consisting of 75% Ordinary Portland Cement and 25% Flyash was used with a small amount of bentonite to aid mixing. This mix was based on laboratory trials on samples of Estuarine clays which were considered to be the critical unit for developing strength of the Columns.

A total of 147 CSM columns were installed. Each column was 2.4m by 0.5m in plan area to a depth of approximately 9m, to just penetrate Unit 4. The CSM layout proposed and adopted for the analysis is given in Figure 1.

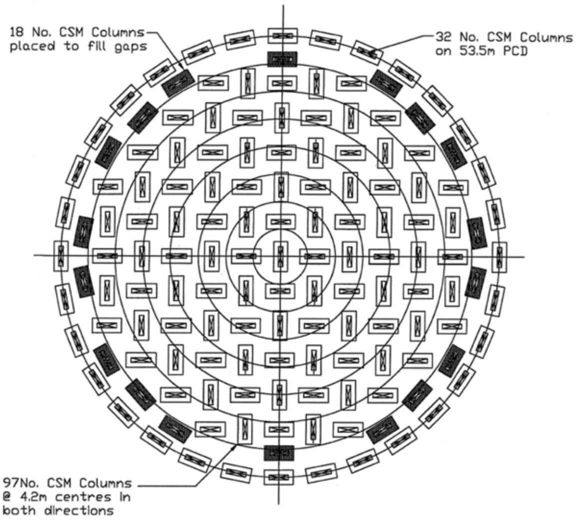

Figure 1: Layout of CSM columns

An innovative change made to the CSM column was the CSM 'pile' cap that was introduced to facilitate the distribution of the vertical load from the structure. The amount of overflow (cementitious binder and native soil) was estimated by assuming the native soils were saturated. To contain this overflow, a "pile cap" was pre-dug at each column location to contain this overflow. After completing the column, this "pile cap" was re-mixed with a paddle mixer mounted on an excavator. In the design, an allowance was made for this cap. The enlarged cap at each CSM column had plan dimensions of 3.6m by 1.75m at the surface, tapering to 2.4m by 0.55m, 1.0m below the surface. In addition to the beneficial effects provided by the cap in facilitating the distribution of the vertical load from the structure, the cap construction provides the following benefits:-

1) Efficient use of cementitious material and minimal waste.
2) No removal of excess, cementitious waste materials from the site.

Bulk samples were collected from the subsurface profile and were subjected to laboratory testing to obtain strength parameters. The samples were mixed with different proportions of cement and unconfined compressive strength (UCS) testing were carried out to obtain 7 day and 28 day strengths. The results allowed to obtain a design value of 4MPa as UCS for the CSM columns and a Young's modulus of 2000MPa.

The CSM column installation (147 Nos.) was completed in 24 working days. During CSM construction, sampling was undertaken to record variation of CSM column strength. Unconfined compression testing of the CSM materials indicated the typical strength gain over time. In all, 168 samples were tested and UCS strength results are summarised as:-

- At 14 days 2.14 MPa
- At 28 days 3.07 MPa
- At 56 days 5.11 MPa

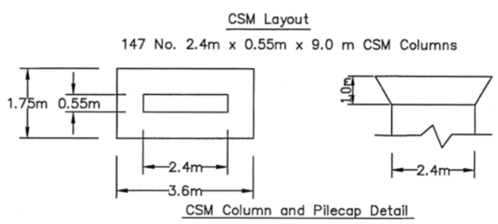

Figure2: Details of CSM and CSM cap

5.1 *Numerical Analyses*

Two dimensional finite element analyses using PLAXIS were carried out to estimate the long-term settlement of the soils due to the tank/oil loading and asses the stresses induced in the subgrade and CSM columns. The PLAXIS program has been developed specifically for the analysis of deformation and stability in geotechnical engineering projects.

In the analysis, the soil and rock materials were modelled as Mohr- Coulomb material and the CSM columns were modelled as a linear elastic material. Rather than adopting 3-D finite element analyses it was decided to carry out an axisymmetric analyses for the design. The axisymmetric model was set up for the circular tank structure with a uniform radial cross section and loading scheme around the central axis, where the deformation and stress state are assumed to be identical in any radial direction. As the CSM columns were not radially placed (see Figure 1) it was necessary to convert this layout to be axisymmetric. This was done using an equivalent area approach. The tank CSM foundation was divided into nine zones and the CSM columns and caps were modelled as equivalent "doughnuts" of stiff material in the axisymmetric PLAXIS analysis. The width of each "doughnut" was assessed using a simplified approach based on the area of CSM at a particular radius.

The PLAXIS mesh adopted for the analysis of the proposed tank with 9m long CSM is presented in Figure 3.

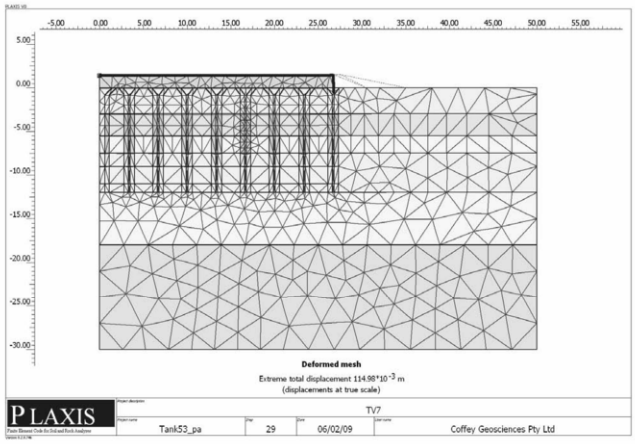

Figure 3: PLAXIS mesh adopted

In order to better simulate the appropriate side friction of the CSM columns generated in the PLAXIS analysis, a narrow zone of elements has been introduced in the PLAXIS model, either side of the CSM columns, and a strength reduction factor of 0.8 applied to the soil in these zones. The following loads were applied to the proposed tank foundation in the PLAXIS model:

- Total load = 502754 kN over 53.5m diameter area (equivalent uniformly distributed load of 224kN/m^2).
- Perimeter ring beam = 154 kN/m (equivalent uniformly distributed load of 342 kN/m^2 over a 0.45m wide strip).

The groundwater level was placed 1m below the existing ground level.

The following construction sequence was adopted in the PLAXIS analysis:

Stage	Description
0	Initialise the existing ground conditions
1	Install CSM columns and caps, apply strength reduction factor to zone of material adjacent to columns and reset displacements to zero
2	Construct compacted fill layer 1.5m thick above the CSM columns and caps, and reset displacements to zero
3	Install tank base
4	Apply tank loading

6 RESULTS OF ANALYSIS

For the base case, analysis indicated that the maximum estimated settlement of the tank foundation was about 115mm, which is within the settlement criterion. The settlement profile across the tank was generally constant as one would expect with reducing at the edges to less than 50% of the maximum. The maximum differential settlement within the footprint of the tank was 53mm over a distance of 10m. The maximum estimated edge settlement over a width of 750mm was about 45mm. These differential settlements are within the settlement criteria prescribed by the client and discussed in a previous section. The analysis indicates that the proposed layout results in fairly uniform settlement of the tank base and stresses across CSM columns. As the analysis was axi symmetric, it was not possible to assess the differential settlement along the ring beam. This was not considered to be critical compared to the differential settlements across the tank base. The assessed maximum vertical stress on a CSM column and cap was about 3.2 MPa.

Sensitivity studies were also carried out to assess the effect of changes to soil and CSM strength and deformation parameters. The results indicated that the effects would not increase the settlements beyond the design criteria specified. The effect of defective CSM columns was also analysed by reducing the strength of an annulus to soil strength. The results showed an increase of vertical settlements and vertical stresses but the order was less than 10%. More importantly, the results indicated that the differential settlements were not adversely affected.

Based on the findings of the PLAXIS analysis, it was assessed that the maximum settlement criterion would be satisfied with the proposed ground improvements using the proposed layout and 9m long CSM columns.

Following tank construction, water testing was carried out to check tank integrity and settlement performance. Eighteen settlement monitoring points were established equidistant around the ring beam and the settlement was monitored before water testing, during water testing, 25% full, 50% full, 75% full, 100% full. 32 hrs after full and empty. The monitoring results are summarised on Figure 4. From these short-term settlements the future long-term settlements were assessed and were compared with the design long-term settlements. The results indicate that the maximum settlement along the ring beam is less than the assessed settlement from numerical analysis carried out for the design. From this it is assessed that the differential settlements across the base would also be within the design settlements across the base and therefore within the design criteria.

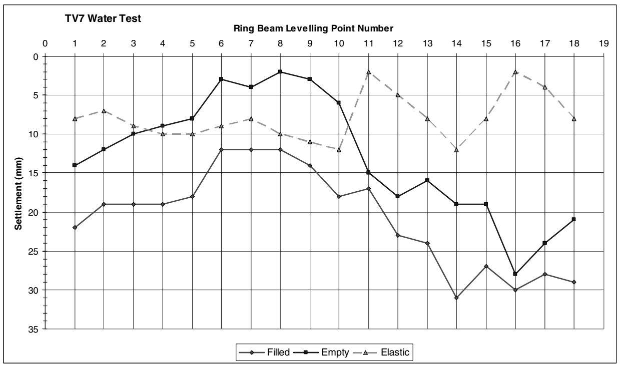

Figure 4: Water test settlement summary plot

7 CONCLUSIONS

Cutter Soil Mix columns are effective in controlling differential settlements of large foundations subjected to tight settlement criteria. Adequate investigations, proper geotechnical design including sensitivity analyses, plus laboratory testing of soil mix prior to and during construction, enable effective and economical outcomes to be produced.

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