SEISMIC EVALUATION OF VIBRO-STONE COLUMN

by

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ABSTRACT

Ground improvement work is crucial in enhancing the characteristics of weak soils commonly encountered in Civil Engineering, and one such technique commonly used is vibro-stone columns. An assessment of the effectiveness of such an approach is critical to determine whether the quality of the works meets the prescribed requirements. Conventional quality testing suffers limitations including: limited coverage (both area and depth) and problems with sampling quality. Traditionally quality assurance measurements use laboratory and in-situ invasive and destructive tests. However geophysical approaches, which are typically non-invasive and non-destructive, offer a method by which improvement profiles can be measured in a cost effective way. Of these seismic surface waves have proved the most useful to assess vibro-stone columns, however, to date much of the previous work conducted has focussed on field based observations making detailed evaluation of this approach difficult. This study evaluates the application of surface waves in characterizing the properties of laterally heterogeneous soil, specifically for using in the quality control of vibro-stone column. Three models were employed which began with a simple model and extended finally to complex model: (1) concrete mortar was used to establish the method, equipment and its system, (2) pilot test on a small scale soft kaolin to adopt a model vibro-stone column and (3) main test contained a configuration of vibro-stone column in soft Oxford clay. A generic scaled-down model of vibro-stone column(s) was constructed. Measurements were conducted using different arrays of column configuration, using sand to simulate stone material. This idealized set of laboratory conditions were used to provide guidelines for the interpretation of field measurements. The phase velocity obtained from the controlled tests showed close agreement to those reported in literature and with those generated through empirical correlations with vane shear test. The dispersive curve demonstrated an increased phase velocity with increasing wavelength for the measurements on the clay (between columns), and decreased phase velocity with increasing wavelength for the measurements on the column. More interestingly, the results showed that in the characterization of lateral non-homogeneities, the phase velocity versus wavelength relationship varies on stone columns of different diameters and densities. This illustrated that the shear modulus profiles are influenced by the effective region that spans both the lateral and depth axes, and also demonstrated how the results can be influenced by the positioning of sensors with respect to the survey target. This research demonstrates how Rayleigh waves can be used for quality assurance when constructing vibro-stone columns.

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A_c/A	Area replacement ratio
A_c	Cross-sectional area of one column
ϕ	Phase angle
2-D	Two dimensional
4D	Ratio of wavelength and column diameter
A	Plan area of the unit cell attributed to a single column
A-B	Sensor pair between A and B
B	Bulk modulus
B-C	Sensor pair between B and C
BNC	Bayonet Neill-Concelman connector
C-D	Sensor pair between C and D
CPT	Cone penetration test
CSW	Continuous surface waves analysis
c_u	Undrained shear strength
d	Distance between the source and the first receiver
d_{col}	Column diameter
d_g	Stone diameter
e	Void ratio
E	Young’s Modulus
E_{op}	Operational stiffness
f	Frequency
f_c	Sleeve friction
FEM	Finite element method
FFT	Fast Fourier Transform
f_n	Frequency of n (n is integer)
f_s	Sampling rate
G_{max}	Maximum or small strain shear modulus
GPR	Ground penetrating radar
G_s	Specific gravity

HEIC	High energy impact compaction
I	Current
L_{col}	Column length
LL	Liquid limit
MASW	Multi-channel analysis of surface waves
M_{max}	Constrained modulus
MSW	Multi-channel surface wave
N	SPT blow count
NI	National Instruments
PI	Plasticity index
PL	Plastic limit
PMT	Pressuremeter test
P-wave	Compression / longitudinal wave
q_c	Cone resistance
q_u	Unconfined compressive strength
r	Radius
R	Resistance
RIC	Rapid impact compaction
s	Columns spacing
SASW	Spectral analysis of surface waves
SNR	Signal-to-noise ratio
SPT	Standard penetration test
S_r	Degree of saturation
S-wave	Shear / transverse wave
V	Voltage
VSC	Vibro-replacement stone column
w	Water content
Δx	Spacing between the receivers
λ	Wave length
ω	Angular frequency ($\omega = 2\pi f$)
υ	Poisson's ratio

v_p	Compression / longitudinal wave velocity
v_s	Shear wave velocity
v_r	Rayleigh wave / phase velocity
$y_n(k)$	Time-domain signal at n discrete sample and time k
$Y_n(f)$	Spectrum of the signal at n discrete sample and frequency f
$\Delta\phi_{mn}(w)$	Phase difference between receivers m and n at frequency w.
ρ	Soil bulk density
ρ_w	Water density

Chapter 1

INTRODUCTION

1.1 Introduction

By necessity, construction developments are increasing in areas where the ground is generally of marginal quality. As a result geotechnical engineers are being challenged to provide cost effective foundation solutions, which increasingly require modification of marginal ground by improvement techniques to improve the properties of the ground (Charles, 2002). Ground improvement work is crucial in reducing the deformation of weak soils that may arise from loads imposed by civil engineering structures. The efficiency and cost effectiveness require the selection of suitable technique(s) of ground improvement for the prevailing site conditions (Serridge and Synac, 2007).

Generally ground improvement techniques are classified under a number heading. For the purposes of this thesis these are: (1) the first densification, which includes both compaction and consolidation, together with reinforcement through stiffening columns, e.g.

stone columns and (2) chemical, which includes additives such as lime and cements (Charles and Watts, 2002). The third includes the general approach using reinforcement elements, which for this thesis is considered to be a separate and distinct group, not relevant to the work presented herein. Densification through increased dry density treatment is normally suitable for gravelly, sandy and silty soils and consolidation used for clay soils. Stiffening columns are suitable for all types of soils especially for deep softer layers and are often considered to act in a reinforcing way, even though they are conducted via densification methods. It is for this reason that this approach is one of the most commonly used techniques globally (Charles and Watts, 2002). This approach can provide an economic and environmental friendly form of ground improvement technique, which enables the ground to take loads from light structural foundations such as supporting foundations for low-rise housing, industrial developments, waste treatment plants and car parks (McKelvey *et al.,* 2004).

Each ground improvement method needs to take into account the types of improvement and the deficiencies that are to be remedied. Thus, assessment of the effectiveness of ground improvement is critical to determine whether the quality of the works meets the prescribed requirements. Therefore, measurement and evaluation of the engineering properties both before and after treatment is of practical importance (Terashi and Juran, 2000). The parameters that control the quality of the ground treatment can be measured using laboratory tests. However, the process of sample retrieval required for laboratory testing often introduces additional difficulties associated with sample disturbance and the reliability of the sample as a representation of the entire site. As a result, in situ field-testing is often used as this overcomes the limitations presented by the soil sampling process. Penetration testing, dynamic probing, field vane shear tests and loading tests are examples of conventional field-test techniques used for quality control testing. In situ zone tests using large-scale loading are one of the best indicators to characterize the foundations on improved ground. However, this method is time consuming and expensive. Moreover, load tests may only demonstrate the stiffness of the upper layers of the ground, and may not give information on the characteristics of the underlying strata (Charles and Watts, 2002).

One of the main parameter sets that can be used to predict ground deformation when loaded are the ground stiffness profiles (Matthews *et al.*, 1996; Abbiss, 2001; Moxhay *et al.*, 2008; Clayton, 2011). In addition, structures are always designed to ensure that they perform far from failure and thus operate at small strain ground deformations. Therefore, a sound knowledge of small strain stiffness is essential to make realistic predictions of deformation (Clayton, 2011). Traditionally, the measurement of stiffness profile was carried out by using a combination of laboratory and in situ, invasive field tests. However, geophysical methods, such as seismic surface wave, offer a non-intrusive and non-destructive approach to carry out these measurements. Moreover, geophysical approaches such as this provide a cost effective way to assess site conditions, while overcoming a key limitation of traditional investigative approaches.

A comparison between geophysical seismic-based techniques and conventional geotechnical load-testing methods for the measurement of the ground stiffness profile were presented by Matthews *et al.* (1995) and Clayton (2011), drawing the conclusion that geophysical testing can deliver results of significant quality. However, care is needed not to overestimate what geophysics can achieve, by understanding geophysical techniques, in particular their limitations (Clayton *et al.*, 1995). Thus, geophysical assessment of any ground improvement must be carried out with physical soundings to ensure proper calibration and validation.

Other geophysical techniques such as electrical resistivity, ground penetration radar and magnetism are useful imaging tools, but require significant skill, good knowledge on the geological model of the area and support from the borehole data to interpret the results (Crice, 2005). For example, the resistivity of soils varies depending upon soil types and moisture content. Soil resistivity is primarily controlled by the movement of charged ions in pore fluids. Hence, salinity, porosity and fluid saturation tend to dominate electrical resistivity measurements (Giao *et al.*, 2003). Meanwhile, ground penetration radar has problems in obtaining deeper results when dealing with high conductivity material such as marine clays. By contrast, seismic wave techniques, which depend on the modulus and density of the materials can be converted to very useful parameters for engineering purposes, such as elastic modulus, shear modulus and Poisson's ratio.

Seismic waves propagate in the form of body waves and surface waves, with the difference being that body waves are usually non-dispersive. In a solid and homogeneous medium, the velocity of surface waves does not fluctuate significantly as a function of the distance propagated. However, when the properties of the medium vary with depth, surface waves become dispersive such that the velocity of the propagation varies with respect to wavelength and frequency. Surface waves are also relatively less attenuated as a function of propagation distance as compared to body waves. These two characteristics make it feasible to apply surface wave analysis for the survey of near-surface soil properties and thus in turn any changes to these properties that subsequently occur.

The conventional surface wave technique using a single pair of receivers, yield one-dimensional results of phase velocity versus depth. To resolve unknown anomalies in a laterally heterogeneous medium, it is necessary to obtain a plot of the phase velocity versus depth as well as a function of lateral distance, and hence using multi-channel receivers is more suitable. Such a method provides information with greater resolution in the lateral dimension and can therefore be used to obtain a qualitative assessment of the variability of geotechnical properties such as stiffness and strength. This enables the detection of features such as voids, fractures and soft spots. The implementation of this technique usually involves the deployment of an array of multiple receivers with the seismic source. This has been successfully demonstrated by Phillips *et al.* (2004), Nasseri-Moghaddam *et al.* (2005) and Xu and Butt (2006) for the detection of sub-surface cavities and Tallavo *et al*. (2009) for the detection of buried timber trestles.

The phase velocities obtained from the surface wave technique will convert to shear wave velocities and thus a shear modulus profile along the tested section. The cross-section of seismic wave velocities will show the lateral heterogeneities of soils due to the inclusion of columns. The key difference in this study is the lateral heterogeneity due to the columns, while being relatively homogeneous with depth. This study is aiming to evaluate seismic wave techniques for use in quality testing of stiffening columns. The method of data processing is a means to success, allowing investigation of the subsurface velocity with alternate changes of density over short distances. In addition, seismic tests and physical tests will be calibrated for better understanding.

1.2 Research Problem

The theory developed for surface wave tests assumes a layered half space with horizontal, homogeneous and isotropic layers. As a result, the majority of surface wave applications for civil engineering are for the characterisation of layered media. In the past, the surface waves were used to evaluate the quality of stone column works laterally assuming a layered block consisting of soil and column to yield an average stiffness for both materials (Sutton and Snelling, 1998; Moxhay *et al.*, 2001; Redgers *et al.*, 2008). For this study, the surface wave test is used for quality control, which aims to assess a stiffness profile of separate materials namely that of the soil, column and the interaction between them. Thus, a better understanding of the seismic surface wave technique can be achieved in order to evaluate the stiffness profile and in particular its limitations. In the majority of applications, the heterogeneous boundaries of the medium are not known a *priori*. However, in ground improvement applications, the locations of the soil stiffening columns are often known to a good degree of accuracy in the field. The planning of the survey using this knowledge can reduce ambiguities and increase the accuracy and confidence in the measurement. Therefore, a key distinction to this application is that the locations of the soil stiffening columns are usually known, and can thus be individually assessed. However, in the case where the column location is unknown such an approach still has the potential to assess the location and properties of such columns.

1.3 Research Aim and Objectives

The aim of the study is to develop the most appropriate seismic surface wave method for attaining and utilizing data in order to investigate vertical and lateral **shear modulus**, and thus be able to evaluate the quality of ground improvement achieved when using vibro-stone columns. To achieve this aim of study, the following objectives were established:

- to identify suitable seismic surface wave equipment for laboratory scale tests,
- to develop a system for seismic surface wave testing in the laboratory,
- using this to establish an optimal surface wave testing array for data acquisition to evaluate the individual columns and non-column material,
- to identify a suitable data-processing technique in order to investigate both the spatial and vertical profiles of the phase velocity (shear modulus) in the vibro-stone column ground improvement, and,
- to understand the effect of lateral heterogeneity due to column inclusion in relation to the seismic surface wave result and the quality of the vibro-stone column.

The originalities of this research are as follows;

i. The new testing equipment and system for the seismic surface wave tests at laboratory scale has been established (see Madun *et al.*, 2010a).

ii. The seismic surface wave test for obtaining the small strain stiffness profile of column and non-column material has never before been experimented at laboratory scale; therefore this research utilised the technique to attain and understand the stiffness change in the vertical and lateral directions of the model stone column (see Madun *et al.*, under review)

iii. This research has introduced a seismic source-receiver array to obtain a higher quality of signal-to-noise ratio for reliably assessing the quality of stone columns.

iv. This research has explained the influence of the column with respect to the dispersive curve (phase velocity profile).

1.4 Outline of thesis

Chapter 2 reviews the literature relating to the research, which includes literature on ground improvement, conventional testing methods, laboratory testing and the geophysical testing. **Chapter 3** reviews the literature relating to the use of geophysics, which includes a review on various geophysics methods and focusing on the seismic surface wave method. **Chapter 4** gives the initial testing method, which involved the development of equipment and its system for laboratory testing. The seismic surface wave experimental work began with a concrete mortar model, which involved sample preparation, and development of the test equipment and measurement procedures. **Chapter 5** presents the results of the initial test conducted on the concrete mortar. **Chapter 6** presents the geotechnical properties of materials used in the stone column model and explains the seismic surface wave testing array for the stone column tests and the data processing techniques. In **Chapter 7**, the test results are analyzed, compared to information from the literature and discussed in detail. This is followed by **Chapter 8,** which discusses the results in relation to stone column interpretation. Correlations are made between the seismic wave results and physical test results. **Chapter 9** summarises the main conclusions from the present work. It also details recommendations for future work based on the author's experience, in the hope that further work will yield beneficial results. A complete list of **References** is included and finally, **Appendices** of relevant topics is found at the end of the thesis.

Chapter 2

GROUND IMPROVEMENT

2.1 Introduction

Ground improvement is used to avoid unacceptable movements, which may occur over the area of a proposed foundation; of particular concern is uneven soil movement. Due to its importance, development of ground improvement techniques has been continuous over the past 30 years and with many new applications being introduced. As a result, the assessment of the quality of the improvement achieved is vital especially as techniques become more sophisticated, to ensure key improvement targets and specifications are met.

2.2 Ground Improvement Techniques

Types of ground improvement can be classified in a number of ways. This thesis concentrates on densification approaches due to their popularity and these include compaction, consolidation methods and stiffening columns (Charles, 2002), as shown in Figure 2.1. A number of the key ground improvement techniques aim to improve the bearing capacity, enhance settlement resistance, increase shear strength and, thus increase soil stiffness modulus. A detailed explanation of the various ground improvement techniques is provided by CIRIA C572 (Charles and Watts, 2002) and C573 (Mitchell and Jardine, 2002) and summarised below (see Sections 2.2.1 to 2.2.3).

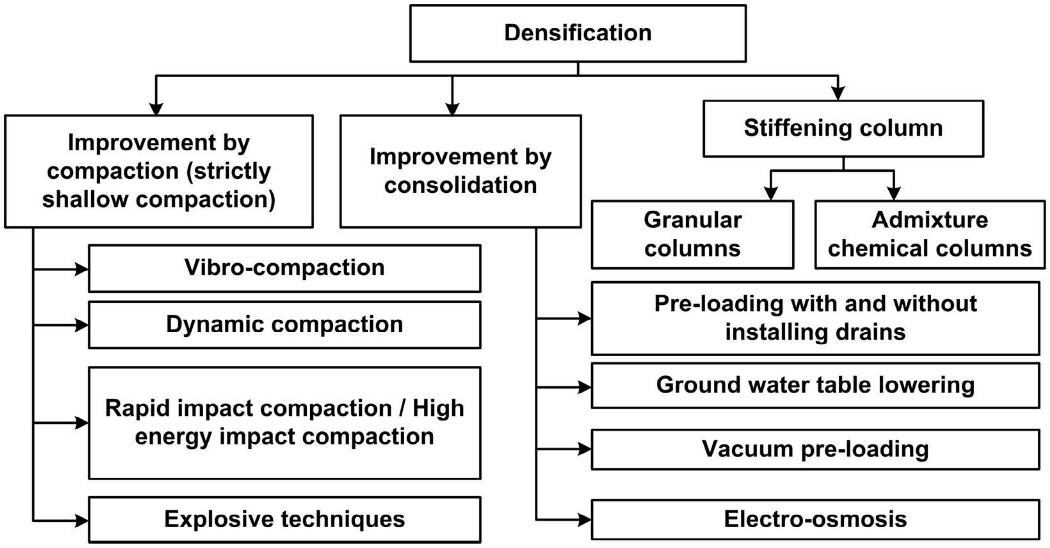

Figure 2.1: Types of ground improvements using broad densification family of approaches (Charles and Watts, 2002).

2.2.1 Densification

Densification of the ground by mechanical means is called compaction. Compaction of loose granular soils, heterogeneous soils, municipal wastes and liquefiable soils is common practice for increasing density and strength, hence reducing the volume of the soil. This prevents excessive settlement when the treated ground is vibrated or loaded (Raju and Sondermann, 2005).

Improvement by compaction is suitable for soils that have larger particle sizes, such as gravel and sand, which allow excess pore water pressures generated during compaction to easily dissipate and, thus the soil grains can readily move closer together. In contrast, compaction in clay is only effective for shallow depths due to water retention by the soil skeleton making fine grained soils difficult to compact. Vibro-compaction is one such technique to densify coarse-grained soils (Charles and Watts, 2002). The soils are densified by the use of a vibrating probe known as a vibroflot or poker (McCabe *et al.*, 2009). The silt and clay fraction in the soil must be less than 15 to 20 % to achieve effectiveness from this method. The vibro-compaction technique is capable of penetrating down to a depth of 65 metres; thus it is commonly applied in major infrastructure projects throughout the world (Raju and Sondermann, 2005). Examples include The World and Palm Island projects off the Dubai coast (McCabe *et al.*, 2009).

Another densification technique is called dynamic compaction, which can be described as systematic tamping of the ground surface with a heavy weight dropped from a given height. Materials for which this technique is suitable include loose fills, loose sand, waste and mine tailings, collapsible soils and fine grained soils (Terashi and Juran, 2000). The final densification technique in this group includes rapid impact compaction (RIC), which uses energy from repeated blows; with compaction occurring as a result of a relatively high frequency generated from a hydraulic hammer through an anvil in a tamping foot resting directly on the ground. In addition, high energy impact compaction (HEIC) can be used, with densification occurring as a result of an eccentric roller being towed behind a moving vehicle. However, both RIC and HEIC compact soils only to a few metres depth (Charles and Watts, 2002).

Densification improvement also includes techniques that use consolidation. The consolidation process mainly involves a combination of seepage developed due to changes in hydraulic gradients and changes in effective stress (Atkinson, 2007). For ground that consists of fine-grained soils that have low strength and low permeability, long-term settlement will cause densification if loaded by structures. Thus, these soils are expected to increase in strength and decrease in compressibility with time when loaded (Haegeman and Baertsoen, 2007). Consolidation methods consist of pre-loading with a surcharge of fill or, if required accelerated by the installation of vertical drains. In other situations, increasing the effective stress via lowering the ground water level will result in consolidation. Generally, this technique can be divided into two categories, either increase in total stress via a vertical load added by surcharge on the top of permanent fill, or increase in effective stress via lowering the ground water level achieved via drainage or vacuum pre-loading (Mitchell and Jardine, 2002).

2.2.2 Stiffening Columns

This is a technique that involves the construction of a composite system of columns of substantially greater stiffness than the surrounding soil. Two different types of columns are used to stiffen the ground: granular columns and admixture chemical columns. The creation of the granular columns uses dynamic replacement, sometimes called vibro-replacement and also includes vibro-stone columns, formed by the replacement of soil with stronger stone materials (Charles, 2002). For the purposes of this thesis these have been classed as a densification approach due to their method of installation using vibro-flot, used also with other densification approaches. The admixture chemical stabilization column was developed in Japan in the 1970s. This method uses mixing blades and chemical additives to create an in situ column of predetermined diameter and length (Terashi and Juran, 2000). The main improvement mechanism with admixture stabilisation is via chemical reactions between the mixtures and the clay mineral, resulting in bonding of the soil particles and filling of the void spaces. The influential factors are the characteristics of the hardening agent, the characteristics of the soil, the mixing conditions, and the curing conditions. Hence, this approach has been classified separately from granular columns.

2.2.3 Vibro-stone Columns

The research repeated herein is primary aimed at examining the properties of vibro-compaction and vibro-replacement granular columns. This is because, firstly, the vibro technique is one of the world's most widely used forms of ground improvement and, secondly, because of the advantages of vibro techniques, compared with traditional techniques using the replacement of unsuitable material, which are often impractical due to economic and environmental issues (McCabe *et al.*, 2009). Therefore, ground improvement using the vibro technique can be employed to overcome this difficulty. The method has a proven record of success (Barksdale and Bachus, 1983) due to its capability to treat a wide range of weak soils from sand to clay.

For application to soil that consists of more than 85 % of coarse grained particles (larger than 63 μm) the technique known as the vibro-compaction column is used. For fine grained soils, the vibro-granular column or vibro-replacement column is used. However, the confining pressure provided by the surrounding weak soil greatly affects the bearing capacity of the stone columns. Thus, it is not suitable for very soft soils or soils with high organic content, such as peat, which have very low undrained shear strengths were the lateral support may be too small (Raju and Sondermann, 2005). Factors of three-dimensional behaviour include: the behaviour of adjacent columns, the dilation of column material (Van Impe and Madhav, 1992) and the rapid increase in the soil shear strength due to the stone column drainage effect (Guetif, *et al.*, 2007).). This rapid increase effects have resulted in the vibro-granular technique being successfully applied in much softer soils (Raju and Hoffmann, 1996).

Completed stone column projects indicate that most of the applications were on soils having an undrained shear strength around 30 kPa and only in a few cases was the strength below 15 kPa (McCabe *et al.*, 2009). For very soft soils, a technique of using geotextile coating around the column is used to obtain lateral support, thus avoiding lateral spreading of the column (Sondermann and Wehr, 2004). In other cases, a sand layer is placed on top of the soft layer, which results in some consolidation and assists in providing lateral support to the columns at the top. This has the added advantage of providing a safe working platform for the heavy equipment (Raju, 2002).

The vibro-granular columns typically consist of crushed rock or alternative material such as recycled materials, for example railway track ballast or crushed concrete (Serridge, 2005). The construction of granular columns within fine grained soils creates a composite soil mass, which has a greater average strength and stiffness, and lower compressibility than the untreated ground. As a result vibro-granular columns have been successfully applied to improve slope stability, increase bearing capacity, reduce total and differential settlement, reduce the liquefaction potential of sand and increase the rate of settlement (Raju 2002; Raju and Yandamuri, 2010).

The stiffness of the stone column is generated by the lateral stresses provided by the surrounding soil thus providing confinement of the stone column. With ultimate vertical load, the failure mechanisms of single stone columns are typically as a result of relatively low lateral support in the upper soil layer causing a bulge to occur at the depth of 2 to 3 column diameters (Barksdale and Bachus, 1983). It can also be a result of the column toe being punched into the underlying soil, such as with ‘floating’ foundations. Bulging causes an increase in the lateral stress within the untreated soil (Sondermann and Wehr, 2004).

The effect of stone column groups when loaded is to increase the ultimate load capacity of each of the single columns, resulting in less bulging compared with a single stone column. In the case of embankment, although strengthened by a group of stone columns, failure occurs due to the untreated soil outside the treatment zone, when the soils move laterally outward from the column area toward non-reinforced soil. This phenomenon is called 'spreading', which causes greater settlement (Tavenas *et al.,* 1979).

There are many design methods for calculating settlement of stone columns such as the equilibrium method, Priebe's method, the incremental method and the finite element method (FEM) (Barksdale and Bachus, 1983). These methods used the extended unit cell concept, which has the same conditions of loading. Priebe's method is commonly used in Europe, where the application is relatively simple as the relevant settlement ratio depends on the number and diameter of the stone columns together with the treatment depth considered (Sondermann and Wehr, 2004). The improvement factors are dependent on the angle of internal friction of the stone column, the ratio of the stone column area and the area being treated by the column material. The improvement factor indicates how many times the compression modulus increases for a grid of stone columns and to what extent the settlement will be reduced. However, there is still no acceptable design method, which can adequately account for all mechanisms that are part of the load transfer process (McKelvey *et al.*, 2004). Therefore, the use of simulation calculations by the FEM to determine the stress-deformation behaviour are recommended in the design phase (Kirsch, 2009). In addition, a trial column using load tests is highly recommended before execution of ground improvement projects to ensure an effective design (Terashi and Juran, 2000).

The vibro-replacement method consists of two approaches: the dry displacement method for soil that has low water content and the wet method for high water content. Currently, for the dry method vibrators are used to produce vibro-stone columns in fine grained soils that must be able to hold the form of the entire cavity after the vibrator has been removed. This allows for the subsequent repeated delivery and compaction of stone column material to proceed without any obstruction. The compressed air from the vibrator tip does not only flush out the drilled product but also prevents the drill-holes collapsing. For the wet method, the use of a strong water jet injects water under high pressure to flush out loosened soil and mud rises to the surface. As a result, the cylindrical drill-holes are temporarily stable. The cavity is then filled and compacted in stages by repetitive use of the vibrator (Raju and Sondermann, 2005). However, the wet method is less commonly used in recent years due to environmental issue. Recently dry top feed or bottom feed approach of installation have been used. Figure 2.2 shows the dry process of stone column installation using both approaches.

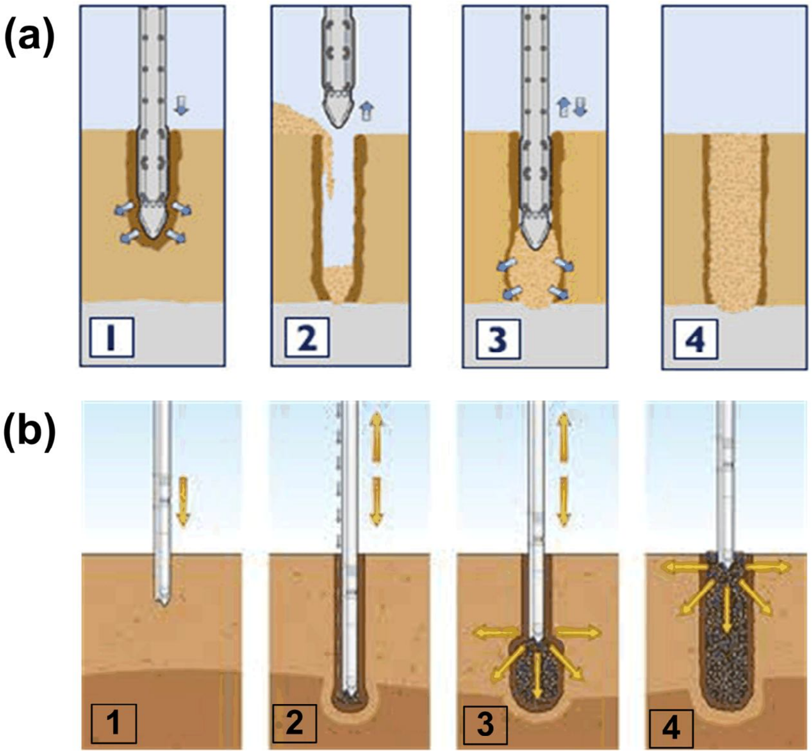

Figure 2.2: Stone column installation methods (a) the top and (b) the bottom feed of stone respectively (Raju *et al.*, 2004).

Uncertainties emerge at most of the stages of ground improvement. They could arise from the choice of the ground improvement technique, which involves identifying soil properties as part of building the soil model. In the design stage of a stone column, uncertainty is involved in the design assumption of estimating the quantities of settlement that will occur. The process of constructing the vibro-stone columns involves issues relating to the ground, people and mechanics such as discrepancies in soil model, lack of adequate site supervision, inexperienced contractors and ineffective machinery, which could affect the quality of the vibro-stone column. Therefore, quality control is needed to ensure the design objectives are achievable.

2.3 Quality Control

In parallel with the development of new techniques of ground improvement, quality control has been developed significantly since the 1970s (Mitchell and Jardine, 2002). Quality control is important to ensure improvements are designed and produced to meet or exceed customer requirements. Quality control tests similar to site investigation tests are commonly used to verify the quality of works.

More recently, geophysical techniques have been applied in quality control tests thus enabling assessment of a greater area of improved soil. The application of geophysical techniques has been steadily growing in civil engineering studies due to the development of new geophysical testing equipment and analysis software. This has led to an increased number of field testing techniques using geophysics. Geophysical testing has significant advantages including being relatively rapid to undertake (and so more cost effective), being non-destructive and providing representative values of soil parameters over a relatively large area (Butcher and Powell, 1995).

The quality and performance of the ground treatment methods are controlled by many factors, such as the accuracy of original soil data, precision of design tools, quality of materials used, employees' experience, construction schedule and weather (Terashi and Juran, 2000). Quality control needs appropriate specification and adequate supervision for success. Testing should be conducted at different times, including preferably before treatment, during treatment and after treatment, to understand the behaviour pre- and post-treatment.

Before treatment, site investigation is used to identify the ground engineering properties, such as load-carrying characteristics, typically using laboratory tests, in situ field tests, geophysical tests or some combination of these. In addition, when construction takes place, inspection by experienced personnel assisted by electronic devices fitted on the plant used in the improvement process, is commonly employed nowadays (Terashi and Juran, 2000). This enables the position, depths, quantities, feed rates, withdrawal and compaction times, for example, to be measured directly and allows indirect correlations to a ground’s response to be determined. Post-treatment testing methods are used to assess the effectiveness of any works. Monitoring of ground improvement may be continued even after the completion using settlement markers, multilevel settlement gauges and pore water pressure monitoring to obtain the necessary information for future maintenance work (Silva, 2005; Chu and Yan, 2005). These stages of quality control are conducted through laboratory tests and in situ field tests.

2.3.1 Laboratory Tests

In laboratory testing, samples are examined according to parameters used in the design to see whether the parameters fulfil the design criteria. Laboratory testing involves retrieving soil samples from the field. An important geotechnical parameters for predicting the soil deformation is stiffness, traditionally determined using various types geotechnical apparatus, including unconfined compression tests, triaxial compression tests, bender elements or the resonant column.

The unconfined compression test and triaxial compression test are destructive tests and usually used for fine grained soils. The triaxial compression test tends to produce more usable values of soil stiffness modulus since the confining pressure stiffens the soil so that a small strain modulus can be obtained (Abdrabbo and Gaaver, 2002).

The bender elements and resonant column tests are increasingly used in the laboratory. Both tests are performed using reconstituted specimens, which have similar soil properties to the improved soil. The bender elements system allows measurement of very small strain stiffness modulus, G_{max}, by measuring the velocity of shear wave transmission through a test specimen as described by Hooker (2002) and Clayton (2011). The bender element uses a piezoelectric strip as a transmitter and receiver at both ends of a test specimen. The transmitter piezoelectric strip is connected to a waveform generator and recorded by a receiver piezoelectric strip via an oscilloscope. The shear wave can be used to calculate the value of G_{max}. To improve the reliability and repeatability of results, Clayton *et al.* (2004) increased the number of receivers along the side of a sample as shown in Figure 2.3, therefore measuring the coherence of the received signals via cross-correlation. This enables the signal-to-noise quality to be measured as a function of frequency, thus reliability data can be assessed.

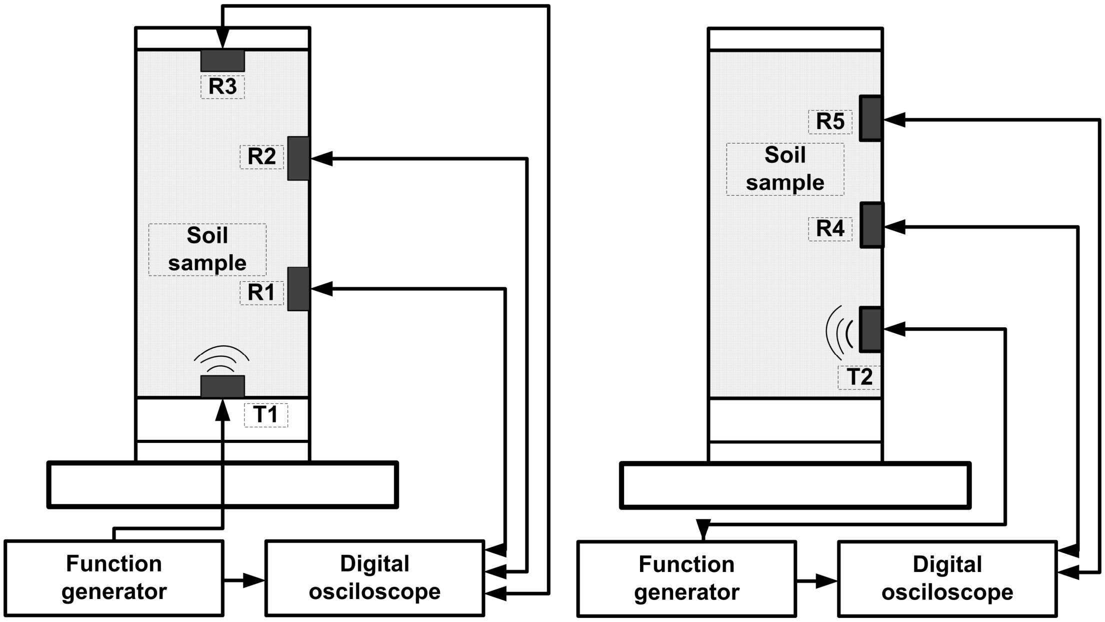

Figure 2.3: Layout of bender elements, and instrumentation, using multiple receivers to increase their reliability and repeatability (Clayton *et al.*, 2004). Note: R represents receivers and T transmitters.

The resonant column testing is similar to the bender element method and measures G_{max} for a cylindrical test specimen. One end of the test specimen is fixed and the other end is excited with a very small, sinusoidal, rotational displacement. Excitation is swept through a range of frequencies to identify the frequency at which resonance occurs. From the information about the specimen and the resonant frequency, the value of the wave propagation velocity can be derived and G_{max} calculated (Hooker, 2002).

As the stiffness modulus is a function of strain (Atkinson, 2007), the laboratory destructive tests always gives the lower bound of soil stiffness modulus compared with laboratory non-destructive tests at upper bound. This occurs due to the different strain level of measurement (see Chapter 3, Figure 3.8 and Section 3.5 for more details). In laboratory destructive tests, the unconfined compression test tends to give conservative values of soil stiffness modulus, where the stiffness modulus value is relatively small compared with the triaxial test. Meanwhile, both laboratory non-destructive tests give maximum stiffness modulus values.

2.3.2 In situ Field Tests

In situ field testing enables larger volumes of soil to be tested and so tends to be more representative of the soil mass compared with laboratory testing. In situ field tests have an advantage as samples do not need to be retrieved. For very soft clays, sands and gravels, sampling is a major problem because these materials easily change their soil structure and, as a result, produce disturbed samples. Good correlations have been produced between field tests and laboratory tests, which has led to acceptance of field techniques (Charles and Watt, 2002). For example, there was a correlation between the undrained shear strength obtained from the laboratory test on undisturbed clay samples and the cone resistance (q_c) from the cone penetration test (CPT) which was carried out in the field (Das, 2007). Of the range of in situ tests, penetration testing, dynamic probing, pressuremeter testing, field vane shear testing, plate loading testing and geophysical testing are used for quality control; with these tests being similar to those used in conventional site investigations. On occasions, some have been modified specifically for quality control testing within ground improvements begs the question what modifications. Table 2.1 summarises the field tests used for evaluating stabilised soils (Hosoya *et al.*, 1996).

The selection of the types of quality control tests to be used is highly dependent on the cost and effectiveness of testing (Clayton *et al.,* 1995; Charles and Watts, 2002). Comparison between laboratory and in situ field test results by Bowles (1996) indicated that the soil stiffness modulus, which was measured in the in situ field test, was found to be 4 to 13 times greater than that obtained from the unconfined compression test and about 1 to 1.5 times that obtained from the triaxial undrained test. Some field quality control tests are considered as destructive tests, which involve preliminary works such as drilling or inserting instruments into the ground. The results from the field tests can be empirically correlated with the parameters, which control mass behaviour (BSI, 2005). For example, pressuremeter test results and penetration resistances are indicators of density. These empirical correlation relationships can be used to estimate other parameters such as shear strength, compressibility and stiffness (Mitchell and Jardine, 2002). A field vane shear test can be used for clayey soil, which directly measures the shear strength of the soil.

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