

CASE STUDY OF SEVEN GROUND IMPROVEMENT TECHNIQUES IMPLEMENTED AT COAL EXPORT TERMINALS ON KOORAGANG ISLAND, AUSTRALIA.

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ABSTRACT

This paper describes a case study in which various ground improvement techniques were implemented to enable the development of one of the world's largest coal export facilities. To service the Hunter Valley coal industry, Coal Export Terminals (CET) with associated rail and coal handling/train unloading infrastructure have been constructed on Kooragang Island, Newcastle, New South Wales, Australia, in the last decade. The coal terminal expansion has brought about fundamental geotechnical challenges. Kooragang Island was formed by dredging and infilling between and around former islands and delta features of the Hunter River estuary. The presence of recent estuarine and alluvial soft clay deposits combined with variable thicknesses of fill comprising dredged materials, coal washery reject and steel slag, introduced significant geotechnical issues in relation to bearing capacity, stability and long term total and differential settlements. To support combined stacker/reclaimers with up to 24m high coal stockpiles, rail loop realignment and a new rail flyover, Ground Improvement was required to address the above issues. In order to limit the post-construction settlements and to satisfy the settlement criteria for machinery and railway operation, a suite of seven ground improvement techniques has been employed to suit the specific performance requirements, programme and geotechnical conditions across the site. These consisted of Wick Drains, Dry Bottom-Feed Stone Columns, Wet Top-Feed Stone Columns, Dynamic Replacement, Mass Soil Mixing, Deep Soil Mixing and Rigid Inclusions. All of the above methods were successfully applied over the course of an eight year development period on a design and construct basis. The process of using ground improvement techniques, their construction restraints and geotechnical design considerations are discussed. The performance based on monitoring data collected under operating conditions is presented.

1 INTRODUCTION

The Coal Export Terminals (CET) built on Kooragang Island comprise two sites. The first to be commenced was the Port Waratah Coal Services (PWCS) terminal, which now exports approximately 90 million tonnes of coal a year. Newcastle Coal Infrastructure Group (NCIG) terminal followed and now exports about 60 million tonnes a year, resulting in a total throughput of approximately 150 million tonnes of coal per annum.

Coal is transported to site by trains up to 1.6km in length, typically carrying 7,000t to 9,000t each. Trains arrive at the CET at 10 to 20 minute intervals and are unloaded at automated 'dump stations', from where the coal is transferred by conveyor to the coal stockyards. The coal is then stacked into stockpiles of 21m to 24m height, which is recovered by reclaimer, transferred to the wharf by conveyor, and loaded onto bulk cargo ships via ship loader. The cargo ships range from 20,000t to 160,000t capacity, with five ships typically being loaded each day.

Construction of the PWCS coal terminal commenced in 2007 and construction of the NCIG terminal in 2010. Construction and commissioning of the terminal was staged to allow a progressive ramp-up in coal exports from 2010 to 2015. The terminal is now operating at full capacity (see Figures 1 and 2).

Kooragang Island was originally a natural estuarine and delta feature that created low lying islands in the Hunter River estuary. These have been augmented by dredging and infilling between and around these islands. The natural deposits typically comprise very soft clay and silt deposits, up to 17m thick. The dredged fill was placed hydraulically into man-made lagoons on and between the islands. Fill from the Newcastle steel works has also been deposited on the island. The combination of these materials has created a general picture of deep, very soft fine grained soils, overlaid by localised thin and thick layers of unconsolidated, hard steelworks fill.

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The deep soft soils and very soft dredge fill present a substantial challenge to the construction of heavy infrastructure, principally due to the potential for long term consolidation settlement and short and long term instability. Ground Improvement was carried out to reduce the magnitude of these problems to acceptable levels. The work was carried out by Keller Ground Engineering in a suite of Design & Construct packages. For each package, the ground improvement techniques were selected to give the most efficient combination of price, programme and technical performance, and so match the Client's requirements and the geotechnical conditions.

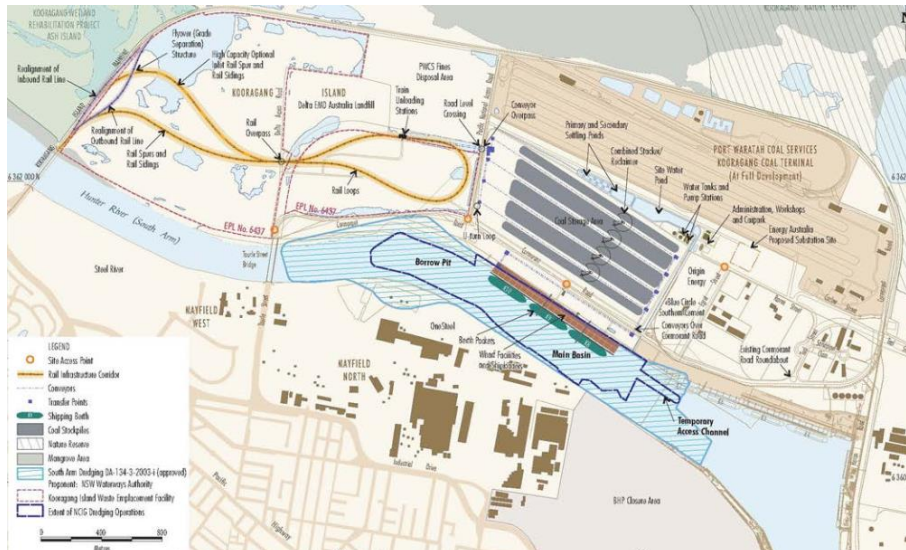


Figure 1: Kooragang Island Coal Export Terminals, showing PWCS & NCIG sites



Figure 2: Coal Stockpiles, Stacker Reclaimers & Ship Loaders

2 ENGINEERING GEOLOGY

Kooragang Island is located in the estuary of the Hunter River. The island is an agglomeration of several natural islands, channels, swamps and mudflats that have been reclaimed and reshaped by dredging and filling activities. The island is approximately 10km long and 3km wide, with the CET occupying approximately 5km x 1.5km of this area. The area of the CET includes the coastal fringe of the island, alluvial and estuarine deposits, natural ponds and wetlands, dredge ponds, and waste disposal areas from historic steelworks operations. Where present, the fill materials from the steelworks were placed onto the natural estuarine deposits and into shallow ponds.

Two main categories of fill have been placed on the island. The first is waste material from the Newcastle Steel Works. This material was predominantly placed in the 1970s and 1980s. The waste was typically placed in landfill cells composed of steel works slag bunds with mixed internal fill materials including slag, coal washery reject, coal fines, tarry sludge, kiln waste and various other wastes produced by the steelworks. The fill is generally 2m to 5m thick, but locally up to 12m thick. The consistency ranges from very soft or loose to very dense and/or cemented.

The second category of fill is dredged sand, silt and clay that was removed from the Hunter River, then placed hydraulically into man-made lagoons on and between the islands.

The natural deposits typically comprise very soft clay, silt and sand layers overlying firm and stiff clay, sands and gravel. The soft to very soft clay is typically 4m thick at the Eastern end of the NCIG Stockyard and increases to a maximum of 17m thick at the Western end of the site (the Rail Flyover). Depth to rock ranges from 30m to 70m.

The combination of these materials has created a general picture of shallow to deep, very soft fine-grained soils, overlaid by localised thin and thick layers of unconsolidated, hard steelworks fill, as illustrated in Figure 3.

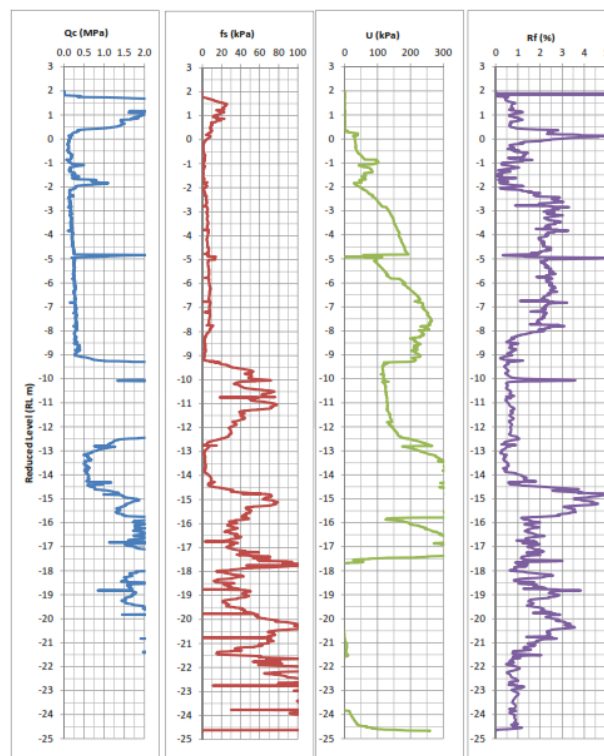


Figure 3: CPT showing <1m fill on soft clay (SP4-Pre018)

The soft, fine grained soils of Kooragang Island experience substantial consolidation when loaded. Other authors (Bozinovski, 2002; Jones, 2003) have reported that 500mm of settlement was created by 9m of surcharge being placed over 4m of soft clay. In a separate area, 1,500mm of settlement was generated by wick drains and preloading of 13m of soft clay. In addition, some of the natural materials are potentially liquefiable.

The wetlands around the industrial area of Kooragang Island include Ramsar and National Park designations, which require that all construction activities are carried out with due consideration to the significance of this habitat.

3 EXAMPLE OF DESIGN CRITERIA

The design criteria for each element of work varied and were related to specific requirements at the time for that particular construction phase. Table 1 below illustrates design criteria for various purposes for the Rail Flyover project, with the minimum applied Factors of Safety (FoS), while Table 2 lists the displacement limitations imposed by the client (with reference to the post-construction embankment, including the specified 30-day rest period).

Table 1: Factors of Safety Adopted for Design of Earthworks

Construction / Loading Condition	Structure Type / Load Event	FoS (min)
Temporary works	Temporary batters; temporary excavation	1.3
Permanent works	All earthworks (permanent)	1.5
Short-term, total stress	Undrained conditions, during and immediately after construction, excess pore pressures	1.3
Long-term, effective stress	Drained conditions, hydrostatic groundwater levels	1.5
Dynamic Loads	Seismic event (PGA = 0.11g)	1.1

Table 2: Displacement Limits for NCIG Railway Embankment

Item	Limiting Value During 1 st Year of Operation	Limiting Value Over 40 Year Design Life
Maximum vertical displacement	100 mm	150 mm
Maximum horizontal displacement	20 mm	30 mm
Maximum transverse differential settlement		1/350 over 25 m chord
Maximum longitudinal differential displacement		1/500 over 8 m chord
Maximum transverse tilt of rails		0.3%

4 SELECTION OF GROUND IMPROVEMENT METHOD

The principal function of Ground Improvement (GI) at the CET site has generally been to reduce post construction settlement and to increase bearing capacity in the very soft, fine grained soils, whether natural or man-made.

There are a number of GI techniques that can deliver these objectives. The scale of the CET project, both allowed and drove a sophisticated ‘best for project’ selection process. For each area of the CET, the ideal GI technique was selected by consideration of:

- Engineering geology
- Required post-treatment performance
- End use
- Environmental constraints
- Project programme
- Cost

Some of the key parameters for each technique are summarised in Table 3 below.

Table 3: Ground Treatment Technique Summary

Technique	Applicable Soil Type	Function	Relative Cost	Programme	Comments
Wick Drains	Fine grained, silts and soft clays	Dewatering, resulting in consolidation and strength gain	Low	Slow (months)	Requires supply and removal of fill material for pre-load 5m to >30m treatment depth
Dynamic Replacement	Silt, clays	Creation of 'composite' soil block, increased bearing capacity and reduced settlement; high permeability drainage paths to accelerate settlement	Medium	Fast (days)	Ground vibrations and movements generated, not suitable for use near structures; exclusion zone required around work area Up to 6m treatment depth
Vibro Stone Columns a) Top Feed method b) Bottom Feed method	Predominantly clay and silt but also can be used for sandy soils	Creation of 'composite' soil block, increased bearing capacity and reduced settlement; improved permeability, accelerates settlement; reduced liquefaction potential	Medium	Fast	Creates ground vibrations Suitable for use within 5m from structures Treatment depth 30+m
Dry Mass Soil Mixing	Very soft and loose soils where natural moisture content >liquid limit	Increased bearing capacity and reduced settlement through cementation of soil particles.	High	Very fast (hours/days)	Can release cement dust Up to 6m treatment depth Suitable for use near structures
Dry Deep Soil Mixing	Very soft and loose soils where natural moisture content >liquid limit	Increased bearing capacity and reduced settlement through cementation of soil particles.	High	Very fast (hours/days)	Can release cement dust Treatment depth 30+m Suitable for use near structures
Rigid Inclusions	Soft and loose soils that are underlain by firm or dense soil	Reduced settlement utilising complex soil-element interaction, thus improving the global stiffness of the compressible materials	Low	Very fast	Very soft and loose soils where natural moisture content >liquid limit Generates moderate ground movements, care required when used near structures

Figures 4 and 5 show where the different techniques were used across the CET, and Figure 6 shows works in progress.



Figure 4: Ground Improvement Types used at CET

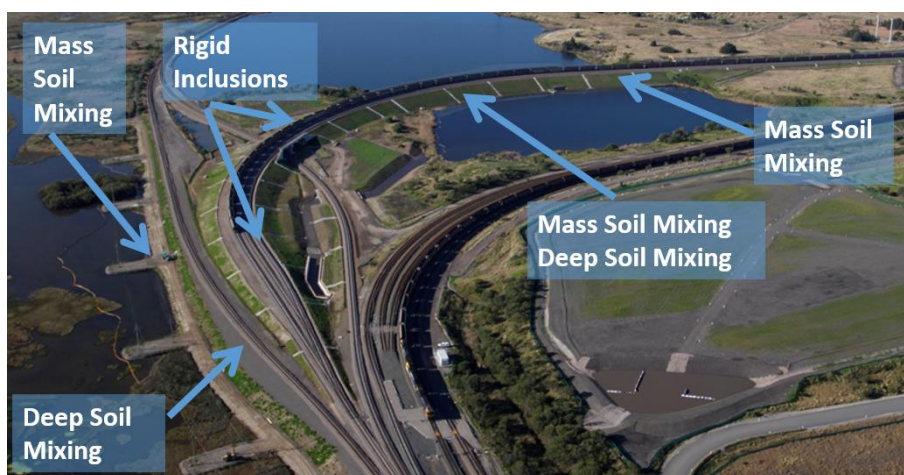


Figure 5: Ground Improvement Types used at Rail Flyover



Figure 6: Simultaneous DMSM, DDSM and RI Installation

4 DESIGN AND EXECUTION METHODOLOGIES

The design methodologies employed for the GI at CET were selected to suit each of the ground improvement methods to be implemented and meet the Clients' requirements in terms of total settlement, differential settlements and slopes, short and long term stability and seismic stability. The following were amongst the software packages used:

- KID – Keller internal ground improvement software to assess the improvement parameters and settlements;
- Plaxis – Finite element program to estimate the settlement at various stages of loading;
- SlopeW – Limit equilibrium analyses to assess the slope stability of the proposed configurations; and
- Talren – Limit equilibrium analysis to assess slope stability for soil-rigid elements configurations.

A detailed discussion of the various design methods is beyond the scope of this paper. General and broad outlines of the design processes are given in the following subsections, along with descriptions of the execution.

4.1 Consolidation only – Wick Drains with pre-load

The mechanical characteristics of the soft soils are improved when loading is applied and time is available for the soft soil to achieve consolidation. This process is accelerated by providing shorter drainage paths within the soft soil mass in the form of prefabricated vertical (wick) drains (PVDs).

The design of this process is an assessment of the probable loading to be applied without causing instability or failure within the soft soils, and the time allowed for the consolidation with the presence of drains, before the stage of loading is placed.



Figure 7: Installation of PVDs at PWCS CET

4.2 Consolidation and reinforcement – Dynamic Replacement and Vibro Replacement (Vibro Stone Columns)

Priebe's design method (Priebe 1995) is used for these cases, where the improvement is generated by the constructed columns in a soil which is otherwise unaltered in comparison to its initial state. Firstly, an improvement factor is established based on the improved performance of the subsoil in comparison to the state without columns. According to this improvement factor, the deformation modulus of the composite system is increased and settlements are reduced. All further design steps refer to this basic value.

The shear performance of ground improved by dynamic replacement is favourable. Under shear stress more rigid elements may break successively; however, the granular columns deform and any overload is transferred to neighbouring columns. The columns receive an increased portion of the total load, which depends on the area ratio of the proposed configurations. According to the proportional loads on columns and soil, the shear resistance from friction of the composite system can be readily averaged. Similarly, the cohesion of the composite system is also obtained from the proportional loads.

The calculated composite parameters of friction angle and cohesion from Priebe's method are input parameters for slope stability analysis using proprietary software such as SlopeW.

4.2.1 Dynamic Replacement

Dynamic Replacement (DR) and Dynamic Compaction (DC) are soil improvement methods where the ground is subjected to repeated tamping (DC) or punching (DR) using a heavy steel or concrete weight, typically between 5t and 25t, dropped from heights up to 25m. The shape of the weights will depend on their intended use, with taller, smaller

cross-sectional weights achieving a deeper penetrating depth, while wider flatter shapes are intended for maximum compaction in the shallower zone. The weight is dropped a set number of times over a grid pattern for a predetermined number of passes. The imprint formed at each grid location is backfilled with in situ or imported granular materials.

The dynamic method is applicable to treat a variety of cohesionless and cohesive soils. In the former, improvement is achieved due to compaction of the impacted soils from the energy delivered by the dropped weight, i.e. Dynamic Compaction.

At the Kooragang Island site, the soils tend to be fine-grained and cohesive, making compaction difficult. Therefore granular columns are formed by punching imported material into the ground, forming reinforcement elements within the soil mass, referred to as Dynamic Replacement.

Depending on the weight and height of drop, the size of the crane is generally between 100t and 120t capacity. The cranes are fitted with an automatic device to ensure the number of drops over the designed height are achieved before moving to the next point. Loaders are used to feed granular material into the crater formed by the weight so as to develop the column elements. Figures 8 and 9 illustrate DR progress at the NCIG CET.



Figure 8: DR pounding



Figures 9: DR craters

4.2.2 Vibro Replacement (Vibro Stone Columns) – Top and Bottom Feed Methods

The Vibro Stone Column (VSC) technique, commonly called Vibro Replacement, builds load bearing columns made of gravel or crushed aggregates, in cohesive soils and granular soils with high silt or fines content, where compaction of the surrounding soils is doubtful. In its technical consideration, it does not assume any compaction in the surrounding soils, and the improvement relies purely on the higher stiffness and shear strength of the installed columns.

VSCs use a depth vibrator to create an annular space which is replaced with gravel or crushed stone aggregate as a backfill medium to form load bearing elements. VSCs are formed either by the Wet Top Feed system, where the granular material is introduced at the surface; or the Dry Bottom Feed system, where the depth vibrator has an associated follower tube to introduce the coarse grained fill.

During the installation process, penetration to the designed depth is assisted by the action of vibrations, compressed air and the self-weight of the aggregate. A special feature of dry method is that, as opposed to the wet method, it does not require water jetting for penetration and hence eliminates the need to handle the slurry that results from the wet method.

Upon completion of the installation process, a compacted column of stone is left in the ground, surrounded by a soil/stone matrix of increased density. The stone column and the in-situ soil form an integrated system having low compressibility and high shear strength. The excess pore water pressure can dissipate through the stone column, which

also acts as a vertical drain. The settlement expected for the treated soil is reduced while the rate of settlement is increased when compared with the untreated soils.



Figure 10: Top feed Vibro Stone Columns at PWCS



Figure 11: Bottom feed Vibro Stone Columns

4.3 Soil mixing and reinforcement - Dry Mass Soil Mixing and Dry Deep Soil Mixing

Design of soil mixing begins with the assessment of probable strength and modulus increase of soil mixed with binder in the laboratory. Then the composite strength of the improved block is assessed by considering the area replacement ratio adopted for the soil mixing.

The design of the soil mixing follows that of the LCM (lime-cement method) originally developed for lime columns (Broms and Boman, 1979a and 1979b). The method has subsequently been revised and developed to incorporate other guidelines. The strength and modulus of the composite block have been averaged based on the area replacement ratio and used in the settlement and stability analysis.

At the Rail Flyover of the NCIG CET, an earth embankment up to 10m height was to be constructed over a pond underlain by very soft silty clay of depths between 4m to 11m. For treatment depths up to 5m depth, mass soil mixing was used. When the soft soil exceeded 5m deep, panels of interlocking soil mixed columns were used to reduce settlement and provide adequate stability of the embankment.

For the former case of mass mixing, the entire soil body below the foot print of the proposed embankment was treated in situ with the binder (cement), to achieve a predetermined target strength. Using the results of laboratory testing of samples, the modulus was obtained and used in the settlement and stability analyses.

For the latter case where panels were used, they were made up of 900mm diameter columns spaced at not more than 800mm centres, essentially providing a minimum interlock of 100mm. The panels are spaced at 1600mm centres which gives a replacement ratio in the region of 30% as shown in Figure 12. The composite improved block parameters are estimated on the basis of this replacement ratio, and used as input to calculate the settlement and stability of the embankment.

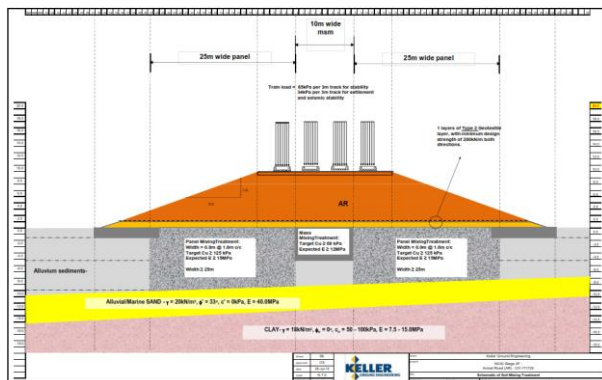


Figure 12: Composite DMSM & DDSM

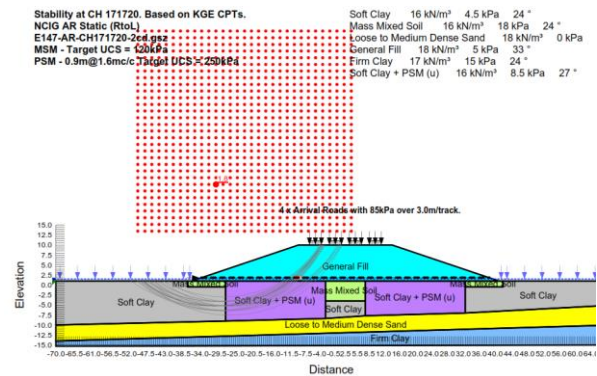


Figure 13: SlopeW, Composite DMSM & DDSM

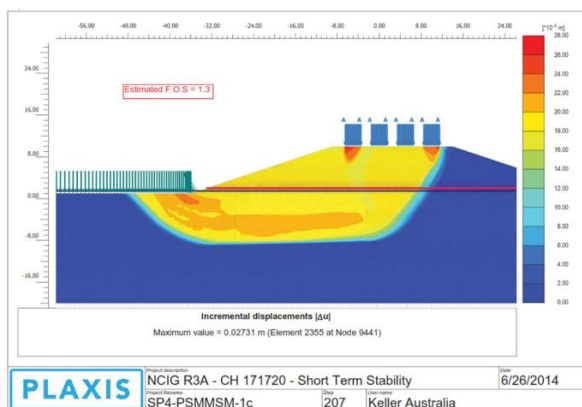


Figure 14: Plaxis, Short Term Stability

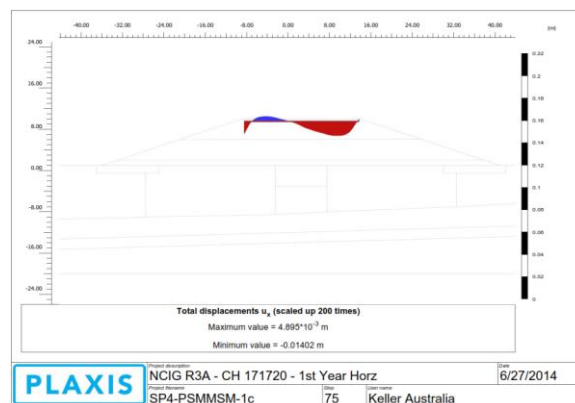


Figure 15: Plaxis, Total Horizontal Displacements

The results of the settlement and stability analyses are presented in Figures 13 to 15. These were considered acceptable and satisfied the project technical criteria. The comparison with monitored results is discussed in Section 5.

4.3.1 Dry Mass Soil Mixing (DMSM)

Dry Mass Soil Mixing (DMSM) is a process where soft soil is mixed in-situ with a dry cementitious powder binder (for CET, General Purpose Cement proved the most cost-effective binder) to create a stronger, less compressible material. The process requires the natural moisture content of the soil to be higher than its liquid limit. This high moisture content allows the soil to be fluidised during mixing, and in turn, dry binder powder can be evenly mixed through fluidised soil.

The mixed soil cures to form a relatively homogenous mass. The strength and compressibility of the mixed soil is dependent on the soil characteristics, the binder dosage, the mixing effort and the age.

DMSM often appears to be a relatively costly process. However, the strength gain is very rapid and so DMSM provides a fast solution and is economic where the value of the time saved outweighs the material cost. DMSM is also a flexible technique. At the CET it was used for the following applications:

- Stabilise soft soils for construction of embankments, hard stands, car parks, warehousing
- Stabilise soft soils for the construction of temporary works including access tracks and working platforms
- Stabilise soft soils to allow unsupported excavation through the treated soils
- Stabilise soft soils to support poles for overhead power lines
- Creation of transition zones between rigid elements (e.g. piled bridge foundations) and approach abutments
- ‘Locking up’ or insitu stabilisation of soil contaminants

DMSM was used at NCIG across areas of natural soft soils and very soft dredged fill (see Figures 16 to 18). The depth of the soft soils ranged from 2m to 6m. Typically the full depth of the soft soils was mixed, but where the settlement, stability and loading criteria allowed mixing was only applied to an upper layer (~2m thickness), with this layer then either ‘floating’ on untreated soils, being supported on Dry Deep Soil Mixed (DDSM) columns or being used as a working platform for the DR cranes. This approach is explained in the next section.

DMSM was used to provide foundations for stacker reclaimer machinery berms, rail embankment, coal stockpiles and to allow pipe trenches to be excavated through very soft soils. The speed of the DMSM technique allowed construction to commence on the treated areas within a day, and occasionally within hours, of the mixing process. A particular advantage of DMSM is that the technique creates ‘its own access’, both for the mixing equipment and the train of support plant that follows the DMSM operation.

DMSM is a mass treatment process, and as such testing should focus on the mass result rather than point results. The quality control process typically includes site investigation, appraisal of laboratory trials, pre-treatment testing, and an array of post-treatment tests, including cone penetrometers (CPT and DCP), Shear Vane, Push In/Pull Out Tests (PIRT and PORT), and, where appropriate, Plate Load Tests.

DMSM is illustrated in Figures 16 to 19.



Figure 16: Dredge Ponds on Kooragang Island



Figure 17: DMSM Treatment on Dredge Ponds

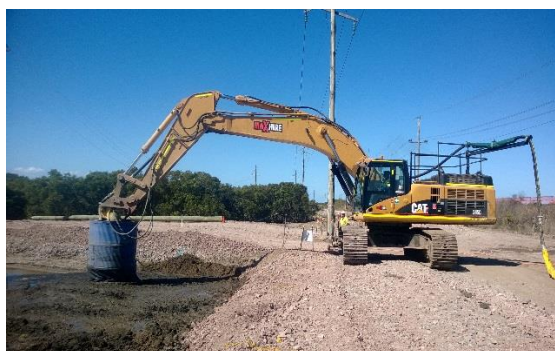


Figure 18: Liquified Soil during Mixing



Figure 19: Cured DMSM Soil

4.3.1 Dry Deep Soil Mixing (DDSM)

Like DMSM, Deep Dry Soil Mixing (DDSM) is a process where soft soil is mixed in-situ with a dry cementitious powder binder to create a stronger, less compressible material. The process requires the natural moisture content of the soil to be higher than its liquid limit. This high moisture content allows the soil to be fluidised during mixing, and in turn, dry binder powder can then be evenly mixed through fluidised soil.

Unlike DMSM, the DDSM process uses a rotating mixing tool that is mounted on a Kelly bar and leader. The use of a Kelly bar allows greater depths to be mixed. The feasible depth range is dependent on the size of the plant and is similar to the depths possible when using a CFA piling rig, e.g. 10m depth for a small rig up to 40m depth for a large rig.

For the work at Kooragang Island, the rigs comprised:

- CAT 345 excavator base unit
- 20m leader giving 18m effective depth capability

The DDSM process was used to construct individual columns of mixing soil and ‘panels’ of mixed soil that comprised multiple overlapping (i.e. secant) columns. The function of the columns varied across the site, with the primary uses being:

- Increasing the composite strength of a soil block
- Load transfer through the column to underlying founding mediums
- Increased shear capacity at the toe of embankments
- Improved seismic stability

The DDSM process typically creates a higher strength and more homogenous mixed soil compared with DMSM. This is achieved by the use greater specific mixing energy, tighter construction tolerances and higher cement binder contents. The construction of each column is controlled and monitored by rig instrumentation. This control includes:

- Mixing tool depth
- Mixing tool rotation speed
- Mixing tool lift rate
- Blade Rotation Number (BRN), a measure of the mixing energy applied to each point in the column
- Binder flow rate

The design minimum shear strength of the mixed columns typically ranges from 100-500kPa at 28 days. Given that these strengths sit somewhere between strong soils and weak rocks, insitu testing of the column strength is not well suited to conventional soil or rock testing. The preferred test method is Pull Out Resistance Test (PORT). The PORT test can be considered to be a ‘reverse’ CPT. The test procedure comprises:

- Construct DDSM column
- Immediately following construction, plunge a PORT vane and pre-stressing cable through the freshly mixed soil to the base of the column
- Allow the column to cure for a short period (typically for 2 to 5 days)
- Setup PORT testing rig above the column
- Pull the vane up and out of the column using an instrumented jack and depth encoder.

The strength of the column is then calculated at 1cm increments by dividing the jack load by the area of the test vane.



Figure 20: DDSM constructing secant column panels



Figure 21: PORT testing of DDSM column

4.4 Soil reinforcement by Rigid Inclusions

Ground improvement by Rigid Inclusions (RI), also called Controlled Stiffness Columns (CSC), is a relatively new ground improvement technique which has gained popularity in recent years.

The principle of Rigid Inclusions is to form a grid of high modulus, stiff vertical columnar inclusions in the soft compressible soil to improve and control the global soil mass stiffness and strength. RI are typically embedded into a

firm stratum and the load transfer mechanism via a complex soil-inclusion interaction increases the overall bearing capacity and reduces total and differential settlements.

In contrast to piled structures, the RI method of ground improvement does not bypass compressible soil layers nor does it transfer the total imposed loads onto the inclusion elements, but utilises both the soil and RI to reduce global deformability, and post-construction settlements. In contrast to traditional ground improvement techniques, the elastic modulus and cohesion of RI is in the order of one magnitude higher than the soil. This results in a higher load share taken by the RI which significantly reduces the required replacement ratio of columnar elements compared to the area treated.

This ground improvement concept of a soil-inclusion load distribution requires the presence of a load transfer platform (LTP) between the inclusions and the structure they support, i.e. the LTP is constructed at and around the top of the RI elements. The LTP and its design is an integral and essential part of the RI ground improvement system.

Long-term settlement from the above RI ground improvement mechanism is predominantly generated by the interaction of differential settlements between soil and columns, and total settlement at the RI toe. Arching within the LTP results in the uniform settlement at the top of the LTP.

Investigation of the embankment stability can be carried out using either limited equilibrium software models such as Talren (Fig 22) or 2D FE numerical models (Fig 23) which also analyse the lateral displacement and corresponding tensile stresses in the RI. The use of the FE method enables assessment of the RI reinforcement requirements should the tensile forces in RI be above an acceptable level. Such tensile forces are typically observed around embankment edges (Fig 24).

The RI solution for the rail Flyover embankment addressed the strict differential criteria for the transition zones to the Flyover bridge as well as variable ground conditions including deep soft clay, partially pre-consolidated clay and thick fill layers. Rigid Inclusions of 0.35m diameter were installed through fill of variable thickness and consistency and very soft silty clay, with depths between 8m and 15m to a deeper firm stratum and a replacement ratio between 2% and 4%.

Comparison of the numerical modelling with the monitored results is discussed in Section 5.

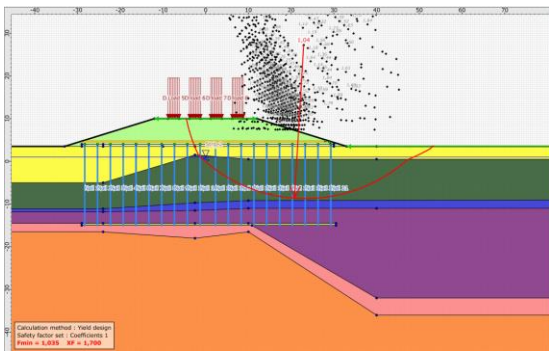


Figure 22: RI Stability using Talren

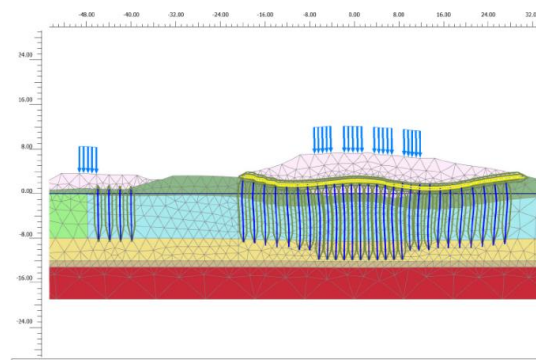


Figure 23: RI Plaxis 2D model

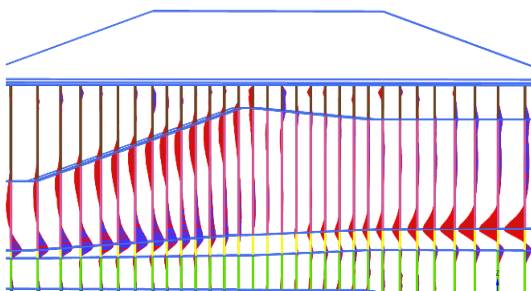


Figure 24: RI Bending moments assessment

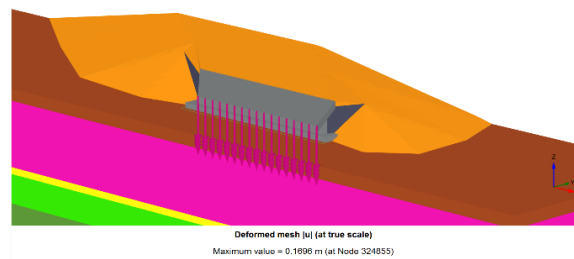


Figure 25: NCIG Flyover 3D Plaxis Model

The construction methodology of rigid inclusions is similar to the methodology used for cast in-situ displacement piles. The typical installation process involves drilling/driving a tubular ‘mandrel’ into the ground by displacement techniques (i.e. no or minimal spoil created at surface). The driving process may be by rotation thrust using a displacement body, or by vibration using a closed end tube. The most appropriate technique is driven by geotechnical considerations and plant availability. For the CET, the RI were installed using the vibratory technique. While this requires more specialised plant, the vibratory installation technique may be technically preferable to the rotary technique in that it maximises the potential compaction of the insitu soil and hence maximises the ground improvement and minimises the potential for damage caused by ground displacement.

The RI installation process between setting up and moving to next location, is summarised as:

- Drive mandrel into ground, using either vibratory or rotation and thrust
- Inject concrete through mandrel to base of hole, withdrawing mandrel while pumping to form column of liquid concrete in the ground
- Plunge steel reinforcement into concrete column if required to resist tensile or shear forces
- Enlarge head of rigid inclusion if required to assist load transfer into LTP

Quality control of RI work should include:

- Concrete mix design
- Concrete testing
- Construction of working platform for rig and potential reuse as LTP
- Actual vs theoretical concrete volume to control column diameter and replacement ratio
- Installation depth and embedment criteria
- Installation sequencing to minimise ground displacement effects on previously installed RI
- Rig and traffic management to minimise traffic over newly constructed columns
- Any requirement to cut down RI after construction (to be avoided)
- Construction of LTP vs potential damage to RI

It is recommended that the relationship between replacement ratio and ground displacement is considered during the design phase. As replacement ratio is increased, ground displacement is increased with a corresponding impact on previously installed RI.



Figure 26: Concrete supply to RI rigs

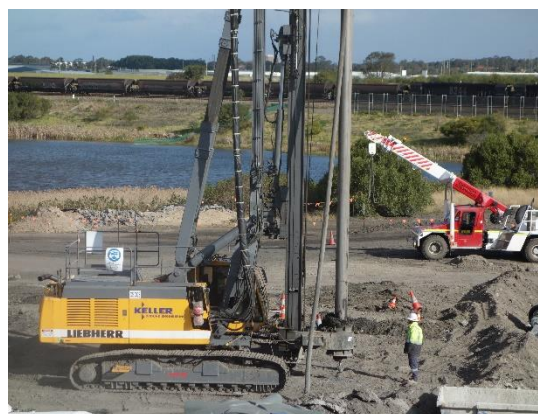


Figure 27: RI in progress at NCIG flyover site

5 MONITORING AND PERFORMANCE ASSESSMENT

The performance of the treated ground was assessed using the following instrumentation:

- Hydraulic Profile Gauges (HPG)
- Settlement plates
- Inclinometers
- Extensometers

Typical monitoring results of various treatment methods are discussed below.

5.1 Stacker-Reclaimer and stockpile area – Dynamic Replacement

The results of a typical HPG placed below the stacker berm plot is shown in Figure 28. The stacker berm is about 5m high. The plot shows that a maximum settlement of almost 300mm was recorded below the berm. For comparison purposes, the results at the position of maximum settlement from a few HPG, and the nearest settlement plates were compared with that of the predicted settlement, it was observed that the estimated settlement of the ground treated by dynamic replacement compared well with the measured data.

Lateral movements of not more than 25mm were recorded in the inclinometers over the period of embankment construction and into the operational phase of the stacker-reclaimer berms, and these inclinations stabilized a short time after the berms were in operation.

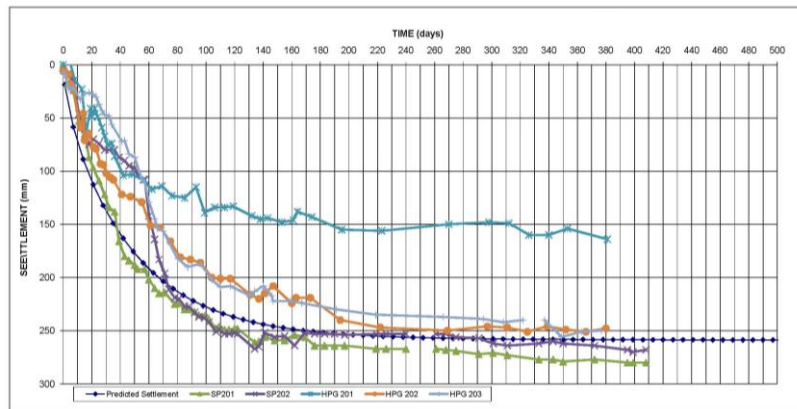


Figure 28: Settlements measured below stacker berm

5.2 Rail Link – Soil Mixing

The rail link project involved the construction of a railway embankment up to 10m in height.

Figure 29 shows the settlement array (Array 4) for treatment below the 10m embankment using deep soil mixing panels with an area replacement ratio of 30%.

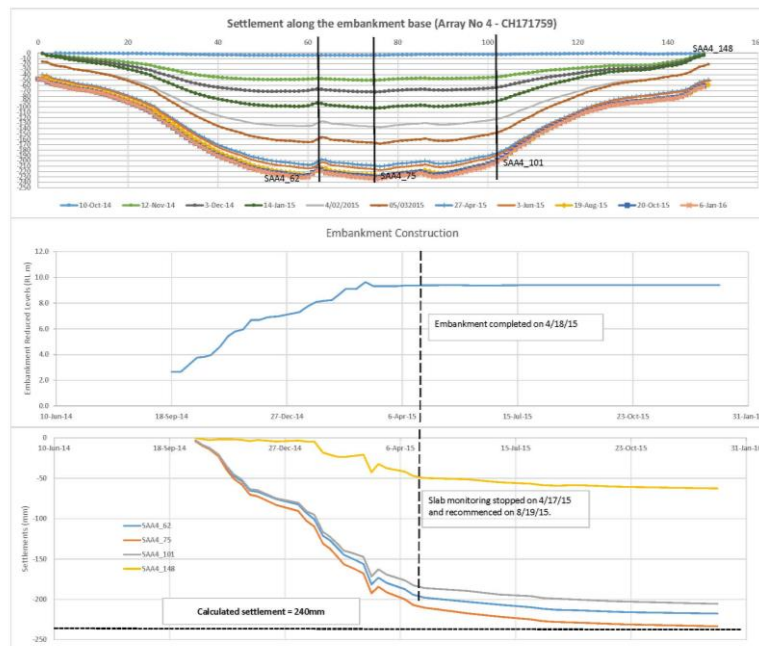


Figure 29: Settlements below 10m embankment with foundation subject to DDSM panels

Figure 30 shows the settlement array (Array 9) for the treatment of the same embankment up to 10m high using mass soil mixing.

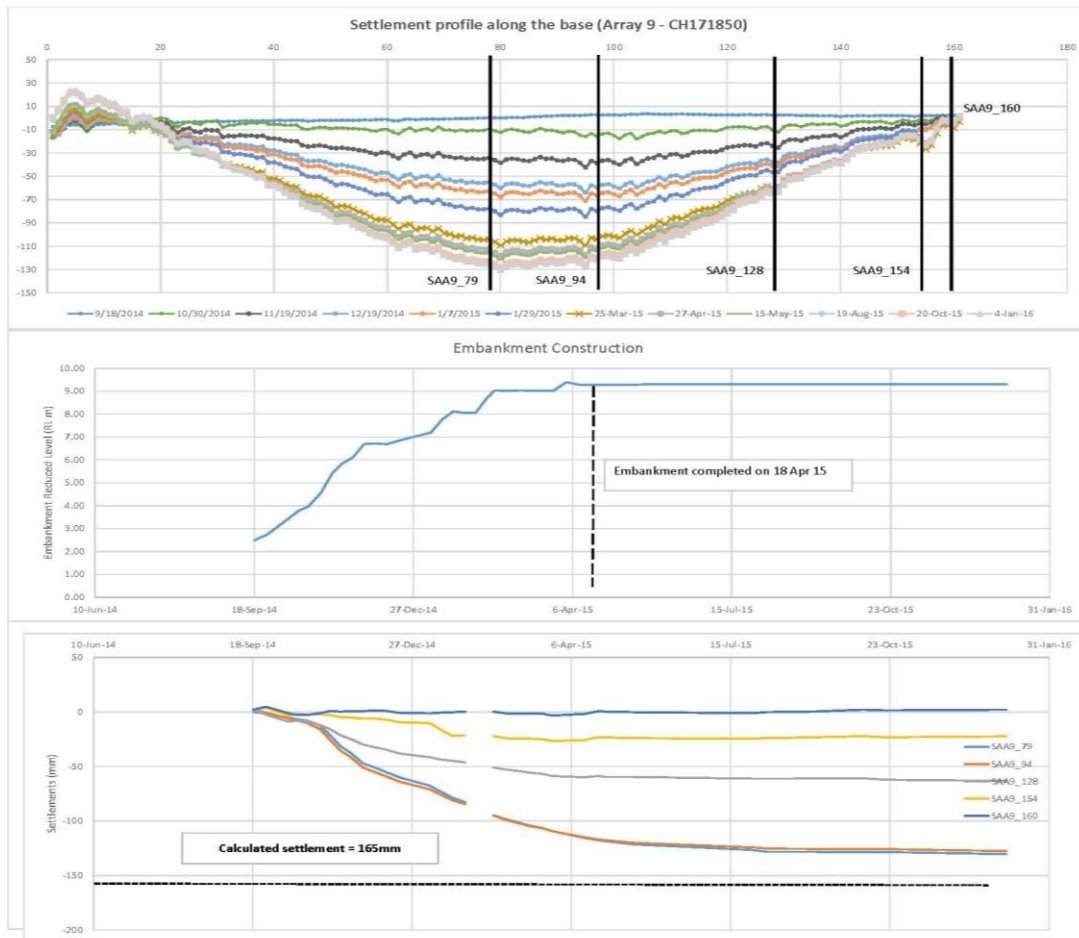


Figure 30: Settlements below 10m embankment with foundation subject to DMSM

The embankment is currently in operation and reported to have experienced little noticeable settlement.

Inclinometer results indicate that lateral movements of the order 50mm were recorded, which is consistent with the estimated value for the improved ground with soil mix treatment under such high embankment loads.

6 CONCLUSION

The development of Coal Export Terminals at Kooragang Island has demonstrated the efficacy of a wide range of ground improvement techniques, each suited to the particular engineering and geotechnical challenges, as well as to specific programming and cost-efficiency aspects. Combined with detailed modelling methods, the designs were regulated and verified by intensive programmes of instrumentation and monitoring,

7 ACKNOWLEDGEMENTS

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