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Research Paper

Research oriented ground improvement projects in Changi, Singapore

M. W. Bo[1], A. Arulrajah [2], V. Choa[3] and S. Horpibulsuk[4]

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ABSTRACT

The Changi East Reclamation projects in Singapore were implemented under 5 Phases commencing from 1991 and completed in 2005 with one phase to another has several of years of overlapping. The total implementation period was 15 years including maintenance. The Phases are named as Phase 1A, 1B, 1C, Area A (North) and Area A (South). Each Phase took about 5 to 6 years to implement. Due to the involvement of large area fills in the form of land reclamation with as thick as nearly 20 meters of hydraulic fills over up to 40 meters thickness of compressible marine clay, significant challenges were present to the geotechnical engineers on geotechnical issues such as slope stability, consolidation settlement and liquefaction potential. Due to the excessive magnitude of settlement likely to occur over a long period of duration caused by consolidation process, extensively large area was required to improve applying ground improvement methods to accelerate the consolidation process. Therefore, a good design of accelerating consolidation process by applying ground improvement method was deemed necessary. Many combinations of pilot tests were implemented to verify the design of ground improvement works. In addition to improving the underlying soils, improvement was also required for the fills which were loosely deposited by means of hydraulic filling techniques. In order to be able to successfully implement these complex projects, applying the most up to date state of the art technologies, implementation of research level planning, investigation, design and implementation processes were required throughout the projects from master planning stage to commissioning stage. Several forms of performance monitoring using geotechnical instrumentation, verification of achieving specified improvement using intermediate and post improvement ground investigation and in-situ testing were implemented during and acceptance of ground improvement works. Quality control and assurance tests of material delivered and used for ground improvement were carried out throughout the implementation process. This paper presents how research oriented ground improvement projects were implemented in the past decade in Singapore.

[1] President and CEO, Bo & Associates Ltd, Mississauga, Ontario, CANADA, mwbo@boandasociates.ca
[2] Professor, Department of Civil and Construction Engineering, Swinburne University of Technology, Hawthorn, Victoria 3122, AUSTRALIA, aarulrajah@swin.edu.au
[3] Professional Fellow, College of Engineering, Nanyang Technological University, SINGAPORE
[4] Corresponding author, Professor and Chair of School of Civil Engineering and Director of Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima 30000, THAILAND, suksun@g.sut.ac.th
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1. Introduction

The Changi East Reclamation projects in Singapore were implemented in 5 phases commencing from 1991 and completed in 2005. Each of these overlapping phases lasted for up to 5 years. The total implementation period was 15 years including the maintenance period. The Phases were named as Phase 1A, 1B, 1C, Area A (North) and Area A (South). The project area is shown in **Fig. 1**. Details of Phases are shown in **Table 1**. Due to the involvement of large areal fill in the form of land reclamation with up to 20 meters thickness of hydraulic fills over 40 meters thickness of compressible marine clay, significant challenges were posed to the geotechnical engineers on issues such as slope stability, consolidation settlement and liquefaction potential.

Due to the excessive magnitude of settlement likely to occur over a long period of duration caused by the consolidation process, an extensively large area was required to be improved using ground improvement techniques to accelerate the consolidation process.

In addition to the improvement of the underlying soils, improvement was also required for the land reclamation fills, which were loosely deposited by means of hydraulic filling techniques.

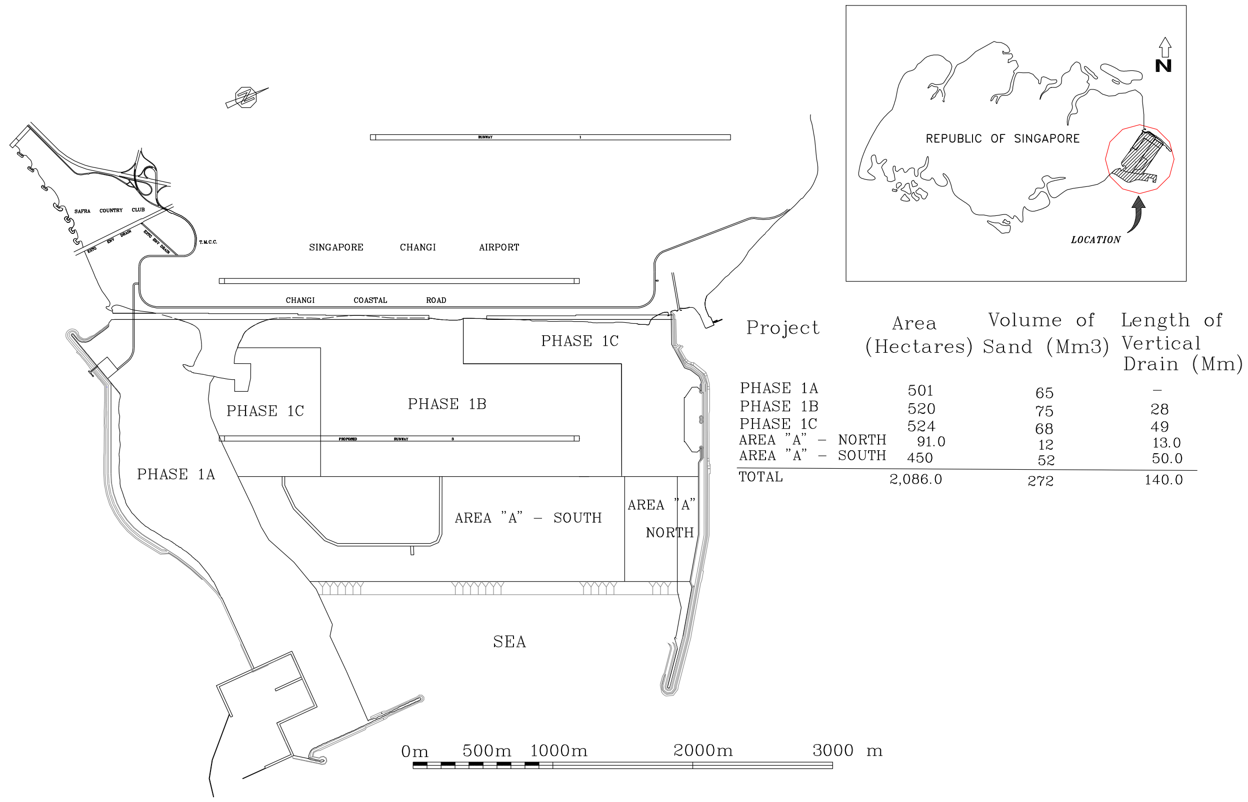
In order to be able to successfully implement these complex projects, using the latest state-of-the-art technologies, implementation of research level planning, investigation, design and implementation processes were required throughout the projects from the master planning to commissioning stages. Comprehensive ground investigations, thorough characterization of geotechnical parameters using specialized in-situ and specialized laboratory tests were implemented in these ground improvement projects to obtain design parameters required for ground improvement works. Several pilot tests were also implemented in this project. Modification of designs as well as required quality control processes were also developed using outcomes from the several pilot tests carried out before the main works. Several types of quality control and quality assurance methods, both laboratory scale and field scale procedures were adopted in this project. A comprehensive system of performance monitoring was implemented using latest geotechnical instruments and in-situ testing methods. Assessment and verification of achievements were made based on geotechnical instrument monitoring, in-situ and laboratory testing results. Many new procedures and new methods developed were documented in several published papers, reports and postgraduate research theses. This paper summarizes how the research oriented Changi East Reclamation and Ground Improvement Projects were implemented in the last decade in the Republic of Singapore.

2. Planning Stage

The need for an airport with a 4.2 km runway and associated taxiways situated outside of residential areas of Singapore was required due to environmental noise pollution and other public concerns. At the same time, limited land space in Singapore like in other Asian countries such as Japan, Hong Kong, Macao and Taiwan, required land reclamation to be undertaken. Construction of land reclamation in the foreshore area, which is underlain by a compressible soft marine clay, required large quantity of fill material including average volume loss caused by settlement of more than 2 meters due to consolidation and densification of granular fills. The entire project was planned to carry out over 15 years duration under five phases to create 3000 hectares of land. A thick layer of compressible layers is likely to cause extensively long duration of consolidation process as long as a few decades to century without ground improvement.

Table 1. Details of the Changi East Reclamation Projects.

	Phase 1 A	Phase 1B	Phase 1C	Area A (North)	Area A (South)	Total
Area (Hectares)	501	520	524	90.7	450	2085.7
Areas improved with PVD (Hectares)	-	224	400	90.7	50.4	765.1
Areas improved with Deep Compaction (Hectares)	-	114	77	-	-	191
Project duration	Jan 92-Jan97	Mar 93-Sep99	Mar96-Sep2002	Mar99-Mar2004	Feb99-Feb2005	Jan92-Feb2005



Project	Area (Hectares)	Volume of Sand (Mm3)	Length of Vertical Drain (Mm)
PHASE 1A	501	65	-
PHASE 1B	520	75	28
PHASE 1C	524	68	49
AREA "A" - NORTH	91.0	12	13.0
AREA "A" - SOUTH	450	52	50.0
TOTAL	2,086.0	272	140.0

Fig. 1. Project Area.

Therefore, comprehensive geotechnical investigations were planned to be able to design the ground improvement project to accelerate the consolidation effectively within the time frame available. The details of research orientated ground investigation approach implemented in this project was recently presented by Bo et.al (2017). Ground improvement techniques using prefabricated vertical drain and preloading was extensively applied in these projects.

In addition to the improvement of the compressible soils, loosely deposited granular fill was designed to improve using deep compaction method in order to improve the modulus of elasticity, to minimize future immediate settlement and also to minimize the liquefaction potential likely to be caused by potential future dynamic forces. Details of ground improvement for these projects are extensively described by Bo & Choa (2004) and Bo et.al (2006)

For the successful implementation of these ground improvement projects, setting up of on-site quality control laboratory, pilot tests, quality control procedures during implementation of ground improvement process, performance monitoring and procedures for assessment and verification of achieving required degree of improvement were adopted and developed the specifications to implement those procedures. Details of quality control and quality management of Prefabricated Vertical Drains (PVDs) were described by Bo et.al (2015) and performance monitoring on such projects are presented by Bo et.al (2004). Various methods developed for assessment of degree of consolidation were presented by Bo et.al (1997).

In addition to the improvement of natural compressible soils, ground improvement on ultra-soft soils contained in the foreshore containment bunds was carried out using multi-stages installation of PVD and preloading applying newly developed theory based on compressibility of ultra-soft soil developed during the implementation of these projects based on experimental and field study carried out by the project staff (Bo et al., 1999b and Bo, 2008).

3. Site Characterization

Ground Investigation was emphasized to determine the depth and top elevation of the compressible layer and their thicknesses which will affect the thicknesses of fill (magnitude of load and lengths of drainage path). The detailed characterization to determine compressibility and consolidation parameters were carried out using in-situ testing methods such as pore pressure dissipation tests, in-situ hydraulic conductivity tests and specialized laboratory tests such as various kind of consolidation tests using hydraulic Rowe cell, constant rate of loading and constant rate of strain tests were carried out both compressibility parameters as well as stress history of compressible soils were characterized in details as these parameters have a significant effect on magnitude and time rate of consolidation as well as efficiency and precision of ground improvement design applying vertical drain and preloading. The details on implementation of research oriented ground investigation projects in Changi was extensively described by Bo et.al (2017) and details on study of compressibility and consolidation characteristics of Singapore marine clay at Changi was presented in details by Chu et.al (2002) and Bo.et.al (1998a, 2016).

4. Design Stage

Design of ground improvement using PVD and preloading were carried out by applying conventional theory as well as utilizing finite element modeling. In the design process, the detailed study to determine preloading magnitude and spacing of PVD were carried out after taking into consideration of loss in preload magnitude due to settlement, submergence and other effects.

Table 2. Details of soil improvement design with PVD in Changi East Reclamation Project (after Bo et al. 2000a).

Area	Year of Design	Thickness of clay: m	Type of clay	Future land use	Design spacing sq. grid::m	Design surcharge el. mCD	Surcharge period: months	Specified acceptance criteria
A	1992	20 - 40	Marine clay	Runway	1.5	+ 10	18	90% consolidation of the fill and surcharge load
B	1992	10 - 35	Marine clay	Taxiway	1.8	+ 8.5	18	90% consolidation of the fill and surcharge load
C	1995	20 - 30	Marine clay	Infrastructure area	1.8	+ 8.5	24	90% consolidation of the fill and surcharge load
D	1995	30 - 45	Marine clay	Infrastructure area	1.8	+ 9.5	24	90% consolidation of the fill and surcharge load
E	1995	30 - 45	Marine clay	Others	1.8	+ 8.5	24	90% consolidation of the fill and surcharge load
F	1995	20 - 40	Marine clay	Roads	1.5	+ 8.5	12	90% consolidation of the fill and surcharge load
G	1998	40	Marine clay	Future material stockpile area	1.5	+12	12	90% consolidation of the fill and surcharge load
H	1998	40	Marine clay	Infrastructure	1.8	+ 10	18	90% consolidation to finished level to +5.5m CD + future load 20 kPa
I	1998	40	Marine clay	Infrastructure	1.5	+ 10	12	90% consolidation of the fill load to +5.5m CD + 20 kPa
J	1998	10 - 35	Marine clay	Infrastructure	1.8	+ 9	18	90% consolidation to finished level to +5.5m CD + 20 kPa
K	1992	10 - 20	Soft slurry	Infrastructure	2.0 3 passes	+ 9	36	90% consolidation of the fill and surcharge load

The predictions of time rate of consolidation were made by taking into consideration the submergence effect, large strain consolidation and non-linear effect, as well as efficiency of PVD in order to be able to arrive an efficiently performing drain spacing to achieve the required degree of consolidation and effective stress gain. **Table 2** gives the details of ground improvement using PVD and preloading for Changi East Reclamation and Ground Improvement Projects.

Deep compaction design was carried out based on the required improvement depths and cone resistance specified. Weights of the pounder, drop height, number of drops per pass, spacing and number of passes were designed applying empirical correlation between effective surface area and energy per square meter. Details of the design is given in **Table 3** and details of the design method can be found in Bo and Choa (2004) and Bo et al. (2014).

5. Implementation Stage

Before implementation of actual ground improvement works several pilot tests were implemented under each phase of the project. The purposes of pilot tests were not only to verify the performance of ground improvement design with PVD but also to verify the effectiveness of using particular types of installation rig, installation mandrel, types of anchors and types of PVD.

5.1 Pilot Tests

The first pilot test in Phase 1 B was conducted to verify the exhibited design spacing with a selected type of PVD (Colbond CX 1000) installed by a typical rig, which was going to be used in the main works. The details of the pilot tests are shown in **Table 4**.

It was found that all types of spacing used in the first pilot test areas with 3 different drain spacings: 1.5m, 1.7m, and 2.0m, a 90% degree of consolidation was achieved within the specified 18 months of surcharge period. Due to a favorable variation in the soil profile, the 1.7m x 1.7m spacing area settled more and faster than the 1.5m x 1.5m spacing area. The 2m by 2m area settled the least due to the occurrence of a thinner layer of compressible soil (**Fig. 2**). Details of the first test area can be found in Choa et.al (2001).

The second pilot test was carried out to study whether a drain spacing greater than 2m could be used without compromising the drain efficiency. The spacings of 2.5m and 3.0m were tested in two test plots. It was found that spacings wider than two meters were not effective and took much longer to achieve the 90% degree of consolidation. Furthermore, the performance of the PVD was also drastically reduced after two and half years of settlement. Details of the second pilot test area can be found in Bo et al. (1999a) and Choa et al., 2001.

The third pilot area was carried out under Phase 1C to check the boundary effect and as a comparative study on different types of PVD. The layout of the third pilot area is shown in **Fig. 3**. It was found that all drain types caused settlements of more or less the same magnitude and rate where boundary conditions were the same (**Fig. 4**) (Bo et al., 1999a). However, the same spacing provided different rates of settlement where boundary conditions were different as shown in **Fig. 5** (Bo et al., 1999a). Faster rates of settlement were registered near the radial drainage boundary. Several settlement plates and piezometers installed across the pilot area showed that the boundary effect extended up to 30 meters from the last row of PVD (**Fig. 6**).

Table 3. Details of dynamic compaction (after Choa et al., 2001).

Method No.	Pounder weight (t)	Drop height (m)	No. of drops per pass	Energy per drop (t)	Spacing at each pass (m x m)	No. of passes	Effective surface area (m²)	Energy per square meter (ton-m/m²)	Comp-acted depth (m)	Cone resistance achieved (MPa)
1	23	25	5	575	6 x 6	2	5.5	160	7	≅15
2	15	20	10	300	6 x 6	2	3.87	166	7	≅15
3	18	24	10	432	8.5 x 8.5	2	3.4	120	7	≅15
4	18	24	12	432	10 x 10	2	3.4	105	7	≅15

Table 4. Details of pilot areas (after Choa et al. 2001).

Area	No. of test plots	Type of tests plots spacing (m)	Type of vertical drain	Objective
1	4	(a) 1.5	Colbond CX 1000	To check the performance of vertical drain with typical installation rig and to verify soil and smear parameter
		(b) 1.7	Colbond CX 1000	
		(c) 2.0	Colbond CX 1000	
		(d) No drain	—	To check possible maximum spacing
2	4	(a) 2.0	Colbond CX 1000	To check long-term performance
		(b) 2.5	Colbond CX 1000	
		(c) 3.0	Colbond CX 1000	
		(d) No drain	—	Comparative study on material
3	11	(a) 1.5	Colbond CX 1000	To check boundary effect
		(b) 1.8	Colbond CX 1000	
		(c) 2.0	Colband CX 1000	
		(d) 1.5	Mebra (Holland) MD-7007	
		(e) 1.8	Mebra (Holland) MD-7007	
		(f) 2.0	Mebra (Holland) MD-7007	
		(g) 1.5	Mebra MD-7007 (Korea)	To check partial penetration effect
		(h) 1.8	Mebra MD-7007 (Korea)	
		(i) No drain		

The pilot test in Area A (North) was carried out not only to determine the performance of the exhibited drain spacing but also to assess the performance of dredged material improved with the PVD. The dredged spoil from the sand key of Phase 1C area were dumped at the deep pocket inside the future Area "A" North area and capped by placing a sand blanket of one to two meters thickness. Since dredged materials were deposited in a thin layer bounded by drainage layers, primary consolidation may be completed within a reasonable time. However, large settlement from this layer could be expected due to the greater stress ratio at the top part of the foundation. Details on reclamation using dredged material could be found in Bo et al. (2001). The pore pressure and settlement behavior of the dredged material under the fill and surcharge load is shown in **Fig. 7**. Based on the characteristics of the deposited material at the borrow source or after disposal, it was estimated that it would contribute a settlement of about one meter. Although slight changes of characteristics together with formation of inter-lump voids occurred, measured settlement was found to be also one meter. The settlement contributed by the closing up of the inter-lump voids when lumpy clay is utilized for reclamation is therefore likely to be small.

5.2 PVD Installations

Before commencing the installation of PVD, selection of suitable types of installation rig was made based on several factors including installation and performance experiences encountered in the pilot tests. The selection of vertical drain rig was also based on the following factors:

(i) Bearing capacity of platform
(ii) Depth of installation
(iii) Type of soil
(iv) Production capacity of rig

Types of rig used in Changi East reclamation projects are given in **Table 5**.

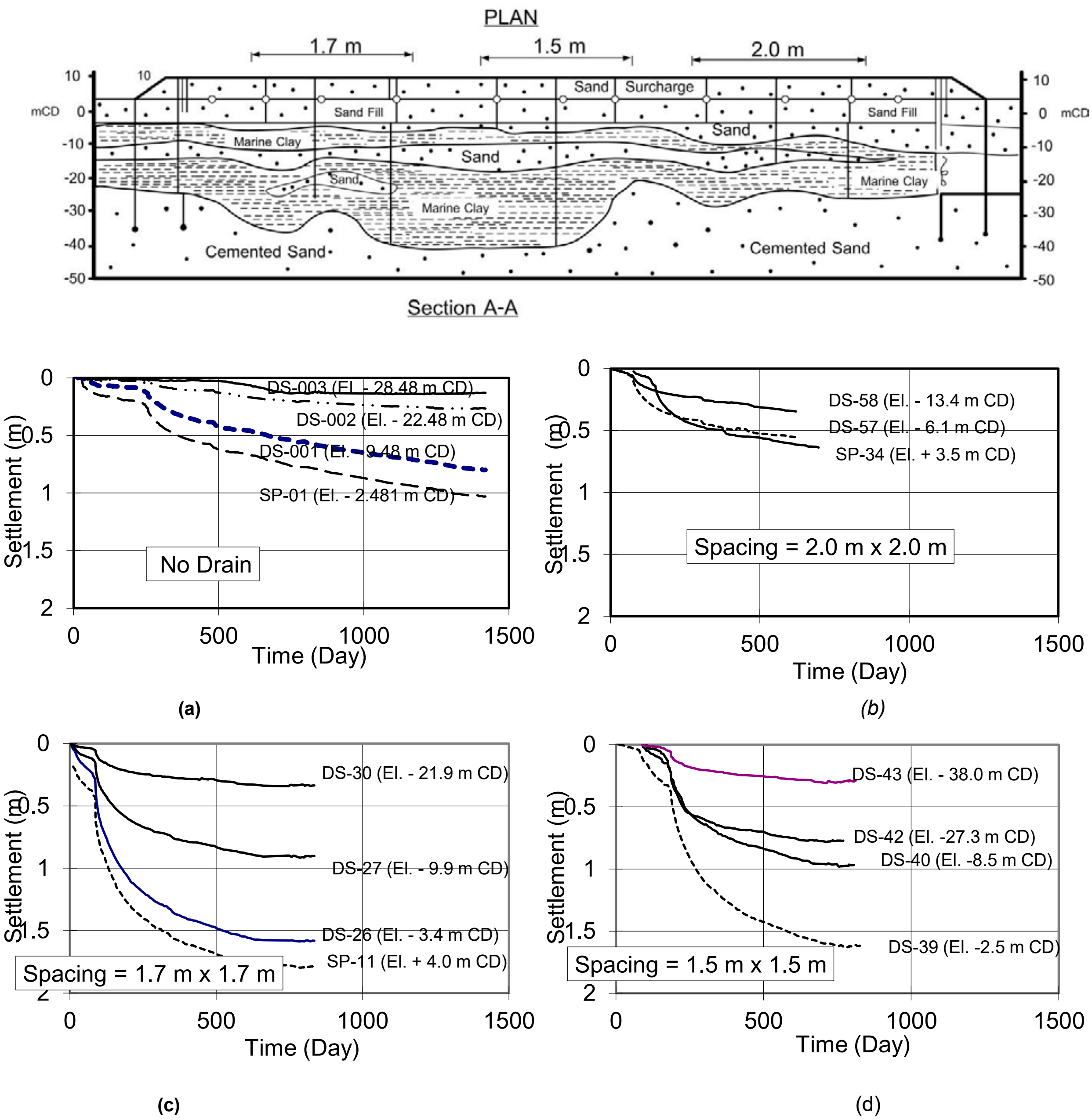


Fig. 2. First Pilot Area at Phase 1B.

4.2.1 Quality Control

In order to achieve ground improvement project requirements, quality control process was implemented both on material used and installation process.

Quality control on selected and delivered PVD material were checked by on-site quality control laboratory in accordance with the frequency required for different parameters. Quality assurance tests were carried out by third party accredited laboratory.

Following quality control tests were carried out in the on-site quality control laboratory:

- Unit weight
- Thickness & width
- Tensile strength on PVD
- Apparent Opening Size
- Discharge capacity
- Permitivity

Quality control was also carried out on the selection of suitable types of mandrel and anchor as well as periodic check on their quality to minimize the soil disturbance due to installation. Types of PVD rigs used are given in **Table 5**. Types of mandrel used are given in **Table 6**.

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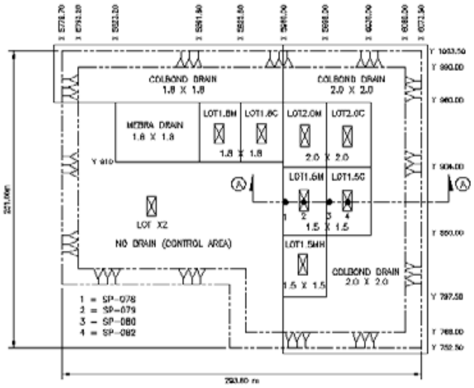

Fig. 3. Layout of Third Pilot Area in Phase 1C.

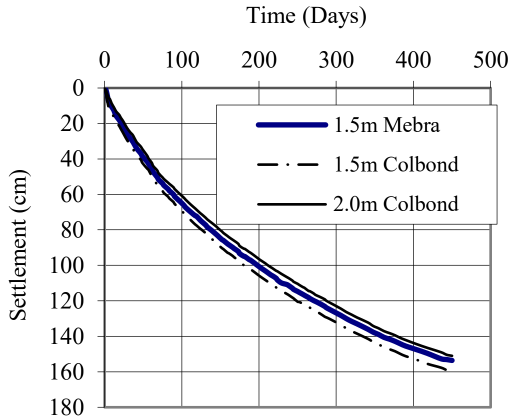

Fig. 4. Same magnitude and rate of settlement caused by various types of drain under same boundary condition.

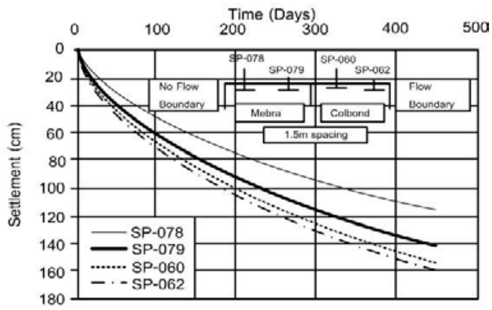

Fig. 5. Different magnitude and rate of settlement caused by different boundary condition.

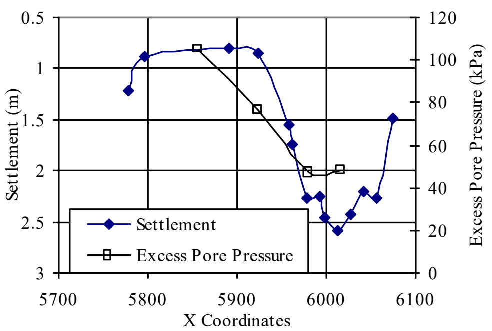

Fig. 6. Boundary Effects Measured by Settlement Plates and Piezometers installed across The Pilot Area.

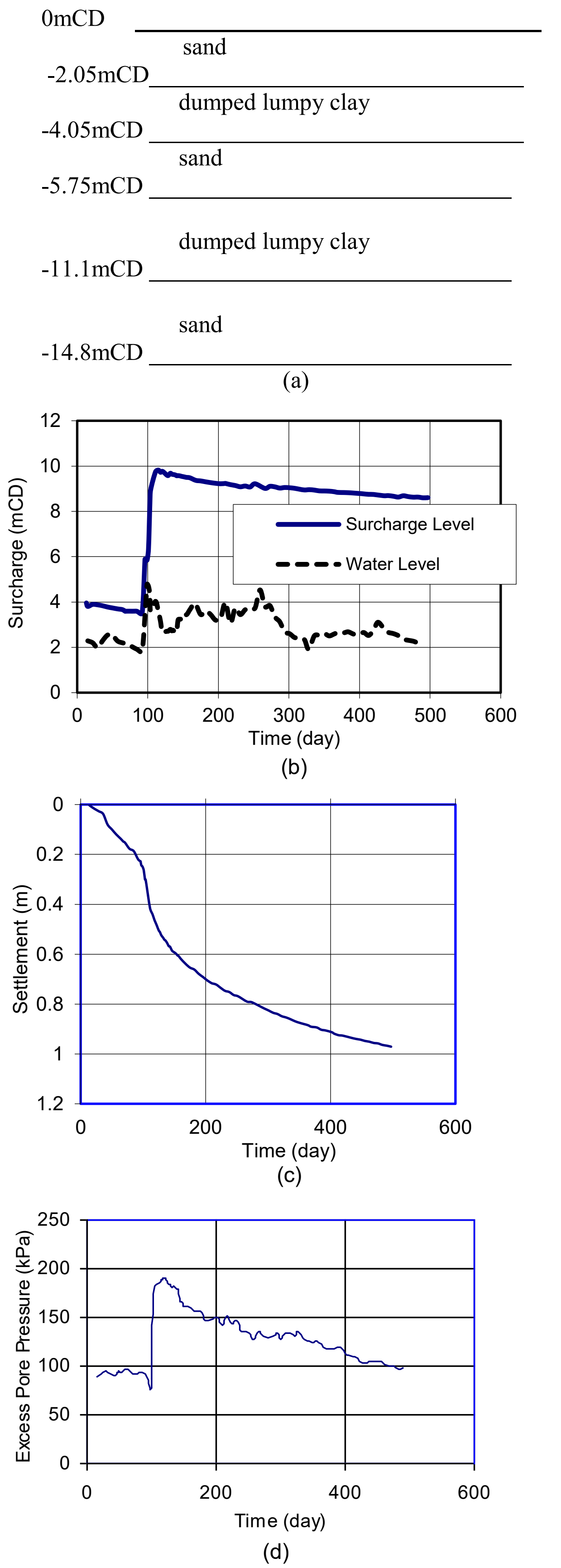

Fig. 7. Pilot Area (Area A North) Using Dredged Clay Fills (a) Profile of Fill (b) Filling Sequence (c) Settlement Vs time (d) Pore Pressure Vs Time.

Table 5. Types of vertical drain installation rig used in Changi East Reclamation project.

Description	Type of base machine	Weight of base machine: (ton)	Penetration power: (ton)	Height of rig: (m)	Maximum penetration depth: (m)	Mechanism of penetration	Maximum production/ day: (m/14h)
Cofra	O & K excavator RH30, RH40	70-110	20-30	36-55.5	50.5	Hydraulic motor, Multi pulley system	33 400
Econ	O & K Excavator RH30, RH40(01) Hitachi Excavator EX1100	70-120	20-30	36-56.1	51.5	Hydraulic motor, Multi pulley system	27 500
Yuyang	Samsung CX800 crane, Daewoo solar 450III Excavator, Zeppelin crane, P & H Crane, Komaso excavator IHI crane	45-100	25-30	43-55.8	53	Hydraulic motor, Multi pulley system, Driven chain and cable system	15 300
Chosuk	Daewoo solar 450 Excavator	45	25	56	51	Hydraulic cylinder, multi pulley system Hydraulic motor Push in roller and clamp system	17 900
Daeyang	Daewoo solar 450III Excavator	33-55	20-34	42-56	52	Hydraulic sprocket and chain	15 200
B + B	Excavator	—	—	31-47	29-45	Vibro push-in	19 200
B + B	Excavator	—	—	43-50	41-48		8 600

6. Performance Monitoring and Assessment of Degree of Consolidation

Performance monitoring of ground improvement works were monitored using geotechnical instruments as well as measuring improved soil parameters during the course of consolidations. Following instruments were used to monitor the progress of consolidation:

- .Surface Settlement Plates
- Deep Settlement Gauges
- Multi-level Settlement gauges
- Pore Pressure Piezometers
- Water Standpipes
- Earth Pressure Cells

While surface settlement plates monitored total settlements, deep settlement gauges and multilevel settlement gauges monitored the settlement of each formation such as upper, intermediate and lower marine clay deposits. Piezometers together with water standpipes measured the excess pore pressures. Earth pressure cells measured change in additional loads. From such monitoring data, progress of degree of consolidations were interpreted and monitored.

Progress of ground improvement was also measured using specialized in-situ testing such as:

- Field Vane Shear Strength
- Cone Penetration Test with Pore Pressure measurements
- Dilatormeter Tests
- Self-boring Pressuremeter Tests

From the measured parameters, both strengths and overconsolidation ratios were interpreted and monitored the performance of ground improvement works. Drilling and sampling were also carried out and collected samples were tested for classification, strength and consolidation tests.

From the tested parameters, change in moisture contents, void ratios, strengths and pre-consolidation pressures were interpreted and progresses of degree of consolidation as well as performance of ground improvement works were monitored. Details on performance monitoring of Changi ground improvement works were described by Bo et al (1997a& b).

Verification and assessment of the achievement of degree of consolidation were also made applying the same approach. **Figure** 8 shows monitoring data using geotechnical instruments and **Figure 9** shows assessment results using monitoring and investigation data.

Table 6. Types of mandrel use in Changi improvement projects.

Company	Mandrel	Length	Width	Thickness
Econ	R	120 mm	60 mm	10 mm
Cofra	R	120 mm	60 mm	10 mm
B + B	R	120 mm	60 mm	8 mm
	Rh	120 mm	50 mm	5 mm
Dae Yang	Rh	145 mm	60 mm	15 mm
Chosuk	R	145 mm	60 mm	10 mm
	Rh	120 mm	85 mm	15 mm
Yuyang	Rh	136 mm	76 mm	13 mm

*Note : R – Rectangular; Rh – Rhombic mandrel

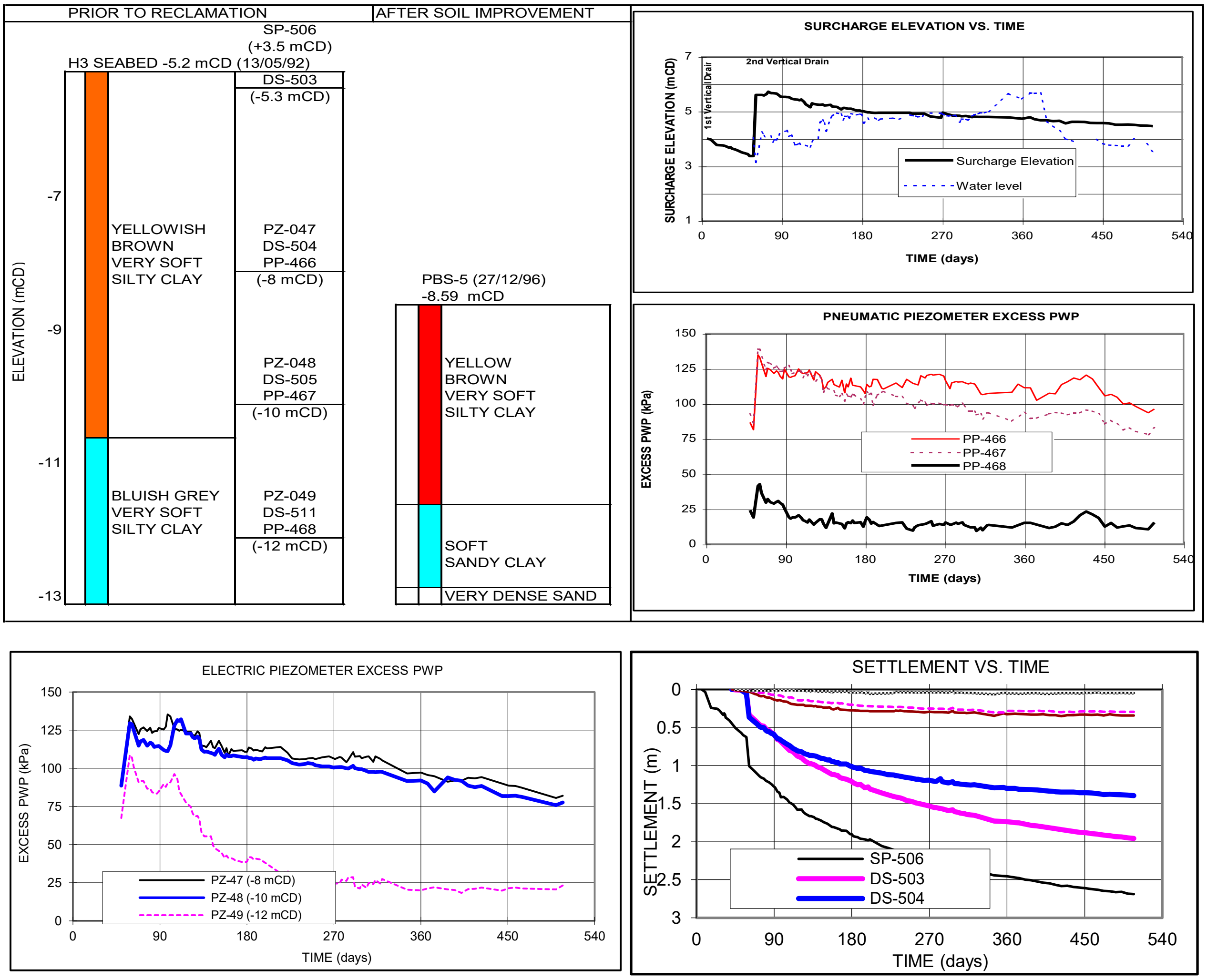

Fig. 8. Monitoring Data Using Geotechnical Instrumentation.

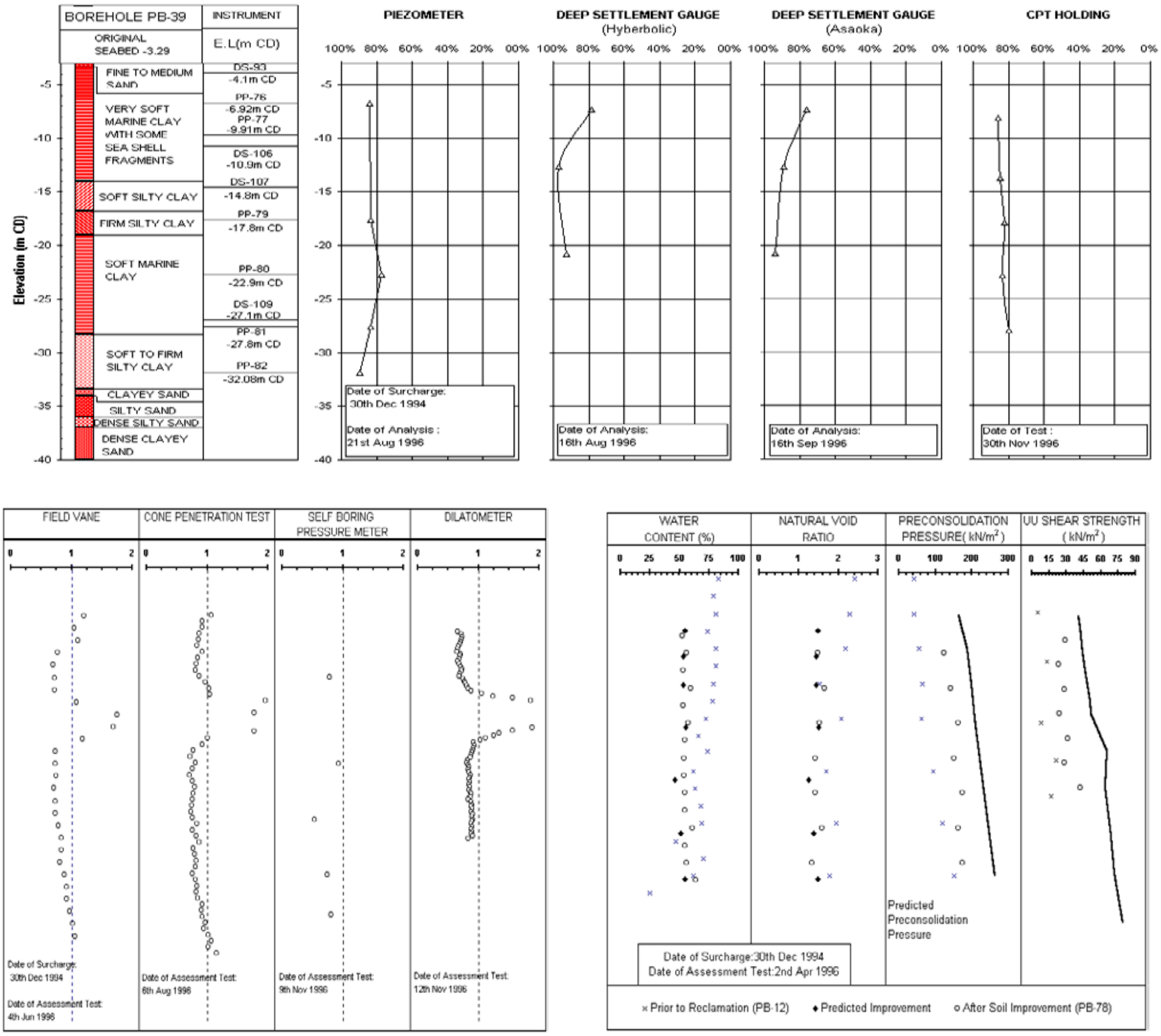

Fig. 9. Assessment of Ground Improvement Using Geotechnical Instrument and Filed Investigation Data.

7. Deep Compaction

An area of about 114 hectares was improved by deep compaction methods for 7 to 10m thickness of granular fill profile. Three types of deep compaction methods namely dynamic compaction, vibroflotation and Muller Resonance Compaction (MRC) were deployed to densify the granular soil in Changi projects. The areas where the three different types of compaction methods were used are shown in **Fig. 10**. The dynamic compaction method was deployed in the area where the required depth of compaction was 5 to 7 meters. The vibroflotation and MRC methods were adopted in the areas where the required thickness of compaction was 7 to 10 meters.

The effectiveness of dynamic compaction is dependent on the combination of weight, geometry of pounder, height of drop, spacing, number of drops and total compactive energy applied. Details of the equipment and the energy applied, together with the achieved densification in the dynamic compaction work are presented in **Table 3**. CPTs were carried out at three locations as shown in **Fig. 11**. The variation of the cone resistance with the distances from the pounding point is obvious.

The MRC does not require water for penetration. In this method, a steady-state vibrator was used to densify the soil. As a result of vibratory excitation, the friction between the soil particles will temporarily be reduced. This facilitates rearrangement of particles, resulting in densification of the soil. A specially designed steel probe was attached to a vibrator, which has variable operating frequencies. The frequency is adjusted to the resonance frequency of the soil resulting in strongly amplified ground

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vibrations and thereby an efficient soil densification is achieved. The type of equipment used in MRC compaction is shown in **Table 11**. As can be seen in the figure, the densification achievement was significant in the bottom of the profile. The combination of spacing and equipment used are shown in **Table 7**.

Another method used for densification of the granular soil was vibroflotation. Several types of vibroflotation equipment with slightly different specifications were used. These were either electric or hydraulic power driven and rated in ampheres or bars, respectively. The spacings used for each equipment to achieve the respective densification requirements are shown in **Table 8**.

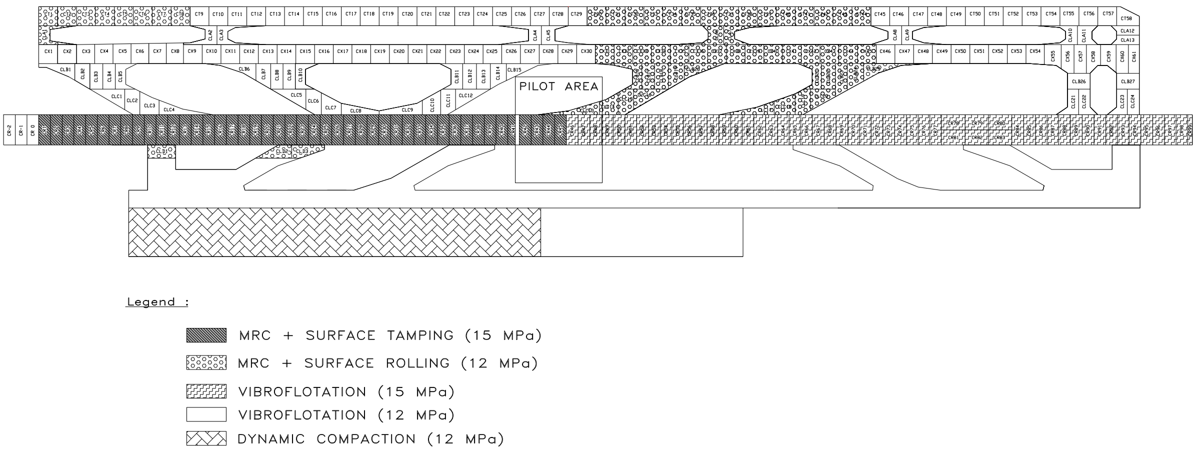

Fig. 10. Areas Showing Deep Compaction Carried Out by 3 Different Compaction Methods.

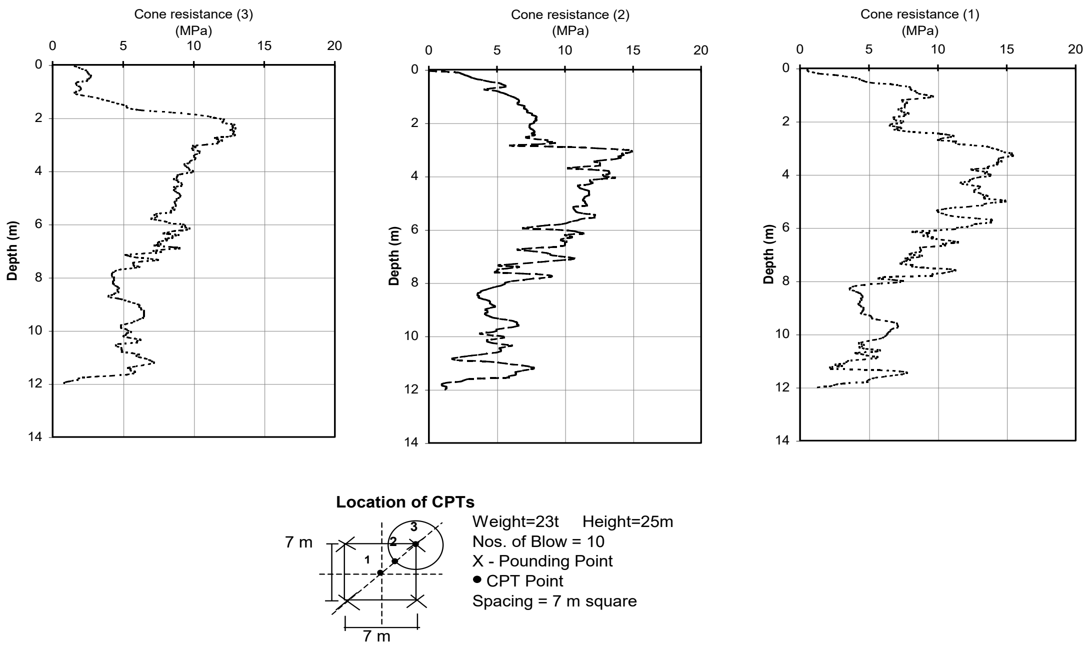

Fig. 11. Cone resistance results after dynamic compaction (after Choa et al. 2001).

Table 7. Combination of spacing and equipment for MRC compaction.

Method	Pass No.	Type of vibrator	Type of probe	Grid pattern	Spacing (m)	Achieved cone resistance (MPa)
A	1	MS 100	550 mm central plate, 800 mm wing plate	Hexagonal	4.2	12-15
	2	MS 200	-do-	At centroid of hexagonal	-	-
B	1	MS 100	550 mm central plate, 800 mm wing plate	Hexagonal	5.0	12
	2	MS 200	-do-	At centroid of hexagonal	-	-

Table 8. Details of vibrofloation equipment and spacing together with achieved cone resistance (after Choa et al. 2001).

Serial Number	Type of equipment	Model	Spacing (m)	Cone resistance achieved (MPa)
1	Vibroflotation	V23	3 plus roller compaction	10
2	Vibroflotation	V28	3.0	10
3	Vibroflotation	V32	3.3	10
4	Agra	V32	3.0	10
5	Keller	S300	2.5	10
6	Pennine	BD-400	2.5	10

8. Conclusions

This paper describes the implementation of the Changi East Reclamation projects which took place in 5 phases over a period of 15 years. Land reclamation was carried out with 20 meters of hydraulic fills over up to 40 meters thickness of compressible marine clay.

Ground improvement methods for soft soil improvement were implemented with PVD and surcharging to accelerate the consolidation process. Ground improvement methods for deep sand compaction were also implemented in this project using dynamic compaction, Muller resonance compaction and vibroflotation compaction methods.

The design of the land reclamation works were undertaken using conventional methods as well as finite element modelling techniques.

Overall this project was well implemented using state-of-the-art techniques inclusive of site characterisation, in-situ testing, ground improvement works and field instrumentation evaluation technique. The Changi Land Reclamation project was a unique large geotechnical engineering project, which was implemented with the most modern geotechnical engineering techniques.

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