COMPARATIVE PERFORMANCE OF LOOSE SANDY SOILS IMPROVED BY DEEP COMPACTION TECHNIQUES

by

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μ	Speed factor of cable drop
α	Soil structure factor
$\rho_{d(field)}$	Achieved dry density in the field (kN/m^3)
$\rho_{d(maximum)}$	Maximum dry density (kN/m^3)
σ_v	Vertical stress
σ'_v	Effective Overburden vertical stress
BSN	Brown Suitability Number
CIRIA	Construction Industry Research and Information Association, UK
CPT	Cone Penetration Test
C_u	Coefficient of Uniformity
D	Depth of improvement
D_{10}	Effective diameter
D_{50}	Mean diameter
D_{60}	Diameter of soil passing 60 % in grading curve
DC	Dynamic compaction
DC 1	Dynamic compaction sampling point 1
DC 2	Dynamic compaction sampling point 2
DC 3	Dynamic compaction sampling point 3
DC 4	Dynamic compaction sampling point 4
DC 5	Dynamic compaction sampling point 5
DC 6	Dynamic compaction sampling point 6
DC A	Dynamic compaction verification point

e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
F	Fine content
F_w	Total fine quantity loss during wet sieving in percentage
F_d	Total fine quantity in the pan after dry sieving in percentage
G	Weight of pounder
G_c	Soil shear modulus
H	Height of pounder drop
I	Normalised improvement
i	Improvement
IRTP	International Reference Test Procedure
ISSMFE	International Society of Soil Mechanics and Foundation Engineering
m_1	Mass of empty container (g)
m_2	Mass of the container and wet soil (g)
m_3	Mass of container and dry soil (g)
Pre-CPT	Cone Penetration Test before soil treatment
Post-CPT	Cone Penetration Test after soil treatment
Q	Normalised initial cone resistance
qc	Cone resistance
q_i	Initial cone resistance
q_f	Final cone resistance
R (%)	Relative compaction in percentage
RD	Relative Density
SPT	Standard Penetration Test

SP	Poorly graded SAND
SW	Well graded SAND
VC	Vibro-compaction
VC 1	Vibro-compaction sampling point 1
VC 2	Vibro-compaction sampling point 2
VC 3	Vibro-compaction sampling point 3
VC 4	Vibro-compaction sampling point 4
VC 5	Vibro-compaction sampling point 5
VC A	Vibro-compaction verification point
w	Moisture content
W	Weight of pounder

PERBANDINGAN PRESTASI TANAH PASIR LONGGAR HASIL PEMBAIKAN OLEH TEKNIK PEMADATAN DALAM

ABSTRAK

Objektif penyelidikan ini adalah untuk mengkaji kesan penambaikan keatas tanah pasir longgar dengan kehadiran kandungan tanah halus, menilai dan membandingkan keberkesanan kaedah pemadatan dinamik dan pemadatan getaran, menyediakan model separa empirik yang bersesuaian dan akhirnya mencadangkan suatu carta perbandingan prestasi bagi memilih kaedah yang memberikan peningkatan rintangan tanah yang terbaik. Kajian telah dijalankan di Kerteh, Terengganu. Berdasarkan pembaikan yang dijalankan, adalah didapati peningkatan rintangan tanah adalah berbeza antara kedua-dua teknik. Sampel tanah selanjutnya telah diambil menggunakan tiub pensampelan yang dibuat khas, dan ujian ayakan basah telah dijalankan di makmal bagi menentukan perbezaan jumlah kandungan tanah halus. Model kemudiannya dibangunkan bagi menentukan kehubungan antara penambaikan dan rintangan tanah. Kehubungan model kuasa tiga didapati adalah terbaik untuk kedua-dua kaedah pemadatan dinamik dan pemadatan getaran. Model–model ini membolehkan penggunaan nilai rintangan tanah secara terus bagi menilai pembaikan kaedah pemadatan dalaman dengan mengambil kira kandungan tanah halus. Model-model ini kemudian digunakan untuk menyediakan suatu carta perbandingan yang dapat membantu jurutera di dalam merekabentuk teknik pemadatan.

COMPARATIVE PERFORMANCE OF LOOSE SANDY SOILS IMPROVED BY DEEP COMPACTION TECHNIQUES

ABSTRACT

The objectives of the study were to determine the effect of fine content on the improvement of cohesionless loose sandy soils, to evaluate and compare the effectiveness of the dynamic compaction and vibro-compaction techniques, to provide suitable semi empirical models on improvement and finally to propose a suitable comparative performance chart that can help select the technique that provided higher improvement. The research was conducted at study sites in Kerteh, Terengganu. Based on improvements made, it was found that the increase in soil resistances after completion of treatment differs between the two techniques. Extensive soil samples were then collected using specially fabricated sampling tube, and wet sieve grading analyses on the soils were performed in the laboratory to determine the difference in fine content. Models were then developed to determine the relations between improvement against soil resistance. Cubic semi-empirical models were found to be the best models for both dynamic compaction and vibro-compaction. The models allowed direct usage of the cone resistance to evaluate the performance of the deep compaction technique incorporating the effect of fine content. The models were then used to produce a suitable comparison chart that can assist engineers in designing the compaction techniques.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Malaysia is a dynamic developing country continuously absorbing and adopting new knowledge and skill to propel itself along the path towards its 2020 vision. Over the decades after independence, much effort has been devoted to develop and enhance various infrastructures, most significantly in the development of land for roads, bridges, highways and buildings.

The advancement in the construction industry has opened up opportunities to research and improved existing knowledge and fine tune several aspects of construction practices.

Soil treatments, for instances, had been used 3000 years ago for the construction of temples by the Babylonian (Van Impe, 1989). In the past decades, they have gathered widespread acceptance in the global geotechnical community. Conventional practice had been either to perform removal and replacement of unsuitable soils such as soft soils, or bypass them with expensive pile foundations. However due to their success in obtaining significant engineering property improvements, as well as the economic benefits of their usage, soil treatment is now common in engineering projects where poor or unstable soils are encountered.

Numerous people have conducted studies to delve into ways and techniques to treat soils. Bell (1992) has listed some of the more popular soil treatment techniques. They include:

i) Deep compaction techniques such as vibro-compaction, vibro-replacement and dynamic compaction.

ii) Freezing techniques such as the use of freon/brine refrigeration and cryogenic liquids.

iii) Drainage techniques such as the use of filter drains, sand drains and lime columns.

iv) Ground lowering techniques such as sump pumping, deep bored filter wells with submersible pumps and vacuum dewatering.

v) Electro-osmosis and electro-chemical stabilization.

vi) Exclusion techniques such as sheet piling, slurry trenches and diaphragm walls.

vii) Reinforcement techniques such as reinforced earth and soil nailing.

viii) Grouting techniques such as cement-clay grouts, resin grouts and compaction grouting.

ix) Soil stabilization techniques such as cement and lime stabilization.

Among those above list, the two most widely used methods of soil treatment for loose sandy soils are vibro-compaction and dynamic compaction (tamping). These two methods are also part of deep compaction techniques.

Assuredly these techniques have gained popularity due to the availability of more powerful equipments such as vibrators and cranes, and also more accurate and reliable field soil investigation equipment such as Cone Penetration Test (CPT). With the highly increasing awareness and concern on the part of the public and government on the detrimental impact of liquefaction of loose sand on foundations due to dynamic loading such as earthquake there has been an increase in the popularity of usage of these techniques.

Loose sands are sandy soils having shear strength of less than 100 kPa (Whitlow, 1997). In Malaysia, developments are also now proceeding to areas of soft soils (Ting et al, 1988). Kuantan-Kerteh railway system and petrochemical plants in the district of Kemaman, Terengganu are examples where developments have proceeded to loose sandy soils area. These places, being rich in natural resources and rapidly growing in development, naturally requires special look into such as the one being conducted in this study.

Report such as in Figure 1.1 relating technical difficulties in constructing a road in Kemaman district, is now common in Malaysia. The project was a road project that took nine years to complete due to weak soil present in the area.

Is it really fair to blame just the consultant as being the culprit in this case? Consultants, at best work with the latest available technology in any construction work, which not necessarily is the best way to do the job. That is why problems occur and thus consequently more research is required to clearly identify the problems and come up with solutions.

Consultant blamed for road work woes

By Rosli Zakaria

KEMAMAN, Tues. — The Finance Ministry has been urged to blacklist a civil and structural consultant involved in the construction of a 21.4km road linking Kampung Mak Lagam, Lubuk Batu and Bandar Cheneh Baru.

Central Terengganu Development Authority made the request following the failure of the Selangor-based consultant firm, Bina Runding Sdn Bhd, to identify technical problems that would be faced by the contractor for the project.

As a result, the cost of constructing the road had escalated more than three-fold from RM21.9 million to RM73.9 million, while a new alignment had to be made because the earlier proposal did not take floods into account.

As a result, the length of the road using the new alignment had to be extended by about one kilometre.

TENGKU PUTERA
... three extensions

In addition, the contractor had to incur higher costs resulting from additional excavation work and landfill and build two bridges.

State Infrastructure and Public Facilities Development Committee chairman Tengku Putera Tengku Awang said with all the problems, the project, which started in 1991, had been delayed for more than five years. The project was scheduled to be completed in February 1994.

"It is not the contractor's fault. The design for the road has been bogged down by too many technical problems which should have been identified earlier by the consultant," he said after visiting the road project site.

He was earlier briefed by Ketengah Public Works Department unit head Yong Ah Wa and the managing director of Sri Minal Construction Siaw Teck Hwa at the project site.

"The failure of the consultant to identify the technical problems, especially the soil tests, and propose ways to overcome them had delayed the project, which is an important catalyst for growth in the area."

Tengku Putera said the contractor had been given three extensions, the first ended in May 1995, second in March this year and the third is October next year.

He said the contractor was also forced to delay the project for a year in 1993 because it did not get the approval from Petronas to build the road across its gas pipeline.

"This problem had been solved by laying concrete slabs over the section of the pipeline affected by the road construction."

Tengku Putera said about 75 per cent of the road had to be build over a peat swamp area and the contractor had to excavate more than 10 metres to lay the foundation.

"To solve this problem the contractor had sought the advice of the Malaysian Public Works Institute which proposed the use of geotextile materials."

Figure 1.1: Soft soil problem in Kemaman district, Terengganu. (NST, anon)

Loose sand has been proven to be detrimental to in construction of roads, railway tracks and buildings because they can experience large settlements and also liquefy under dynamic loading. In areas where there are thick loose sands, special technique is required to treat and stabilize the ground before further construction can proceed over it. With the frequent earthquakes in the Asian region in recent years, the need for densification of loose sand is extremely important to prevent damage to structures constructed at the loose sandy beach areas. Mitchell (1995) has published one of the most widely referred publication reporting success of soil densification techniques such as vibro-compaction and dynamic compaction in mitigating the effect of earthquakes relating experiences in Japan. Further research in these techniques is surely needed to help us improve our understanding on the technique and its applicability.

Admittedly, the use of surface compaction to densify thick layers of loose sandy soils is not suitable. This is because densification to the required depths cannot be achieved through mere surface compaction. Alternatively pile embankment could be constructed (Plate 1.1) to bypass the weak soil and found the development on the firm strata below the ground.

Typically in Malaysia 250 mm to 300 mm diameter piles at 2 m center to center were driven to achieve the required embedded length. A large pile cap would then be constructed to transmit loadings to the piles. Due to many activities and large material quantities involved, piled embankment is a very expensive alternative. Thus ground treatment such as deep compaction is an attractive and viable construction technique as opposed to surface compaction and deep piled embankment foundation.

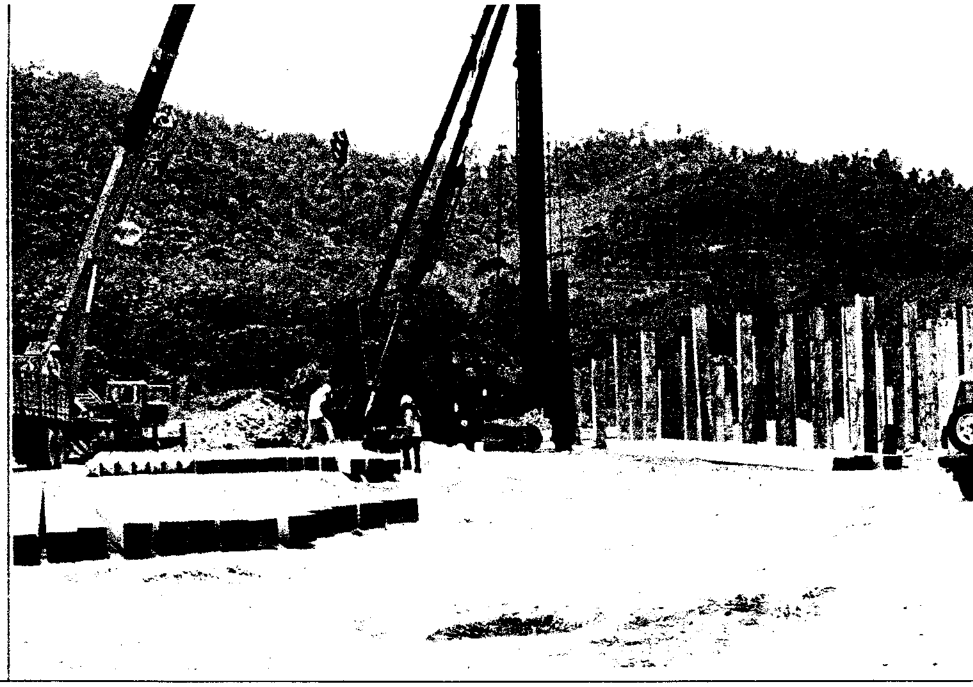

Plate 1.1: Piled embankment under construction

1.2 Definitions

The following definitions are critical for the understanding of this study:

i) Compaction

According to Whitlow (1997), compaction is the process of bringing about an increase in soil density, with a consequent reduction of air-voids volume, but no change in volume of water. It is affected by mechanical means such as by tamping or vibrating. Further the effectiveness of compaction depends on several factors:

i) The nature and type of soil (i.e. sand or clay; uniform or well graded; plastic or non plastic). This is reflected in grain size distribution, shape of soils grain, amount of fine soil and type of clay minerals present.

ii) The water content at the time of placing of soil. This is because maximum dry density of soil can only be achieved at the optimum moisture content.

iii) The maximum possible state of compaction possible for the soil. Different soil will produce different compaction curve and thus different maximum dry density and optimum moisture content.

iv) The maximum amount of compaction possible under field conditions. Higher compaction energy able to be transmitted will result in higher density of the soil. This will result in higher compaction degree of the soil.

v) The type of compaction machinery being used. Suitability of compactors has to be ascertained before employing the compactor as it influenced the efficiency and degree of compaction to be achieved.

CIRIA C572 (2002) has defined compaction as the process in which densification of the ground is achieved by mechanical means such as rolling, ramming or vibrating.

ii) Deep Compaction

In areas where thick loose sandy soil is prevalent, deep compaction techniques are attractive choices. Deep compaction technique refers to the in-situ deep densification of loose sandy soils using methods such as blasting, vibro-compaction and dynamic compaction (Mitchell, 1981). According to Charles (2002), the in situ densification performed as a ground improvement technique due to:

i) Increased in the density of the soils also results in improvement in stiffness and strength.

ii) Hazards on untreated ground are associated with volumetric compression of the ground. Thus in situ densification actually introduced the hazard for the volumetric compression to occur before construction on the site take place.

iii) Soils are generally inelastic and will remain densified after treatment.

Deep compaction is performed to improve the strength and deformation characteristics of sandy soils to such a degree, that structures can be supported safely and economically on or below the improved ground surface (Massarsch, 2001). The most common applications of these techniques are for improvement of reclaimed land and the mitigation of liquefaction risk in the seismic areas (Van Impe et al, 1985);(Chan, 1986); (Raju, 1998); (Philips, 2002). In these techniques, sandy soils are compacted by effecting energy for densification to the required depth.

This study focused on dynamic compaction and vibro-compaction. Vibro-compaction is also called vibro-flotation.

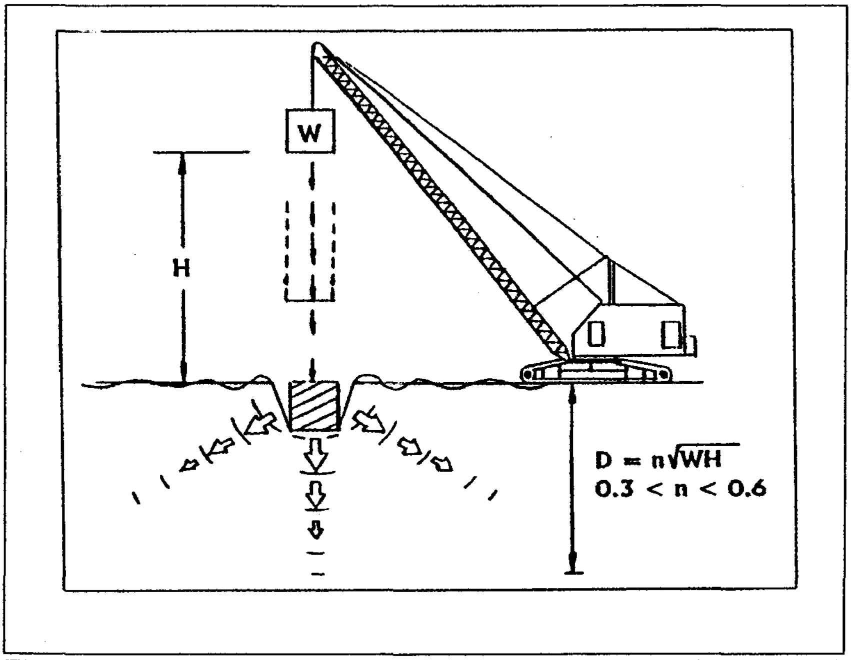

Figure 1.2: Dynamic compaction technique (Lukas, 1986)

Dynamic Compaction technique requires tamping of the ground with pounder that is dropped from height to compact the soft soils at the required depths. Varaksin (1990) has reported the success of dynamic compaction down to depth of 15 m.

Vibro-compaction on the other hand is a vibratory technique. In this technique, a vibrator is inserted into the ground to compact the loose sandy soils at the required depths. The holes created due to the vibrations of the ground are filled with selected sand fill material. The sandy soil then is better able to support proposed development on top of it. Slocombe et al (2000c) reported that vibro-compaction has successfully been used to densify soil to depths down to 56 m.

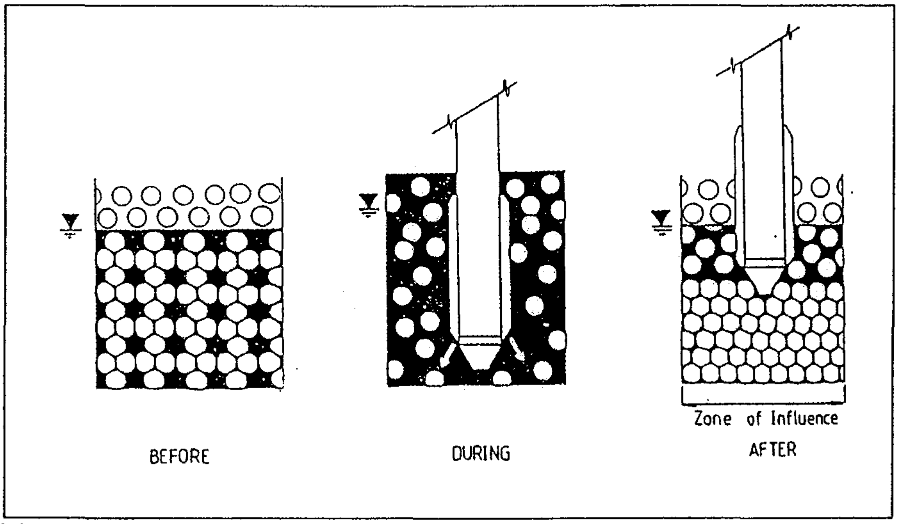

Figure 1.3: Vibro-compaction technique (Bergado et al, 1996)

According to Bergado et al (1996) deep compaction is achieved by transmitting vibration energy into the subsoil with the objectives of reducing of total and differential settlement, increasing shear strength and resistance to earthquake, and reducing the foundation cost.

Further, Bergado (1996) stated that the parameters influencing deep compaction include type of soil, backfill material, site location, construction equipment and construction procedure. In this study, backfill material, site location, construction equipment and construction procedure were controlled parameters and maintained throughout the study so that the focus could be on the in situ soil type.

iii) Fine Content

Sieve analysis is a standard test of soil for civil engineering purpose. This test involves the sieving of sampled soil through various sieve sizes. British Standard BS 1377: 1990 specifies fine soil as soils with more than thirty five percent of the material having sizes smaller than 0.06 mm after through going through sieve analysis. These cover soils such as silts, clays and, gravelly or sandy silts and clays.

Unified Soil Classification System specifies fine grained as soils having fifty percent or more passing through No. 200 sieve (Das, 1999). These cover such soils as silts and clays.

Based on the above definitions, fine content is thus defined as the percentage of fine soil such as silts and clays present in the soil. This can be obtained by measuring the percentage of soil that passes the No. 200 or the 0.06 mm sieve (67 μm sieve).

1.3 Objectives of Study

The focus of this study is on the dynamic compaction and vibro-compaction techniques. Consequently the objectives of this study are:

i) To determine the effect of fine content on the improvement of cohesionless loose sandy soils Cone Penetration Test (CPT) results.

ii) To evaluate and compare the performance of the dynamic compaction and vibro-compaction techniques.

iii) To provide suitable semi empirical models to describe the effect of fine content on improvement.

vi) To propose a suitable correlation chart to select the technique that provided higher improvement.

1.4 Rational of Study

Early application of deep compaction ground improvement techniques dated back to the days of the Babylonians and Ancient Egyptians. The subject was considered a novelty in the 1960's when it became part of geotechnical engineering (Munfakh, 2002). Advances made in deep compaction technique have generally resulted from the initiative and imagination of contractors (Kramer, 1996). Charles (2002) also concluded that ground treatment such as deep compaction technique has not received sufficient attention in the past from geotechnical engineers. This results in slow acceptance of the deep compaction techniques in engineering fraternity. The slow acceptance results in the techniques being suited to mega infrastructure projects and not common techniques that are cost effective and efficient.

In addition, the widespread acceptance and application of the deep compaction techniques was also delayed by:

i) Lack of unbiased literature which detailed objectively the advantages and disadvantages of the techniques (Dhir, 1988). This is the result of innovation and advancement of the techniques which has been led by contractors. What has happened was that the publications available on the techniques were more focused on the successes achieved. No doubt it is because of the difference in objectives between the contractors and the other parties

ii) As the innovations were being led by contractors, proven theories on the mechanics of the techniques have yet to be developed and accepted (Kramer, 1996). This resulted in successes of the techniques were continuously questioned. An example of this is the improvement made by vibro-compaction technique in loose sandy soils with higher fine content.

iii) Lack of understanding on improvement made to the loose sandy soils after the performance of the techniques. As a result of this lack of understanding, stringent pre and post-testing were required to verify the improvement made by the techniques. For example was the improvement of cone resistance results at the weak soils area between the sand columns. The issue raised was whether dissipation of pore water pressure occurs within the construction time to allow for strength gain in the soil. Failure of this understanding has resulted in mushrooming effect that could be seen on the earthwork embankment supported by the treated soil. This has resulted in unnecessary maintenance cost to be incurred.

iv) Massarsch et al (2002) has put the blame on the lack of financial resources to research on the soil treatment area due to the costly nature of the work. Large funds are needed to study the various impact and parameters affecting the actual construction work.

v) No direct comparison has been made between the techniques to assist the selection of the more suitable technique.

vi) Knowledge of ground improvement failure even though not published was well known within the construction industry. This created a need for research to be conducted in the country to assess the suitability and effectiveness of the technique.

Bad experience in the implementation of the deep compaction techniques has also slowed the acceptance of the infrastructure developers to undertake the techniques. Plate 1.2 shows a deep compaction failure site along the north-south highway where the uneven pavement surface could be clearly seen. Improvements only occur at the treatment points whereas area between the points only improves later during the operation of the highway. This results in settlement between the treatment points.

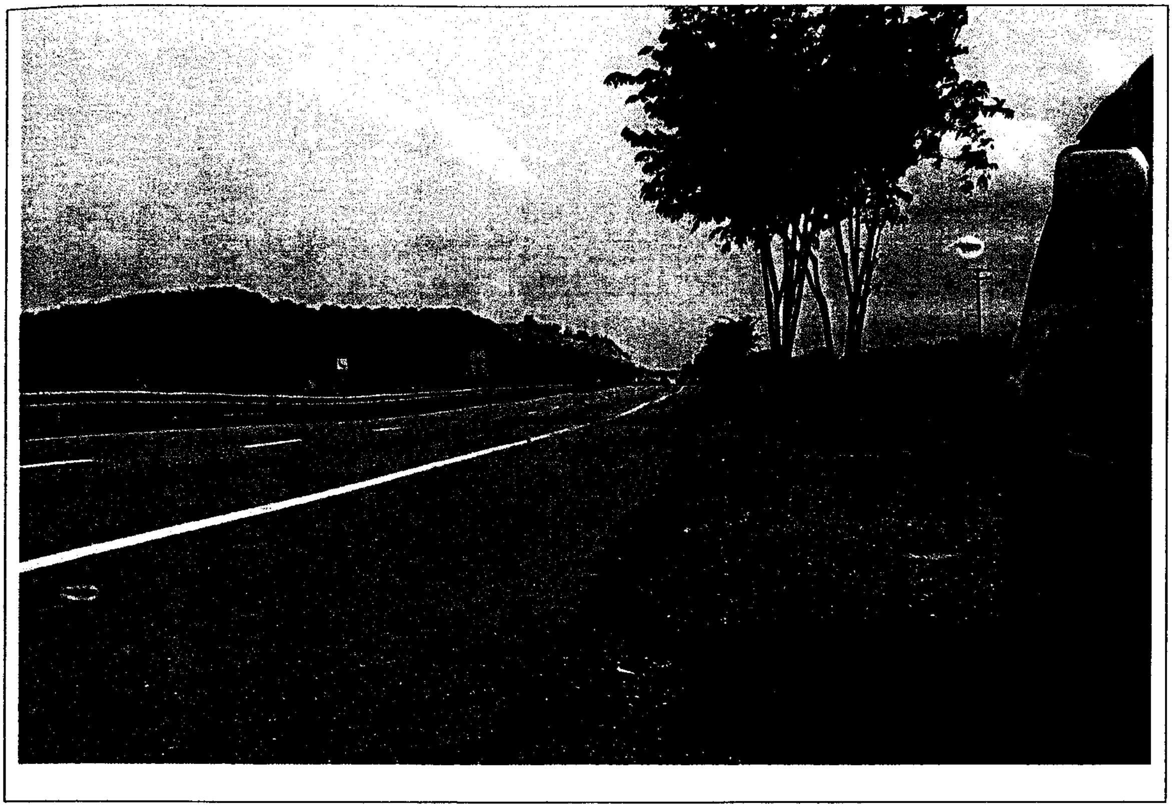

Plate 1.2: Uneven pavement surface at a stretch along north-south highway near km 70 due to failure in ground improvement work.

Finally, in practice, the final decision of the technique to be performed depended on the lowest cost quoted by contractors to achieve the performance specification tendered. For example, in an open bid tender, performance specification is typically provided in the contract with a suggested deep compaction technique based on suitability of the soil in the area. Bidding will come from contractors proposing various techniques to improve the ground meeting the specification. The experienced contractor submitting any suitable technique with the lowest cost will be accepted. This reflects lack of confidence in specifying and judging between the techniques by the engineer and has resulted in negative image for the techniques and the engineering profession. Clients are at the mercy of the contracting strategy of contractors bidding for the work. This is especially true considering that as deep compaction work is part of earthwork activity in a tender document, and typically a re-measured item, the cost implication of this is significant.

Because of slow acceptance and negative experience faced, there was a need for a study to take place for a better understanding on the deep compaction techniques. To geotechnical engineering fraternity, the improvement behaviour of loose sandy soils after performing of the techniques needed to be understood. This will assist Malaysian engineers in selecting the technique that can provide the most beneficial improvement in bearing capacity among the deep compaction techniques. This is also in line with recommendation by Professor Balasubramiam in his Professor Chin Fung Kee 2002 Memorial lecture when he emphasized the need for study to be conducted on South East Asian countries in field behaviour of tropical soils.

1.5 Significance of the Study

In this study, large amount of data has been utilized. The cost impact was substantial. The opportunity to conduct this type of study was rare and the contribution will assist Malaysian engineers in the selection and performance of dynamic compaction and vibro-compaction work.

The study will provide a better understanding on the improvement behaviour in cohesionless soil, after the performance of vibro-compaction and dynamic compaction techniques.

The selection of deep compaction technique is still based on Mitchell (1970). As in Figure 1.4, the chart only provides suitability of the technique with ranges of soil particle sizes. In the chart, there are overlapping techniques. The chart did not provide indication of the effectiveness or efficiency of the technique. As such the technique that can give the best improvement and economy cannot be selected.

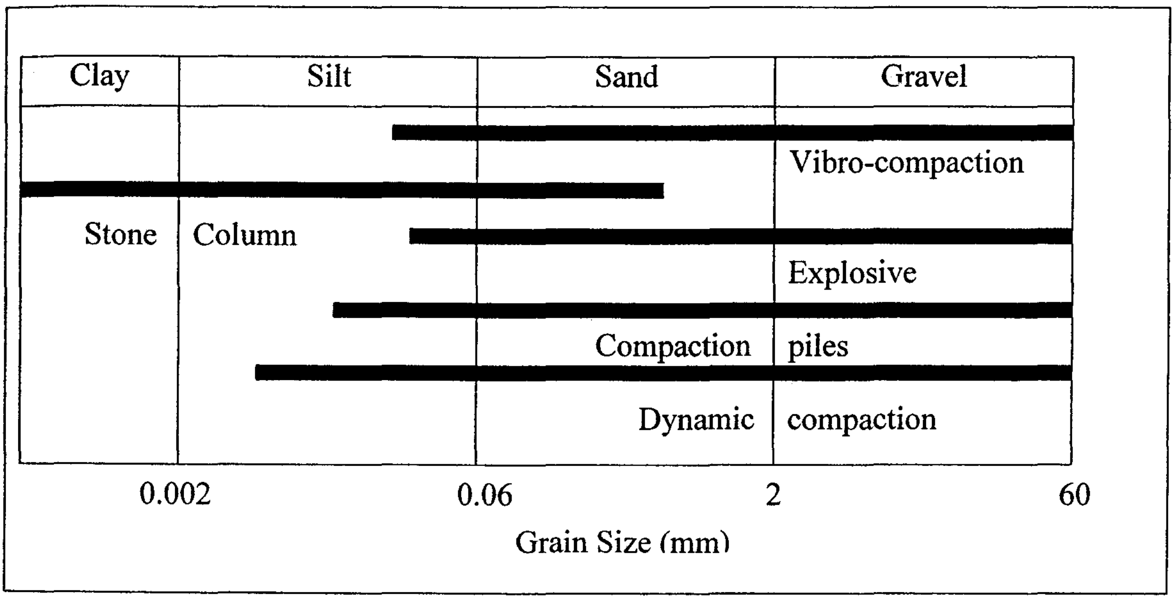

Figure 1.4: Selection of deep compaction technique (Mitchell, 1970)

This study provides an analysis of the effectiveness of deep compaction techniques on Malaysian soil. It will become a significant reference in selection of the techniques for future work in Malaysian.

Globally, research till date has focused on the improvement to dredging sand fill in reclamation work and to an extend also on the improvement of bearing capacity of fill material such as ash fill and landfill (Yee et al., 2004). Reclamation work possesses a different situation as compared to beach sand. Sand placed by hydraulic means for reclamation work, leads to segregation of the coarser and finer particles (Covil et al , 1997). This coarser sand is called clean sand and they have minimum fine content, if any. Thus according to Cao et al (1998), the influence of fine content on the improvement of the deep compaction techniques has not been investigated. So, the choice of research relating to the fine content is indeed a welcomed contribution to the engineering and construction industry.

The importance of considering fine content was summed up by Massarsch et al (2002) when he said that in the selection of deep compaction technique, the assessment of compatibility of technique has been based on quality test such as Cone Penetration Test (CPT) results because of high cost incurred in finding soil fine content to determine the suitability of the techniques. Without doubt, cost has been the main obstacle for a study on the effect of fine content to be conducted. Costs involved are soil boring, sampling and finally laboratory work itself.

1.6 Summary of Chapters in the Thesis

The thesis has been divided into seven chapters. In Chapter One, the definition of deep compaction technique and objectives of the study are provided. This is to allow for clear understanding on the subject and also the need of this study.

Chapter Two presents selective literature review on deep compaction techniques. Initially the selection process is reviewed. Then the mechanics of the deep compaction techniques are described. After that current knowledge on the effects of fine content for each technique are discussed. Finally an overview of Cone Penetration Testing is provided. In particular the effect of depth or effective vertical stress, on cone resistance is studied. Summary of this chapter discusses the limitation of existing knowledge on selection of ground improvement technique and further emphasis the need to study the effect of fine content.

Chapter Three is titled Methodology and limitations, Sampling and Laboratory Test. It describes the study methodology, soil sampling and laboratory study. Major issues such as rational of the study, limitation of the study and site variability are also discussed. The summary for this chapter also describes the challenges faced in undertaking the soil sampling and laboratory study.

In Chapter Four, construction techniques and quality testing performed for assessment of the techniques are described. In addition the chapter discusses the field constraints and mitigation measures for the field work.

Chapter Five presents the results and discussions of all the cone penetration, site measurement and laboratory test part of the study. This includes pre-CPT, post-CPT, unit weights, fine content and moisture contents.

In Chapter Six, Model Development, the models for the study are developed. The improvement of cone resistances is the main focus. Comparisons are then made between the techniques, having considered the amount of fine content, to gauge increase in cone resistances of loose sandy soils after performance of the different techniques. Based on the comparison of improvement made, a correlation chart guide is proposed to assist the selection of the more suitable technique. The guide is the end product of the research.

Chapter Seven consisted of conclusions and recommendations for further work. Finally, appendices are made available and it includes photographs of site activities and laboratory activities, and raw data from the study.

CHAPTER TWO

REVIEW OF SELECTED DEEP COMPACTION TECHNIQUES

2.1 Introduction

Bergado et al (1996) defined deep compaction as the process of the reducing the compressibility and increasing the strength of soil by packing soil particles together with high energy. No cohesion is however added to the soil.

Due to the limited choice available in selecting sites for infrastructure development, the need to utilize poor soils for foundation and earthwork construction cannot be avoided.

Thus loose sandy soils deposits are to be compacted to eliminate the subsequent excessive settlements and to minimize the possibility of liquefaction under dynamic loading. Example of a dynamic loading is the earthquake. Earthquake causes liquefaction.

Liquefaction is a phenomenon where the strength of the saturated soil is reduced to the point where it cannot support structures or remain stable and appeared to flow as fluid (Kramer, 1996). Here, the value of total overburden stress is equal to pore water pressure.

Plate 2.1 shows a picture of an earthquake hit airport in Seattle, where the effect of sand flowing or sand boiling after liquefaction could be clearly seen.

Plate 2.1: The runway at King County Airport, after an earthquake (Seattletimes, 2001)

The improvement can be done through compaction processes. With the introduction of larger and more powerful machinery, the quantity of compaction work on loose sandy soils becomes better over the years and the amount of work that could be undertaken has also increased.

Soil has three phases that is solid, liquid and gas. Liquid and gas filled up the void within soil. By undertaking a compaction process the soil particles will be packed closer together due to a reduction in the volume of the void space (Bell, 1992). The process results in improvement in soil properties such as reduction of void ratio, increase in bearing capacity of soils and reduction in settlement potential.

The main objectives of deep compaction are:

i) To reduce the void ratio and thus the permeability of the soil. Soil has three phases which can be represented by volume of air, water and solid. Volume of void is represented by volume of air and volume of water. Compaction causes reduction in air volume. This ultimately reduce air void ratio of the soil. This results in the reduction of void spaces available for flow of liquid through the soil and thus the permeability of the soil is reduced.

ii) To increase the shear strength and thus the bearing capacity of the soil. Compaction increases the density of the soil. This results in the soil being able to take higher load and this consequently increases the shear strength of the soil.

iii) To reduce susceptibility to volume changes and thus settlement under load. The reduction of void volume due to compaction effectively reduces the potential for volume change and thus the settlement under load.

For deep compaction techniques, the water level during compaction dictates the likely water content in the soil. During construction it becomes important to ensure that water table remains as planned or corrective actions are required to be undertaken.

Then, consideration of depths is also important as Cone Penetration Test (CPT) will be used to determine the increase in bearing capacity at depths due to the compaction. This is due to the higher effective overburden stress being subjected to deeper soils by the soil on top of it.

This study covered the use of two different equipments namely vibrator probe for vibro-compaction and weight or pounder for dynamic compaction. Some of their reported performance is shown in Table 2.1.

Table 2.1: Performance of selected deep compaction technique (After Mitchell, 1995)

Treatment Method	Treatment details	Post Treatment soil Properties	Response of treated ground	Response of untreated ground
Vibro-compaction	More than 1000 probes spaced 2.4 m, extending 6 m beyond perimeter of tower structure, using gravel as backfill.	Based on SPT; D_R>100%, where D_R is relative density of the soil.	No ground settlement observed for the 30 storey tower.	Not available.
Dynamic compaction	Applied energy of 4524 and 5254 kNm/m^2, over an area of 27 m and length of approximately 1.2 km.	Average CPT resistances were 1kN/cm^2, except in some areas where lenses of fine soils were found.	No evidence of liquefaction due to an earthquake	Extensive liquefaction detected after an earthquake (large sand boils and sink holes).

Where;

D_R is the relative density

CPT is cone penetration test

SPT is the standard penetration test

The post treatment test results and the responses of treated ground under dynamic loading and structural loading had shown that the soil had an improved settlement and shear strength characteristics for the dynamic compaction site and vibro-compaction sites. Regional successes for the vibro-compaction technique includes the increase of relative density to 70 % at the 500000 square meter runaway and taxiaway at Changi airport, Singapore as reported by Raju (1998) and in increase to 70 % relative density below the crude oil pipeline on Jurong island, Singapore as reported by Wehr et al (2002).

For dynamic compaction, success has also been reported by Philips (2002) on compacting loose Sabkha sand deposits for airports and runaways in Dubai International Airport to an increased required density.

According to CIRIA C572 (2002) apart from capable of significantly densifying loose granular deposits, deep compaction techniques had also been shown to reduce compressibility of fill as much as fifty percent of its original value.

2.2 Selection of Deep Compaction Techniques

Several researchers had conducted work on identifying scientific technique of selecting deep compaction techniques. The earliest available scientific technique of selecting the deep compaction techniques was proposed by D'Appolonia (1953).