01 May 2013, 2:00 pm - 4:00 pm

Planning and Implementation of a Mega Geotechnical Engineering Project in Singapore

Myint Win Bo
DST Consulting Engineers, Canada

A. Arulrajan
Swinburne University of Technology, Australia

Commemorate the Legacy of Ralph B. Peck
Seventh International Conference on Case Histories in Geotechnical Engineering
and Symposium in Honor of Clyde Baker
April 29 - May 4, 2013 CHICAGO

PLANNING AND IMPLEMENTATION OF A MEGA GEOTECHNICAL ENGINEERING PROJECT IN SINGAPORE

Myint Win BO
DST Consulting Engineers,
Thunder Bay, P7B5V5, CANADA

A. ARULRAJAH
Swinburne University of Technology,
Melbourne, Vic 3122, AUSTRALIA

ABSTRACT

Implementation of mega geotechnical engineering projects requires a systematic approach and detailed planning. A mega land reclamation and ground improvement project which consists of various components of geotechnical engineering applications was planned and implemented in the Republic of Singapore from 1990 till 2005, a total period of one and a half decades. Due to the extensive ground improvement required to treat the underlying highly compressible soil, with the presence of highly variable ground profile and ground conditions due to the natural geological process, a detailed ground investigation was necessary. This was furthermore necessary due to the importance of various critical infrastructure planned for future usage in the land reclamation site. Extensive ground investigation was planned based on input from desk study and reconnaissance survey carried out using geophysical method under foreshore conditions. Progressive ground investigation included ground investigation carried out in foreshore area prior to land reclamation, on land prior to ground improvement, during and after ground improvement to assess the degree of improvement. The ground investigation involved large numbers of in-situ tests using numerous methods and collections and testing of undisturbed soil sample for further laboratory testing to drive necessary geotechnical parameters for design purpose or decision making for acceptance of ground improvement works. Due to the nature and speed of the project on-site geotechnical and geotextile laboratories were set up for characterization and quality control. In addition to the improvement of underlying soils, hydraulically filled granular soils were required to be densified by application of deep compaction methods to minimize future immediate settlement and to increase resistance to liquefaction. A large quantity of geotechnical instrumentation were installed and monitored for construction control as well as performance monitoring of ground improvement works. This paper describes the procedure and process of implementation of geotechnical works in the mega Changi East Land Reclamation and Ground Improvement project in Singapore.

INTRODUCTION

Limited land space in many countries in the East and South-East Asian region has prompted consideration of large reclamations projects for diverse uses such as housing, recreation, industrial estates, sea and airport developments in the late 1990s and early 2000s. In China, Japan, South Korea, Hong Kong, Indonesia and Singapore, ports and airports have been built recently on large reclaimed land. These land reclamation projects are sited on near shore or just offshore locations. Much land has been reclaimed using hydraulically filled sand.

Thick soft marine clay deposits frequently underlie these large reclamation sites. Such deposits undergo considerable settlement over a long period of time. A suitable type of ground improvement work is required to adopt to accelerate consolidation of soft marine clay under large reclamations. Land reclamation works usually involve construction of temporary and permanent shore protection structures such as rock bund or sheet pile walls, filling of land with imported fill to the desired level, and implementation of ground improvement works to strengthen underlying soils and to densify loosely packed granular fill where necessary. The common methods used for improving soft compressible soils are preloading, vertical drain system and sand and stone column; whereas dynamic compaction, vibroflotation methods are often used for densification of granular fill. In order to successfully implement such a land reclamation project, geotechnical engineering plays a major role.

This paper describes the geotechnical engineering works carried out at the various stages of the reclamation works in Changi East Reclamation projects and to illustrate how geotechnical engineering could be applied fruitfully in the planning, design and construction control in various phases of project implementation of a mega geotechnical engineering project.

CHANGI EAST LAND RECLAMATION PROJECTS

The Changi East reclamation project consists of an extensive amount of geotechnical engineering works, located in Changi in the Eastern part of Singapore. It is a mega project that involves multiple phases of construction. Phase 1 comprised Phases 1A which commenced in 1991, 1B in 1993 and 1C in 1995, with each phase lasting about five years in duration. In addition, two other phases of land reclamation, namely Area A (South) and Area A (North), commenced at the same time in 1999. All major works were completed in March 2005 lasting total project duration of 15 years. The projects include a total hydraulic placement of 272 million cubic metres of sand in waters of up to 15 metres deep to reclaim about 2000 hectares of land for the extension of Changi Airport and other infrastructure developments.

Figure 1 presents the Changi East reclamation project site and the location of reclaimed areas in various phases. Table 1 presents the details of the various Phases of the project.

Table 1. Project specifications

Project	Area: ha	Volume of sand: Mm³	Length of vertical drain: Mm
Phase 1A	501.0	65	-
Phase 1B	520.0	75	28.0
Phase 1C	524.0	68	49.0
Area A – North	91.0	12	13.0
Area A - South	450.0	52	50.0
Total	2,086.0	272	140.0

PLANNING OF CHANGI EAST LAND RECLAMATION AND GROUND IMPROVEMENT PROJECTS

Most reclamation projects carried out on soft clay require substantial geotechnical engineering works. This type of geotechnical engineering works necessitates proper planning and implementation. The steps in the planning stage of Changi East Reclamation and ground improvement project are as follows:

- (i) Identification of the Clients' requirements.
- (ii) Identification of the site conditions.
- (iii) Development of design.
- (iv) Preparation of Contract Documents including the specifications.
- (v) Choice of geotechnical engineering sub-contractor.

While pre-tender ground investigation were carried out using third party ground investigation contractor under a separate contract, all the pre-tender ground investigations for subsequent phases were carried out using ground investigation crews and equipment available under the on-going phase of the contract. Design were carried out using data from pre-tender ground investigation and included in the tender as exhibited design. Specifications and Bills of quantity prepared were based on the exhibited design. However contractors were allowed to propose alternative design with technical and economic justifications. Contract document was mainly based on the Institution of Civil Engineers (ICE) Condition of contract with some modifications and improvement based on Federation Internationale Des Ingenieurs-Conseils (FIDIC). Special conditions were included especially for qualification of specialist ground investigation contractor and ground improvement contractor. Selection of all contractors was made based on their track records, capabilities and financial background.

IMPLEMENTATION OF GEOTECHNICAL WORKS IN STAGES

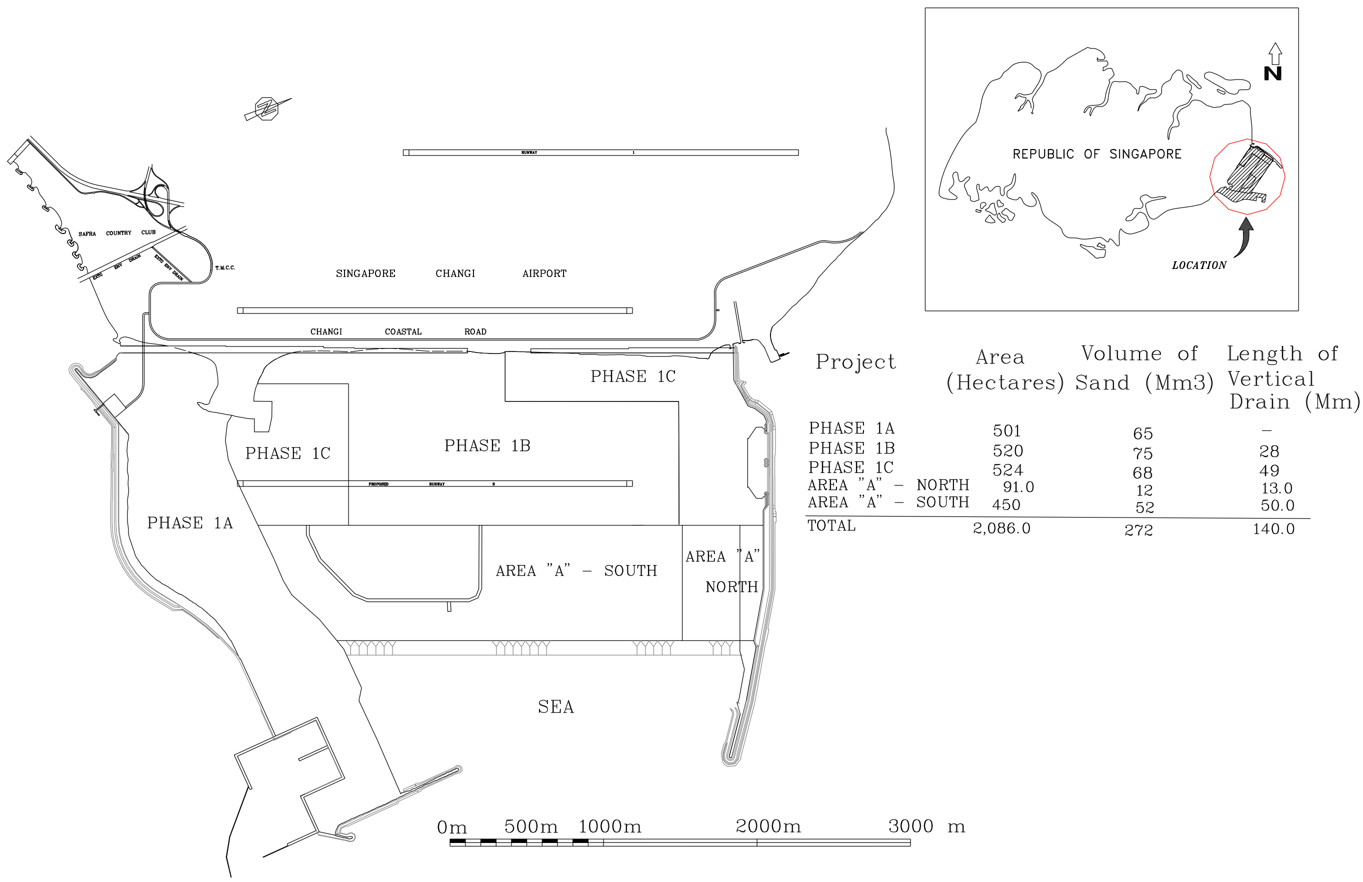
Geotechnical works were involved in every stages of project implementation until hand over of the completed projects to the owner. In many cases there could be post contract monitoring works to monitor the long term performance of reclaimed land. Therefore geotechnical works were planned and implemented on a stage by stage basis. The following geotechnical works were included in the project implementation stages:

- Ground Investigation
- Geotechnical Laboratory Testing
- Geotechnical Design
- Ground Improvement
- Geotechnical Instrumentation

Implementation of above stages will be described in details in the following sections.

GROUND INVESTIGATION

Ground Investigation works were involved in every stage of the project implementation of Changi East Land Reclamation projects. Due to the extensive amount of ground investigation works required each phase of the project had a provision for procurement of drilling rig and accessories, specialist in-situ testing equipment and supply of drillers and laborers by the contractor but was managed by the prime consultants. The followings are types of ground investigation works generally carried out in all phases of the projects. The purposes of these investigations varied, depending on the type and the time of investigations.



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

Figure 1. Site plan of Changi East Reclamation (after Choa et al. 2001)

Pre-tender Ground Investigation

Geotechnical information required for design of land reclamation, shore protection and ground improvement were collected through pre-tender ground investigation. Preliminary large-scale investigations were generally carried out by applying geophysical survey methods such as seismic reflection survey followed by confirmatory widely-spaced conventional boring sampling and in-situ testing. Numbers of conventional boreholes with standard in-situ tests such as Standard Penetration Tests (SPT), field vane shear tests (FVT) and collection of disturbed and undisturbed samples using 75 to 100 mm Shelby tubes or 75 mm piston samplers were carried out. In most cases continuous sampling of undisturbed samples were carried out in the compressible cohesive soils followed by field vane shear tests and SPT were only used to carry out in the granular soils and in most cases to determine the termination of boreholes in the competent formation. Termination criteria of boreholes were set as 3 continuous SPT blow counts of 50. As each Phase of the project is approximately 500 hectares in area, with approximate shore protection length of 3 to 4 km especially for those phases at the edge of entire land reclamation area, a grid of boreholes with a suitable grid spacing of 500 m by 500 m were generally carried out in the land reclamation and ground improvement areas and boreholes with a spacing of approximately 200 m were carried along the shore protection areas.

Pre reclamation Ground Investigation

Ground investigations were carried out in each project area, as well as in the fill borrow area. Investigation works in the project areas were carried out for each stage of the project. In the borrow area, the purpose of the investigation was to explore the quality and quantity of the borrow material. The investigation in the project areas, on the other hand, aimed to fill the information gap regarding stratification of the underlying soil in detail and to characterize the geotechnical properties of the underlying formations in detail to be used as input for fine tuning of design of land reclamation, shore protection and ground improvement. Supplementary boreholes were generally positioned in between the existing boreholes locations available in the tender documents. Ground investigations in this stage were generally carried out in phases starting from preliminary large-scale investigation and supplemented with intrusive detailed ground investigation. The detailed intrusive ground investigations usually concentrated on boreholes, continuous quality sampling, and selected in-situ tests for accurate characterization of the underlying soils. Several types of in-situ tests, including the Standard Penetration Tests, the field vane shear test (FVT), the piezocone penetration test (CPTU), the dilatometer test (DMT), the self-boring pressuremeter test (SBPT), the cone pressuremeter (CPMT), the seismic cone test (SCT), BAT permeameter (BAT) and the auto ram sounding test (RST) were used. In addition to ground investigation of the general area, extensive ground investigation at the pilot test area was carried out to characterize underlying soil characteristics in detail using conventional boring and sampling as well as various type of specialist in-situ testing. Sampling at pilot test locations were carried out with 150 mm large diameter sampler especially in upper marine clay. All of the pre-reclamation ground investigations are carried out from the offshore jack up pontoon which is capable of sitting on the seabed of deeper than 20 m depth. Details use and application of such in-situ tests are described in details in Bo et.al 2012.

Ground investigation prior to ground improvement

Land reclamation are generally carried out as first target lift to the level slightly above the maximum high tide level to use as platform level for Prefabricated Vertical Drain (PVD) installation as well as working level for other construction activity such as shore protection. For this particular project the first lift of platform level is +4mCD (with +1.6mChart Datum being the mean sea level at the time of investigation).
In this stage, majority of ground investigation carried out were to determine the required penetration depth for Prefabricated Vertical Drain (PVD) and to characterize the baseline characteristic of underlying soils at the proposed geotechnical instrument cluster locations. For the determination of PVD penetration length, CPTs were carried out with a suitable regular grid pattern to determine the bottom of compressible layer as well as competent layer for PVD anchorage. In addition CPT data were also used to detect the possible disturbance and seabed level change due to hydraulic filling of sand in the land reclamation process as well as any mud trap in the reclaimed fill which could affect the settlement magnitude, bearing capacity and stability of the upcoming infrastructure. Those boreholes carried out at the geotechnical instrument cluster location include sampling and in-situ filed vane tests and in some places CPTs and dissipation tests are also involved.

Ground investigation during ground improvement

Ground investigation during ground improvement are generally carried out at the geotechnical instrument cluster location to confirm the degree of improvement where substantial improvement of ground close to specification requirements is detected through the instrument monitoring data. Such ground investigation consists of boring and sampling, filed vane shear tests, CPTs and CPTUs at the instrument cluster locations.

Post-improvement ground investigation

In the Changi projects, post-improvement ground investigations were usually carried out in the underlying clay to verify its extent of improvement from pre-compression when monitoring results from geotechnical field instruments indicated that the improvement achieved the specified degree of consolidation. In this stage of investigation, the same types of ground investigation methods as those used prior to reclamation were employed. One unique feature of this stage of investigation is that careful interpretation is required because of the transient porewater pressure condition and hence the none-equilibrium effective stress state in the ground. The investigation methods carried out in the post-improvement stage at Changi site included boring, sampling, the FVT, CPT and CPTU tests, DMT, SBPT, CPMT, SCT and RST tests.

Boring and sampling were generally carried out from the surcharge level and through the sand fill. Figure 6 shows a comparison of the pre- and post-improvement borehole logs and FVT results together with other geotechnical parameters obtained from the laboratory tests. Although settlement observations from settlement plates and selected laboratory results indicated that the clay had generally achieved the targeted degree of consolidation and field excess pore pressures, laboratory results, such as the undrained shear Strength and the pre-consolidation pressure could show a degree of improvement that was lower than expected. In reality, undrained shear strength could be under-estimated in the laboratory due to sample disturbance. Pre-consolidation pressure could also be under-predicted by the consolidation test due to the chosen method of testing, interpretation and non-linearity of the stress strain behavior of the soil. These were widely discussed, for example by Arulrajah et al. (2005), Arulrajah et al. (2006) and Bo *et al.* (1999).

It is a well-known behavior that the average degrees of consolidation as indicated by field settlement observations and that inferred by the effective stress gain are usually different, with the effective stress gain generally lags behind. However, as the main purpose of most pre-compression of clay strata in land reclamation projects is usually to eliminate future settlement, achieving a degree of consolidation defined in terms of percentage of soil compression achieved will be a more relevant criterion to adopt.

Table 2 shows numbers of specialist in-situ tests carried out in 5 phases of Changi East Land Reclamation and Ground Improvement projects. It can be seen that extensive numbers of CPTs were carried out in the projects.

Table 2. Total number of specialist in-situ tests

	Projects					
	Phase 1A	Phase 1B	Phase 1C	Area A (North)	Area A (South)	Total
CPT	2424	4,546	6,537	885	2,127	16,339
FVT	75	292	306	72	119	864
DMT	0	11	10	2	4	27
SBPT	0	11	10	2	4	27
BAT	0	8	27	2	6	54
CPMT	0	85	31	0	0	116
RAM sounding	78	1,463	0	0	243	1,784
Seismic cone	0	3	0	0	0	3
In-situ permeability test	0	0	10	0	3	13

GEOTECHNICAL LABORATORY TESTING

Due to the nature of project and large quantity of samples expected to be collected and tested together with a possibility of urgency in obtaining geotechnical parameters during project implementation in many cases, each contract has a provision for setting up of advanced on site material testing laboratory. All the laboratories are under controlled environment with majority of laboratory equipment are automated in nature. Each laboratory is equipped with all equipment required for classification test such as various scales of balances, oven, thermometers, sieves, hydrometers, Casagrande cups, dessicators, laboratory vane and sample extruder etc:. In addition to the basics equipment required for classification tests following equipment are also set up and installed in the laboratory.

- Oedometer
- NGI Direct Shear Equipment
- Hydraulic Rowe cellConstant rate of strain consolidation cell
- Triaxial equipment capable of carrying out all types of shear strength tests
- Bishop and Horsley stress path triaxial cell GDS pressure and volume controllers
- Automatic data logging system for all of the above equipment

Almost all the equipment was supplied by Wykeham Farrance, UK. The laboratories are capable of carrying out quality control tests on geotexile such as, tensile strength, Apparent Opening Size (AOS) tests and Discharge capacity tests for PVD. Testing for other geotexile parameters and rock testing were carried out at third party accredited laboratory in Singapore. Electron-microscope and X-ray reflection tests for clay mineralogy determination were carried out in British Geological Survey in United Kingdom.

GEOTECHNICAL DESIGN

Geotechnical design in land reclamation involves magnitude of settlement calculations in each stage of filling to determine volume loss considering construction sequences. Design and stability analyses of various types of shore protection structures such as rock berms, breakwater, rock groynes and sheet pile wall etc:. Ground improvement design were also carried out for improving compressible soils to accelerate the consolidation process as well as improving loosely fill granular soil to increase the resistance to liquefaction potential as well as to minimize the elastic immediate settlement upon application of the additional stresses.

Shore protection Design

As the reclamation fill is as thick as 21 m at the edge of the land reclamation, net fill thickness after the completion of consolidation settlement could be as thick as 23 m. In order to be able to successfully construct the very high shore protection structure on the soft marine clay as well as to maintain the stability of the berm in long term condition, a suitable sand key was provided in order to improve the global stability as well as sliding of the structure. Provision of sand key required removal of soft upper marine clay to three to four meters depth which also helps in minimizing the settlement of the shore protection structure. Several stability berms were also provided to improve the overall stability of the shore protection structure. Overheights were provided both at the crest of shore protection structure as well as intermediate stability berms based on the settlement calculations. While overheights at the crest were allowed to nicely complete the crest elevation at the long-term proposed finished levels, overheights at the intermediate levels were also allowed to finish the elevation above high tide level or well below low tide level in order to prevent the navigation vessels not to be grounded at any time.

At the corner of land reclamation where significant wave and current are predicted from hydraulic model, a suitable breakwaters and rock groynes are provided. Stability of such structures was checked and settlements of the crest were predicted to provide sufficient overheight to finish at the designed elevations. All the stability check were carried out using Geosolve finite different software while settlement analyses were carried out using Consol99 or Plexis finite element modeling.

In Phase 1A area where future jetty development is required, a vertical retaining wall using sheet pile was installed. As the retained height of the sheet pile was as high as up to 17 meters above seabed levels with penetration length of less than 30 m, support from both sides of the wall using raker piles which were strengthen by compression toe pin and tension anchor at the passive side and active side respectively. Stability, bending moment and shear forces on the wall were checked using either WALLAP or Plaxis finite element software. The length of shore protection works in this project is about 10 km. A total of 3 million m^3 of rock was used to form the shore protection. Extreme care was taken in the construction of the rock bunds which were closely monitored by soil instruments such as inclinometers and piezometers. The observational method used in the construction of these works has been described by Choa, (1994). The other half of the boundary at Phase 1A, was retained by a vertical sheet pile retaining structure using sheet-piles and pipe-piles since the area will be used for future berthing facilities. A total of 7,276 nos of sheet and box piles of 600mm width were driven over 3.9 km length along the boundary and 1590 nos. of raker pipe piles of 610mm diameter were driven to cater for compression and tension forces arising from berthing of vessels on the wharf structure to be built in front of the retaining structure. The landside pipe piles were flushed out and ground anchors with 1000kN working load were installed below the toe of these piles.

GROUND IMPROVEMENT

In the land reclamation project ground improvement were required to accelerate the consolidation process of underlying soils as well as improving the loosely deposited granular fill to be able to withstand the dynamic and seismic forces as well as to minimize the elastic settlement of granular soil upon application of additional stresses. At some localized locations where excessive mud trap was occurred a specialized soil improvement method such as stone or sand column installations was required. Each method of ground improvement design is described in the following section.

Improvement of Compressible Soils

Generally prefabricated vertical drains were designed to improve the drainage system of the seabed compressible soils. The spacing of vertical drain was selected to achieve 90% degree of consolidation with fill and surcharge load after taking into consideration the submergence effect caused by sinking of fill below groundwater level within a certain surcharge period. For such cases at least a minimum preloading pressure of equivalent to two to three meters thickness of sand (35 to 50 kPa) were achieved over and above of fill load. For the locations where no special treatment was required for future load, soil improvement works were carried out to achieve 90 % degree of consolidation due to fill load plus a general future load of 20 kPa. At locations where future loads were known, the equivalent magnitude of surcharge load after taking into consideration of submergence effect and ground water level rising were applied. PVD spacings were designed based on thickness, parameter of underlying clay and duration allowed for surcharge period. As the reclamation covers an extensive area, the soil profile and characteristic of the soil are different from one area to another. In addition to that the future loading and timing of land usage are different within the area. Therefore design of the soil improvement works were based on the existing soil profile, future land use and allowable duration for soil improvement works. The acceptance criteria of the soil improvement works were also varied since the design criteria and future land use varied. Details of the basic design concept shown in Table 3 were discussed by Bo et al. (2000) and Choa et al. (2001). It can be seen in the table that vertical drain spacings used are ranging between 1.5 m to 2.0 m square spacings depending on the duration of surcharge period. The magnitudes of surcharge are reclamation was carried out under four phases since vast quantities of fill material and prefabricated vertical drains were required. As the majority of the reclamation area is underlain by up to 50m thick, highly compressible layer of Singapore Marine Clay, about 140 million meters length of prefabricated vertical drains in combination with up to 8m thick of surcharge have been used to improve the engineering properties of the seabed soils. The total area of soil improvement is about 1200 hectares.

Table 3. Details of soil improvement design with PVD in Changi East Reclamation Project (after Bo et al. 2000)

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

Pilot tests

In order to successfully implement the ground improvement works with the proposed design, pilot tests were carried out in the early stage of each phase to verify the performance of the proposed design. Any deviation of performance from the prediction could bring attention to the implementing engineer and necessary remedial action or correction can be made based on the actual performance monitoring data.

Most pilot test areas consist of areas with prefabricated vertical drains with various spacing as well as control area with no vertical drain but applied the same magnitude of preload. In some pilot tests a few different types of prefabricated vertical drains were installed. While most pilot test areas had separations between one type of spacing to another, in one of the pilot tests no separation was provided in order to observe the boundary effect. The entire pilot area in each phase was applied with same magnitude of preload. Instrument cluster consist of various types of geotechnical instrument were installed in each sub-area of pilot test with and without prefabricated vertical drain. Every geotechnical instrument cluster consists of deep settlement gauges, multilevel settlement gauges, both types of pore pressure piezometers (pneumatic and vibrating wire piezometers), inclinometers and surface settlement gauge. While most of the instrument clusters were installed after formation of general platform level of +4 mCD but before installation of PVD, instrument cluster in the control area was installed under offshore condition from the offshore instrument platform in order to catch the base line condition of pore pressure as well as to catch magnitude of settlement occurred during the placement of general fill level to +4 mCD. In addition, a deep reference point is usually installed in the instrument cluster in the control area in order to achieve the accuracy of survey works carried out for monitoring exercise. Details of the pilot test area can be found in Bo et al. (1999b), Choa and Bo (2000), Choa et al., 2001 and Bo et.al (2003). Details of the pilot areas carried out in each of the phase are shown in table 4.

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

IMPROVEMENT OF GRANULAR FILL

An area of about 114 hectares was improved by deep compaction methods through 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. The areas where the three different types of compaction methods were used along the runway and taxiways in Phase 1B are shown in Figure 2. The dynamic compaction method was deployed in Phase 1A where about 100 hectares of land, immediately behind the wharf structure, is to be utilized for low-rise infrastructure development. Dynamic compaction was used in other Phases where the area where the required depth of compaction was 5 to 7 metres. Details of the compaction methods use and combinations of spacing, energy and equipment used are shown through Table 5 to 9. In Phase 1A project, in order to avoid any damage to the sheet pile retaining structure, the area from the wharf face up to a distance of 30 metres was compacted using the vibroflotation method.The vibroflotation and MRC methods were adopted in the areas where the required thickness of compaction was 7 to 10 metres. Areas compacted with Dynamic compaction (Area A) and vibroflotation (Area B) in Phase 1 A projects are shown in Figure 3.

The specifications called for densification were a minimum cone resistance of 15 MPa, and 12 MPa for runway, taxiway and associated areas respectively. For the other areas where compactions are required, the compaction is carried out for the top 5m and the minimum requirement was a cone resistance of 10 MPa.

Each of the three compaction methods has its own advantages and disadvantages depending on the site and soil condition in the various areas. Nevertheless, the specified degree of compaction was achieved in all the areas. The dynamic compaction method can produce a uniform degree of densification in each layer. However, the degree of densification varied with the depth. Furthermore, the depth of compaction is limited. The Muller Resonance Compaction method is able to compact with a wider spacing. However, frequent maintenance of the probe is required due to wearing of the probe. With MRC, the degree of densification achieved is uniform along the depth, but it varied with the distance from the probe points. The compactable depth is also limited due to the flexibility of the probe. The vibroflotation can compact to a greater depth. The degree of densification is uniform along the depth, but also varies with distance from the probe points. It requires a smaller spacing grid and a supply of water. Details on densification works using the three methods of compaction are described in Choa et al., (1997, 2001) & Bo et.al (2009).

GEOTECHNICAL INSTRUMENTATION

Changi East Reclamation Project is a multi-phase land reclamation project which included vast areas of soil improvement works. Since prefabricated vertical drains were used for acceleration of consolidation process, several geotechnical instruments were required to monitor the settlement and pore pressure dissipation hence effective stress gain. Edges of newly reclaimed land are either retained by vertical retaining structure or coastal shore protection rock bund with suitable slopes and berms. Therefore sufficient monitoring and measurement of magnitude and rate of movement were essential in order to complete the construction of retaining structures without stability problem. During the implementation of 5 phases of reclamation and soil improvement projects, thousands of geotechnical instruments such as settlement plates, deep settlement gauges, multi-level

Table 5. Details of dynamic compaction (after Choa et. al 2001)

Method	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 metre (ton-m/m²)	Compacted 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 6. Type of equipment and probe used in MRC (after Choa et al. 1997)

Muller vibrator	MS-100HF	MS-200
Maximum centrifugal force (kN)	2500	4000
Maximum static moment (Nm)	1000	1900
High frequency step (Nm)	480	-
Maximum oscillation frequency	2156	1500
(rpm)	10 900	15 500
Total weight without grip (kg)	7700	11 750
Dynamic weight without grip (kg)	26	34
Oscillation amplitude (mm)	600	800
Maximum pulling power (kN)	3.235	3.655
Vibrator height (m)	0.66	1.352
Vibrator width (m)	2.41	2.3
Static mass width (m)	0.6	0.75
Static mass thickness (m)		

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. Specification of vibroflotation equipment (after Choa et al. 1997)

Company	Vibrofloatation			Keller	Pennine
Model	V23	V28	V32	S-300	BD-400
Power rating (kW)	130	130	130	150	215
Speed of rotation (rpm)	1800	1800	1800	1775	1800
Rated current (amp)	300	300	300	300	350 bar
Centrifugal force (kN)	280	330	450	290	345
Amplitude (mm)	23	28	32	25	30
Vibrator diameter (mm)	350	360	350	400	406
Vibrator length (mm)	3.25	3.3	3.25	2.9	4.0
Vibrator weight (kN)	22	25	25	24.5	19.5

Table 9. 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

settlement gauges, liquid settlement gauges, pneumatic piezometers, vibrating wire piezometers, Casagrande open type pieometers, water stand pipe, inclinometers and earth pressure cells were installed to monitor the behaviours of ground movement. Some brief description on instrumentation and monitoring of soil instrument can be found in Bo et al. (1998).

In order to control the geotechnical problems within the manageable process, geotechnical instruments are deemed necessary and followings were measured during the process of reclamation and soil improvement.

Category A Measurement of Ground behaviour during construction in order to control the construction process.

Category B Monitoring of performance of ground during loading, unloading and soil improvement process.

<u>Selection of Geotechnical Instrument Locations</u>

Selection of location for geotechnical instruments varied depending upon types of measurement. To measure the total settlement of the ground, surface settlement plates were installed in a certain grid pattern. In the case of Changi East reclamation project, the thickness of compressible layer is highly varied along the north south line and less varied along east west line. Therefore 50 m x 100 m spacing with 50 m spacing along north south direction was used for settlement plate interval. Settlement plates were also installed along the runway and taxiway area with certain interval. On top of the settlement plates, another major instruments installed were an instrument cluster. Instrument clusters were also planned and implemented throughout the site at certain spacings. However more clusters were installed in the critical area and area with greater thickness of compressible soil. Deep settlement gauges were usually installed on top of sub-layers whereas piezometers were installed at the center of sub-layers. A water stand pipe was installed in each of the cluster in-order to measure the static water level of the area. With this arrangement, deformations and effective stresses of sub-layers can be correlated. Total earth pressure cells were installed in order to measure the total pressure imposed on the ground. Inclinometers were installed to monitor the lateral movement of ground at the edge of reclamation or shore protection works. The locations were selected based on slope stability analysis. Generally an inclinometer was installed at the trash of possible slip circle. One each could be installed on the crest and the toe. Settlement plates were also installed together with inclinometer in order to be able to relate the lateral and vertical displacement. For the vertical wall, inclinometers were attached to the inner side of the wall.

<u>Geotechnical Instrument used in Changi Projects</u>

Instruments were installed at the platform level where vertical drain was going to be installed or on the special platform erected at the offshore. Majority of the instruments were installed at platform level during or before installation of vertical drain since settlement occurred before vertical drains were small magnitude and installation and protection of instruments installed at offshore condition were difficult and costly. Instrumentation at the project has been described by Arulrajah et al. (2004a, 2004b, 2009) Bo et.al (1998, 2002).

Table 10. Total numbers of instruments installed in Changi East Reclamation Project.

Soil Instruments	Phase 1A	Phase 1B	Phase 1C	Area "A" North	Area "A" South	Asean Aerospace	Total
Pneumatic Piezometer	26 Nos.	781 Nos.	458 Nos.	122 Nos.	227 Nos.	12 Nos.	1626
Open Type Piezometer	9 Nos.	70 Nos.	84 Nos.	29 Nos.	54 Nos.		246
Electric Piezometer		122 Nos.	150 Nos.				272
Settlement Plate	125 Nos.	778 Nos.	1092 Nos.	173 Nos.	707 Nos.	16 Nos.	2891
Settlement Gauge		72 Nos.					72
Deep Settlement Gauge	23 Nos.	790 Nos.	450 Nos.	131 Nos.	266 Nos.	12 Nos.	1672
Multi-Level Settlement Gauge	3 Nos.	17 Nos.	11 Nos.		25 Nos.		56
Deep Reference Point		8 Nos.	10 Nos.	3 Nos.	12 Nos.	1 Nos.	34
Water Standpipe		29 Nos.	59 Nos.	14 Nos.	49 Nos.	3 Nos.	154
Inclinometer	25 Nos.	52 Nos.	47 Nos.	23 Nos.	24 Nos.	3 Nos.	174
Inclinometer with Measrement of Vertical Displacement		9 Nos.	2 Nos.				11
Earth Pressure Cell	3 Nos.	12 Nos.	7 Nos.	5 Nos.	11 Nos.		38
Total	214 Nos.	2740 Nos.	2370 Nos.	500 Nos.	1375 Nos.	47 Nos.	7246

Normally instruments were installed in a form of instrument cluster and following instruments were included in a cluster. Total numbers of instruments installed in Changi East Reclamation project is shown in Table 10.

Only very few instrument clusters were installed in offshore condition with proper protection in order to monitor the settlement occurred during reclamation.

CONCLUSION

Changi East Reclamation Project in the Republic of Singapore comprised five different phases of work.

This mega-land reclamation project commenced in 1992 and was completed in 2005. The project involved a total sand fill volume of 270 million cubic metres to create reclaimed land 2,000 hectares in size. The soil improvement works involved installation of 142 million metres of prefabricated vertical drains and compaction of over 300 hectares of sand fill.

Several pilot tests were carried out in order to validate methodology and monitor the consolidation behavior of Singapore Marine Clay including performance of dredged material and very soft slurry treated with PVD.

With experience gained from each project, contract documents, technical and performance specifications were updated for subsequent projects covering aspects pertaining to dredging, reclamation and shore protection works, soil improvement works on natural clay, dredged clay and ultra-soft slurry using prefabricated vertical drain and densification of granular fill by various deep compaction techniques.

REFERENCES

Arulrajah, A., Nikraz, H. and Bo, M.W. (2004a). "Factors Affecting Field Instrumentation Assessment of Marine Clay Treated With Prefabricated Vertical Drains", Geotextiles and Geomembranes, Elsevier, Vol. 22, No. 5, October, pp. 415-437.

Arulrajah, A., Nikraz, H. and Bo, M.W. (2004b). "Observational Methods of Assessing Improvement of Marine Clay", Proceedings of the Institution of Civil Engineers (UK), Ground Improvement, Vol. 8, No. 4, October, pp. 151-169.

Arulrajah, A., Nikraz, H. and M. W. Bo (2005). "In-Situ Testing of Singapore Marine Clay at Changi", Geotechnical and Geological Engineering: an international journal, Springer, Vol. 23, No. 2, pp. 111-130.

Arulrajah, A., Nikraz, H. and Bo, M.W. (2006). "Assessment of Marine Clay Improvement under Reclamation Fills by In-Situ Testing Methods", Geotechnical and Geological Engineering: an international journal, Springer, Volume 24, No. 1, pp. 219-226.

Arulrajah, A., Bo, M.W., Chu, J. and Nikraz, H. (2009). "Instrumentation at the Changi Land Reclamation Project, Singapore", Proceedings of the Institution of Civil Engineers (UK), Geotechnical Engineering, Vol. 162, no.1, pp. 33-40.

Bo Myint Win, Arulrajah, A. and Choa, V. (1998), "Instrumentation and Monitoring of Soil Improvement Works in Land Reclamation", 8th International IAEG Congress 1998, Balkema, Rotterdam.

Bo Myint Win, Bawajee, R. and Choa, V. (1999a), "Comparative Study on Performance of Vertical Drain", *11th Asia Regional Conference on Soil Mechanics and Geotechnical Engineering*, August 1999, Hong et al. (eds) Balkema, Rotterdam, Seoul, Korea.

Bo Myint Win, Chu, J. and Choa, V. (1999b), "Factors Affecting the Assessment of Degree of Consolidation", *International Conference on Field Measurements in Geomechanics*, *1999*, Leung, Tan and Phoon (eds), Balkema, Rotterdam.

Bo Myint Win, Bawajee, R. and Choa, V. (2000), "Implementation of Mega Soil Improvement Works", *International Symposium on Coastal Geotechnical Engineering in Practice*, September 2000, Nakase & Tsuchida (eds) © Balkema, Rotterdam, IS-Yokohama, Japan.

Bo Myint Win and Choa, V. (2002), "Geotechnical Instrumentation for Land Reclamation Projects" *A Conference on Case Studies in Geotechnical Engineering*, 4 & 5 July 2002, Singapore.

Bo, M W. Chu,, J. Low, B K. & Choa, V (2003), "Soil Improvement – Prefabricated Vertical Drain Techniques" *Thomson learning*, Singapore.

Bo, M.W., Arulrajah, A., Na, Y.M & Chang, M.F. (2009) "A case study on densification of soil by dynamic compaction" *Ground Improvement*, *Institution of Civil Engineers UK*, Volume 162, Issue GI3, August, pp. 121-132.

Bo, M W. Chang, M.F. Arulrajah, A. & Choa, V. (2012), "Ground Investigation for Changi East Reclamation Projects" *Geotechnical and Geological Engineering, Springer*, Vol.30, Issue 1, pp. 45-62.

Choa, V. (1994), "Application of the Observational Method to Hydraulic Fill Reclamation Projects", *Geotechnique*, 44, No. 4, pp. 735-745.

Choa, V., Bo, M. W., Arulrajah, A. & Na, Y. M (1997): "Overview of Densification of Granular Soil by Deep Compaction Methods", *1st International Conference on Ground Improvement Techniques*, May 1997, Macau.

Choa, V. and Bo Myint Win (2000), "Quality Assurance of Prefabricated Vertical Drain in Changi East Reclamation", *International Seminar of Geotechnics*, September 2000, Kochi, Japan.

Choa, V., Bo, M. W. and Chu, J. (2001), "Soil Improvement Works for Changi East Reclamation Project", *Ground Improvement (2001)*, Vol. 5, No. 4, pp. 141-153.

Choa, V. (2001), "Reclamation and Soil Improvement on Ultra-soft Soil", *Symposium 2001 on Soft Ground Improvement and Geosynthetic Applications*, 22-23 November 2001, Bangkok, Thailand, pp. 1-20.

.