SOFT GROUND IMPROVEMENT – ISSUES AND SELECTION

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ABSTRACT

Issues that affect the successful application of ground improvement in soft ground are studied, with emphasis on the design, construction and long-term performance of the improved ground, and recent developments relevant to Australian geotechnical practice.

This paper discusses various technical issues affecting typical soft ground improvement techniques including: densification, consolidation, weight reduction, structural support and chemical treatment. Several factors that can influence the selection of a ground improvement technique, or a combination of techniques, are discussed. Case studies are provided to demonstrate the recent application of ground improvement techniques to the design and construction process.

1 INTRODUCTION

Ground improvement techniques applied in geotechnical engineering practice are tools used by the geotechnical engineer for "fixing" the problems of poor ground. By imaginative use of techniques, the engineer forces the ground to adapt to the project's requirements, by altering its natural state, instead of having to alter the design in response to the ground's natural limitations. Ground characteristics have affected the decisions made by builders since the days of early settlement. The location, height and configuration of some of the historic monuments and infrastructure seen today were influenced to a certain degree by the anticipated behaviour of the ground. Where poor ground existed at a project site, the early builder was faced with the following questions:

- Should the soft ground be removed and replaced with a more suitable material?
- Should the soft ground be bypassed laterally by changing the project's location, or vertically by the use of deep foundations? or
- Should the design of the facility (height, configuration, etc.) be changed to reflect the ground's limitations?

With the development of ground improvement, the modern builder has a fourth option - to "fix" poor ground, making it suitable for the project's needs - instead of having to alter the original plans to reflect the ground's limitations. The new questions facing the current builder are then:

- Should the problematic ground at the project site be fixed instead of bypassed?
- What are the critical issues that influence the successful application of a specific fixing tool? and
- Which fixing tool should be used out of the comprehensive and diversified set currently available in the toolbox?

Technical, practical, economical and political factors influence the answers to the first and third questions. In order to provide credible answers, the second question needs to be answered first. In this paper, the critical issues affecting the feasibility of the main ground improvement methods in the current state of the practice are evaluated from both design and construction points of view.

2 GROUND IMPROVEMENT IN SOFT SOIL

Ground improvement in soft soil has five major functions, namely to:

- increase the bearing capacity
- control deformations and accelerate consolidation
- provide lateral stability
- form seepage cut-off and environmental control and
- increase resistance to liquefaction.

These functions can be accomplished by modifying the character of the ground, with or without the addition of foreign material. Improving the ground at the surface is usually easily accomplished and relatively inexpensive. At depth, however, the task becomes more difficult, usually requiring more rigorous analyses and the use of specialised equipment and construction procedures.

3 THE CURRENT STATE OF PRACTICE

The soft soil improvement methods most commonly used today can be divided into categories as follows:

- densification (vibrocompaction, dynamic compaction, blasting, compaction grouting)
- consolidation (preloading, surcharge, vertical (wick) drains, electro-osmosis, vacuum consolidation)
- weight reduction (wood chips, fly ash, slag, tyre chips, flowable fill, geofoam)
- reinforcement (reinforced soil wall systems, soil nailing, piles, stone columns, fibre reinforcement)
- chemical treatment (permeation, jet or fracture grouting, soil mixing, lime columns)
- thermal stabilization (ground freezing, vitrification).

Additional methods such as electrotreatment and biotechnical stabilization more applicable to other soils are addressed in Munfakh and Wyllie (2000).

Some the above methods are suited to a specific ground type, while others apply to a wide range of soils. Table 1 presents the ground improvement techniques used for granular and cohesive soils and the main objectives of their applications. This table is by no means completely comprehensive, as new methods and applications are constantly evolving. With the development of new machinery, inexpensive construction materials, geotechnical instrumentation techniques and flexible contracting policies and procedures, the application of innovative methods for improving the natural state of weak soils is limited only by the imagination of the engineer.

4 GROUND IMPROVEMENT ISSUES

Many issues affect the successful application of ground improvement; some of these require resolution by the designer and others by the contractor. While detailed studies and extensive research by government agencies, research institutions and academia have focused on the major issues, some equally important issues are not well recognised, except by specialty contractors. Such contractors have developed many of the ground improvement techniques currently used, including some that are still considered 'state-of-the-art'.

When highway and railway embankments are built over compressible alluvial deposits, ground improvement is often required to ensure stability and allow construction of steep side slopes which, in turn, reduces cost and minimizes impact on adjacent facilities or encroachment on environmentally sensitive areas, such as wetlands. If the native soil is granular, the improvement usually consists of densification. If the soil is cohesive, the ground improvement techniques applied may include consolidation, weight reduction, or reinforcement using vertical reinforcing elements. Detailed discussions of the design and construction aspects of these methods can be found in Munfakh (1997), Munfakh (1999) and Elias *et al.* (1999). To follow is a brief description of the ground improvement methods currently on the market, and the key issues that affect their application.

4.1 GROUND IMPROVEMENT BY DENSIFICATION

Loose granular soils can be densified to increase their bearing capacity, reduce settlement and increase resistance to liquefaction. At the surface, densification is achieved through compaction with conventional or high energy impact compaction rollers. See Figure 1 which illustrates the use of impact compaction of loose sand at a high-rise, residential and commercial development site in Sydney. On this site, adoption of ground improvement techniques allowed use of an alternative stiffened raft foundation, instead of piles, to "fix" poor ground, making it suitable for the project's needs.

When applied at depth, however, more complicated techniques are used, which often require specialist equipment.

Figure 1: Densification to increase the bearing capacity and reduce settlement in marine sand.

4.1.1 Methods of Application

Densification at depth is accomplished using the following methods:

- vibro-compaction
- dynamic compaction
- dynamic replacement
- blasting
- compaction (displacement) grouting.

During vibro-compaction, loose granular soils are densified at depth by insertion of vibrating probes into the ground. Compaction is achieved by impact and vibration, with or without the use of a water jet or compressed air and with or without the addition of granular material. Densification can be achieved to depths of 30 m.

During dynamic compaction, large weights are dropped repeatedly onto the ground surface over a predetermined grid pattern. The resulting high-energy impacts cause densification of the soil mass to depths from 3 m to 8 m. The drop heights are usually 12 m to 24 m, with drop points several metres apart in a grid pattern. Sometimes the generated craters are filled with select granular material.

Dynamic replacement uses large diameter stone columns driven into the ground using a 15 tonne to 30 tonne drop weight.

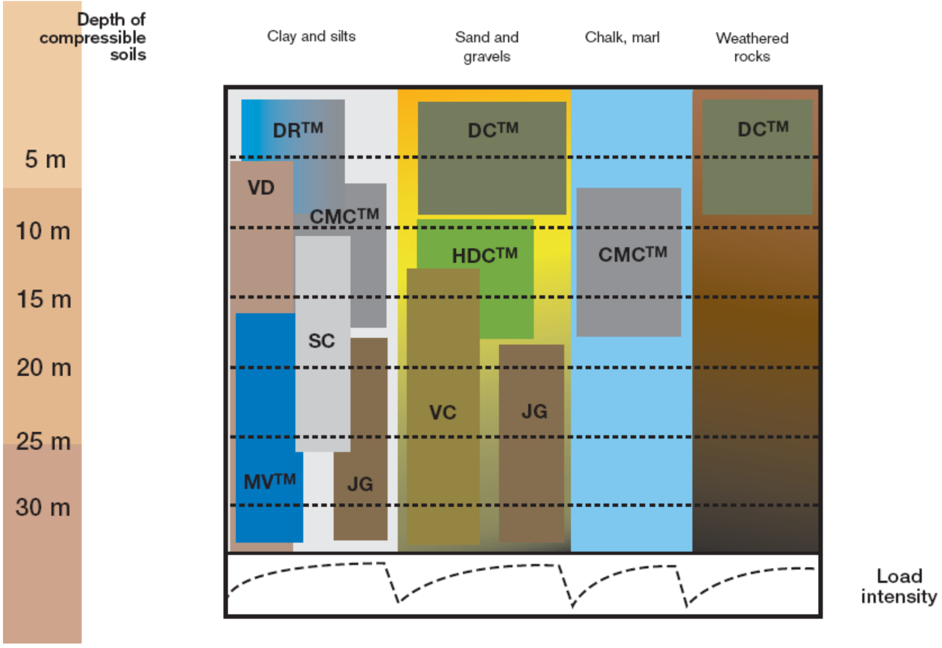
Densification by blasting is accomplished through the detonation of explosives buried in loose soils. The shock waves generated by the blast, break down the initial structure of the soil, and create a liquefaction condition, enabling the soil particles to rearrange themselves in a denser packing.

During compaction grouting, a very stiff mortar grout is injected into the ground under relatively high pressure to densify loose soil formations. The grout does not generally enter the soil pores, but remains in a homogeneous mass that displaces and compacts the surrounding soil. The grout mix typically consists of silty sand, cement, additives and water.

Table 1: Ground improvement methods and their main objectives.

GROUND IMPROVEMENT METHOD	Type of soil		Ground improvement objectives				
	Granular	Cohesive	Bearing Capacity	Settlement Control	Lateral Stability	Environmental Control	Liquefaction Resistance
Vibro-compaction (VC)	●		●	●			●
Impact compaction	●		●	●			●
Dynamic compaction (DC)	●		●	●		●	●
Dynamic replacement (DR)		●	●	●		●	●
Blasting	●		●	●			●
Compaction grouting	●			●			
Preloading/drains (VD)		●	●	●			●
Electro-osmosis		●	●	●			
Vacuum consolidation		●	●	●			
Lightweight fill	●	●		●			
Mechanical stabilization	●		●	●	●		
Soil nailing	●				●		
Soil anchoring	●				●		
Micropiles	●		●	●	●		
Stone columns (SC)		●	●	●	●		●
Fibre reinforcement	●		●	●	●		
Permeation grouting	●		●	●		●	
Jet grouting (JG)	●	●	●	●	●	●	●
Deep soil mixing (DSM)	●		●	●	●	●	●
Lime columns		●	●	●	●	●	●
Fracture grouting		●	●	●		●	
Ground freezing	●	●			●	●	
Vitrification	●	●				●	
Electro-kinetic treatment		●		●		●	
Electro-heating		●		●		●	
Biotechnical stabilization stabilisation	●				●	●	

Figure 2 illustrates the selection of soil treatment method as a function of soil type and the depth of compressible soil.



Legend:

SC	Stone columns	DR	Dynamic replacement
CMC TM	Controlled modulus columns	VC	Vibro-compaction
DC TM	Dynamic compaction	MV	Vacuum consolidation
VD	Vertical drains	JG	Jet grouting

Figure 2: Selection of ground treatment in soil (Menard, 2006).

4.1.2 Key Issues

The key issues influencing the effectiveness of soil densification include the:

- percentage of fines in the soil
- ability of the soil to dissipate excess pore water pressure
- energy felt by the soil
- presence of boulders, utilities and adjacent structures and
- the somewhat mysterious phenomenon of ageing.

Presence of Fines

The presence of fines has a negative impact on the densification process, as the fines act as lubricants, which reduce the frictional resistance between the rearranged soil particles within the densified mass. With vibro-compaction, for instance, a fines content of 20% renders the process ineffective. The amount of fines in the soil also affects soil drainage properties, which are a key factor when the densified soil is in a saturated state.

Pore Pressure Dissipation

When densification is applied to a saturated cohesionless material, a micro-liquefaction process takes place, allowing the soil particles to rearrange themselves. If excessive fines or cohesive soils are present, dissipation of the excess pore water pressure (generated by the densification process) is slowed down, or prevented. This can affect the feasibility of the applied method. To safeguard against this, pore pressure dissipation is facilitated by fissuring, or through the use of vertical drains, which are usually located equidistant from the points of densification application (the points of vibroprobe penetration, weight drop, blast holes, etc.).

Level of Energy

The level of energy applied in densification can be estimated from the characteristics of the equipment used (vibrating frequency, tamper weight, amount of explosives, etc.) and the configuration of application (probe spacing, drop height, depth of charge, etc.). The amount of energy actually felt by the soil is influenced by factors related to the ground characteristics, the effectiveness of the applied procedures, and the experience of the equipment operator. In dynamic compaction, for instance, the depth of influence of the process is calculated using the weight and height of drops, and a soil-related empirical coefficient (Lukas, 1985; Mitchell and Jardine, 2002). This depth is also influenced by other factors like the stratigraphy of the soil, the degree of saturation and the method by which the weight is dropped. (A crane drop is less efficient than a free drop.) The presence of soft cohesive layers or peat has a damping effect on the dynamic forces penetrating the soil, and thus the depth of influence is reduced.

Proximity to Structures

The presence of utilities and buried structures affects the choice of densification used and the level of energy applied. The impact of the process on adjacent structures is a major concern and there are no set criteria in present practice to guide how close vibro-compaction or dynamic compaction can be implemented next to an existing structure without adverse effect. On a recent project involving the vibro-compaction of hydraulic fill adjacent to a bulkhead structure, inclinometer data near the bulkhead measured horizontal deflection of less than 10 mm when the vibroprobe was 3 m away from the bulkhead, increasing to more than 50 mm as the probe got within 2 m of the bulkhead. Therefore, a safe distance of 3 m was established for that project.

Ageing

Densification of the soil continues for a period of several weeks after "disturbance" due to the little-known phenomenon of "ageing". Mitchell and Solymar (1984) attribute the increase in strength and deformation modulus with time to the possible action of silica bonding between grains. Mesri *et al.* (1990) credit the phenomenon to the continued rearrangement of sand particles during secondary compression, which results in a gradual increase in particle interlocking. Debats and Sims (1997) illustrated the increase in strength with time as reported for various applications of vibro-compaction, blasting and dynamic compaction (see Figure 3). They reported a strength increase of 35% from the second to the sixth week after a major vibro-compaction application in Hong Kong. On a recent project in Norfolk, Virginia, in the United States, one of the authors of this paper (George Munfakh), measured a 15-30% increase in the relative density of a hydraulic fill, approximately 20 days after vibro-compaction, due to ageing.

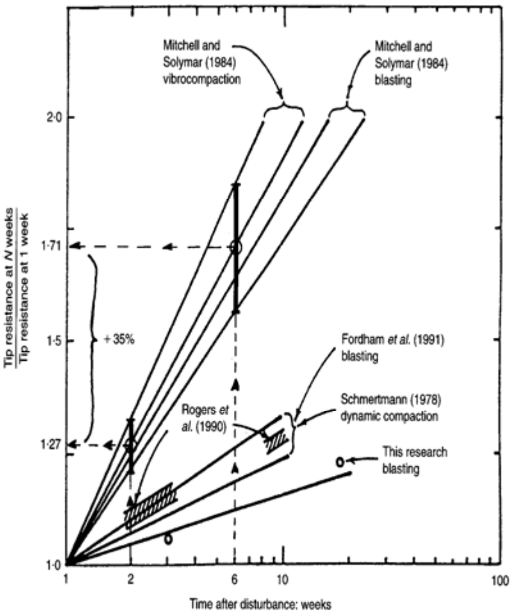


Figure 3: Strength gain due to ageing (Debats and Sims, 1997).

4.2 GROUND IMPROVEMENT BY CONSOLIDATION

Consolidation of a soft cohesive soil improves the engineering characteristics of the soil. Both the strength and unit weight of the soil are increased and hydraulic conductivity is reduced when the soil is consolidated. Unfortunately, these improvements are accompanied by a decrease in soil volume and ground deformation. To mitigate the impact of deformation on the structure, the soil is often pre-consolidated under loads higher than the design load, so that design deformations occur prior to installation of the structure.

4.2.1 Methods of Application

There are three basic methods of ground improvement through consolidation:

- preloading with or without vertical drains
- electro-osmosis
- vacuum consolidation.

In Australia, preloading is the more commonly adopted method. Preloading is usually accomplished by placing surcharge fills which apply a load in excess of the permanent load to accelerate the rate of settlement. Controlled filling of tanks or lined ponds, electro-osmosis or vacuum consolidation are alternative means of preloading. To accelerate consolidation, vertical (sand or prefabricated wick) drains are often used with preloading.

Consolidation by electro-osmosis is the same in many aspects as consolidation under externally applied stresses, except that the driving force for drainage is induced internally by an electric field.

During vacuum consolidation, both liquid and gas (water and air) are extracted from the ground by suction induced through the creation of a vacuum on the ground surface and assisted by a system of vertical and horizontal drains. As illustrated in Figure 4, an airtight membrane is usually placed on the ground surface and in peripheral trenches to seal the soil from the atmosphere and allow the creation of the vacuum. For construction of a highway embankment over a compressible, highly organic, clay layer with a moisture content of 140% to 210%, vacuum consolidation was applied for a period of 3 months. The effect of vacuum consolidation was equivalent to that of preloading with 5 m of fill (Cognon *et al.*, 1994).

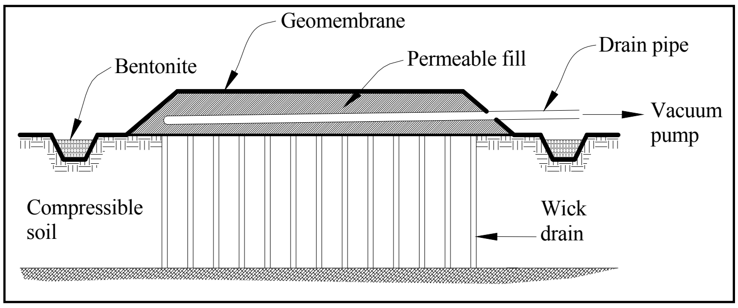


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Figure 4: Vacuum consolidation concept.

4.2.2 Key Issues

The key issues associated with ground improvement by consolidation are:

- stability during surcharge placement
- clogging of vertical drains
- maintaining the vacuum.

System Stability
To safeguard against stability problems, surcharge loads are often placed in stages, with each stage added only after the soil has acquired sufficient strength, under the influence of the previous stage, to support the new load. A good knowledge of consolidation characteristics is needed, especially if timing is critical. The build up and dissipation of excess pore water pressure and the accompanying soil deformation are usually monitored to pinpoint the timing for stage placement. When electro-osmosis or vacuum consolidation is applied, no stability problem is anticipated and the staging requirement of preloading is eliminated.

Clogging of Drains
The clogging and smear of vertical drains is a key issue affecting the feasibility of ground improvement through consolidation. A major advantage of plastic wick drains over sand drains is their flexibility and their ability to sustain large deformations of the consolidating cohesive soil, which may otherwise shear and clog the sand drains, rendering

them ineffective. The hydraulic conductivity or discharge capacity of wick drains, on the other hand, is influenced by potential crimping of the material when large deformations take place, or clogging of drainage channels due to an ineffective filter jacket. A non-woven geotextile fabric is usually used to provide filtering and ensure the hydraulic conductivity of prefabricated drains.

Maintaining the Vacuum

The provision of an all-around seal to maintain the vacuum at ground level is critical for the successful application of vacuum consolidation. Resistance of the membrane to tearing during and after placement is an important factor affecting the ability of the system to do so. Often, the membrane is covered by a layer of soil or by water ponding to prevent tearing by vehicles, animal or bird attacks or vandalism. A new system developed recently in France eliminates the need for the membrane, as the required vacuum is generated by circulation of air through a series of specially designed drains installed to the depth of the layer to be consolidated (Robinet and Juran, 1999).

4.3 GROUND IMPROVEMENT BY WEIGHT REDUCTION

This method of ground improvement involves reduction of the weight applied to a soft compressible soil through the use of lightweight fill material. The lightweight material is either used as a fill placed on the ground surface, as in the case of embankment construction, or as a replacement to an excavated native soil layer, resulting in an overall reduction in the in situ stress on the soil beneath it.

The overall benefits gained from the use of lightweight fill materials include reduced settlement, increased slope stability, and reduced lateral earth pressure on retaining structures. A key benefit is the material's high resistance to earthquake effects. (The low unit weight results in lower seismic inertial forces.)

4.3.1 Methods of Application

The lightweight materials used most commonly in geotechnical applications are listed in Table 2, based on Stark *et al.* (2004), and Riad *et al*. (2004). The lightweight materials are placed over the native soil in one of three ways:

- spread in a loose form, then compacted
- cut in block forms, then stacked according to a certain arrangement or
- pumped in a flowable liquid form.

Table 2: Lightweight material used for ground improvement.

Fill material	Source/process	Dry unit weight (kN/m^3)
Wood fibres	Sawed timber waste	5.4 – 9.6
Shredded tyres	Mechanically cut tyre chips	5.9 – 10
Expanded shale/clay	Vitrified shale or clay	5.9 – 10.4
Fly ash	Residue of burned coal	11.2 – 14
Air-cooled slag	Blast furnace material	11 – 15
Flowable fill	Foaming agent in a concrete matrix	3.4 –7.7
EPS/Geofoam	Block moulded expanded polystyrene	0.12 – 0.32

4.3.2 Key Issues

The key issues associated with the weight reduction method of ground improvement are usually related to the method of placement of the fill material and the properties of the fill material used, namely the durability and long-term performance of the fill.

Material Placement

When fly ash is wet during placement, it may become spongy and difficult to compact. When dry, it may become too dusty and, therefore, environmentally unacceptable.

Durability

The flotation characteristics of geofoam, and its susceptibility to fire and deterioration from fuel spills or insect burrowing, are long-term durability issues that require special measures. Continued crushing and knitting of shells (oyster, or similar) under the influence of vehicular traffic may reduce the drainage potential of the embankment, thus resulting in ponding of water at the surface. Otherwise, it may reduce the frictional angle of the material, thus increasing its lateral pressure on supporting structures.

4.4 GROUND IMPROVEMENT BY REINFORCEMENT

In situ reinforcement of a poor soil is accomplished by the addition of reinforcing elements to the soil to improve its engineering characteristics. The soil and its reinforcing elements act in combination to increase the shear strength of the soil mass, reduce its settlement under load, and improve its resistance to liquefaction. The reinforcing element can be either inserted in the *in situ* soil or placed in the soil mass as it is constructed.

4.4.1 Methods of Application

Reinforcing the soil is usually accomplished by one of the following methods:

- mechanical stabilisation
- soil nailing
- soil anchoring
- micropiles
- stone columns and/or
- fibre reinforcement.

In mechanical stabilisation, the reinforcing elements are placed between layers of compacted soil. Different materials (metals, polymers, geotextiles, etc.) and shapes (strips, grids, sheets, rods, etc.) are used for reinforcement. When used in the construction of retaining walls or embankment slopes, the reinforcing elements are usually attached to facings that retain the compacted soil at the face and protect the reinforcing elements from weathering effects. The types of facing used include pre-cast concrete panels, cast-in-place concrete, metallic plates or baskets, geosynthetic grids or sheets, timber, modular blocks and rubber tyres. The backfill material usually consists of granular soil with high frictional resistance.

Used primarily to support excavations and reinforce slopes, the concept of ‘soil nailing’ involves placing closely spaced reinforcing elements *in situ* to increase the shear strength of the soil and to restrain its displacement during and after excavation. Construction is accomplished using a top-down process that involves three repetitive stages:

- excavation to a limited depth
- installation of nails and drainage
- placement of a facing.

The reinforcing elements (soil nails) are usually in the form of metal bars, tubes or rods, which are installed by driving, drilling and grouting, jet grouting, or firing (launched nails). The facing can either be built on-site (with shotcrete or cast-in-place concrete) or built from prefabricated steel or concrete panels. When excavating below the groundwater table, an appropriate vertical and/or horizontal drainage system should be installed behind the permanent facing. Figure 5 illustrates soil nailing to support an excavation on EastLink in Melbourne, and for road widening beneath a rail bridge on the Lane Cove tunnel project in Sydney.

Figure 5: Soil nailing on EastLink, Melbourne and Lane Cove tunnel project, Sydney.

During soil anchoring, pre-stressed soil anchors are installed in the ground to reinforce the soil and support vertical or inclined excavations. The anchors are attached at the surface to concrete panels or “elements,” forming what is sometimes called an element wall. As with soil nailing, the reinforcements and the soil form a coherent body that resists applied loads. To accomplish this, anchors are placed closer than in a typical anchored wall and the need for structural elements (soldier piles, lagging and walers) is avoided.

When micropiles are used for soil reinforcement, small-diameter, usually less than 300 mm, piles are installed vertically, or in a reticulated fashion, to support excavations, slopes or foundations. For these applications, the piles are spaced closer than in conventional pile foundations and the loads are supported by a complex soil-pile structure. The structure is analogous to reinforced concrete, with the ground acting like concrete and the micropiles acting like steel reinforcements. Micropiles are installed by drilling and grouting, displacement or jet grouting.

Although constructed using the same equipment and procedures as vibro-compaction, stone columns function as reinforcement rather than a method of densification. They are applied to soft cohesive soils in order to increase bearing capacity, reduce settlement and accelerate consolidation, improve slope stability and control liquefaction. The presence of stone columns transforms the ground into a composite mass of granular cylinders with intervening native soil, providing lower compressibility and higher shear strength than observed in the native soil alone. Stone columns can be installed using a variety of methods, including vibro-replacement, vibro-displacement, dynamic impaction, rammed columns, vibro-concreted columns and many others.

More recent concepts of earth reinforcement techniques involve the mixing of continuous polymer fibres (yarn), or elastomeric sprays with granular soil to form a composite material capable of resisting tensile forces. Individual fibres can also be mixed with the soil to improve strength and deformation characteristics. Although polyester fibres are generally used in actual applications, other materials, such as wood and rubber tyre chips, can be mixed with the soil to provide reinforcement. Reinforcement with these natural or processed elements is still in the experimentation stage. Recently, an elastomeric cementitious spray was used to address instability of a weathered sandstone batter at a former brickworks site in the Southern Highlands, New South Wales.

4.4.2 Key Issues

The key issues affecting soil reinforcement are:

- load transfer to the reinforcing elements
- failure surface of the reinforced soil mass
- strain compatibility between the soil and the reinforcement
- arrangement of the reinforcing elements
- durability and long-term behaviour of the reinforcements.

Load Transfer

In mechanical stabilisation design, the maximum tension in the reinforcing element is compared to the tensional capacity of the reinforcement, and the bond between the soil and the reinforcement (the pull-out capacity). The tension in the reinforcement is determined from the lateral earth pressure in the reinforced soil layer. The lateral earth pressure is calculated by multiplying the vertical earth pressure a coefficient (K) ranging from 'at-rest' to 'active', depending on the degree of restraint imposed on the soil by the reinforcing elements. When extensible reinforcing systems are used, such as those made by polymers or geotextiles, a substantial yield is allowed in the soil, resulting in lateral pressures that are closer to the active case. For fully restrained systems that include rigid reinforcing elements (metal strips, grids or bars), the soil yield is restricted and the developed earth pressures are closer to the at-rest condition at the surface. However, the pressures are gradually reduced with depth to values closer to the active case.

The stress transfer between the soil and the reinforcing elements is a critical factor affecting the method of reinforcement with stone columns and use of basal layers incorporating geotextile reinforcement. As the rigidity of the column is substantially higher than that of the surrounding soil, a larger portion of the applied load is transferred to the stone, which improves the load carrying capacity of the treated ground and reduces its settlement. The higher the ratio of stress in the stone column to the stress in the soil between the columns (the stress ratio), the more significant the ground improvement. Generally, stress ratio values lie between 2.0 and 5.0, with higher values corresponding to very weak soils and very close column spacings, and lower values representing stronger soils and wider spacings. Although theoretical solutions are available for predicting the stress ratio (Priebe, 1995), the value used in the design is usually based largely on experience. For preliminary design, a conservative stress ratio of 2.5 to 3.0 is often used.

When micropiles are used in soil reinforcement, they are placed closer than in conventional pile design, or arranged in a reticulated fashion so that the soil and the piles act as a monolithic unit to resist loads. In this case, it is assumed that the stresses are distributed to the soil and the piles, rather than the piles alone. To achieve this, a "knot effect" is assumed, by which the stress acting on the pile is partially transferred to the nearby piles, owing to the interaction between the piles and the ground generated by the high bond between them. The knot effect has been confirmed by both model and field tests (Lizzi, 1978; Plumelle, 1984).

The ability of the soil-pile system to generate this knot effect depends on the density and arrangement of the system. When a reticulated micropile system is used to support excavations and slopes, the density and configuration of the piles should also be selected to minimise the possibility of plastic flow between the piles. The stability against plastic flow can be verified by comparing the horizontal pressure exerted by the soil mass with the limit resistance developed by the arching effect between two adjacent piles (Ito and Matsui, 1975).

A preliminary configuration of six to seven piles per linear metre is recommended for reticulated micropile walls (see Figure 6) to allow for generation of the knot effect.

Figure 6: Knot effect in a reticulated micropile system.

Failure Surface
The failure surface in the reinforced soil mass usually divides the soil into two zones: active and resistant. This is particularly important in mechanical stabilisation and soil nailing design, where the pull-out resistance of the reinforcing element is calculated along its embedded length in the resistant zone. When inextensible reinforcements are used for mechanical stabilisation, the failure surface is assumed to be bilinear. With extensible reinforcements, that surface coincides with the Coulomb or Rankine active failure plane. Figure 7 illustrates applications of reinforced soil wall systems on the Sydney Lane Cove tunnel and Melbourne Tullamarine-Calder Interchange projects.

Strain Compatibility
The behaviour of the reinforced soil mass is influenced by the ‘strain compatibility’ between the soil and the reinforcing elements. The influence of strain on the stress distribution and failure surface in reinforced soil wall systems was discussed above. Strain compatibility is also important in the selection of appropriate shear strength properties for the soil to be used in calculating the composite soil-reinforcement strength for use in the design of stone columns and basal reinforcement layers in embankments built over soft ground. Compatibility controls are also necessary to ensure that no greater load is transferred to the column than that which is assigned according to the stress ratio used in the design. As the soil between columns experiences larger strains than that of the columns, further transfer of the load takes place from the soil to the columns by arching, which increases the stress acting on the column.

Arrangement of Reinforcing Elements
When used for excavation support, the inclination of the reinforcing element (nail or micropile) affects the behaviour of the system. The direction of the reinforcement with respect to the potential failure surface plays a role in mobilising tension and shears and, therefore, in the overall shear strength of the reinforced soil. Inclining the inclusions downwards, for instance, would lead to an increased failure surface and reduced pull-out resistance. In a parametric study on the subject, Bang *et al.* (1992) presented optimum inclusion inclinations of 5 to 20 degrees for which the safety factor against pull-out resistance was the highest. It was also shown that, for shorter nail lengths, the optimum inclination angle was higher than that for longer nails.

The length and spacing of the inclusions also affect the behaviour of the reinforced-soil system. When the inclusion is relatively short, slippage is usually the dominant failure factor. When the inclusion is very long, breakage is the most probable cause of failure.

Bang *et al.* (1992) showed that the average measured safety factor gradually increased from 1.1 to 1.8 as the nail increased in length from 6 m to 18 m. The factor of safety becomes constant after a certain length, however, due to the yielding of the inclusions. Finally, as the spacing between inclusions increases, the contributions of the tensile forces in the inclusions to the global stability become smaller.

Figure 7: Reinforced soil wall installation using: (a) Inextensible reinforcement - Lane Cove tunnel project, Sydney, and (b) Extensible reinforcement - Tullamarine Calder Interchange, Melbourne.

Durability of Reinforcement

The service life of a reinforced soil depends to a great extent on the durability of the reinforcement and, to a lesser extent, on the durability of the facing elements. The durability of metallic reinforcements is usually measured by their resistance to corrosion. Geosynthetics are assessed by their resistance to hydrolysis (polyester), oxidation (polyethylene and polypropylene), stress cracking, biological degradation and ultraviolet light exposure (Sullivan *et al*., 1990). The choice of a reinforcing system and its design are sometimes influenced by long-term durability requirements. When geosynthetics are used for reinforcement, for instance, the tensile strength of the reinforcing element is divided by three reduction factors, representing creep, installation damage and durability. Depending on the material used, the creep reduction factor ranges from 2 to 5, the installation damage factor from 1 to 3, and the durability reduction factor from 1.1 to 2.0 (Munfakh *et al.*, 1999).

4.5 GROUND IMPROVEMENT BY CHEMICAL TREATMENT

Cement, lime, fly-ash, asphalt, silicate and other materials can be used to stabilise weak soils. These materials generally bind the soil particles together, resulting in higher strength and lower compressibility. For lime stabilisation, an ion exchange reduces the soil's plasticity and improves its workability. The ion exchange is then followed by a chemical reaction that increases the shear strength. In surface stabilisation, the chemicals are mixed with the soil and an appropriate amount of water, and then compacted using conventional compaction equipment and procedures. At depth, the chemicals are applied by injection, or by deep mixing methods. Further guidance is given in AustStab (2004), and Wong (2004).

4.5.1 Methods of Application

The chemical treatment methods discussed here are those applied at depth in soft ground. They are defined in Bruce (2005) and include:

- permeation grouting
- jet grouting
- deep soil mixing
- lime columns
- fracture grouting.

For permeation grouting, cement, lime, bentonite or chemical grouts (silicates, etc.) fill the voids in the soil, resulting essentially in increased strength and cohesion and reduced permeability, with no change in the volume or structure of the original ground. Organic compounds, or resins, are also used for special applications. Microfine and ultrafine cement grouts are the latest addition to permeation grouting. Grout additives may be used to enhance penetrability and strength and to control setting time. Grouting is performed by drilling holes in the ground and injecting slurry grouts through the end of a casing, or through the use of specialised equipment such as a tube-a-manchette.

Jet grouting uses high-pressure fluids, applied through a nozzle at the base of a drill pipe, to erode the soil particles and mix them with the cement grout as the drill bit is rotated and withdrawn, thereby forming hard, impervious columns. Excess soil cuttings are carried to the surface in the form of waste slurry. The grouted columns can be formed vertically, horizontally or at an angle. A row of overlapping columns forms a wall. Jet grouting is used mainly for excavation support, underpinning, tunnelling and groundwater cut-off. It is probably the most applied method of ground improvement on soft ground tunnel projects. Jet grout columns are installed to provide barriers for the movement of soils and groundwater into the tunnel excavation, as well as, underpinning and support for existing structures and utilities in the vicinity of tunnelling.

For excavation support in water-charged, soft ground, jet grout technology has recently been used in projects in Sydney and the Gold Coast to form a seal between bored piles using a cement and bentonite mix to depths of 28m. For this application, a drill pipe was placed in the ground between the piles which rotates horizontally eroding the soil into which cement is pumped, mixing with the soil to create a seal between the structural members.

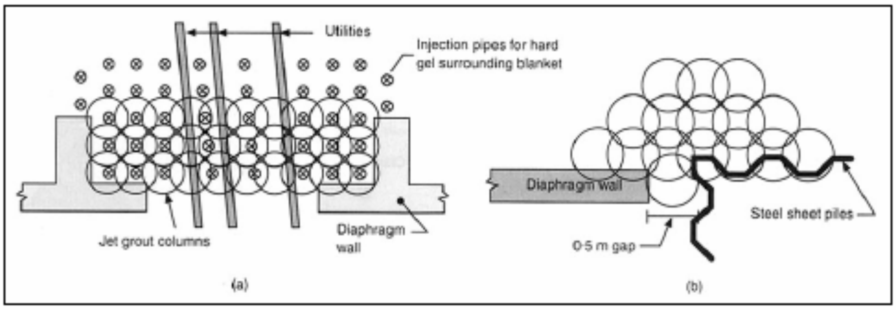

Figure 8: Miscellaneous jet grouting at Cairo Metro.

Figure 8 illustrates miscellaneous jet grouting applications on the Cairo Metro. In addition to providing ground treatment at the cross passages between adjacent tunnels, and at the departure and arrival points of the TBM out of, or into, the stations, it was also used to provide water cut-off at utility gaps in diaphragm walls and for underpinning of two buildings directly above the tunnel (Morey and Campo, 1999).

The deep soil mixing (DSM) technique involves mixing in-place soils with cement grout or other reagent slurries, through the use of multiple-axis augers and mixing paddles, to construct overlapping stabilised-soil columns. By arranging the columns in various configurations, the system can be used to strengthen weak soils, for groundwater cut-off, or liquefaction control. If required, steel reinforcement can be inserted into the column to provide bending resistance. When used for liquefaction control, the DSM system is performed in a block or lattice pattern to resist stresses associated with embankment or surcharge loading when loose cohesion-less soils liquefy during seismic ground shaking.

The lime column method is a variation of deep soil mixing, in which unslaked quicklime is used in lieu of, or mixed in with, the cement. The lime columns are suitable, at best, for stabilising deep, soft clay deposits. A pozzolanic reaction takes place between the lime and the clay minerals, resulting in a substantial increase in the soil strength and a reduction in the plasticity of the native material. The heat generated by hydration of the quicklime also reduces the water content of the clayey soils, resulting in accelerated consolidation and strength gain. Lime columns can be used for load support, for stabilising natural and cut slopes, and as an excavation support system.

Soil fracture grouting was developed to stabilise and consolidate cohesive soils that are not injectable by conventional permeation grouting techniques. The method involves controlled fracturing of the soil unit using a fluid grout, without significantly affecting the soil structure. Cementitious or chemical grouts are injected in a uniform fashion beneath structures to create a reinforced mass of soil and grout. Improvement of the soil follows three basic mechanisms: reinforcement, densification and ion exchange. Because the process requires that the soil be fractured and not permeated, fracture grouting can be used in all types of soil.

4.5.2 Key Issues

Chemical treatment is influenced by the following key issues:

- soil-grout compatibility and reactivity
- operational parameters
- column verticality
- weathering effects.

Soil-Grout Compatibility and Reactivity

The type of grout used and the make-up of the grout mix depend on the properties of the ground. Figure 8 illustrates the compatibility of the various grouting techniques with the grain size ranges of the grouted soils (Elias *et al.*, 1999). In permeation grouting, the principal parameter affecting permeation is the size of the intergranular voids, which is usually represented by the soil's coefficient of permeability. As the grout permeates through the ground under pressure, it displaces water and air from the voids at a rate dictated by the ground permeability. In homogeneous, isotropic, uniform soils, a spherical flow of grout takes place. Normally, however, the ground is non-uniform, and the penetration depth is affected by the soil's stratigraphy.

Although jet grouting may work in most types of soil (see Figure 9), because the initial structure of the soil is broken down by the jetting process, its success is nevertheless influenced by ground characteristics, such as the size and frequency of boulders and the presence of peat or organic materials. The humic acids generated by these materials may affect the hydration of the cement and delay, or prevent, the hardening of the soil-grout mix. The presence of boulders or obstructions in the soil is even more limiting in the deep soil mixing method, since the columns are usually constructed to fixed dimensions; therefore, the cement grout cannot penetrate or engulf larger-diameter objects as is usually done in jet grouting. Recently developed equipment, however, allows the use of jetting or spreadable mixing tools at the tip of the auger to enhance the grout penetration and increase the column diameter at a specific depth (Probaha, 1998).

When using lime columns, the feasibility of stabilisation and the amount of lime needed to trigger the pozzolanic reaction are influenced by the type of soil being treated. In general, lime stabilisation is applied to cohesive soils (both inorganic and organic). For inorganic soils with low to medium plasticity, the lime content used is usually 6 to 8% of the dry unit weight of the stabilised soil. In highly plastic soils, more lime is added. When organic soils are treated, a lime content of 2 to 3% is required to neutralise the acidity of the organic matter. The remainder of the added lime (10 to 12% in total) is used to trigger the pozzolanic reaction (AustStab, 2004). Gypsum is mixed with unslaked lime to stabilise organic soils with high water content. In low-reactive clays, fly ash or kiln dust may be added to enhance the soil-lime pozzolanic reaction. Lime-cement mixes of equal proportions are used when higher strength is required.

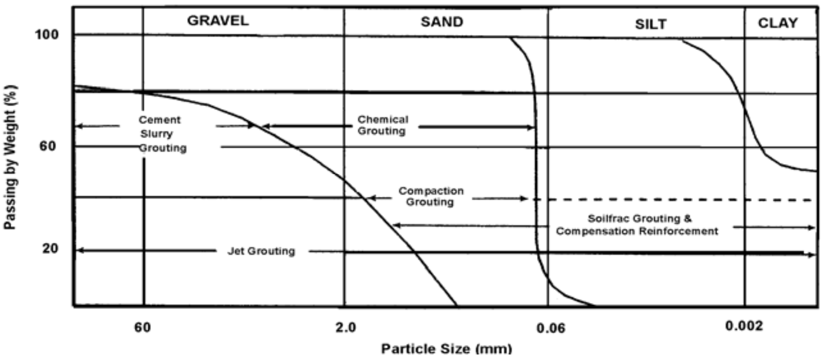

Figure 9: Range of groutable soils (Elias *et al*., 1999).

Operational Parameters

All deep chemical treatment methods are operator-sensitive and their success depends on 'operational parameters' controlled by the construction crew. Both the strength and the permeability of the treated mass, for instance, are influenced by the net amount of cement in the ground, which in turn is influenced by the controlled volumes of cement, water and additives mixed at the grout plant or at the top of the deep mix auger. They are also influenced by the level of the soil-grout mixing achieved *in situ*. In deep soil mixing, the grout flow is usually adjusted constantly to accommodate varying drill speeds in different soil strata, so that the design volume of grout per unit volume of the *in situ* soil is maintained.

The diameter of the column is a function of the method of installation used. It is influenced by a number of operating parameters, such as injection pressure, grout flow and rod withdrawal and rotation rates. A triple fluid system, for instance, produces a column with a larger diameter than that produced by a double fluid system. For a given soil type, the slower the withdrawal and rotation rates, the larger the column diameter that can be achieved. All operating parameters are usually determined through initial field trials at the beginning of construction (Hewitt and Spaulding, 2006).

When fracture grouting is applied, performance-type specifications are normally used and the grout mix is adjusted by the operator to provide the required performance. Portland cement is used in the grout mix, and additives are sometimes provided to control the grout gel time, so that controlled lifting of the ground in discrete areas under the structure is provided by repeated injections at short intervals. A detailed, high-precision, instrumentation monitoring program is usually used as an integral part of the fracture grouting scheme. Continued monitoring of the movements of the structure and the ground allows the contractor to adjust the grouting operation to suit the project's performance requirements.

Column Verticality
The verticality of the constructed column is an important issue in jet grouting, particularly when the system is used to construct fluid barriers. When used for construction of a cut-off wall, multiple rows of overlapped columns are usually designed on the basis of the assumed permeability of the jet grouted column (a minimum overlap of 0.3 m is usually used). When two adjacent columns deviate from their vertical alignments in opposite directions, the required column overlap may not develop and voids (or windows) may occur in the jet grout wall, substantially increasing its hydraulic conductivity and rendering it ineffective as a cut-off wall.

The column's verticality is monitored by the operator, and the presence of windows is detected by a pumping test or exposure of the completed columns. The verticality and overlapping of the columns are less of an issue in deep soil mixing, since the columns are constructed to fixed diameters and the overlapping is ensured by the construction process.

Durability and Long-term Performance
Although the strength of the chemically-treated soil increases with time until a certain age, the long-term behaviour of the soil structure is influenced by weathering, particularly if there is continuous exposure to weathering elements such as water, wind or temperature. Test results on the subject show that lime-treated soils absorb less water with time than do untreated soils, and they also dry faster. Contrary to cement stabilisation, the frost heave in lime-stabilised soils is greater than that in untreated soils, particularly if the soils are frozen within one month of compaction. The resistance against frost-thaw effects, however, increases rapidly with curing time as the strength of the stabilised soil is increased. Generally, the depth and speed of frost penetration are reduced with the addition of lime, because the larger void ratio generated by flocculation allows less heat conduction through the soil. The resistance of the chemically treated soils to weathering effects is tested through durability tests involving wet-dry or freeze-thaw cycles.

4.6 GROUND IMPROVEMENT BY THERMAL STABILISATION

Although both heating and freezing can be used for ground improvement, soil heating is still in the experimental stage and has seen little application due to its cost. Ground freezing, on the other hand, has received wider acceptance as a temporary measure for excavation support especially in soft ground in urban areas. Examples include the 11 m diameter, 65 m deep Swan Street shaft, in permeable water-bearing gravel, on Melbourne CityLink (Tagaza, 2002), and the Kranji shaft on Singapore's Deep Tunnel Sewer System (Lees, 2006).

4.6.1 Methods of Application

The thermal stabilisation methods discussed in this paper are:

- ground freezing
- vitrification
- thermal desorption.

Ground freezing has two main functions: to prevent groundwater seepage into excavations and to increase the shear strength of the soil and improve its structural capacity. Two basic systems are usually followed in freezing. In an open system, the refrigerant (liquid nitrogen or carbon dioxide) is lost to the atmosphere after it has absorbed energy and vaporised. Alternatively, a closed-circuit hydraulic system uses conventional mechanical plant and a circulating coolant. In either case, the groundwater is frozen and prevented from entering the excavation. In addition, the shear strength of the soil is increased as the ice acts as a binding agent to the soil's particles. Ground freezing can be applied to a wide range of soils.

In vitrification, the soil is electrically melted at very high temperatures, typically in the range of 1,600 to 2,000° Celsius. This is accomplished through the use of graphite electrodes to conduct electricity through the soil. As the soil melts, the flowing electricity is converted into heat that moves outwards, melting new soil. The melted soil becomes electrically conductive and forms a heat-transfer medium, allowing the melt to move downward and laterally through the soil. The inorganic portion of the soil typically breaks down into major oxide groups, such as silica and alumina. Upon cooling, these groups form glass and crystalline products with excellent environmental properties.

Thermal desorption is generally classified as either indirect or direct. Direct thermal desorption separates contaminants from the soil matrix by directly exposing the soil to hot combustion gas. Following desorption, gas phase contaminants require treatment, which typically involves a secondary combustion step at temperatures greater than 1,000° Celsius. Indirect thermal desorption involves volatilisation of contaminants by indirect heating in a low oxygen atmosphere. Formation of dioxins and furans are avoided in the indirect method due to low oxygen levels and the absence of combustion gases. In Australia, thermal desorption is being used at sites such as Homebush Bay in Sydney (Parsons Brinckerhoff, 2002) and trials have been undertaken at the former BHP Steelworks site and gasworks site in Newcastle.

4.7 GROUND IMPROVEMENT BY ELECTRO-TREATMENT

Developed mainly for use in the remediation of contaminated sites, electro-treatment methods involve the application of electric currents through the ground to remove contaminants in an unobtrusive fashion. These methods involve limited excavation and transport, and result in minimal environmental impacts. In Australia, electrical currents have been applied to the soils and wastes at Maralinga in South Australia to melt the toxic and radioactive components in the soils to form a solidified vitreous/ceramic mass with good physical, chemical and weathering properties. While this process was successful for a number of pits, the works were abandoned following damage to the electrical/vitrification unit and the uncertainties of the outcomes of the process (Commonwealth of Australia, 2003).

Further details of methods used in environmental applications are given in Munfakh and Wyllie (2000); and Holtz (1989).

4.8 GROUND IMPROVEMENT BY BIOTECHNICAL STABILIZATION

This form of ground improvement uses vegetation as reinforcing elements. It is used for stabilization of cut or fill slopes, or construction of earth-retaining structures on parkland and in environmentally-sensitive areas. Biotechnical stabilization is economical and more environmentally friendly than other forms of ground improvement. The biotechnical stabilisation techniques currently used include:

- brush layering
- contour wattling
- reed-trench layering
- brush matting
- live staking.

Of these, brush layering is the most commonly used. Descriptions of these methods are included in Gray and Leiser (1982), and RTA (1998). Coppin and Richards (1990) gave illustrative examples of slope stability analyses using the suction effect of vegetation both ways (i.e. as reduced pore water pressure and as increased artificial cohesion).

5 SOFT GROUND IMPROVEMENT SELECTION

The selection of a soft ground improvement method is a function usually provided by the design engineer. Owing to the proliferation of the available techniques on the market, the many benefits associated with each method and the rapidly developing nature of the ground improvement field, selection of the most appropriate method for a specific project is not an easy task. Selection can best be carried out through a thorough evaluation of many factors, and with extensive reliance on intuition and experience, so that the intended outcomes are achieved.

The key factors affecting the selection of a ground improvement method include:

- the ground
- the groundwater
- specification requirements
- construction considerations, including schedule, materials, accessibility, right-of-way, equipment and labour
- environmental and sustainability concerns
- durability, maintenance and operational requirements
- contracting, politics and tradition
- cost.

5.1 THE GROUND

The characteristics of the soil have a major impact on the effectiveness of the ground improvement technique adopted. Densification and reinforcement techniques, for instance, rely heavily on the internal friction between the soil particles, or the friction along the soil-reinforcement interface. So these methods are suitable for use with frictional soils such as sands and gravels. Some reinforcement methods (stone columns) and consolidation methods (preloading and vacuum consolidation) are suitable for use with fine cohesive soils. Strain compatibility is another factor affecting the design.

When the ground is reinforced with extensible elements such as geotextiles, the strain required to mobilise the full strength of the reinforcing elements is much larger than that needed to mobilise the full strength of the soil. Therefore, large internal deformations usually occur, and the soil design parameters are measured at large strains (residual strength). Obviously, these systems are less compatible with soils of relatively low residual strength.

Chemical stabilisation applies to a variety of soils. While permeation grouting is not suitable for fine-grained clayey soils, lime stabilisation is suitable for clayey soils, but only those that have enough silica and alumina constituents to induce the pozzolanic reaction. In jet grouting, the specific soil type is not as important as with other methods, since the in situ structure of the soil is broken down by the improvement process. The effectiveness of the method, however, is influenced by some soil elements, such as boulders and organic materials. In electrotreatment, soils with high levels of electric conductance produce better results. When biotechnical stabilisation is used, fertile soils are preferred.

5.2 GROUNDWATER

The level of groundwater and the degree of saturation of the soil affect many techniques. In the densification method, micro-liquefaction is induced in saturated soils below the groundwater table. Groundwater is also needed for ground freezing, or biotechnical stabilisation, to be effective. On the other hand, a high groundwater level may have a damaging effect on certain methods of ground improvement, such as soil nailing and the use of foam for weight reduction.

5.3 CONSTRUCTION CONSIDERATIONS

Schedule, materials availability, site accessibility, equipment and labour considerations are important factors affecting the selection of a ground improvement technique. Where preloading and wick drains are used, and to a lesser degree with lime stabilisation, time is of paramount importance. When the site is inaccessible to heavy equipment, such as in rough mountainous terrain or in soft ground, a method that can be implemented with a minimum of equipment, such as geotextile reinforcement, is preferred. On the other hand, labour-intensive systems, such as vacuum consolidation and biotechnical stabilisation, are usually not cost-effective in areas with labour shortage or strong labour union requirements. When low headroom does not allow the use of certain equipment, such as those required for deep soil mixing or stone columns installation, methods that can be implemented from remote areas, such as the various grouting or specialist low-headroom equipment techniques, are preferred (see Hewitt and Spaulding, 2006). Right-of-way and easement requirements may affect the feasibility of certain methods like mechanical stabilisation and soil nailing. The impact of construction on nearby facilities is an important factor in the selection. The use of the economical method of dynamic compaction, for instance, is precluded quite often because of its potential impact on existing structures and utilities.

Materials availability is an important factor in the selection of the preferred technique. When fill material is abundant, preloading is a very cost-effective method of ground improvement. If the required amount of surcharge material is not available within a short hauling distance, an alternative preloading scheme, such as vacuum consolidation, can be used. If industrial by-products, such as fly ash, kiln dust or slag, are available in large quantities, their use for enhancing lime stabilisation, or for weight reduction, may be cost-effective, as may be the use of waste materials such as shredded tyres or wood chips.

5.4 ENVIRONMENTAL AND SUSTAINABILITY CONCERNS

Sensitivity to environmental impacts is a key factor in the selection process. For contaminated sites, methods involving the discharge of large quantities of water, such as vibro-replacement, stone columns, vacuum consolidation and wick drains are avoided. On the other hand, methods that preserve the environment, such as geotextile reinforcement and biotechnical stabilisation, are welcome in environmentally-sensitive areas, such as parkland. Methods that allow construction of embankments with vertical faces (mechanical stabilisation) are preferred in or near wetland areas. Where a site is underlain by contaminated plumes, and if the contaminated site is to be cleaned and re-used instead of contained, electrotreatment or thermal consolidation techniques may be selected.

5.5 DURABILITY, MAINTENANCE AND OPERATIONAL REQUIREMENTS

The durability of materials used in ground improvement is a strong governing factor, particularly where the ground is exposed to heavy weathering elements. The use of metallic reinforcements, for instance, is avoided near stray currents or in highly corrosive soils. When geosynthetics are used, they require protection from the effects of heat, chemicals and exposure to ultraviolet light. Although all geosynthetic materials degrade upon exposure to ultraviolet radiation, their reaction to other durability effects varies. This should be taken into account in the selection process. For instance, although polyester is susceptible to hydrolysis and loss of strength when in contact with water, polyethylene and polypropylene are not affected. However, these materials do tend to break down upon thermal oxidation in the presence of heat and oxygen, contrary to the behaviour of polyester.

The effects of wet-dry and freeze-thaw cycles are particularly important in chemical stabilisation. Extreme weather conditions, such as dry heat or ice, may have damaging consequences on biotechnical stabilisation. Thus, this technique should not be selected in areas with arid or frigid climates, and where there is a shortage of maintenance staff to take care of the foliage. The selection process is also influenced by the operational requirements of the facility. If there is ample time before the facility is operational, a rolling surcharge can be used. If the available time is relatively short, vertical drains and/or vacuum consolidation may be selected. To further reduce the ground improvement time, stone columns can be used, but at a relative cost penalty.

5.6 CONTRACTING, POLITICS AND TRADITION

Contractual requirements play a role in the selection process. Sometimes a method preferred by the design engineer cannot be specified because it is patented by a specialty contractor. National policies, free-trade agreements, labour union requirements, tradition and political influences sometimes affect the selection. Sometimes, certain methods of construction are not recommended, simply because they cannot be done by local contractors or because they require certain labour skills unavailable locally. One trend that will encourage adoption of new ground improvement techniques is the use of performance specifications, rather than process or product specifications.

5.7 COST

This is usually the most important factor in the selection process. If all other factors are satisfied, cost becomes the governing parameter. When analysing the cost, however, the long-term behaviour of the system and the required maintenance cost should be considered. A scheme with the lowest construction cost may not necessarily be the most economical, if it will require substantial maintenance and repair costs in the future. When different schemes are close to each other in cost, alternative ground improvement methods may be specified.

6 CASE STUDIES

The following case studies describe the use of a combination of ground improvement techniques on a single project. The factors affecting the selection of the multiple schemes are also discussed.

6.1 WHARF STRUCTURE

The expansion of the Norfolk International Terminal in Norfolk, Virginia, in the United States, involved the construction of a wharf structure and a storage area on land that had been previously reclaimed using dredged material placed over soft clays (Munfakh & Wyllie, 2000). Figure 10 illustrates a cross-section of the wharf structure and the storage area behind it. The 3 horizontal to 1 vertical slope under the wharf structure was established to minimise the width of the pile-supported platform and to avoid encroachment on existing facilities behind the wharf, including a sewer outfall pipe that could not be relocated.

As the new facility would place additional loads on the *in situ* soils, and the soft compressible soils were too deep to be practically or economically removed, ground improvement was needed at the site to: allow dredging of the soil to the required slope, minimise the soil's long-term settlement and down-drag impact on the piles, and reduce the lateral earth pressure on the bulkhead. Selection of an appropriate ground improvement method was a challenge. After evaluating the many selection factors discussed above, and to satisfy economical, operational, environmental and construction-related requirements, a combination of ground improvement techniques was adopted.

Preloading of the soft clay was the most economical solution. However, due to operational requirements, the wharf structure was positioned partly on land and partly over water. Since placing fill in the water was prohibited by environmental restrictions, the surcharge load had to be placed on the land side of the bulkhead. However, this preloading configuration was not adequate to achieve the minimum shear strength required for the stability of the dredged slope and the design of the bulkhead behind the structure. To accomplish that, a large enough section of the soft soil at both sides of the bulkhead was removed and replaced with sand forming a sand shear key. Preloading of the soft soil on land was still needed to allow safe excavation of that section for construction of the sand shear key. Furthermore, because the sand shear key material was placed underwater, it had a relative density of only 10 to 40%, which was substantially lower than the 70% relative density used in the design. To achieve the required relative density, the shear key material was densified using vibro-compaction.

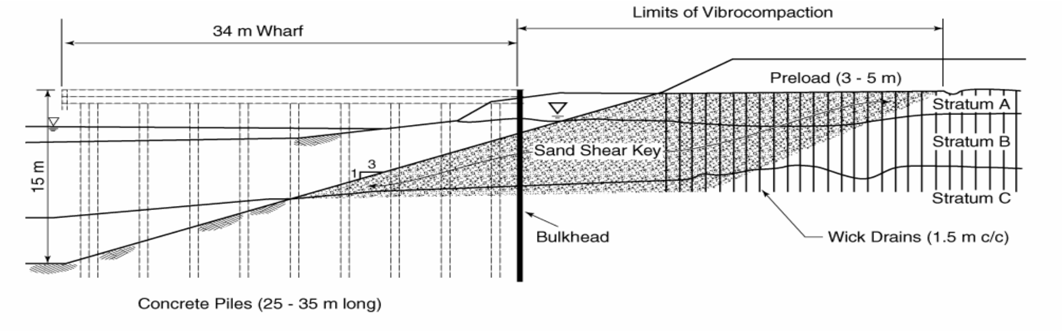

Figure 10: Cross-section of wharf at the Norfolk International Terminal.

Preloading was accomplished by placing 3 m to 5 m of surcharge fill. To accelerate consolidation, wick drains were installed to depths of 10 m to 17 m, at a spacing of 1.5 m centres, in a triangular array. The preloading program increased the shear strength of the soft clay from 10 kPa to up to 75 kPa, with over 90% of the long-term settlement completed within the 9-month construction period. Vibro-compaction was achieved with an electric vibroprobe, using water jetting and vibration. A probe spacing of 3 m was applied and sand was added during compaction to achieve the required 70% relative density.

The selection of ground improvement techniques was controlled by many factors, including the ground conditions, right-of-way limitations, operational requirements, environmental restrictions, construction issues, time constraints, and cost.

6.2 HIGHWAY EMBANKMENT

A significant part of the bridge approaches for a highway project in Eastern Australia was built over soft soils, with the prospect of significant settlement of the embankments. Building one particular approach over soft soils would have caused major stability issues and ongoing settlement problems. Following consideration of stability control methods such as staged embankment construction, vertical (wick) drains, geotextile reinforcement and stabilising berms and settlement control methods such as preloading and surcharge, ground treatment and timber and precast piles, blocks of light, high density foam blocks (geofoam) with transition treatment at bridges to reduce the settlement to an acceptable level was adopted. Prior to using 7,000 m^2 of geofoam fills, the original design consisted of various types of structures such as bridges, and fill over slab-on-piles.

Where the use of lightweight foam was not justified for cost or other considerations, the designs used combinations of piled embankments and wick drains at bridge approaches to ensure a smooth transition from piled bridge structures.

A typical example from a highway embankment built over soft compressible alluvial deposits is shown in Figure 11.

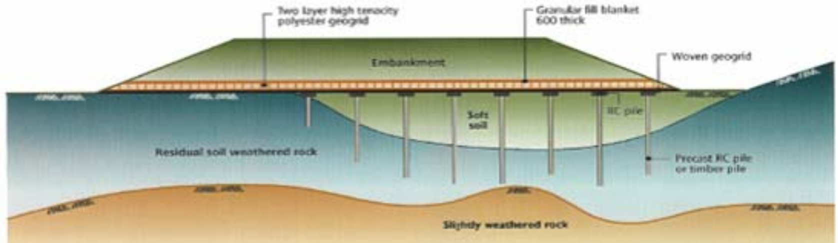

Figure 11: Piled embankment layout showing use of geotextile to transfer embankment load to pile caps.

On other sections of highways located over alluvial valleys in Eastern Australia, foundation treatment adopted in soft ground areas has included:

- staged embankment construction, to allow pore pressures to dissipate at each stage
- ground treatment using prefabricated vertical (wick) drains
- geotextile reinforcement
- stabilising berms
- preloading and surcharge and
- piled embankments using timber and precast piles at transition areas.

7 CONCLUSIONS

The successful application of ground improvement in soft soils is influenced by many technical issues related to the characteristics of the soil, the materials added to the soil and their interaction. Other technical issues affecting performance are subject to the equipment and procedures used, the skills of the operator and external factors, such as weather and proximity to existing structures. Technical, practical, economical, contractual and political factors affect the selection of a particular type of ground improvement for a specific site. The several factors discussed in this paper reflect the diversity of the ground improvement techniques available on the market and the complexity facing the design engineer in the attempt to select the most appropriate method, or combination of methods, to be applied to each project.

The following general conclusions can be drawn:

- the use of ground improvement in soft ground has clear advantages over conventional construction techniques and, sometimes, is necessary to make building of certain projects feasible and/or economical.
- the application of ground improvement techniques is almost a routine event on today's underground engineering projects in soft ground.
- one trend that will encourage adoption of ground improvement techniques to better suit a project's needs is the use of performance specifications, rather than process or product specifications.
- although ground improvement is still considered a novelty by some engineers and its applications are based, to a certain extent, on intuition and experience, the subject is rapidly evolving into a full-fledged field of geotechnical engineering with established analytical procedures, detailed construction specifications and documented, monitored performance.

5 ACKNOWLEDGEMENTS

This is an edited version of part 1 of a paper presented by Munfakh & Wyllie (2000) at GeoEng 2000. The original paper concentrated on ground improvement in both soil and rock, whereas this paper covers soft ground and recent developments relevant to Australian geotechnical practice.

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