Recent application of ground improvement technology in Australia and the Pacific Region (1/2)

Charles Spaulding
Austress Menard, Macquarie Park, NSW, Australia
Ernst Friedlaender
Keller Ground Engineering , Baulkham Hills, NSW, Australia
Patrick Wong
Coffey Geotechnics, NSW, Australia
Stephen Jones
Douglas Partners, Newcastle, NSW, Australia

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ABSTRACT

Australia and the Pacific Region have recently experienced an unprecedented growth in diversity and application of soil improvement technologies, and enable construction on soft or unstable grounds. In addition to conventional preloading, stone columns, vibroflotation, and piled embankments, recently introduced ground improvement technologies now available in Australia and the Pacific Region include jet grouting, dynamic replacement, dynamic compaction, vacuum consolidation, deep soil mixing, controlled modulus columns as well as compaction grouting.

As the types of projects become more complex, and the pressure on building on poorer sites increases due to social, economic and environmental constraints, these new techniques provide valuable tools to enable the development of these sites. This paper is the first of two papers presenting a summary of available ground improvement techniques. Their range of applicability is discussed and a number of recent case histories are presented.

1 INTRODUCTION

In a general sense, soil improvement technologies are techniques applied to the ground at depth. They rely on geotechnical engineering to assess how the characteristics of the in-situ soils can be modified to meet the design objectives, making the soil formation part of the solution. In the case of road construction on thick clay deposits, it may be necessary to add rigidity to the subsoil in order to control differential settlements in the long term. This can be achieved in several ways, such as by artificially reducing the void ratio of the clay, or by incorporating vertical rigid inclusions in order to achieve a composite soil with the desired stiffness.

For convenience, these technologies have been here divided into three main types as follows:

I. technologies with a drainage effect component, suitable for improvement of soft and compressible soils – such as saturated clay, silts and peats,
II. technologies with an quasi-immediate compaction effect which are generally suited for granular soils, above and below ground water, such as sands, gravels & man-made fills,
III. technologies relying on the installation of grout columns or soil mix columns, with marginal improvement of the soil, except at the soil/column interface.

The objective of this presentation is to give a description of these technologies, keeping the above classification. Grout or soil mix column technologies (Type III) are presented in the second paper.

2 RANGE OF APPLICABILITY

The following figures provide a preliminary tool to select a suitable ground improvement technology depending on the type of soils. The main factors are construction depth limitations, allowable differential settlement capacity (from 1/100 for a road to typically 1/750 for a sensitive building) and cost. For soft soils less than 2 to 3 m in thickness, the excavation – replacement method is usually more cost-effective, except in presence of contaminated or acid sulphate soils for example.

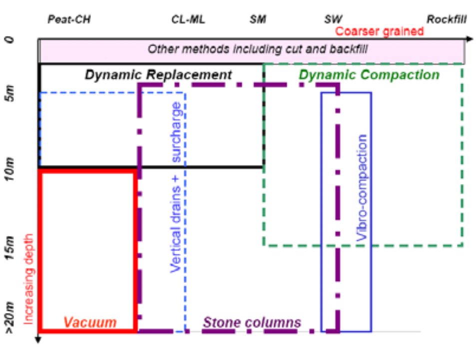


Fig.1 – Selection of **type I or II** SI technology for different improvement depths and type of soils

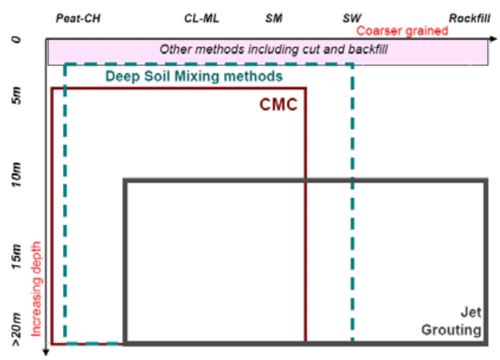


Fig.2 – Selection of **type III** SI technology for different improvement depths and type of soils

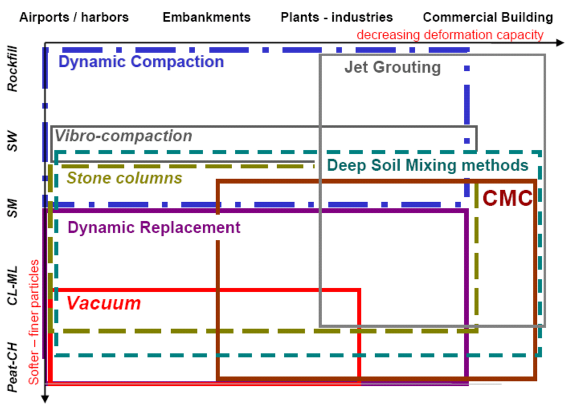


Fig. 3 – Selection of type I, II or III SI technology as a function of structure and soil types

3 TYPE I TECHNOLOGIES (DRAINAGE ASSISTED CONSOLIDATION OF FINED GRAINED SOILS)

Compressible, saturated soils, like soft clay and peat, are characterised by a deformable structure associated with high void ratios and water content. Loading of these materials by construction of say a road embankment could result in stability problems and long term settlements which would affect the constructability and serviceability of the structure. The following techniques are designed to solve this type of problem: vertical drains, stone columns, dynamic replacement and vacuum consolidation; in all cases, they facilitate the drainage of the fine grained soils.

3.1 Vertical drains

Vertical Drains (VD) are generally used in combination with a preload and a surface drainage layer. Even though the first VD were prefabricated (made of cardboard, in Sweden 1937), sand drains became the most common method until synthetic drains were introduced in Holland (1972). Further to their low cost of installation synthetic drains are today effectively the only VD system used.

The main advantage of VD are the relatively low cost of installation. The limitations lie in the time required under preload, the risks associated with the stability of the preload, the area beyond the treated area taken up by the surcharge slopes, and the need for considerable volumes of surcharge.

3.2 Vacuum consolidation

Vacuum consolidation (VC) was first introduced by Dr. W. Kjellman in 1952, but it has only been successfully and reliably applied to large-scale soft ground projects in the last decade or so. Two main types of vacuum consolidation systems are now available in Australia as described below.

Membrane system: the basic procedure consists of removing atmospheric pressure from a confined sealed medium of soil to be consolidated and maintaining the vacuum during a pre-determined period of time as illustrated by Masse et al (2001) and as reproduced in Figure 4 below.

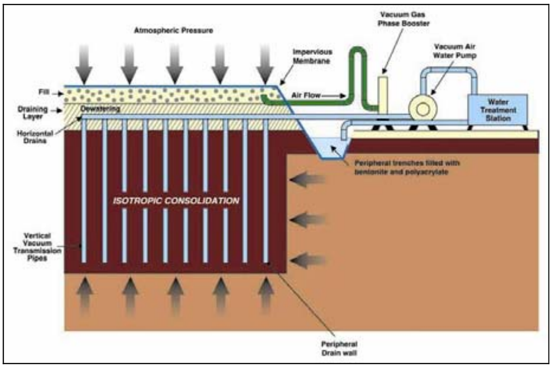


Fig. 4– Vacuum consolidation (Menard system - Typical Cross Section after Masse et al., 2001)

Fig. 5 – Vacuum consolidation (membrane system) in progress at Ballina (NSW)

This method, developed by Pr. Cognon of France, relies on the following approach:

- installation of an effective drainage system (vertical and horizontal) which is able to convey water and air throughout the whole soil mass over the whole pumping duration; the Vacuum Transmission Pipes (VTP) have to remain functional even when settlements exceed 5m,
- maintain a "dry" layer below the membrane (even if during the consolidation process the membrane actually moves below the groundwater level),
- use of efficient air / water pumps units to maintain a constant level of depressurization equivalent to 0.75 to 0.85 of the atmospheric pressure measured under the membrane,
- maintain a leak-proof system in particular at the pumps / membrane connections and over the whole membrane area, including sealing of the membrane at the periphery.

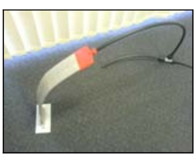


Fig. 6 – Drain connection for non-membrane vacuum consolidation system

Non-membrane system: instead of using an impermeable membrane over the area to be treated each wick drain is individually connected to the vacuum pipe system with the connection located sufficient deep below the clay to form a "seal" as shown in Fig. 6.

The advantages of vacuum consolidation include the following:

- With systems shown as on Fig. 4, the vacuum within the granular zone above the saturated horizontal drainage zone causes an apparent cohesion within this zone to act as a "reinforced mattress" for the embankment.
- Significant strength gain within the soft soil takes place even in the first few weeks when the vacuum is being established, due to pore pressure reduction effects.
- When an applied load is placed in an "undrained" manner, the stress path moves towards the failure envelope defined by the K_f line. With vacuum consolidation, the vacuum assists the stress path to move along the isotropic, K_o line rather than towards the K_f line, until more surcharge is placed.
- Lateral displacement at the toe of the embankment is reduced due to the isotropic consolidation nature of the stress increase from the vacuum component.

3.3 Stone columns

Vibro-replacement, developed in the 1970s as an advancement of the vibro compaction system for use in fine grained soils, involves the insertion of granular material through a weak compressible layer to form load-bearing stone columns. This effectively increases the overall (composite) stiffness and strength of the compressible layer.

Two main installation techniques are employed: the wet top-feed (WTF), and dry bottom feed (DBF). With WTF, a replacement method, the coarse granular material is introduced at the surface and falls down the annulus created between the probe and surrounding soil during penetration. The stone is compacted as the probe is withdrawn. Columns of up to 1.5m diameter, using stone size of up to 75mm can be formed in this manner. In the DBF, a displacement method, the stone is fed through a central stem in the vibrating probe and compacted as the probe is withdrawn. The dry system enables greater control over the placement of the stone, uses smaller aggregate sizes of about 50mm and forms a smaller column size. Due to easier environmental controls the dry system is suitable for use on relatively small sites.

In 2006 vibro-replacement stone columns were used at the Kooragang Coal Terminal (KCT) in Newcastle NSW, to reduce post-construction settlements of the machinery berm and coal stockpile area. The soil profile included soft to firm silty clay up to 4.5m thick. Using the WTF method, 6000 columns were installed to depths of 8 to 9m. This method saved about 6 months off the schedule compared to preloading which had been used in previous stages of the coal terminal. The predicted primary settlement of 550mm to 800mm were reduced to 150mm to 250mm while addressing stability aspects during and after construction. Further details of the design of the stone columns for this project can be found in Chan et al (2007), and the performance of a large-scale load trial is presented in Jones and Friedlaender (2007).

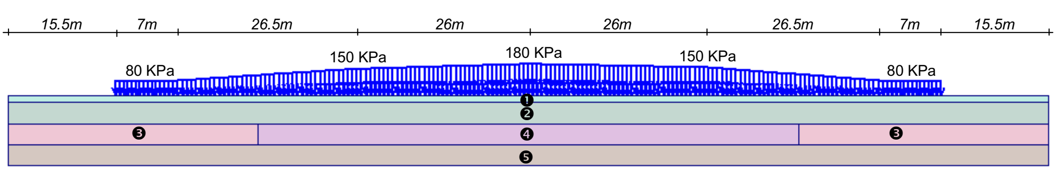
3.4 Dynamic Replacement

Dynamic replacement (DR) is widely used where the thickness of compressible soils is limited to 6 to 7m, has been successfully applied on high profile jobs overseas such as the Arianespace transport pad in French Guyana (Liausu 1998) and Alexandria City Center in Egypt (Wong 2004).

Fig. 7 – DR construction in Townsville (QLD)

This method is derived from Dynamic Compaction (DC) but adapted to cohesive soils. Craters, formed by repetitively dropping a large heavy pounder are progressively backfilled with sand, gravel or rock until large vertical ballasted pillars - typically 1 to 2m in diameter - are created - see Fig. 7. Common applications in Australia include ground stabilisation for industrial buildings and road embankments.

Construction of a 480,000t bulk storage facility sugar shed terminal in Townsville (QLD) on compressible clays required subsoil stabilisation. High construction costs disqualified initial proposals of piled foundations and suspended floors as well as excavate and replace options, which also had practical limitations and significant environmental impact. Preloading was trialled (using a 10.8m surcharge) and ruled out due to timing constraints, before deciding on a combined DC/DR treatment with slab-on-ground and isolated footings.



Material n°	1 Compacted Fill	2 Sand + DC	3 Clay + DR	4 Clay + DR	5 Clay stiff
Target E_Y(kPa)	***3,000***	***2,400***	***600***	***800***	***1,600***
Thickness (m)	***1.00***	***3.00***	***3.00***	***3.00***	***3.00***

Fig. 8 – Cross-section of bulk sugar terminal building showing loads and target soil elastic moduli to be reached after improvement to achieve less than 100mm total and 3/1000 differential settlement

The typical profile, shown in Fig. 8, consisted of 3m of loose sand overlaying 3m of soft to firm clay with a water table found at 2m below platform. The underlying firm clays were improved using variable DR columns grids to account for the load variability of 80 to 180kPa across the building resulting in 17 to 26% columns replacement ratio.

Due to variable site conditions within the 350m long by 110m wide building, the South West corner or roughly one third was treated by dynamic compaction (described in the next section). The long term settlement monitoring results are reported in the summary table in the second paper.

4 TYPE II TECHNOLOGIES (COMPACTION)

4.1 Dynamic Compaction

Dynamic compaction (DC) uses the kinetic energy of a 'free' falling heavy weight, typically 10 to 40 tons, dropped from heights ranging from 15 to 40m, to rearrange the coarse soil particles thereby decreasing the soil void ratio and increasing stiffness. This method, developed by Louis Menard in the late 1960s, is applicable to granular soils below the groundwater to depths of up to 15m, and can also be applied to non-saturated, fined grained soils such as silts and clays.

The Whisper Bay Aerlie Beach (QLD) residential development is located over a disused quarry backfilled with primarily basalt rock with UCS of up to 50 MPa and boulder sizes of up to 1m^3 to depths of 2m to 8m, partially below the water table. DC treatment was carried out on a design and construct basis to a performance specification of 30mm maximum total settlement. Due to the close proximity of the adjacent buildings vibrations were limited to PPV values below 15mm/sec. The site was treated with relative low energy impacts of 150 to 225 tm with compaction achieved partially by consolidating the insitu rockfill boulders, as well as their partial crushing, resulting in mechanical interlock of the larger boulders.

4.2 Vibro-compaction

In Vibro-compaction soils are treated by a vibration probe that is lowered into the soil to the required depth of treatment and the soils are densified during the extraction process. The probe transfers horizontal shear waves into the soils causing the rearrangement of the soil particles under the overburden pressure of the overlying soils. The vibro-compaction process, which was developed by Johann Keller in the mid 1930's, can be carried out to depths of 50m or more without loss of efficiency. The effectiveness of the system relies primarily on the particle sizes of the soil being treated as well as the efficiency of the vibro probes and the experience of the contracting team. Vibro-compaction is commonly used for the treatment of seismic sensitive soils to reduce their susceptibility to liquefaction and increase the stiffness and shear strength of the soils.

In 1974, in what is possibly still the largest vibro-compaction project carried out to date in the Southern Hemisphere, some 1 million m^3 of sands to depths of 25m were compacted in Kwinana, WA, for the foundations for the bulk grain silos.

Vibro-compaction work is often used on smaller projects for the stability of road embankments, industrial buildings and similar and for the stabilisation of sands against liquefaction in seismic areas, most recently on a new township development in Christchurch, New Zealand.

4.3 Compaction grouting

Compaction grouting, a displacement grouting system, was developed in the USA, with much of the work credited to James Warner. Compaction grouting comprises the injection of a stable low slump grout, normally a sand/cement, with a grading that provides plasticity as well as internal friction to contain the grout. The grout remains a homogenous mass which instead of permeating or hydro-fracturing the soils allows controlled displacement to compact loose soils. The system was originally used as a remedial measure for the treatment of soils displaying excessive settlements under load. It has since been developed for applications in controlled lift of structures, upgrading of existing foundations to accommodate higher loads as well as soil improvement for new structures.

Grout is injected at a slow and controlled rate, which can be as low as 0.01m^3 per minute, through casings inserted to the treatment depth under pressures of up to the order of 80 bar, to make allowance for line losses. While target grout volumes are predetermined, typically between 5% and 12% of the treated volumes, the system is site dependant and subject to on-site adjustments based on the observed behaviour and grout-take inevitably varies with site conditions.

Compaction grouting is typically carried out on a 1.25m to 2.50m grid layout, generally through predrilled and cased vertical or near vertical holes. While this technique inevitably results in the formation of rigid inclusions in the soils, its main benefit is the overall compaction achieved in the soils which normally obviates the need of capping beams or similar. Compaction grouting can be used in most soils above the water table and in predominantly granular soils below the watertable. Typically soils with SPT values in the range of 0 to15 can be treated with improvements of the order of 10 achieved – see Studland Bay case study in the final summary table in Part 2.

Recent applications of compaction grouting in Australia include the underpinning and partial correction of settlements of a large commercial development on the Gold Coast and apartment buildings in Sydney, the compaction of deep alluvial sands under a wind farm in Tasmania to control the risk of liquefaction under seismic conditions and the improvement of the soil under the foundations of existing apartment buildings in Sydney to allow for the additional loads imposed due to the redevelopment the structures.

5 CONCLUSION

This paper presented an overview of ground treatment technologies for soft cohesive and loose granular soils. Figures 1 to 3 provide guidelines for preliminary selection of possible ground improvement techniques. The use of vertical drains, vacuum assisted preloading, stone columns and dynamic replacement methods for improvement of soft cohesive soils have been described, followed by discussions on the use of compaction techniques for granular soils such as dynamic compaction, vibro-compaction, and compaction grouting. Further details of case studies associated with recent application of these techniques in Australia and the Pacific Region are provided in Part 2 of this paper which will also provide discussions on grout or soil mix type column ground improvement techniques.

The introduction of relatively new ground improvement technologies in the Australia and Pacific Region has benefited the construction industry in terms of the range of solutions that can be employed to solve site specific challenging ground conditions. Subsurface conditions, soil types, available time for construction, the type of structures to be supported, environmental and cost considerations must all be considered in the selection of appropriate ground improvement strategies to meet performance criteria or design specifications. Soil improvement is a specialist field and therefore geotechnical consultants and specialist contractors must work together to ensure the project expectations are met.

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