Recent Application of Ground Improvement Technology in Australia and the Pacific Region (2/2)

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ABSTRACT

Three main types of ground improvement technologies (Type I – consolidation assisted by drainage including the use of stone columns, Type II – Improvement by compaction, and Type III – Grout based vertical columns) and their range of applicability were introduced in Part 1 of this paper. This paper (Part 2) is intended to provide a summary of ground improvement methods using the Type III approach to increase the composite strength and stiffness of the overall foundation.

There are three technologies described in this paper: jet grouting, deep soil mixing and controlled modulus columns. The methods currently used and range of applicability are described together with a number of recent case histories from Australia and the Pacific Region.

1 INTRODUCTION

In contrast with the technologies described in the first paper, which all result in improvement of the whole soil mass, the use of grout based vertical columns act in essence as reinforcing elements within the soft soil. The shear strength and stiffness of the composite material is a function mainly of the strength, stiffness and replacement ratio of the vertical columns formed. These methods only bring marginal improvement of the soil mass between the columns and therefore acceptance tests are either performed inside the columns or reliant on full scale loading.

There are two main techniques, depending whether the binder is mixed in-situ with the soil - hence resulting in a 'soilcrete' column - such as deep soil mixing and jet grouting – or whether the grout mix is introduced in the soil without blending, which involves a soil displacement mechanism, such as with Controlled Modulus Columns (CMC).

2 JET GROUTING

Reportedly a Japanese invention, this technology was also developed into a construction process in Italy and has been applied on projects in Australia since 2000 (Walsh Bay). In this technology, a cement grout is injected at very high velocity to break down the soil formation and bring it to a near homogeneous liquid suspension state, which hardens into a cementious column.

Simply put, the treatment is carried out with the following steps:

- A small diameter drill hole (70mm to 150mm) is drilled to the depth to be treated,
- The liquid grout is forced by a high pressure pump into one or several small diameter nozzles positioned horizontally on a 'monitor' at the tip of the rod strings; as a result, the grout is expelled at very high velocity nearing the speed of sound and flow rates of 100 to 500 l/min)
- The rods are extracted whilst they are rotated slowly to form the "soilcrete" column with the grout intimately mixed with in-situ soils.

Although the columns are generally cylindrical, other shapes can be obtained depending on the application, including construction of thin walls (see Fig. 1). There is a wide range of applications for jet grouting, including the underpinning of structures, ground water control and improvement of soil for new structural loads (Hewitt 2006).

Lihir Gold was the first soil improvement application using jet grouting carried out in PNG. The construction of a geothermal plant in the caldera of a former volcano at Lihir (PNG) was complicated by the presence of a compressible silt layer with high organic content found between 9 and 23m depth and with variable thickness; the top layer, was a reclaimed fill of volcanic origin comprising rock material up to boulder size with silty clay infill.

Figure 1: Example of jet grouting shapes (Sydney helipad)

A study by the design consultant estimated that differential settlement (tilt) across the powerhouse foundations and the cooling towers foundation slabs would reach 80 mm in absence of treatment and was deemed not structurally acceptable. Jet grouting was selected as the optimum method to penetrate the overlying layer of fill to improve the underlying layer of compressible silt. Jet grouting, which relies on drilling small diameters pilot holes (80 to 110mm), was well adapted to the presence of obstructions. In addition, the columns were installed only where needed, e.g. in the lower stratum, which translated into 50% reduction in quantities compared to a piling approach.

The treatment objective was to limit maximum settlement and hence differential settlement to of less than 20 mm. The adopted design was a grid of 800mm diameter columns with a minimum UCS of 4.5MPa and a replacement ratio (RR) of 10%.

The conditions under which the JG works were carried out was complicated due to the presence of sulphuric acid in the groundwater as well as the presence of organic silts (see table 2&3). Even though it is practically difficult to predict with accuracy the impact of these contaminants on the final soilcrete product (ability to set, ultimate resistance, porosity, etc.) preventive methods can be used to ‘neutralise’ these contaminants in-situ. The first measure is to use special sulphate resisting cements, which unfortunately were not available locally. The design objectives were finally met relying on a combination of ‘pre-cutting’ of the columns with low density grout and use of high ‘displacement ratios’ (proportion of cement grout as a percentage of the total volume of ‘soilcrete’ column), in the range of 70%.

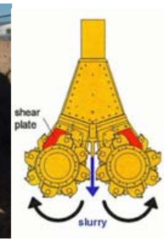
3 DEEP SOIL MIXING

Deep soil mixing has been used on large projects since 1970's mainly in Scandinavia and Japan. It is now more common in all parts of the world and significant refinements and developments are still continuing today.

The prime factors that influence the properties of the mixed soils are the soil parameters and moisture content, the nature and dosage of the material added and the efficiency of the mixing tools and process. A range of cementitious materials such as lime, cement, flyash and slag products may be used for deep soil mixing. The technique can be sub-divided into two classifications namely wet systems, in which the additives are premixed with water, and dry systems, in which the materials are added in dry powder form. Various systems have been developed for both the wet and dry techniques, targeted primarily at mixing efficiency for the targeted soil conditions, be they granular or cohesive, relatively wet or dry, and their insitu density and cohesion. As such a general "one for all" system in soil mixing does not exist.

The attached Table 1 presents a brief comparison of different DSM techniques that are currently available in the Australia and New Zealand region. The soils targeted and treated with the different systems vary significantly and as do the parameters of the finished product. The systems should therefore not be compared relative to each other, but rather on a best for project selection. Established design methods (Carlsten, P. and Ekström, J. 1995 and EuroSoilStab 2002) for DSM give guidelines for design of deep soil mixing.

Table 1 – Brief Comparison of Various DSM Techniques

Dry Soil Mixing **Single Auger / Mixer**	**Wet Soil Mixing** **Single / Multiple Augers**	**Wet Soil Mixing** **using Cutter Soil Mixing (CSM)**
		 
Applications • Relatively light rig allows site access with limited platform preparation • Used on very low strength soils S_u < 40kPa • Size of column varies typically from 0.6m to 0.8m diameter. • Composite shapes readily treated to suit site conditions	• Large high torque rigs often with multiple augers facilitating use in construction "walls" or panels • Size of column varies with auger arrangement • High torques suitable for sands and stiffer clays	• Rectangular tool shape (2.4m x 0.55m or larger) suited for "wall" or panels • A large column head can be constructed to enable relatively large spacing. • High torque suitable for sands and stiffer clays

The upgrade of the railway network at Sandgate in the Hunter valley required the construction of two new railway lines immediately adjacent to the working track, which included the crossing of an environmentally sensitive wetland area (see Fig. 2) comprising very soft silty clays to depths of 6 to 30m. A lattice pattern of interlocking 800mm dry-mix columns was installed, as shown on Fig. 3, between 5m and 8m deep using the Swedish Keller-LCM technique. The treatment was carried out under the new rails to provide the required shear strength and stiffness to ensure the serviceability of both the existing and new track. The treatment improved the insitu shear strength of the clays from the original 8 to 15 kPa to 100 to 200kPa. Key aspects of the dry DSM system were the light and compact equipment that enabled access to the site, the immediate stiffening of the soils after addition of the binder and the absence of spoil. The programme schedule required the rail embankment construction following immediately the soil stabilisation. Monitoring of the line since commissioning is ongoing and indicates performance within the design parameters, and will be the basis of a future paper.

Fig. 2 - Sandgate site and wetlands

Fig. 3 - View of the site installation

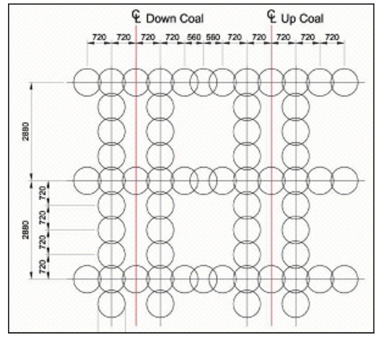


Fig. 4 - Typical plan of lattice columns layout (DSM)

4 CONTROLLED MODULUS COLUMNS

The Controlled Modulus Columns (CMC) is a ground modification system that reinforces soil by screwing a full displacement hollow auger into the soft soil and installing a low pressure cement-based grout column, as shown on Fig. 5 (Plomteux, 2004). The grout mixture then flows under low pressure out of the auger base as it is retracting to obtain a high capacity column that can be used in close vicinity of sensitive structures. The grout is injected under low pressure, typically less than 10 bars, and no soil mixing takes place during the pressure grouting. To ensure that the soil above the auger remains compacted, the top of the auger is equipped with reverse direction flights. The result is a composite system with column reinforcements bonded to the surrounding soil.

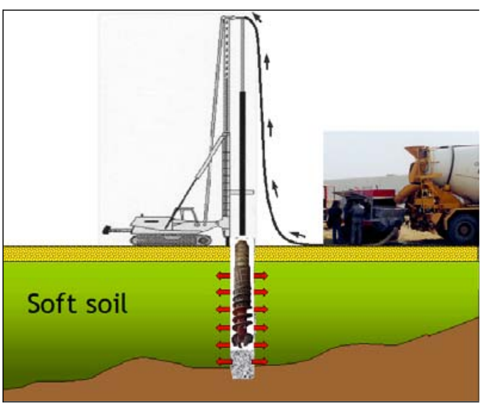


Fig. 5 – Schematics of CMC installation

The main features of CMC technology are:

- deformation modulus is 100 to 3000 times that of soil.
- soil properties are improved in the close periphery of the columns by compression resulting from the lateral displacement
- diameter is determined based on size of the auger (usually in range from 250 to 500 mm).
- common installation practice is based upon square grids with center-to-center spacing in range from 1.2 to 3 m
- no spoil

An atypical example of soil improvement for the construction of a commercial building at Bermuda Street (QLD) is presented, with deep CMC columns founded to 23m deep through very soft to firm, highly compressible clays.

The first phase of the project, which had been completed in 2001, used a combination of Dynamic Replacement method and preload to stabilise several building pads lying over 2 to 7m of clay below 2m sand layer. The proposed buildings were never built and instead replaced by a single building, 60m longer, extending over a deep alluvial channel, as shown on Fig. 6, with almost vertical sides and filled with highly compressible clay (Qc values between 0.2 and 0.5MPa). The CMC were installed with variable grids to accomodate for the different building loads and site improvement history, with generally a slab-on-ground design except in the heavily loaded dock area where the CMC also included partial reinforcement in the top 5m to resist the design horizontal breaking forces.

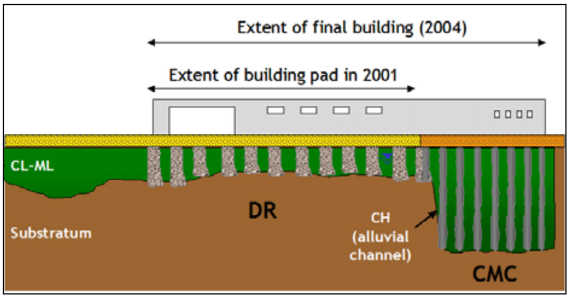


Fig. 6 - Schematic of soil profile & foundations system at Bermuda street (QLD)

Fig. 7 View of the project at transition area three years after construction

5 CONCLUSION

The case studies presented in this paper are not an exhaustive list of all the recent soil improvement jobs carried out in Australia and the Pacific Region. However, the authors have selected representative technologies of modern practice in this region. A technical summary table of recent case studies presented, and others, is provided in the last page of this paper. As the pressure increases for building on poorer sites, it is hoped that the information provided will encourage engineers and professionals to further investigate the application of these technologies when confronted by settlement and bearing capacity problems.

Soil improvement is a specialist field requiring caution and experience to ensure that the appropriate system is chosen and that the design considers the limitations and restrictions of both soil conditions and soil improvement systems. Furthermore, the success of a soil improvement contract rests primarily in its proper execution, therefore soil improvement projects should be carried out by specialty contractors with the relevant design and field experience.

Hence, it is essential that, from design to construction, geotechnical consultants and specialist contractors work together in order to ensure that the project expectations are met.

6 REFERENCES

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Table 2 – Summary of soil improvement case studies

Technique	Location (State)	Year	Depth (m)	Soil	Initial geotech. conditions	Structure / Specifications / Design criteria	Comments
				Type I - technologies with a drainage effect component			
Vertical drains	Northern Side of Emigrant Creek North, Ballina (NSW)	1998 to present	15-21	CH	Su = 15-50kPa; w = 60-130%; Cc/(1+eo) = 0.1-0.5 (typ. 0.35); Cα/Cc= 0.05; cv < 1m^2/yr above 15m depth, cv=1-20 m^2/yr > 15m	Trial embankment for a 4.5m high bridge approach embankment. Post-construction settlement < 50mm in 40 years.	Flodrain FD-4 installed to average of 22m depth at 1.35m triangular spacing. Embankment raised in a number of stages over 7 years to the current thickness of 8.5m. 90% consolidation for each stage was achieved in about 25 months. Back analysed c_h = 2.5m^2/yr with smear zone to wick radius ratio (rs/rw) and permeability of in-situ soil to smeared zone ratio (kh/ks) both set to 5. Max. settlement has reached almost 3.5m over 8.5 years and is on-going.
Vacuum	Southern Side of Emigrant Creek North, Ballina (NSW)	2007	8 - 25	CH	Su = 5-25kPa increasing with depth; w = 60-120%; Cc/(1+eo) = 0.3 to 0.4 (typ. 0.35); Cα/Cc= 0.05; c_v < 1m2/yr	Trial embankment for a 4.5m high bridge approach embankment. VC performance requirement was to maintain average of 70kPa suction over 8 months.	Menard VC system used with 32mm diameter vertical transmission pipes installed at 1m square grid spacing. VC is being used in conjunction with 7.7m thickness of preload fill (preloading in progress)
Stone columns	Kooragang Island, NSW	2006	5 - 10	CL-ML	Su = 10-25 kPa (avg 15 kPa); Cc/(1+e0) = 0.33; cv= 2-3.5 m2/yr	Coal Handling facility with 20 m stockpiles. Max settl. 200mm -350mm in 17 years; diff settl.0.15% - 0.3% ; horiz. displ. .075%	Improvement of sands and installation of WTF SC in clays to ensure stability and control settlments and displacements to ensure long term serviceability of coal handling facility .
	Gladstone, QLD	2007	10	CL-ML	Qc=5-15MPa (sands), Qc=2-4MPa(clayey and silty sands),	Tanna Coal Terminal stockpiles SP19-21; FOS(long term)=1.5; FOSseismic=1.1; coal height=20m; slope 1:1; Φi=45deg; density 10kN/m3	Installation of WTF SC using 16 and 20% aerial ratios to improve the foundation soils (silts, clay and sands) and increase shear resistance of composite soils.
Dynamic Replacement	Townsville Phase 2 (QLD)	2002	6	SP+CH	3 m loose sand layer over 3m of soft to firm clay and 2m of stiff clay; Qc(sand): 3-7MPa; Qc(SClay) < 1MPa; E_Y(SClay)=4.5MPa	Structure & Specifications as for DC below; DR replacement ratio: 17% in [80-125kPa] area &26% in[125-180kPa] area; Ep,col>10MPa, Ep,sol=3MPa	Long term settlement monitoring under building load indicated max 77mm total settlement and max 82mm differential movement between two adjacent columns at 30 m distance (2.8/1000)
	Old Wallgrove Interchange (NSW)	2005	12	Landfill	Alternance of landfill and compacted clay layers	6.6 m road embankment at WM7 interchange; ΔS<1/250; Sresidual<75mm; PLcol>1.2MPa, Ey,col>32MPa	10 years old landfill; residual biological decomposition estimated at 2%; additional surcharge placed for 3 months.
				Type II - technologies with an quasi-immediate compaction effect			
Dynamic compaction	Sydney West (NSW)	2006-07	8 - 10	GW, SW, ML	Unsaturated, heterogeneous man-made fill	95% of Standard Compaction	Improvement of collapsible soils in a large quarry using up to 500tm energy per blow to achieve a depth of compaction of 10m or so.
	Townsville (QLD)	2002	5	SP	5 m loose sand layer over 1m of soft to firm clay and 2m of stiff clay; Qc(sand): 3-7MPa; E_Y(S Clay)=3MPa	Sugar shed building with 80-180kPa distibuted load; Specifications: max. total settlement < 100mm; max. diff. settlt. <3/1000	Criteria of Ey,min=30MPa verified by correlation to PMT and CPT tests in improved sand, as well as by plate load tests (65tons, 290KPa, 5mm settlement); refer to DR area for long term settlement monitoring values.
	Airle Beach (QLD)	2007	2 - 8	Rockfill	Residential appartments on rockfilled disused quarry	30mm max total settlement	compaction 10m from adjacent buildings, max allowable vibrations ; PPV < 15mm/sec
Vibro-compaction	Kwinana	1974	25	SP	25 m loose sands over firm clays	Grain silos	Settlement and stability control
Compaction grouting	Gold Coast (QLD)	2002	3 -5	SP-ML	Loose sands and silts	remedial work for a new structure founded on suspect piled foundations	Foundation treatment for a convention centre
	Studland Bay (TAS)	2006	10	SP	Very loose to medium dense sands to 10m depth below surface 'hard pan'	Wind farm - densification below turbine footings (20mx20m) & void filling	4-10% grout takes achieved; N-SPT(ave,initial)=5, N-SPT(ave,final)=14
				Type III - technologies relying on the installation of grout columns or soil mix columns			
Jet grouting	Lisarow (NSW)	2005	18	CL-ML	Firm to stiff clay (Qc=0.5-2MPa) w/ interbedded sand layers	Less than 50mm total settlement, UCScol>4.5MPa	Rigid inclusions under existing rail bridge
	Lihir (PNG)	2005	10 - 23+D3	CH, CL-ML	Top 10m reclaimed material: hard boulders in a matrix of silty clay; below to 20m organic silts	Achieve EY>100+G3MPa in composite soil, UCScol>4.5MPa; RR=10%	Rigid inclusions under geothermal plant
Deep soil mixing	Sandgate (NSW)	2006	5 - 8		Su = 10-15 kPa; w = 65-70 % LL = 70-90; PL = 30-40 ; PI =50-55;	Stabilisation of soft clays for 2m high railway embankment.	Cry DSM adjacent to existing active main railway line in environmetally sensitive wetlands.
Controlled Modulus Columns	Bermuda street (QLD)	2004	15-23	CH	Qc = 0.2 to 0.5MPa, 2 to 21m thick	Stabilisation of soft clays for warehouse extension for commercial / light storage use - max. 50mm total settlement - CMC w/ grids 2.5 to 3.0m square, dia. 420mm; max depth 23m; UCS=10MPa	Several building pads treated using DR in a previous phase. Main building finally founded on 2 different types of treatment (DR and CMC) to adress distinct geotechnical conditions (presence of a deep clay-filled alluvial cliff under 1/3 of the building).
Legend	PL: Limit Pressure (pressuremeter); UCS: Unconfined Compressive Stress in column; EY: Young's (elastic) modulus; XXcol: test or sample in column; Φi: internal friction angle; FOS: Factor of Safety						