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THREE-DIMENSIONAL GEOLOGICAL MODELING OF PHNOM PENH SUBSOILS

Ms. Samphors Touch

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Civil Engineering
Department of Civil Engineering
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Thesis Title	THREE-DIMENSIONAL GEOLOGICAL MODELING OF PHNOM PENH SUBSOILS
By	Samphors Touch
Field of Study	Civil Engineering
Thesis Advisor	Associate Professor Suched Likitlersuang, D.Phil.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

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นาย วาริน จัน : การพัฒนาระบบการประเมินมลพิษทางเสียงสำหรับคนงานก่อสร้าง. (DEVELOPING A SYSTEM OF NOISE HAZARD ASSESSMENT FOR CONSTRUCTION WORKERS) อ. ที่ปรึกษาวิทยานิพนธ์หลัก : ผศ.ดร.วัชระ เพียรสุภาพ,อ. ที่ปรึกษาวิทยานิพนธ์ร่วมรศ.ดร.ธนิต ธงทอง 106หน้า.

มลพิษทางเสียงเป็นปัจจัยหนึ่งที่ต้องตระหนักทางด้านสุขภาพและความปลอดภัยในงานก่อสร้าง คนงานก่อสร้างจำนวนมากปฏิบัติงานโดยขาดการป้องกันผลกระทบอันเนื่องมาจากการได้รับหรือสัมผัสเสียงดัง ซึ่งแสดงให้เห็นว่าคนงานก่อสร้างยังขาดการตระหนักถึงผลกระทบต่อสุขภาพและความปลอดภัยในการทำงาน ในปัจจุบันเครื่องวัดปริมาณเสียงสะสม (Noise Dosimeter) เป็นอุปกรณ์ที่ถูกนำมาใช้ประเมินระดับเสียงที่คนงานได้รับตลอดเวลาการทำงานภายในวันหนึ่ง ๆ อย่างไรก็ตามอุปกรณ์ดังกล่าวยังมีราคาแพง ซึ่งทำให้มีการใช้งานอยู่อย่างจำกัด และอาจไม่เหมาะสมกับประเทศที่กำลังพัฒนา ดังนั้นจุดมุ่งหมายของการวิจัยครั้งนี้ เพื่อเสนอกรอบแนวความคิดเกี่ยวกับการประเมินอันตรายและผลกระทบจากเสียงสำหรับคนงานก่อสร้าง และพัฒนาระบบสำหรับประเมินผล ตลอดจนเปรียบเทียบและทดสอบผลลัพธ์ที่ได้จากระบบกับระเสียงมาตรฐานและความตระหนักของคนงานก่อสร้าง การศึกษานี้ทำการพัฒนาระบบสัญญาณอิเล็คโทรนิคที่สามารถประมาณค่าเทียบเท่ากับระดับเสียงมาตรฐาน เพื่อระบุว่าเสียงที่เกิดขึ้นในสถานการณ์นั้นเป็นเสียงที่อันตราย จากนั้นทำการทดลองระบบที่ได้รับการพัฒนาขึ้นในห้องทดลองเสียงและสนามก่อสร้าง เพื่อทดสอบความตรงและความน่าเชื่อถือของข้อมูล แบบสอบถามและระบบที่พัฒนาขึ้นเพื่อเก็บข้อมูลเสียงในงานเสาเข็มจากสถานที่ก่อสร้าง 8 แห่ง ซึ่งข้อมูลที่นำมาวิเคราะห์ประกอบด้วย ข้อมูลจากเครื่องวัดปริมาณเสียงสะสมจำนวน 24 ข้อมูล และข้อมูลจากระบบ ที่ได้เก็บข้อมูลจากกลุ่มตัวอย่าง 72 ตัวอย่าง ผลการวิเคราะห์พบว่าผลลัพธ์ที่ได้จากระบบมีแนวโน้มเป็นไปในแนวทางเดียวกัน และมีความสัมพันธ์กันสูงกับอุปกรณ์มาตรฐาน และระบบที่พัฒนาขึ้นนี้มีความน่าเชื่อถือและมีความเที่ยงตรงภายใต้ข้อจำกัด (83.6 ถึง 87.3 dBA) อีกทั้งยังพบว่าคนงานก่อสร้างเสาเข็มร้อยละ 37.5 ไม่ได้รับอันตรายจากผลกระทบของเสียงในการปฏิบัติงานก่อสร้าง แต่ก็จำเป็นที่จะต้องระวังอันตรายที่จะเกิดขึ้นในระยะยาว

ภาควิชา............วิศวกรรมโยธา.................ลายมือชื่อนิสิต...

สาขาวิชา..........วิศวกรรมโยธา............. ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก..................

ปีการศึกษา 2011 ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์ร่วม ....

5270856021 : MAJOR CIVIL ENGINEERING
KEYWORDS : NOISE HAZARD / EQUIVALENT NOISE LEVEL / DOSE OF NOISE / CONSTRUCTION WORKERS' PERCEPTION OF NOISE HAZARD

VARIN CHAN : DEVELOPING A SYSTEM OF NOISE HAZARD ASSESSMENT FOR CONSTRUCTION WORKERS. ADVISOR: ASST. PROF. VACHARA PEANSUPAP, Ph.D., CO-ADVISOR : ASSOC. PROF. TANIT TONGTHONG, Ph.D., 106 pp.

Many research studies attempt to assess the noise hazards at construction worker level. Different occupations of workers may receive different equivalent noise levels under the same construction activity due to the diverse distance and working time. However, the use of many current noise dosimeters for noise hazard assessment was expensive to measure. In addition, this method may not be the practical method for assessing and reminding workers about their health hazard. Therefore, this research aims to propose alternative system for assessing noise hazard for multiple construction workers. This research methodology is classified as the experimental research approach. The piling work is used as case study to design and experiment. The research starts with development of the conceptual framework of noise hazard assessment and development of a system to evaluate equivalent noise level, dose of noise and status of noise hazard from electronic sound signal. Next, this system was experimented in acoustic laboratory and in construction site for testing reliability and validity. On the other hand, questionnaire was also used to explore workers' perception and awareness of noise hazard in construction site. Data was analyzed based on 24 samples from noise dosimeter, 24 samples from questionnaire and 72 samples from system. It is found that results of proposed system present the same trend and high correlation with that of standard equipment. Proposed system is reliable and it is valid under some limitations (83.6 to 87.3 dBA). Finding also shows that some piling workers (37.5%) does not perceive noise hazard as their problem but they seem to aware of noise as a long term impact.

Department : Civil Engineering	Student's Signature ....
Field of Study : Civil Engineering	Advisor's Signature ....
Academic Year : 2011	Co-advisor's Signature ....

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CHAPTER I
INTRODUCTION

1.1 Significance of Research

Phnom Penh is wealthiest and most popular city in Cambodia which has a population of about 1.5 million people with a total population density of 2,213 inhabitants per square kilometers in 2009. The municipality of Phnom Penh consists of 8 districts, 96 communes and 897 villages within the 678.46 km^2 of Phnom Penh City (Wikipedia, 2011: Online). It is located at 11°33′00″N 104°55′00″E as shown in Figure 1.1. Phnom Penh has been the national capital since the French colonized Cambodia in 1865, and has grown to become the national center of economic activities. Phnom Penh has grown to become the industrial, commercial, cultural, tourist and historical center of Cambodia.

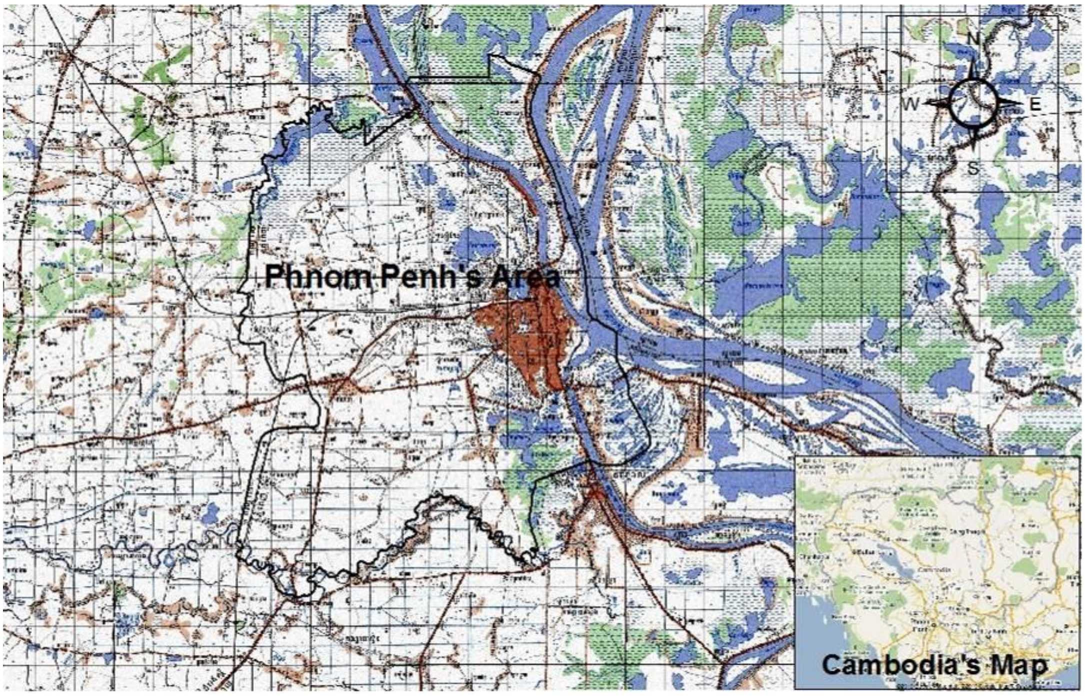


Figure 1.1 Location of Phnom Penh City (The APSARA National Authority of Cambodia, 2003)

The capital of Cambodia was selected as the studied area because the growth rate of construction has dramatically increased these days. The subsurface geology of Phnom Penh city is not yet well understood. Many ground investigation including soil boring log have been performed separately site by site in Phnom Penh. It is important to understand the variation of the ground as it is the first requirement for all constructions activities. In addition, Phnom Penh city is lying next to the Mekong River and it is well-known for sand investigation as a construction material.

1.2 Scope of Research

1200 soil boring logs reports are collected randomly around Phnom Penh City which is gathered from one well-known company named Research and Design Enterprise (RDE) from the year 2004 to 2010. This company has been working on soil investigation for more than 20 years. After successfully collected, soil boring log data have been digitalized in GIS format and reproducing into three-dimensional geological subsurface modeling.

In another part of this research study is statistical analysis of geotechnical properties of Phnom Penh subsoil. This operation analyzed statistical characteristics of geotechnical (physical and mechanical) properties of geotechnical parameters according to soil boring log reports and cross-section of solid model.

The last part of this master thesis conducts some experiment of soil properties of Mekong River sand such as specific gravity (Gs), gradation curve, e_{max}, e_{min} and scanning electron microscope (SEM).

1.3 Research Objectives

- To illustrate three-dimensional geological modeling for understanding the complex variation of subsoil condition in Phnom Penh city using Geography Information System (GIS) via Groundwater Modeling System (GMS).
- To determine the statistical value of geotechnical properties of Phnom Penh subsoil.
- To evaluate engineering properties of the Mekong River Sand in Phnom Penh city.

1.4 Research Methodologies

To accomplish the above objectives of this research, the methodology can be separated into three main parts respectively.

- ***Three-dimensional geological modeling of Phnom Penh subsoils*** which can be divided into seven steps as following:

1. Import boreholes into GIS format via Groundwater Modeling System (GMS) computer program.
2. Assign horizon IDs on the top of soil stratigrapgy in order to connect from one layer to another layer.
3. The primary triangulated irregular network (TIN) is defined as a template for all horizon surfaces in the models. It is used as the boundary of the solid modeling.
4. The horizon surfaces are interpolated by the elevation of the corresponding contracts on the boreholes according to the primary TIN.
5. The horizons are intersected and the primary TIN is modified according to the resultant lines of intersection in step four.
6. Adjust the elevation of the horizons in order to eliminate their intersection.
7. Horizons are extruded to build the solid models.

- ***Statistical analysis of Phnom Penh subsoil*** is performed by four steps bellow:

1. From three-dimensional geological modeling of Phnom Penh subsoils, cross-section can be cut in any direction inside the solid boundary to view typical cross-section.
2. Typical soil profile is decided according to the cross-section in every district of Phnom Penh city.
3. Statistical analysis is performed by gathering all the physical and geotechnical properties from boring log reports to the typical soil profile which is already created.
4. Finally, statistical values can be determined such as minimum, maximum, mean, standard deviation and sampling number.

❖ ***Soil properties of Mekong River sand*** is conducted by taking sand sampling taken from the Mekong River in Phnom Penh city to conduct some experiments at geotechnical laboratory at Chulalongkorn University such as sieve analysis, specific gravity (Gs) based on ASTM standard. Moreover, void radio (e_{max} & e_{min}) based on Japanese standard and scanning electron microscope (SEM) is also conducted at Tokyo Institute of Technology (TIT).

1.5 Scheduling

The research was carried out from early October 2010 to late September 2011 as shown in table 1.1. Firstly, there were some related documents of data collection conducted in early October, 2010 in Phnom Penh city such as the soil boring log reports and sand sampling. After data collection, some studies on computer application, Groundwater Modeling System (GMS), statistical studies on geotechnical properties of Phnom Penh subsoils and some properties of Mekong River sands were performed during the second year of this master research. Proposal exam was taken on 8th March 2011. Furthermore, all of the rest of research works need to be completed before 30th September 2011 according to the deadline of final defense. Importantly, several papers for conference proceedings have been submitted to both national and international conference. All in all, final exam was taken on 12th September 2011.

Table 1.1 Time table of research study

Research program	Year	2010			2011								
	Month	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Data Collection	1												
Study on GMS	3												
Proposal preparation	2												
Processing 3D model	4												
Geotechnical properties	2												
Writing thesis	2												

1.6 Research Outcome

This study is designed to develop a three-dimensional geological modeling toward Phnom Penh subsoils. Upon the completion of the study, the following outcomes are expected:

- Subsoil condition of Phnom Penh city is well presented in three-dimensional view.
- Geotechnical properties of Phnom Penh subsoils are summarized according to in-situ and laboratory tests from previous soil boring logs.
- Research results will be kept as geotechnical database of Phnom Penh city.
- The analysis results could be useful for future research and study on subsurface condition in Phnom Penh and other civil engineering practices.

CHAPTER II
LITERATURE REVIEW

The objective of this chapter is to give a summary of literature reviews related to research study on the basic knowledge and theory about this research study. The explanation in this chapter can be categorized into two main parts. First of all, it begins with the review of history and geological background of Phnom Penh city. Next, it will focus on Geographic Information Systems (GIS) and Groundwater Modeling System (GMS). Furthermore, the explanation of the previous works related to geological modeling will be presented such as some important theories regarding to 3D view, borehole system, Horizons method for 3D geological modeling and others important topics.

2.1 History and geological background

2.1.1 General background

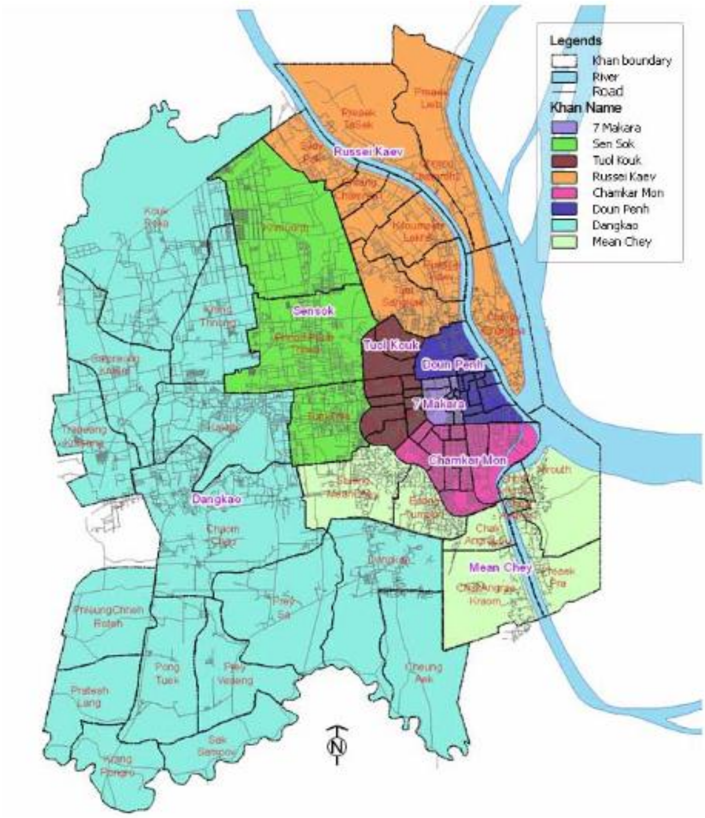


Figure 2.1 Phnom Penh city municipality map (Phnom Penh, 2011: Online)

The municipality of Phnom Penh consists of 8 districts named Chamkar Morn, Daun Penh, Prampi Makara, Toul Kok, Mean Chey, Russei Kao, Sen Sok and Dangkao. The boundaries of eight districts can be presented in Figure 2.1 (Phnom Penh, 2011: Online).

Table 2.1 Population in Phnom Penh City by District (Phnom Penh, 2011: Online)

No	District	Population	Area (m^2)	Density (Peoples/km^2)
1	Chamkar Mon	182 004	10 788 213	17 468
2	Daun Penh	126 550	7 412 767	17 479
3	Prampi Makara	91 895	2 228 027	44 395
4	Toul Kok	171 200	8 432 543	21 977
5	Dangkor	257 724	340 184 643	757
6	Mean Chey	327 801	44 000 448	2 951
7	Russey Keo	196 684	63 948 255	1 827
8	Sen Sok	147 967	40 021 647	1606

2.1.2 Phnom Penh history

Phnom Penh was founded in 1431, immediately after the Khmer kings abandoned Angkor (Coedès, 1989). King Ponhea Yat, who initially established himself at Basan, sent two ministers on a reconnaissance mission accompanied by dignitaries well-versed in the art of finding favorable locations. The ministers came to a hill called Phnom Daun Penh- the hill of the old lady Penh- and decided that the area southeast of the hill was favorable for a capital. Following a report of their mission to the king, all provincial governors were ordered to send laborers to build the city (Molyvann, 2003).

The site adopted for the new capital purportedly stretched along the Tonle Sap River, east of present day Monivong Boulevard. King Ponhea Yat's early city had a palace and royal apartments as well as an encircling wall, and a canal dug to lead river water to a basin in the royal residence. Officials and inhabitants of the early settlement constructed their houses with in the city enclosure, reserving areas south of the city for rice field. The elevated sanctuary first built by the old lady Daun Penh was reconstructed into a large chides. Abandoned as the capital after about thirty years, Phnom Penh occasionally served as a site for royal residences or refuge (Molyvann, 2003).

In 1865, under the French Protectorates, Phnom Penh was once again chosen to become the capital and center of royal power. At that time, Phnom Penh was a small village, consisting of boats and wooden houses stretching along the river. In 1953, Phnom Penh became the capital of the independent nation of Cambodia under the leadership of Prince Norodom Sihanouk, then Head of State (Molyvann, 2003).

2.1.3 Geology

Figure 2.2 The confluence of Mekong River, Bassac River and Tonle Sap

Phnom Penh is located at the confluence of Tonle Sap, Mekong River and Bassac River. The Mekong River is the main river in Asia and one of the longest rivers in the world with length of 4,090 kilometers. The original source of the Mekong River is from highland in Tibet of China. This river crosses Cambodia from North to South with total length of 486 kilometers and passes Phnom Penh as an intersection of river to create attractive freshwater and ecosystem for the city (Wikipedia,2010).

Central Cambodia lies between two different geological zones which are the basin of the Great Lake to the north and the Mekong Delta to the south. The basin of the Great Lake and the whole western portion of Cambodia have been sinking since the Quartenary Period – the most recent period of prehistory.

The Bassac River is undergoing a gradual displacement toward the east. The western bank of the river is expanding while the eastern riverbank is eroding. Sedimentation is reducing the flow of water from the Mekong River into the Bassac River and is causing the continuous growth of the peninsular of Chrui Changvar zone as well as the appearance of an island south of the peninsular. During the past fifty years, the tip of Chrui Changvar zone has moved one hundred meters southward. Geologists have found that sedimentation in the area of the two rivers is the natural and unavoidable phenomenon.

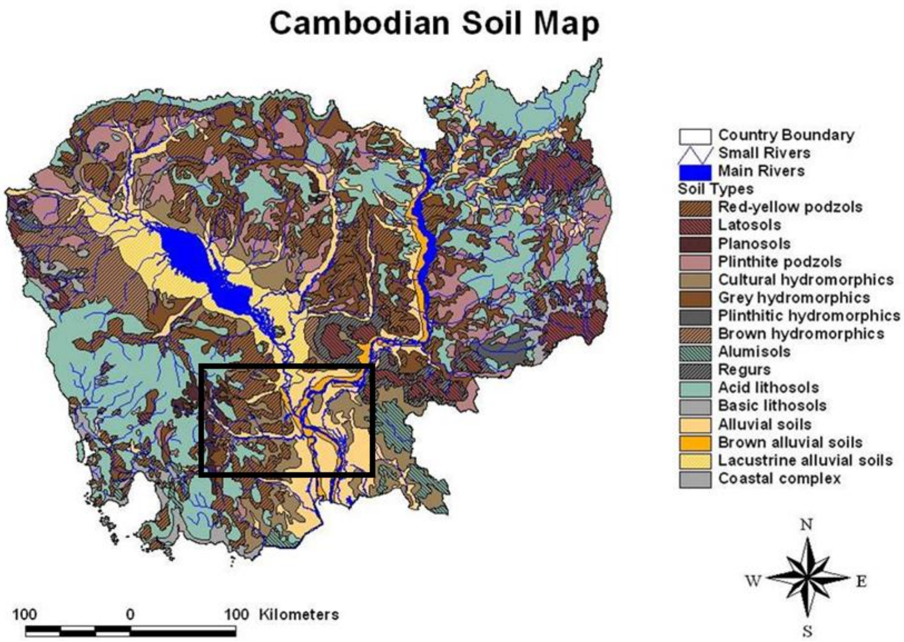


Figure 2.3 Cambodian soil map (Geological Department of Cambodia, 2002)

The banks of the Mekong River cover approximately 5,000 km^2. Along the banks of the Mekong and Bassac River, and to a lesser degree along the banks of the Tonle Sap and Tauch River, very fertile land is found. This is due to the fact that nutrients in the soils are renewed each year by the flood water and the silt which the waters bring with them. Deposits of gravel and sand are found on beaches along the river as well as on the slopes of the riverbanks. As shown in figure 2.3, the flood waters deposit the following types of soils:

- An alluvial sandy soil is deposited primarily on the riverbanks. This sandy soil is slightly alkaline, very light, and susceptible to humidity.
- The best and richest alluvial soil in Cambodia is deposited in areas where water runs slowly with very little current. Alluvial deposits are found on the sides of the riverbanks. The percentage of sand and gravel in this rich alluvial soil is considerably less than in the sandy alluvial soil described above. More clay is found in the rich alluvial deposits as well.
- Behind the banks of the rivers, the plains are covered with a heavier clay-filled soil that is more compact. This soil is found in low lying areas which emerge only slowly after the floods. The area covered by this soil is less easy to cultivate during the dry season unless it is intensively irrigated. The fertilizing action of the Mekong River is limited to the narrow band which makes up the most fertile land in Cambodia (Molyvann, 2003).
- The fertile land of the banks and the plain which lie behind them results from the annual flooding, which renews these areas each year with deposits of silt from the river. The fertilizing action of the Mekong River is limited to the narrow band which makes up the most fertile land in Cambodia. Phnom Penh remains very vulnerable to flooding. The city, first established on the high riverbanks, has extended into lower plains lying behind these banks which are actually below flood levels. These low-lying areas have been protected by the creation of successive concentric dikes. Phnom Penh is one of a long line of Khmer cities built on, or even incorporating, a river. The fertilizing action of the Mekong River is limited to the narrow band which makes up the most fertile land in Cambodia (Molyvann, 2003).

2.2 Data available

This section explains the relevant data used for this research study which have been gathered from several official sources such as Cambodian geological department, Apsara national authority and soil Investigation Company named Research and Designed Enterprise (RDE).

2.2.1 Map

Several kinds of maps need to be used for this research study which is collected from two main sources, namely Cambodian geological department, and Apsara national authority.

-Digital map which represents such contour map, boundary map, river map in GIS format used for building terrain for modeling. This kind of map is used to determine the elevation, boundary of the solid modeling.

-Raster map of the top surface in Digital Elevation Model (DEM) which is used to visualize the reality of solid modeling.

2.2.2 Soil boring log reports

All geotechnical reports conducted from 2004 to 2010 are provided by one well-known soil investigation company in Cambodia named Research and Design Enterprise (RDE). These reports required some simplification process before employing in the analysis, which will be explained more in the next chapter. The following report is the example of soil boring log report which created by Research and Design Enterprise (RDE):

TABLE OF CONTENT

1. INTRODUCTION

For safety reason of construction, the soil under foundation should be investigated and calculated. The main objectives of the soils investigations give the information for the engineer of the Engineer's method defining type of foundations (Strip footing, mat foundation, foundation piers, and foundation piles…).

On January 14, 2009, Research and Design Enterprise of Soil Testing Laboratory was awarded a contract to undertake the soil investigation for House Project, located **at Phum Borei 100 Khnorng, Sangkat Tek Thla, Khan Russey Keo, Phnom Penh City and Kingdom of Cambodia**.

The works are following:

- Soil boring one (01) borehole 13.00 meters depths.
- In-situ Test by Standard Penetration Test (SPT) 1.50 meter intervals at the bottom of each boring hole.
- Laboratory testing of collected samples.

The field work were carried out on January 14, 2009 and finished in that morning.The laboratory testing and Report was carried out from January 15, 2009 and finished on the January 18, 2009. The report presents the ground conditions, soil mechanics, Standard Penetration Test (SPT) results, and field boring log recording.

2. SCOPE OF WORK

The scope of work for investigation included the following:

2.1-FIELD WORK

All field works activities were supervised by: Mr. MEN THARITH, Civil Engineer. One borehole of 120mm nominal diameter and 13.00m depths with Standard Penetration Test (SPT) was done by rotary auger machine model УГБ-50М (Russian equipment). The location of borehole is indicated in Figure 2.

2.2-STANDARD PENETRATION TEST (SPT)

Standard Penetration Test was carried out at 1.50m intervals inside the boring hole. A standard split spoons of 50.8mm diameter with a ball check value on the top and harden steel cutter was used. A Standard spilt spoon was installed and drives into the soil by a 63.5Kg, automatic drop hammer falling freely from a fixed height of 760mm along a guide rod.

The blow counts were defined for each 150mm penetration of the seating drive. The total penetration of the spoon is 450mm and the numbers of blow N-value for last 300mm. Penetration was recorded as the N- value of the soil stratum encountered which indicated the relative density of non-cohesive soil as well as the consistency of the cohesive soil.

2.3-SAMPLING

- Undisturbed samples: The Undisturbed samples were taken in the natural state of the soil from firm to stiff clay and sandy clay. The undisturbed samples were taken by thin wall tube sampler in the natural state.

- Disturbed samples: The disturbed samples were taken at a rate of 1.5m and all strata in each borehole. The disturbed samples were also collected from soft to stiff clay and sandy soil.

3. LABORATORY TESTING PROGRAM

The laboratory testing was supervised by:

- Mr. PHAT BONE, Master Engineer of Geology
- Mr. MEN THARITH, Civil Engineer.

The Laboratory Testing Program Included:

1- Natural water contents determination

2- Density and dry density determination

3- Atterberg limit tests of selected cohesive or sandy soil

4- Specific gravity determination

5- Sieves distribution Test

7- Unconfined Compression Test

The testing-procedure was conducted in accordance with ASTM Standard and classified soil by USCS. The present report was prepared by Mr. SIENG PEOU, Master engineer of geology. The summary of testing result is presented in the table characteristic of Soil Mechanic at the end of this section.

4. RELATIVE DENSITY AND CONSISTENCY

The relationships between Standard Penetration Test result and consistency clay, silt soil (Cohesive soil) and relative density for sandy soil (non-cohesive soil) are shown in table No 1 and No 2.

The relation between SPT results and Consistency for Clay, Silt, Clay-Silt and Silty-Clay (Cohesion Soils)

Table 1

S.P.T N Value (blows/ 300mm)	CONSISTENCY
0 to 2	Very soft
2 to 4	Soft
4 to 8	Medium stiff
8 to 15	Stiff
15 to 30	Very Stiff
30 over	Hard

The relation between SPT results and relative Density for Sand and Gravel (Cohesion less Soil)

Table 2

S.P.T N Value (blows/ 300mm)	RELATIVE DENSITY
Less than 4	Very loose
4 to 10	Loose
10 to 30	Medium dense
30 to 50	Dense
Over 50	Very dense

5. GROUND CONDITION AND SOIL PROPERTIES

Ground condition from the ground surface to 13.00m depths for this site consisted of filling process of Mekong River was in 4th Era (Young alluvium). The soil condition encountered in each borehole has been put into strata as follows:

BOREHOLE No 1

Stratum	Description of soil strata	N-value Blows /300mm
1	- Made ground Yellow very loose Clayey SAND, encountered from top to 4.50m.	N-2
2	- Brown stiff Lean CLAY, encountered from 4.50m to 6.00m.	N-14
3	- Grey very stiff Lean CLAY with sand, encountered from 6.00m to 7.60m.	N-20
4	- Grey stiff Lean CLAY, encountered from 7.60m to 8.50m.	N-12
5	- Yellow stiff Sandy Silty CLAY, encountered from 8.50m to 9.80m.	N-17
6	- Red hard Sandy Lean CLAY, encountered from 9.80m to 11.50m.	N-32
7	- Red dense Clayey SAND, encountered from 11.50m to 13.00m.	N-50

6. GROUND WATER CONDITION

The ground water level is important for soil investigation, because the variation of the ground water level and the characteristic of soil mechanic can be changed. During the boring activities, water is found at a greater depth (Water strike), but a few hours after the boring is completed, water table is stabilized at a higher level (Ground water level as shown in table 3).

Table No 3

Borehole No	Boring started date	Boring finished date	Water strike (m.)	Water level (m.)	Date measured
BH-1	14/01/2009	14/01/2009	4.5	4.5	14/01/2009

The ground water table varies according the season: it increases in rainy season and decreases in dry season.

7. SOIL LABORATORY TESTING RESULTS

The results of Laboratory testing for boreholes BH-1 are shown in Appendix. The soil characteristics cover:

- Water content
- Liquid and Plastic Limits
- Plastic and Liquid Index
- Unit weight and dry density
- Particle size distribution
- Undrained Shear strength:
- Cohesion (C)
- Internal angle friction (ϕ),
- Undrained cohesion (Cu)
- Specific gravity
- Soil class
- Void ratio
- Young' modulus

8. CONCLUSION AND RECOMMENDATION

Based on the soil data from boring hole, the recommendation for foundation can be presented as following:

8.1- Shallow foundation

For this area the soil from ground surface to 4.50m deep is back filling soil, characterized very loose clayey sand, so shallow foundation is not recommended.

8.2- Pile foundation

Pile foundation is necessary for this project. The allowable bearing capacity for single driven pile foundation is presented in the Table No 4. TABLE 4

Borehole number	Pile size	Pile depth	Pile length	End pile load	Friction load	Allowable Pile Load
(No)	(m^2)	(m)	(m)	(KN)	(KN)	(KN)
BH-1	0.20 x	6	5	24.53	23.73	**48.3**
	0.20 x 0.20	7	6	53.33	35.73	**89.1**
	0.25 x 0.25	7	6	83.33	43.73	**127.1**
	0.25 x 0.25	9	8	88.54	70.44	**159**
	0.30 x 0.30	7	6	120	51.35	**171.4**
	0.30 x 0.30	9	8	127.5	67.95	**195.5**
	0.30 x 0.30	10	9	183.75	105.71	**289.5**
	0.30 x 0.30	11	10	240	142.46	**382.5**

9. GENERAL

The analysis and recommendation submitted in this report are based on available information. Since significant variations in soil conditions may occur between the boring, it is recommended that pile experienced soil engineer is used to assure that the bearing capacity conform to the design and specifications.

The suggestion and recommendation herein are based on available data obtained from limited specified soil information, the homogeneity of soil formation assumption, and equations involved in the calculation, which are believed to be reliable. However, such prediction or recommendations should be verified by full-scale test of investigation during construction period to obtain more precise reliable data. Construction method must be adapted to best suit the analysis method assumption. We do not make any representations as to its accuracy or completeness. Any data or design criterion is only current solutions which are subjected to change or revision.

This report has been prepared in order to help the engineer in the evaluation of the site conditions only, to assist the engineer for designing the project based on our understanding of the detail design, criteria & utilization of the project as outlined herein. If our understanding of the design and utilization is not acceptable, we should be promptly informed of the correct data, and then we may revise our recommendations as appropriate as needed.

Appendix:

Summary of Laboratory Testing Results (BH-1)

Figure 1 to 2   : Maps and Location Plans

RESEARCH AND DESIGN ENTERPRISE
SOIL TESTING LABORATORY

SUMMARY OF LABORATORY TESTING RESULTS

BOREHOLE No **1**

Date: 16/01/2

Sheet No

Project name: House Project.
Site: Phum Borey 100 Khnorng, Sangkat Tek Thla, Khan Russey Keo , Phnom Penh.

SAMPLE	DEPTH		DESCRIPTION OF STRATA	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION			UNDRAINED SHEAR STRENGTH Direct Shear		UNDRAINED SHEAR STRENGTH Unconfined compression	UNDRAINED SHEAR STRENGTH Field vane test	UNDRAINED SHEAR STRENGTH Pocket penetration	SPECIFIC GRAVITY	SOIL CLASS	VOID RATIO	CONSOLIDATION Cosolidation coef	CONSOLIDATION Compression Index	CONSOLIDATION Young's modulus
No	From	to		W	WL	WP	IP	IL	γ	γd	M&C	Sand	Gravel	C	ϕ	Cu	Cu	Cu	Gs		e	Cv	Cc	E
	(m)			%	%	%	-	-	KN/m^3	KN/m^3	%	%	%	kN/m^2	Degree.	kPa	kPa	kPa				m^2/s	1/ kPa	Kpa
-	0.00	4.50	Made ground	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1			Yellow very loose Clayey SAND(SC)	18.03	43.42	19.78	23.64	< 0	18.00	15.25	41.77	58.23	-	-	27	-	-	-	2.70	SC	0.77	-	-	8500
2	4.50	6.00	Brown stiff Lean CLAY(CL)	21.64	46.52	24.56	21.97	< 0	20.00	16.44	100.00	0.00	-	-	-	109	125	-	2.70	CL	0.64	-	-	19000
3	6.00	7.60	Grey very stiff Lean CLAY with Sand (CL)	18.14	19.83	11.20	8.63	0.80	20.00	16.93	76.62	23.39	-	-	-	-	75	-	2.70	CL	0.59	-	-	19000
4	7.60	8.50	Grey stiff Lean CLAY(CL)	23.62	23.89	15.49	8.40	0.97	20.00	16.18	100.00	0.00	-	-	-	-	85	-	2.70	CL	0.67	-	-	19000
5	8.50	9.80	Yellow stiff Sandy Silty CLAY(CL-ML)	13.91	16.69	11.60	5.09	0.45	20.00	17.56	51.27	48.73	-	-	-	-	111	-	2.70	CL ML	0.54	-	-	20000
6	9.80	11.50	Red hard Sandy Lean CLAY(CL)	14.51	33.29	19.87	13.42	< 0	20.00	17.47	50.82	49.19	-	-	-	-	208	-	2.70	CL	0.55	-	-	37000
7	11.50	13.00	Red dense Clayey SAND(SC)	12.02	37.07	20.08	16.99	< 0	20.00	17.85	30.60	69.41	-	-	39	-	-	-	2.70	SC	0.51	-	-	32500

Boring activity

2.3 History of development of Geographic information system (GIS)

Geographic Information Systems (GIS) or Geospatial Information systems is a tool-set used for capturing, storing, analyzing, managing and presenting data that are linked to locations. Basically, GIS is the combination of cartography, statistical analysis, and database technology. GIS can be probably used in many applications such as geography, cartography, remote sensing, land surveying, public utility management, natural resource management, precision agriculture, urban planning,

2.3.1 History of Development

The first geographical information systems (GISs) were developed around 40 years ago to automate the production and the analysis of maps, and have since evolved from their origins (Coppock and Rhind, 1991). Before computers became widely available, the map-making process was tedious and time-consuming for the cartographer, and the analysis and interpretation of different themes for a given area was cumbersome because it had to be done visually (with the help of transparent map sheets layered one over another). Computers and GISs changed that during the 1960s. An example of one of the earliest GIS is the Canadian GIS (CGIS), which was developed to store, manipulate and analyze data collected by the Canada Land Inventory. The CGIS was probably the first large-scale system to structure geographical data in a database, to partition data into themes (map layers), and to have functions for the measurement of areas and for the overlay of polygons (Tomlinson, 1988); many of its key innovations are still being used in today‘s commercial GISs. The Canadian government still uses a similar system for the planning and management of its natural resources, but the system in place obviously has more power and a much broader scope.

2.4 Borehole data standard

There is no single standard type or format of soil boring log reports. It is because construction works and site investigations are conducted by many different governmental and nongovernmental organizations. For this matter, several different types of site investigation reports and borehole logs should be examined against possible problems such as discrepancy and redundancy in data items before the design of the standard and database of geological data. Example of amount and diversity of geological data shows in Figure 2.4. Geological data, especially borehole data, can endow with useful information about both surface and subsoil conditions of the earth; it can consist of various types of data: borehole records, topographical information, rock and soil data, geophysical data and hydrology. Importantly, Geographic Information System (GIS) may be the most efficient solutions for the management of geological data for the reason that most geological data are based on locations of the ground (Chang and Park, 2004).

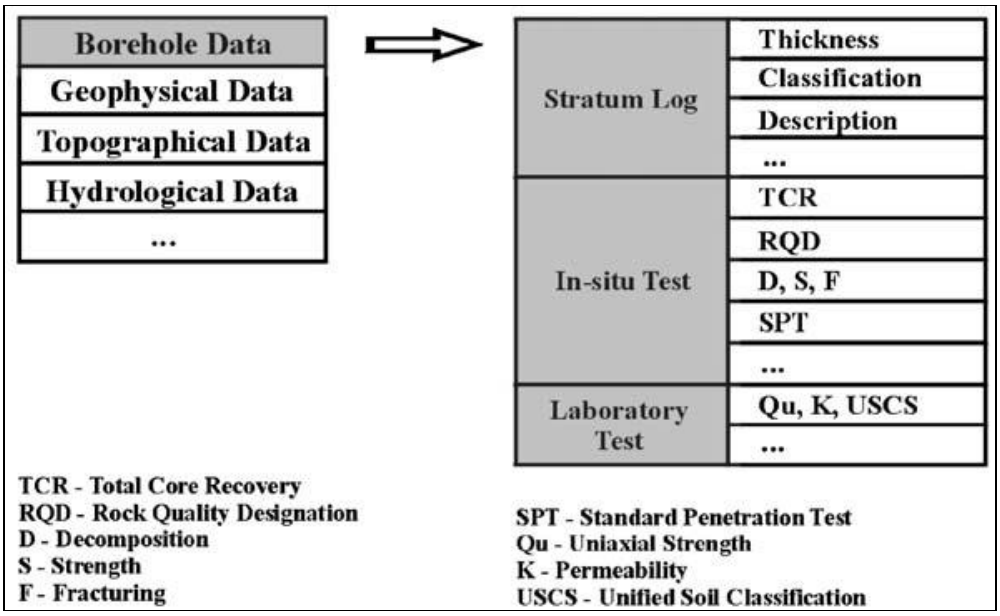


Figure 2.4 Example of amount and diversity of geological data

Chang and Park also mentioned that geological data from many construction projects should be standardized, structured, archived and properly used through suitable system and applications for efficient management especially in urban area because of limits from continuing urbanization. Moreover, each geological data has its own type, description, characteristic and source necessary to use database and GIS for management.

According to the experience of site investigation among various types of borehole data, borehole information can be classified into three categories:

- General information about individual borehole includes project description (project name and company), drilling (drilling method, equipment, date, purpose and name of drilling engineer), borehole location (coordinates and elevation) and geometry (drilling depth, ground water table, casing depth and hole diameter).

- Stratum information such as into rock and soil information. It includes the detail of stratum shape (thickness, depth and symbolic log).
- Tests and engineering properties which include color, field and laboratory testing.

Table 2.2, 2.3 and 2.4 are the examples of the borehole standard suggested by Korea Institute of Construction Technology (KICT) used as one of the borehole data standard in Korea.

Table 2.2 Details of stratum information of boreholes

Information of soil	Information of rock
Depth	Depth
Elevation	Elevation
Thickness	Thickness
Casing	Casing
Symbolic log	Symbolic log
Soil and rock type	Soil and rock type
Color	Color

Table 2.3 Details of sampling method and in situ tests of boreholes

Information of soil	Information of rock
SPTa	SPTa
TCRb/RQDc	TCRb/RQDc
Sample number	Sample number
Sampling method	Sampling method
Depth	Depth
Sample type	Sample type
Fracture log	Joints (weathering, strength, fractures)
Permeability	Drilling condition (velocity, rotations, leakage)

Table 2.4 Details of general information about boreholes

Information of soil	Information of rock
Sheet number	Sheet number
Project name	Project name
Client	Client
Hole number	Hole number
Location	Location
Coordinates	Coordinates
Elevation	Elevation
Date	Date
Hole depth	Hole depth
Ground water level	Ground water level
Drilling machine	Drilling machine
Drilling method	Drilling method
Drilling engineer	Drilling engineer
Inspector	Inspector
Casing depth	Drilling direction
	Drilling angle

Remarks: aSPT—standard penetrations test.

bTCR—total core recovery.

cRQD—rock quality designation.

Additionally, engineering properties from various tests in laboratory are also recorded in site investigation reports. Example of soil properties are as follow: water content, density, saturation, void ratio, permeability, Poisson‘s ratio, Young‘s modulus, direct shear test and seismic test (Chang and Park, 2004). Various laboratory tests are usually carried out using samples from boreholes in order to obtain important engineering properties for the site. The borehole data was typically stored in MsExcel spreadsheets (McCarty and Graniero, 2006).

2.5 Three-dimensional modeling

The use of geotechnical data for planning purposes has always required a three-dimensional (3D) viewpoint, and a large number of computer programs for geotechnical planning have been developed with this in mind. Computers have been used to store and output geotechnical data from the mid-1970s onwards (Lemon and Jonh, 2003).

Initially, the starting-point for a three-dimensional examination is a GIS-type database, usually consisting of binary files, although a relational database is preferable for the management of large amounts of data. This database contains detailed drilling, sampling and measurement information and 3D topology of the investigation points (Vihiiaho, 1998).

Artimo et al., 2002 have found that a few studies have focus on specific depositional setting of landform, for example eskers. Undergrounded geological and structural analysis has undergone a considerable evolution due to the use of three-dimensional reconstruction techniques: the conventional methods for geological reconstruction can be speeded up and rendered more precise by using computer and finding are useful in various engineering geological themes (Tirén et al., 1999; Pinto et al., 2002). Moreover, geological cross-sections with different orientations can be automatically created by starting from a 3D model which can present the geometry of the geological structure along the underground segments of the alignments. This can be used to provide correct geological information for perceptive technical and financial preliminary design (Vähäaho, 1998; Elkadi and Huisman, 2002; Hack et al., 2006).

To sum up, a sample solid model of a set of geologic units is shown in figure 2.5. Each component of the stratigraphy is represented by a separate solid. With a properly constructed set of solids, the boundaries of the solids all match precisely with no voids or overlaps. Solid modeling can be used to model stratigraphy at almost any level of complexity. Pinchouts, embedded seams and faults can all be directly represented in the solid model geometry (Lemon and Jone, 2003).

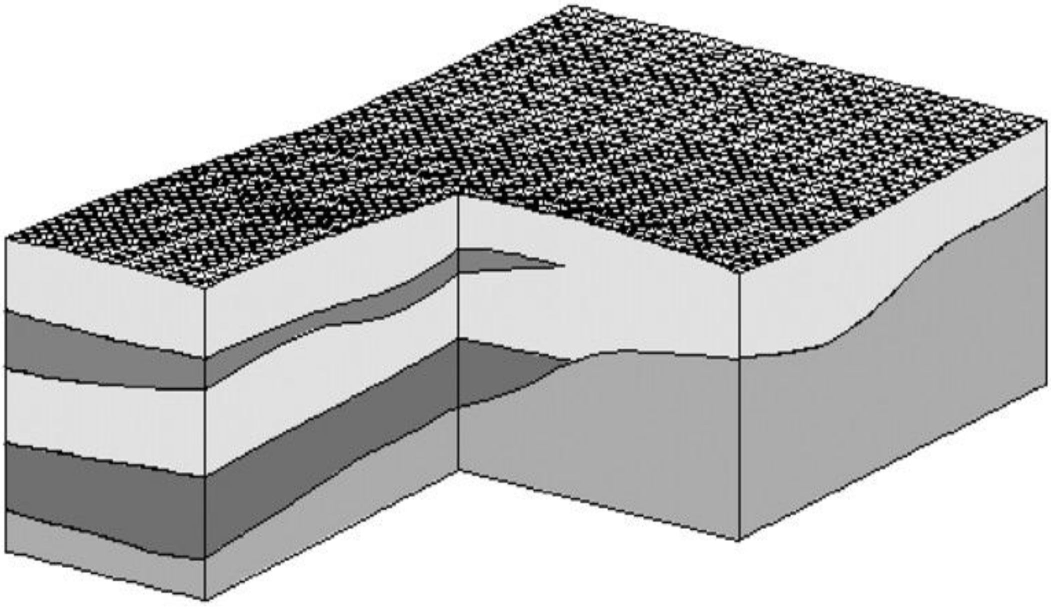
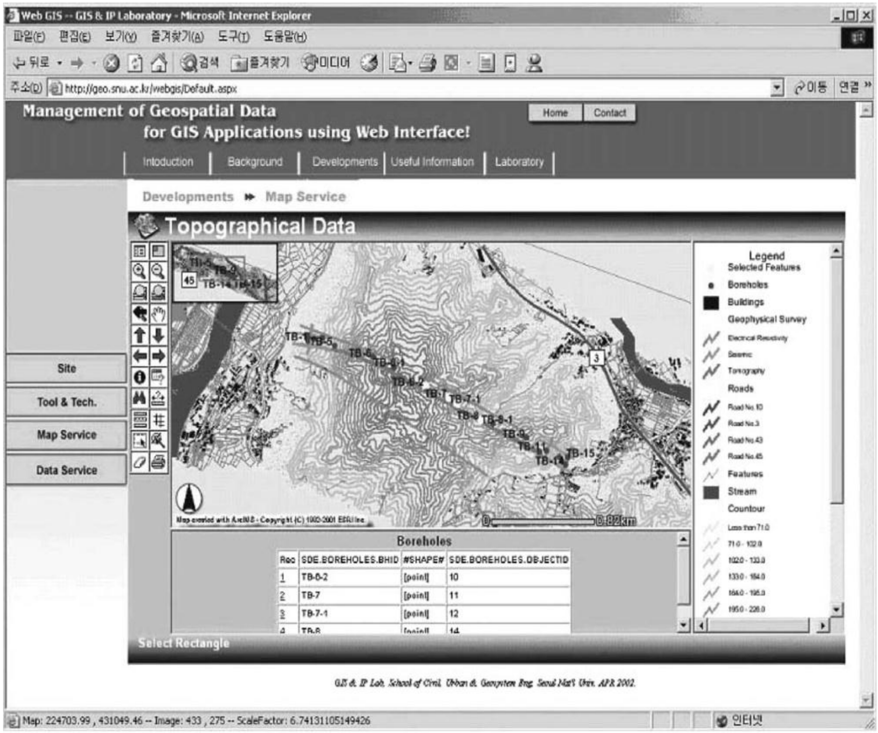


Figure 2.5 Sample solid models in cut-away view

2.6 Review of the previous studies on GIS

2.6.1 Web-based on geological modeling by KICT



(a)

Figure 2.6 Example of web-based Geographic Information System for the management of borehole and geological data

KICT (Korea Institute of Construction Technology) is a Web-based GIS system that deals with road, railway, and highway construction in South Korea as shown in figure 2.6. Nowadays, borehole data standard is operated while KICT was using 3D visualization system to run the Web-based system. Experimental tests are conducted for borehole logging which contains information of the borehole, project, strata information, sampling and in situ test results and properties. Thus companies are able to use essential data with ease and govern their projects properly (Chang and Park, 2004).

2.6.2 Geo Virtual Reality

As presented in figure 2.7, GeoVR (Geo Virtual reality) is a useful toolkit designed for interactive building up of virtual environments from existing GIS data (Huang and Lin, 1999, 2002; Huang et al., 2001). Virtual reality (VR) allows users to interrelate with and to explore 3D geological data. GeoVR is created to generate 3D VRML (Virtual Reality Model) models from 2D GIS data and to give user interface for interaction with GIS data on the Internet. It also provides 3D visualization, 3D analysis and VRML interaction. In GeoVR, it is possible to build 3D model from existing 2D GIS data.

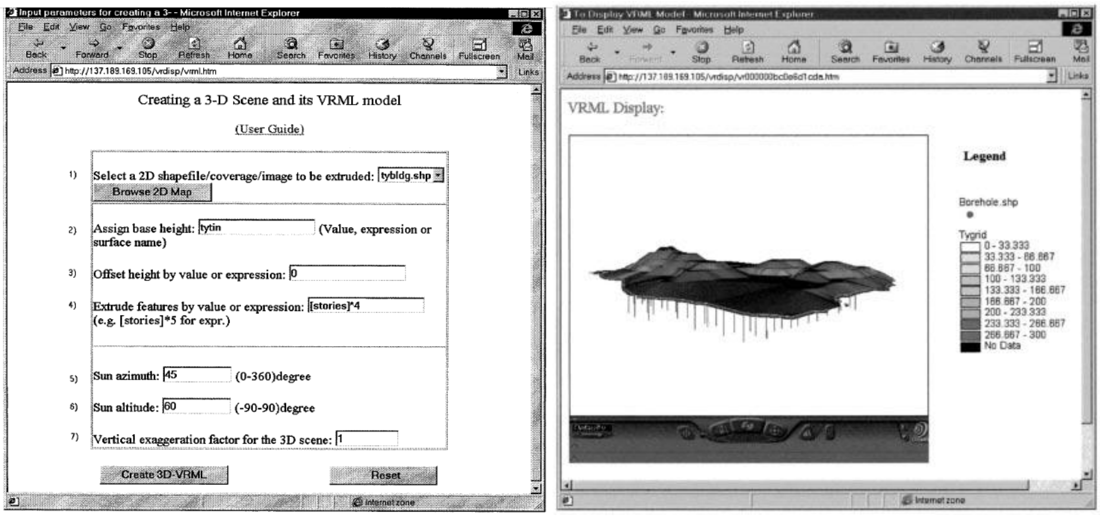


Figure 2.7 GeoVR (Geo Virtual reality)

2.6.3 Borehole Information System (BoreIS)

The Borehole Information System (BoreIS) was developed as an add-on toolbar in order to help for the management, visualization, querying, and analysis of borehole data building on ESRI(Environmental Systems Research Institute) ‘s established ArcScene 3D software which is a part of the ArcGIS software package. It is a simple conversion between ArcScene and BoreIS as long as the user is already familiar with GIS software. BoreIS is projected to give a subset of the functionality of larger enterprise-scale subsurface visualization systems with a streamlined set of features tailored for well and borehole data. Importantly, BoreIS interactively explores the user‘s data stored in Excel spreadsheets; a common format used by engineers to store and organizes their data. According to the use of the BoreIS data discovery wizard, the restructuring of datasets is minimized, saving time and reducing the risks associated with these types of change.

By loading the extension into the ArcScene environment as shown in figure 2.8, BoreIS will automatically add on to the existing extensive functionality of ArcScene. In conjunction with the BoreIS suite of tools, the user can use ArcScene‘s existing tools and capable with any custom tools they may have already developed. This meant that development was mainly focused on the creation of new features. Existing operations such as shapefile creation and symbology definition, which are ordinary to a knowledgeable GIS user but may be problematic for a beginner, are handled automatically by BoreIS (McCarthy and Graniero, 2006).

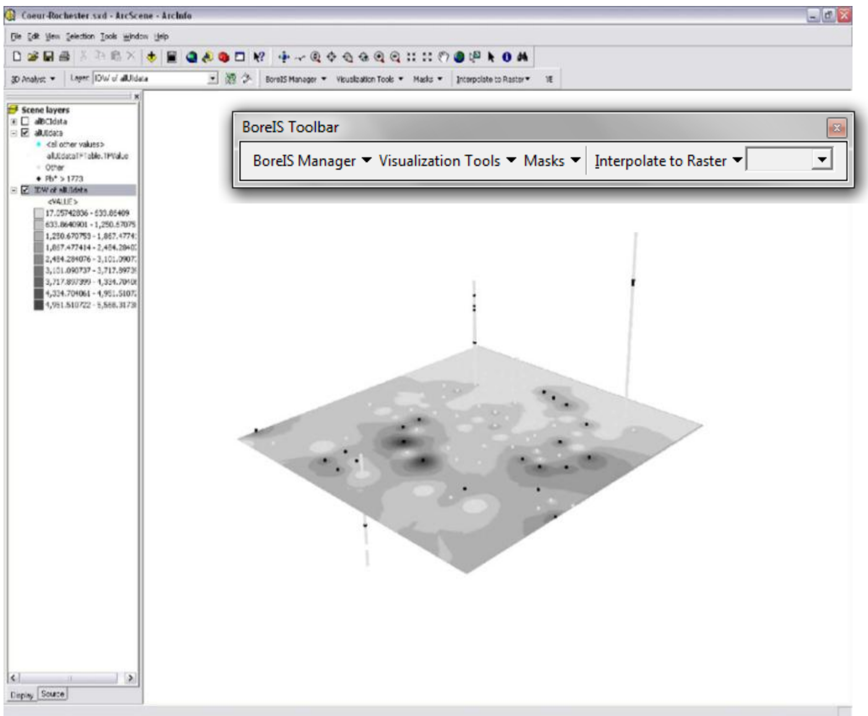


Figure 2.8 BoreIS tool in Arcsence

2.7 Groundwater Modeling System (GMS)

The GMS software is commercially available from Environmental Modeling System, Inc. As GMS was specifically developed for environmental engineering, it has an extensive tool to create three-dimensional models of geological sites which is also useful for geotechnical modeling illustrated in figure 2.8 and figure 2.9 (Njamnsi, et al., 2008).

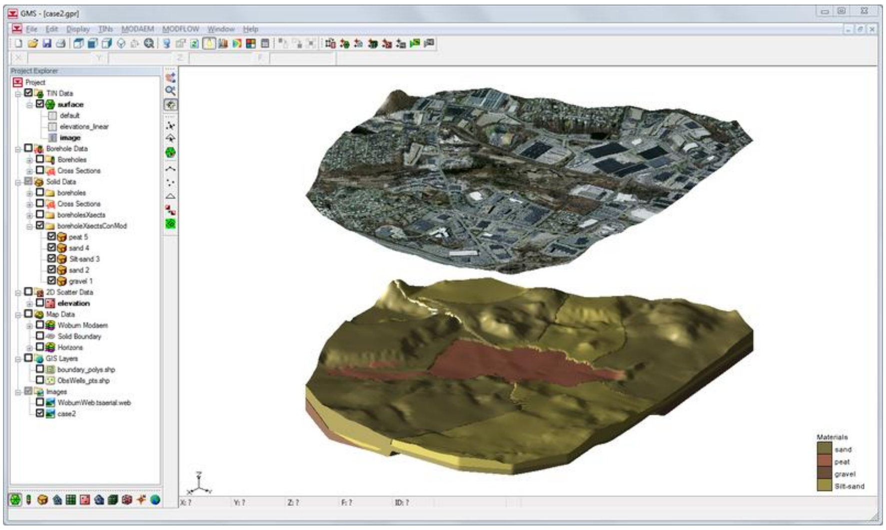


Figure 2.9 Subsurface modeling using GMS

GMS was designed as a comprehensive modeling environment. Several types of models are supported and facilities are provided to share information between different models and data types. Tools are provided for site characterization, model conceptualization, mesh and grid generation, and geostatistics (GMS, 2010).

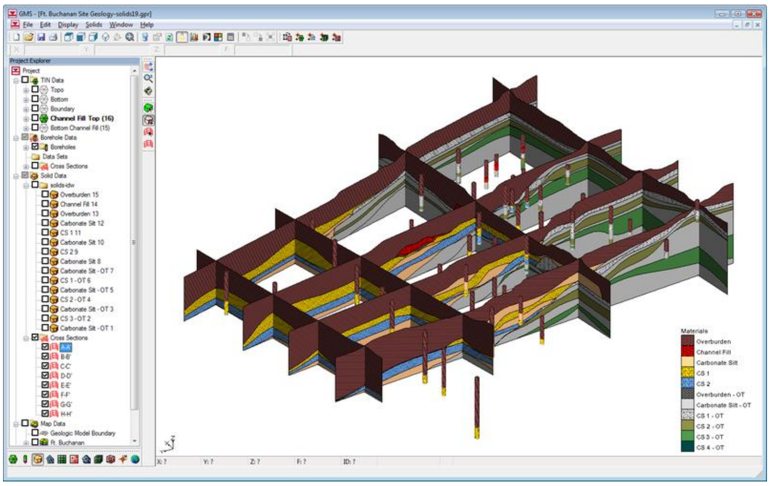


Figure 2.10 Subsurface cross-section using GMS

The main purpose of GMS is to provide a complete tool for the groundwater modeler. It is designed to provide tools throughout all aspects of the modeling process, some of which include geometric characterization of earth masses, geo statistical analysis, finite element and finite difference mesh generation, model input for specific flow and transport analysis engines as well as complete three-dimensional visualization of results. This paper covers some of the main components of GMS, addressing how this new tool is applicable to the groundwater modeling process.

There are several modules used in GMS which will allow the user to escape from subsurface problem as shown in table:

Table 2.5 Description of modules used in GMS:

Module	Name Description
TIN	Tools for building and editing triangulated irregular networks
Borehole	Tools for viewing and manipulating borehole data
Solid	Tools for constructing solid models of geologic units
2D finite element mesh	Tools for building and displaying a 2D finite element mesh
2D finite difference grid	Tools for building and displaying a 2D finite difference grid
2D scattered data	2D interpolation and geostatistical tools
3D finite element mesh	Tools for building and displaying a 3D finite element mesh. Pro/post-processing for 3D finite element code
3D finite difference grid	Tools for building and displaying a 3D finite difference grid. Pre/post-processing for 3D finite difference code
3D scattered data	3D interpolation and geostatistical tools

2.7.1 Stratigraphy modeling

The borehole, TIN and solids modules within GMS provide tools for modeling the three dimensional stratigraphy of a region. Jones and Wright describe some of the solid modeling techniques provided with GMS and how they are applicable to site characterization. GMS provides modeling tools that have been designed specifically for defining surfaces and solids of geologic origin. The program will accept field data in the form of borehole logs and allow the user to process the data to directly define a solid model (GMS, 2010).

The Borehole module of GMS can be used to visualize boreholes created from drilling logs. Also three-dimensional cross sections between boreholes can be constructed. These cross sections show the soil stratigraphy between two boreholes. Once a set of cross sections is built, they can be displayed in 3D space to help characterize and visualize the soil stratigraphy at a site (GMS, 2010).

2.7.2 Set operation approach

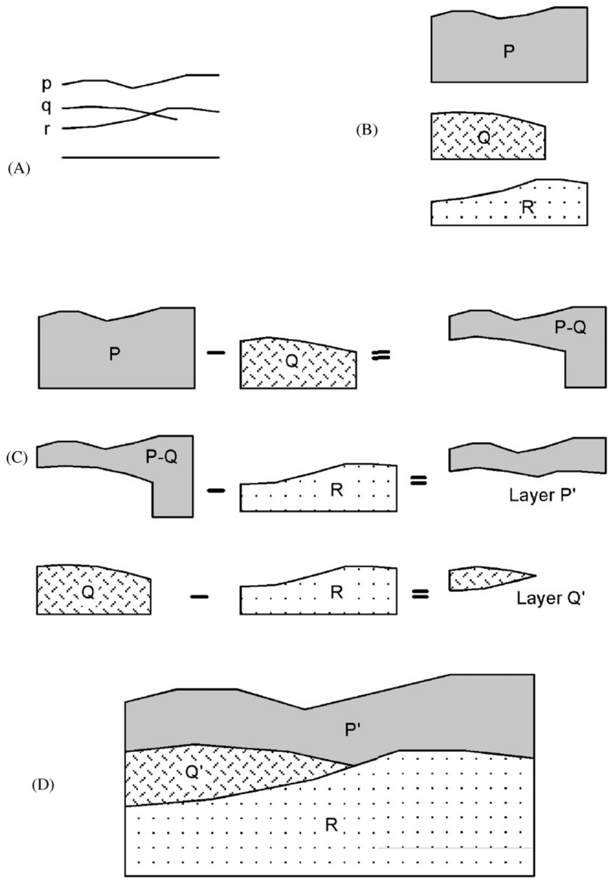


Figure 2.11 Set operations approach for building solid models: (A) TINs representing tops and bottoms of geologic units, (B) primitive solids produced by extruding TINs, (C) set operations used to modify primitive solids, and (D) final solids resulting from set operations.

While solid models have a variety of applications, constructing solid models of complex stratigraphy can be challenging. One method that has been used considerably is the ‗set operations'' approach illustrated in figure 2.11. In the first step of the process, triangulated irregular networks (TINs) are created at the tops and bottoms of geologic units (Figure 2.11A). In the next step, the TINs are extruded vertically to build primitive solids (Figure 2.11B). The overlapping primitive solids are then modified using set operations (Figure 2.11C) to generate the final non-overlapping solids (Figure 2.11D).

2.7.3 Horizon Method for 3D Geological Modeling from Borehole

The ‗solid modeling‘‘ approach has been investigated by several researchers as a tool for constructing three-dimensional models of geologic structures (Bak and Mill, 1989; Bayer and Dooley, 1990; Fisher and Wales, 1990; Gjoystdal et al., 1985; Jones et al., 1993). The solid modeling approach was originally developed for representing three-dimensional objects in the Computer- Aided Design/Computer-Aided Manufacturing (CAD/ CAM) industry (Braid, 1975; Krouse, 1985; Mantyla and Tamminen, 1983). The solid modeling approach completely and unambiguously defines the volume of a three-dimensional object. Solid models can be manipulated via set operations.

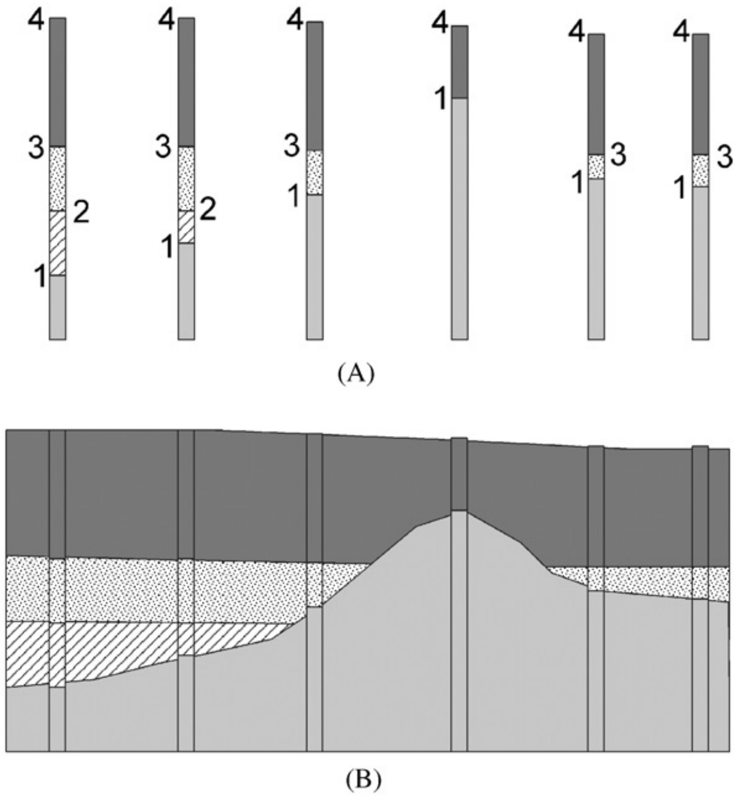


Figure 2.12 Horizons concept: (A) Horizon ID‘s assigned to borehole contacts, and (B) Solids resulting from horizon assignments made in (A).

The horizons concept is illustrated in Figure 2.12 set of boreholes with horizon id's assigned to the contacts shown in Figure 2.12A. The set of solids resulting from the horizon assignments is shown in Figure 2.12B. Conceptually, the solids are formed by an ordered extrusion process that proceeds from the bottom to the top, with the oblique view of boreholes set shown in figure 2.13.

3D geological modeling is often used to build solids for spatial information systems addressing environmental and geological problems. Lemon and Jones proposed the original horizons method in 2003 (Ming and Pan, 2009), which can be used to construct the solid models of geologic structures directly from boreholes and additional cross-sections data. The ―horizons-to-solids" algorithm, which only uses boring log data, consists of the following six steps: (i) define the primary TIN, (ii) assign horizon IDs, (iii) interpolate horizon elevations, (iv) intersect horizon surfaces, (v) adjust horizon elevations and (vi) build solids (Limon and Jonh, 2003).

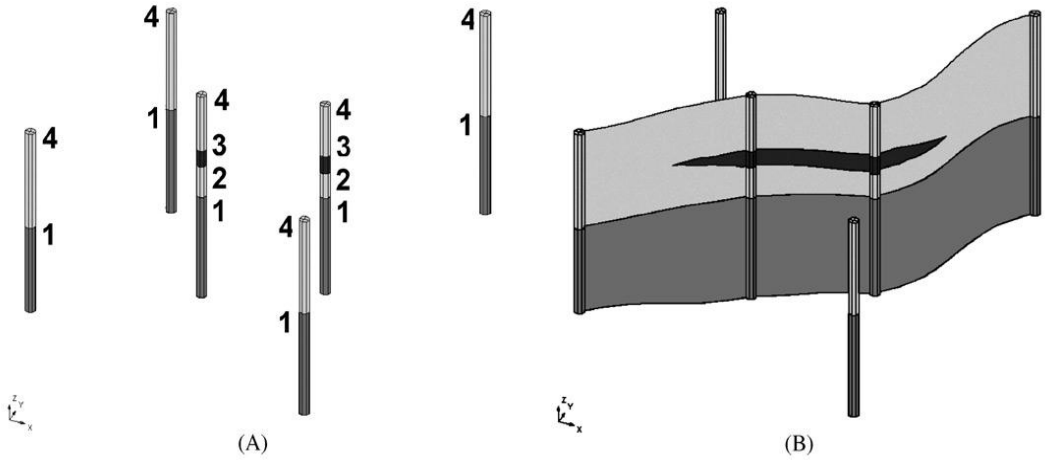


Figure 2.13 Example of horizons algorithm with cross-section data: (A) boreholes with assigned horizons, (B) user-defined cross-sections

2.8 Conclusion

From literature review aforementioned, it is viewed that there are several ways to store subsurface data using GIS within using add-on toolbar and related software. The 3D modeling is popular topic for new technology as there are many complex structures which are hard to understand. For three-dimensional modeling of Phnom Penh subsoils, horizon method proposed by Lemon and Jones (2003) is chosen to build a solid method with some hypothesis from human knowledge according to some geological background and soil boring log information. In general, subsoil is varied naturally by nature phenomena. Horizon method is flexible because there is a correlation between the solid and the boreholes by cutting cross-section exactly at the boreholes.

CHAPTER III
RESEARCH METHODOLOGY

3.1 General

This chapter will explain the method used in this research study after getting some ideas regarding the research objective. Importantly, this Chapter presents the methodology in order to create three-dimensional subsurface geological modeling based on the theory of horizon method via groundwater modeling system (GMS) which follows steps of this method. Furthermore, some method of laboratory tests will be demonstrated in the second part of this chapter.

3.2 Data Collection

Figure3.1 Location of site investigation

There are two types of data collection which were collected in October, 2010 namely sand sampling and soil boring logs. First of all, sand sampling was collected at two sand investigation companies along the Mekong River in Phnom Penh city. Sand exploration is conducted at the riverbank by using exploration machine. After extracting sand, cleaning process was performed in order to separate type of sand. Generally, there are two types of sand which are chosen for the construction sector. The first sand categorized as the biggest is used for construction purpose. Meanwhile, the second type of sand which is smaller than the previous sand is used for fill material purpose. Another data collection is soil boring reports which were gathered from the year 2004 to the year 2010. Physical and geotechnical properties were included in these reports as well.

Figure 3.1 shows the location of sand investigation site along the Mekong River. The Mekong River is the largest and most popular river where the sand materials are taken to supply most of construction in Phnom Penh city. Sand is collected at the ground of the river by exploration machine.

3.3 Three-dimensional geological modeling of Phnom Penh subsoil

Three-dimensional geological modeling of Phnom Penh is the main purpose of this research study. There are several steps needed to conduct in order to develop a subsoil modeling such as data analysis, terrain processing as well as several step of horizon method.

3.3.1. Data analysis

❖ ***Soil boring log processing***

A number of site investigation reports and borehole logs were analyzed to reveal principal components among various borehole data. The data were chosen from different construction works covering around Phnom Penh city.

Table 3.1 describes the soil classification used in this study. In order to simplify the ground condition, only ten different soil types are used to represent all soil types found in the Phnom Penh subsoil. The soil identifications (IDs) must be assigned for each material and it is recorded in the program database.

Table 3.1 Soil classification most of Phnom Penh Subsoil

Soil Type		Soil ID
Made ground	Made ground	1
Sand	Very dense to Dense sand	2
	Medium dense sand	3
	Very loose to Loose sand	4
Clay	Very stiff to Stiff clay	5
	Medium Stiff clay	6
	Very soft to Soft clay	7
Silt	Hard silt	8
	Soft silt	9
Organic	Organic soil	10

An example of soil stratigraphy as shown in figure 3.2 is obtained from the soil boring log report and it was categorized by soil classification in table 3.1. These representative soil strata in each borehole will connect to each other via the same horizon ID. The soil layers then generate from the linear interpolation across the boreholes. The assigned number at the contact (the interface between two different materials) might help the program to track soil layering.

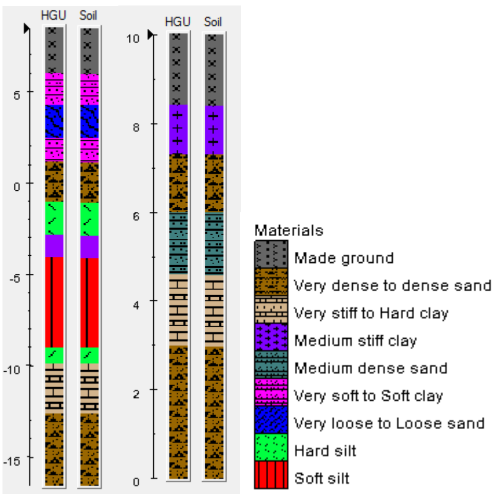


Figure 3.2 Soil stratigraphy sample

Remark: HGU: Hydrogeologic Units of borehole

1200 boreholes of Phnom Penh soil as shown in figure 3.3 have been uploading into GMS software. Most boreholes were located in downtown area; however, it is very hard to find borehole in urban area. This is because only a few construction projects happen in urban area.

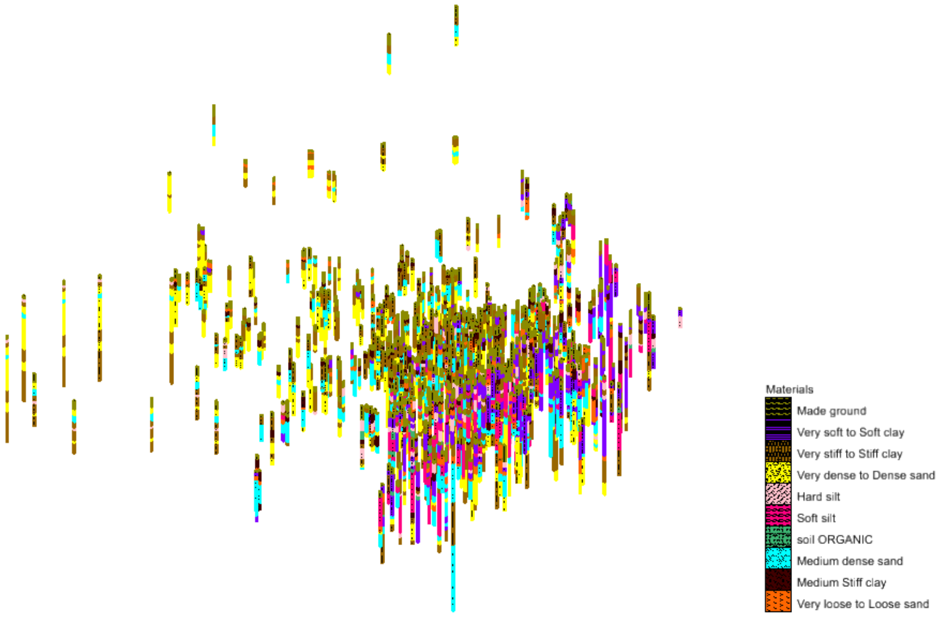


Figure 3.3 1200 boreholes over Phnom Penh city

3.3.2. Terrain processing

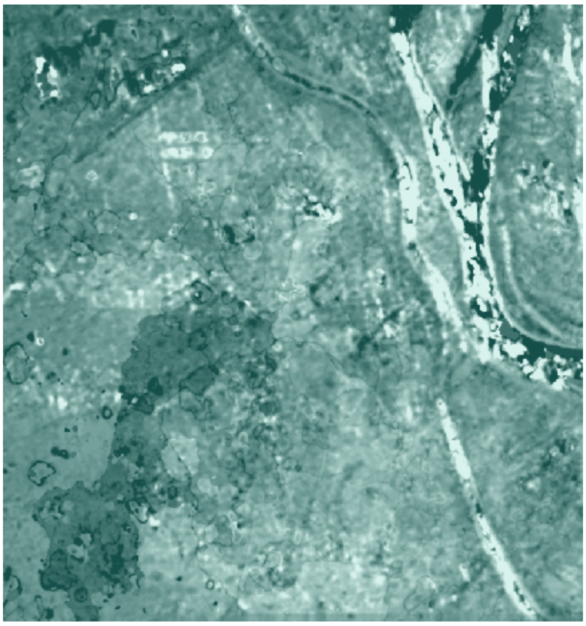


Figure 3.4 Aerial image map (The APSARA National Authority of Cambodia, 2003)

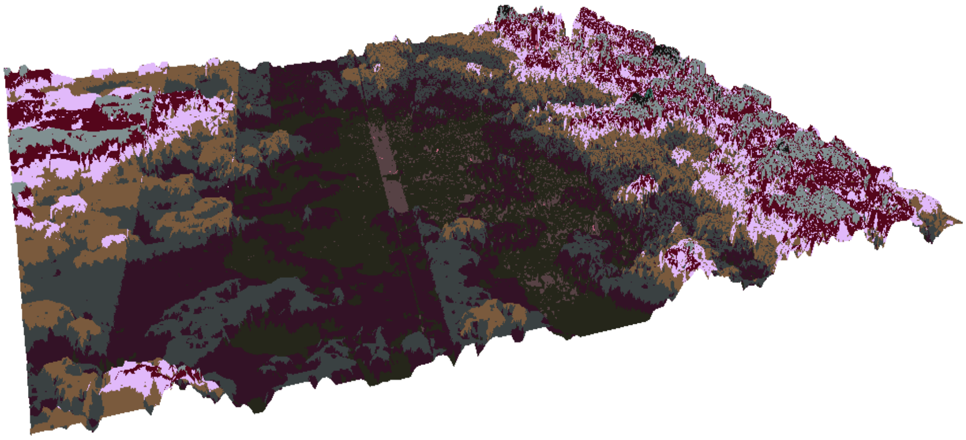
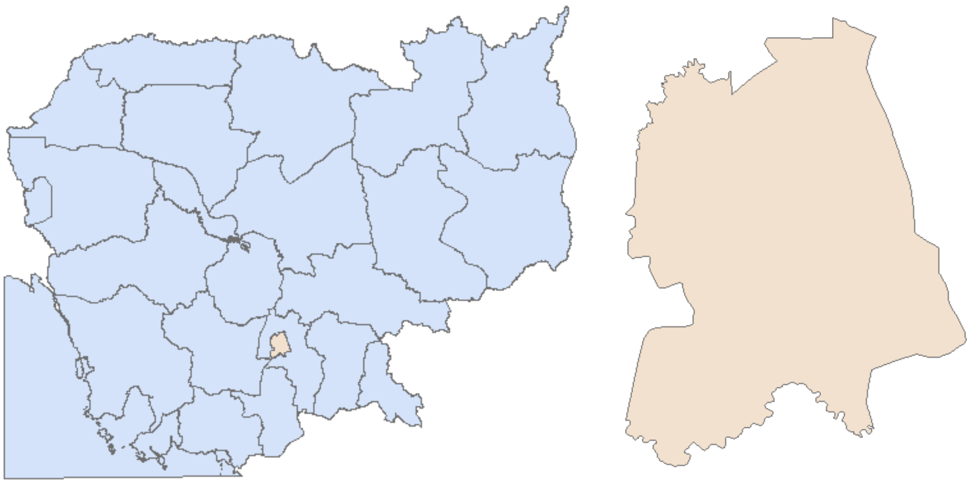


Figure 3.5 Aerial image map in oblique view (The APSARA National Authority of Cambodia, 2003)

Figure 3.4 and 3.5 respectively present an aerial image map and an elevation contour map of Phnom Penh city. They are from The APSARA National Authority of Cambodia. These maps are used for terrain processing in order to create the boundary, elevation and surface background.



(A) (B)

Figure 3.6 Base map geographic (A) Province map (B) Phnom Penh map after clipping (Cambodia geological department, 2005)

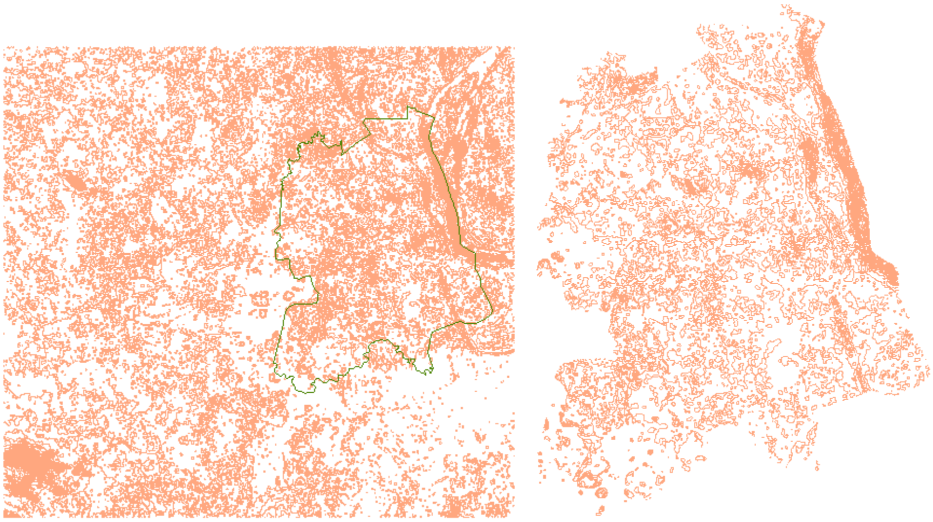
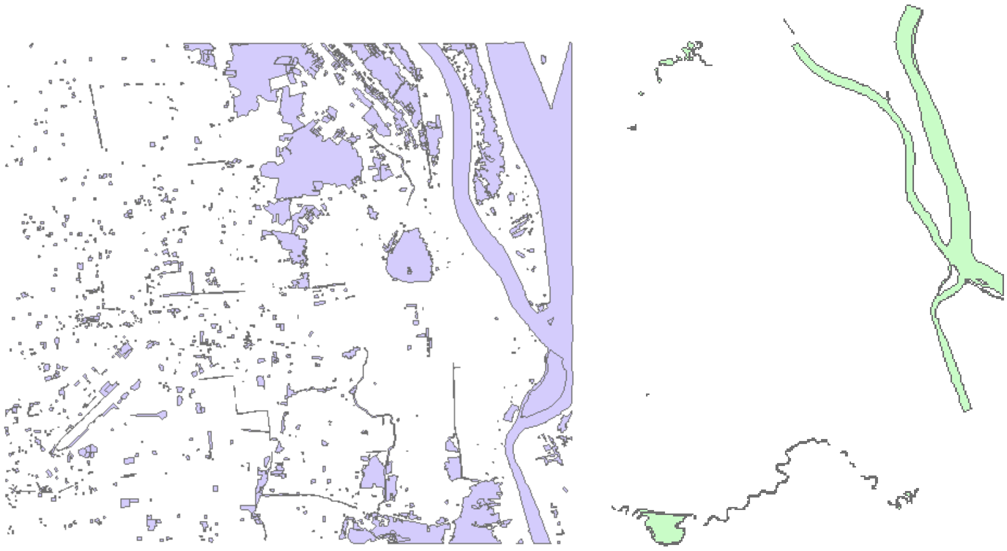


Figure 3.7 Base map geographic (A) Contour map (B) Phnom Penh contour map after clipping (The APSARA National Authority of Cambodia, 2003)



(A) (B)

Figure 3.8 Base map geographic (A) water map around Phnom Penh city (B) River map cross Phnom Penh city contour map after clipping (The APSARA National Authority of Cambodia, 2003)

Base map refers to map showing certain fundamental information and it also contains all the information regarding terrain data. There are many processes for terrain processing which are illustrated in figure 3.6, 3.7, and 3.8. From base map of Cambodia, Phnom Penh city boundary was clipped for boundary of geological subsurface modeling. Furthermore, contour map is used for elevation of the boreholes as well as the top surface of Phnom Penh subsoil solid modeling. As Phnom Penh city is located at the confluence of three rivers, Mekong River, Tonle Sap and Bassac River, the location of these three rivers needs to take into account this solid modeling. From figure 3.7(A), there are many locations for water area including river, small lack and reservoir. On the other hand, small area related to the water location is ignored in this study in order to simplify the model. As a result, only Main River as shown in figure 3.7 (B) is included in the further process of this research study.

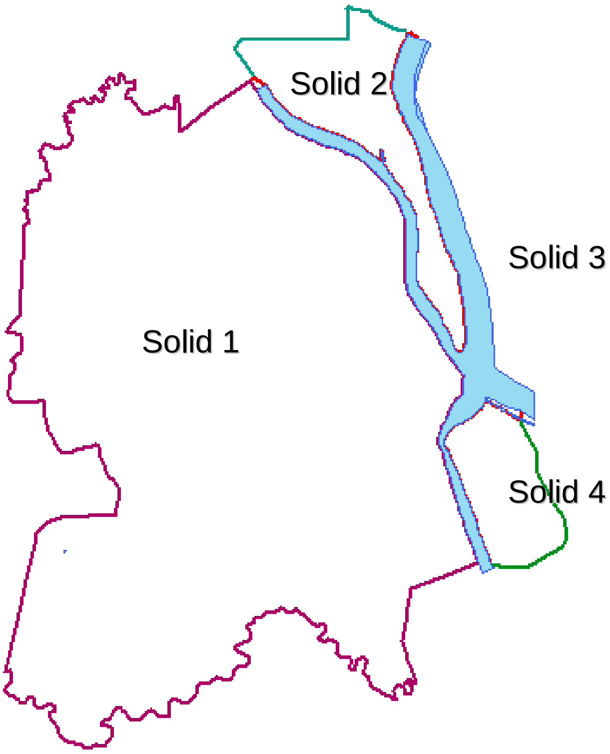


Figure 3.9 Boundary of solid model for the whole Phnom Penh city

After some processing of clipping the boundary for solid model, figure 3.9 presents the final result for the number of solid which will be created for the whole Phnom Penh city. Additionally, figure 3.10 also presents the boundary of solid of each district and the results will be shown in the next chapter.

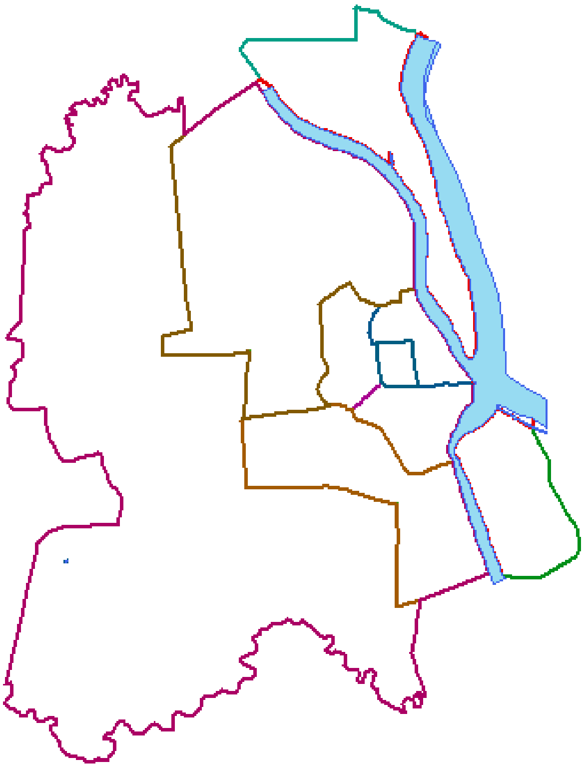


Figure 3.10 Boundary of solid model for each district

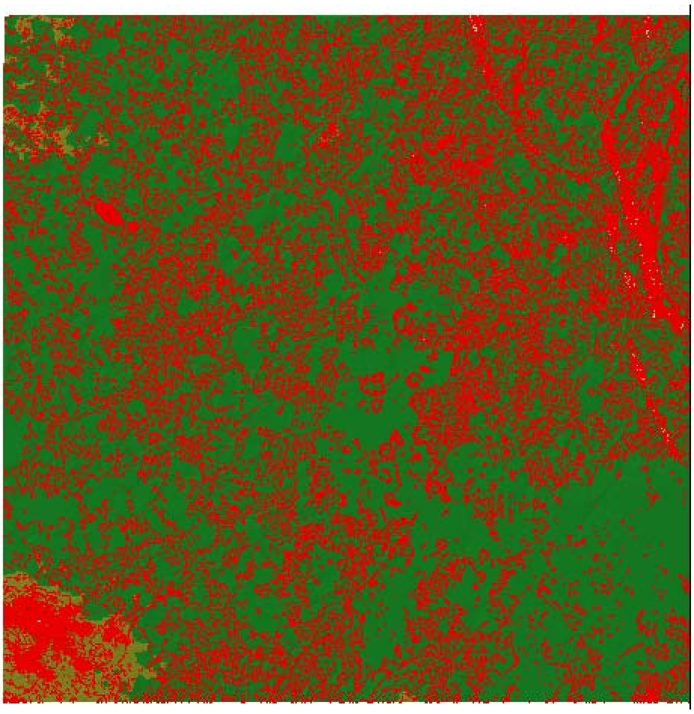


Figure 3.11 Triangular Irregular Network (TIN) map of Phnom Penh city (The APSARA National Authority of Cambodia, 2003)

Triangular Irregular Network (TIN) map of Phnom Penh city as presented in figure 3.11 is built from contour map in order to read each borehole elevation. From the TIN file, any elevation which is inside the Phnom Penh boundary is able to be read to understand some other geological conditions.

3.3.3. Groundwater Modeling System (GMS) software

Groundwater Modeling System (GMS) software is used for data preparation and analysis as well as modeling. As mentioned, the GMS is selected to build ground models in this research. Importantly, GMS is a graphically based software tool providing facility through all aspects of the groundwater flow and transport modeling process. Facilities also include geometric modeling, 2 and 3 dimensional mesh generations, graphically based model input for specific flow and transport codes, interpolated to complete three-dimensional scientific visualization.

❖ ***Horizon to Solid***

The steps defined below represent the horizons approach applied to borehole data only. The modifications required to the algorithm in order to support cross-sections in addition to the borehole data are described in the next section.

Step 1: Assign horizon IDs. The first step in the process is to assign horizon IDs to the borehole contacts. A horizon is defined as a surface representing the top of a geologic unit in a depositional sequence. Conceptually, the solids are formed by an ordered extrusion process that proceeds from the bottom to the top.

For example, a surface is created firstly by interpolating all of the contacts with a horizon IDs equal to 1. At the time, the solid corresponding to this horizon 1 is then found by extruding the resulting surface down to a bottom elevation. Furthermore, a second horizon surface is also formed by interpolating the contacts with a horizon ID=2. This horizon surface is extruded down to the top of the solid for horizon 1. In some regions of the site, the surface for horizon 2 will be below the top of the solid for horizon 1. This is because the solid for horizon 2 is clipped at the intersection of the surfaces for horizons 1 and 2 so that it does not extend into these regions. Generally, each horizon is extruded down to a surface which represents the topmost profile of all of the preceding horizons. As noticed that there is no limit of number of horizons IDs that may be used. Moreover, if a horizon has an ID of zero, the corresponding contact will be ignored in the extrusion process. This makes it possible to ignore small seams in the borehole data that are not sufficiently significant to be explicitly represented in the final model.

Figure 3.12 is an example of horizon ID constructed for the contacts of each borehole. Finally, volume of soil layer is created according to horizon IDs from each borehole as shown in figure 3.13.

Figure 3.12 Boring logs after assigning horizon IDs

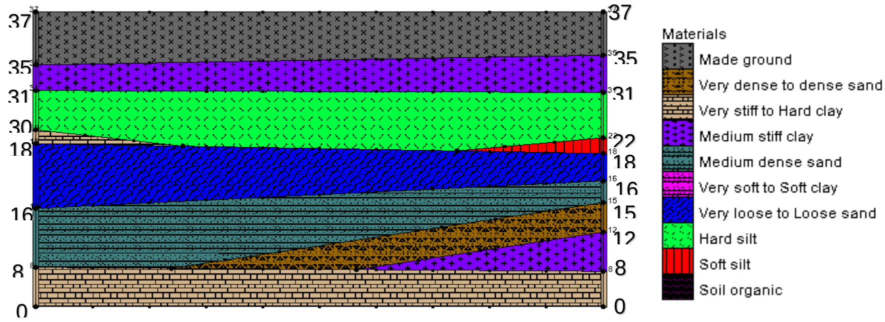


Figure 3.13 Example of layer connection of soil strata

Step 2: Define the primary TIN. The second step is to define the ‘‘primary TIN’’ using a standard triangulation algorithm (Field, 1991; Lawson, 1986; Watson, 1981). The primary TIN serves two basic purposes: (1) It defines the outer boundary of the solids, and (2) it is used to establish the topology of the solids. The faces defining the volume enclosed by a solid model are composed of triangles. The primary TIN defines a common triangle topology or ‘‘template’’ that is used for extruding each of the horizon surfaces.

Figure 3.14 Triangular Irregular Network (TIN) map of Phnom Penh

Figure 3.14 shows Triangular Irregular Network (TIN) of Phnom Penh city for building solid boundary in this research study. It is noticed that this TIN does not contain any elevation; however, TIN illustrated in figure 3.15 represents the geological condition of Phnom Penh city containing set of surface elevation.

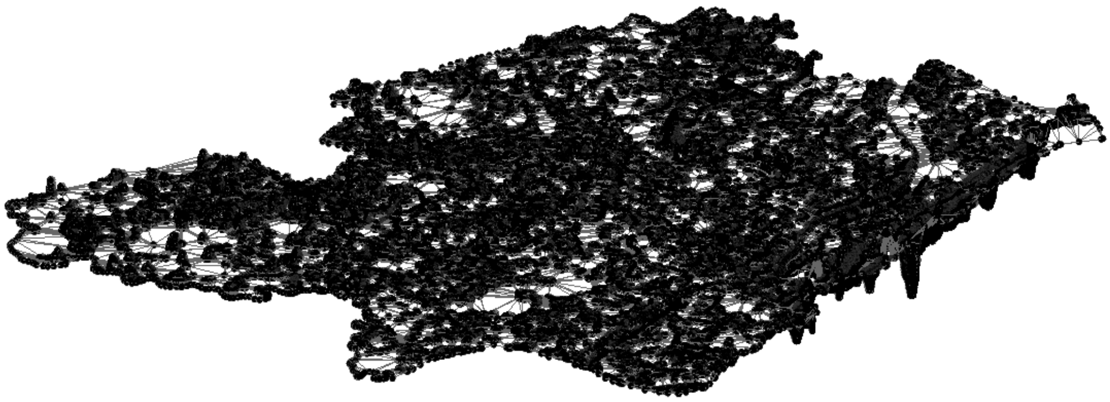


Figure 3.15 Triangular Irregular Network (TIN) map of Phnom Penh

Step 3: Interpolate horizon elevations. The third step is to interpolate the horizon elevations from the borehole contacts to the primary TIN to define the horizon surfaces. Conceptually, a simpler approach is to represent each horizon surface as a separate elevation array associated with the vertices of the primary TIN. In addition to the TINs defined by interpolating the horizon elevations, it is also useful to define two additional TINs: a top TIN and a bottom TIN. The top TIN is used to define the very top of the depositional sequence and it corresponds to the terrain elevations. In general, the top TIN is generally interpolated from digital elevation data. On the other hand, the bottom TIN typically represents the bedrock elevations.

Step 4: Intersect horizon surfaces. The fourth step is to intersect the TIN surfaces defining the horizons. Each TIN is intersected with each of the other TINs. Normally, intersecting two TINs can be a computationally expensive process since each triangle of one TIN must be checked against each triangle of the other TIN. However, since each of the horizon TINs have the same topology (they are identical in plan view), the intersection process can be significantly accelerated. This is because a triangle from the first TIN can only intersects the corresponding triangle from the second TIN.

Step 5: Adjust horizon elevations. The fifth step is to adjust the elevations of the different horizons on the primary TIN. By keeping the horizon concept of ‘‘bottom to top’’ described in Step 1, the elevation of a given horizon cannot go below the elevation of any of the lower horizons. For a given TIN vertex, it is needed to loop through each horizon from the bottom to the top. At each horizon, there is also a comparison the current elevation with the elevation of the next horizon which is higher. Therefore, if the elevation of the next horizon is below the current horizon then the elevation of the next horizon is set equal to the elevation of the current horizon. This process is needed to repeat for all horizons.

Step 6: Build solids. At this step, the horizon surfaces are extruded and the solids built. In the simplest approach, one solid is constructed for each horizon. Each solid is constructed by building a set of triangles defining the faces of the solid from the horizon surfaces. This includes a set of triangles at the top and bottom of the solid coinciding with the triangles of the primary TIN and it may include a set of vertical triangles on the outer boundary of the site connecting the top and bottom of the solid.

❖ ***Interpolation***

For sites with complex stratigraphy, defining layer data can be challenging when creating multi-layer models. Fortunately, GMS contains a suite of tools for interpolating and manipulating layer elevation data. With these tools, even complex geologic strata can be modeled quickly and easily (GMS, 2010).

Any interpolation scheme could be used to interpolate the horizon elevations. However, the selected scheme must support extrapolation. This is necessary since the primary TIN may cover an area larger than the convex hull of the boreholes. It is also helpful to use a relatively simple interpolation scheme since it makes it easier to automate the interpolation process.

3.4 Mekong River sand properties

- ***Size particle***

The materials used to conduct the test are sands from Mekong River at two different sites located in eastern part of Phnom Penh, wherein the sand commercial investment takes place. These two sites are located along the Mekong River which obtained from ground surface. Sand particles greater than 4.75 mm were taken out. The grading curves are presented in Figure 3.16.

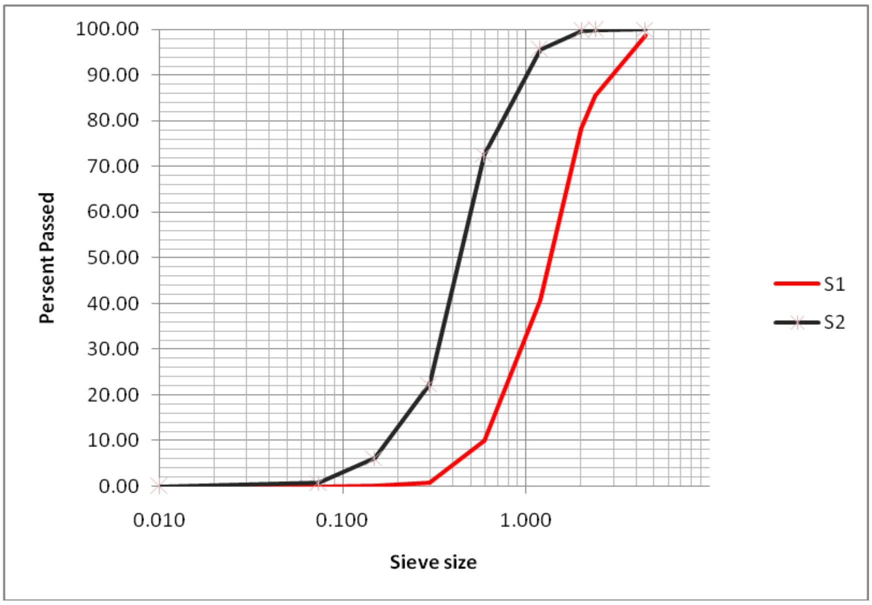


Figure 3.16 Gradation curve of Mekong River sand

- ***Specific Gravity (Gs)***

Specific gravity was conducted at geotechnical laboratory at Chulalongkorn University by using ASTM standard. The result of this experiment will be addressed in the next chapter.

❖ ***Void Radio (e_{max} & e_{min})***

Mekong river sand was taken to Toyko Institute of Technology (TIT) to do some more physical experiments such e_{max} & e_{min} and scanning electron microscope (SEM). In fact, Chulalongkorn University's laboratory also can conduct this kind of experiment except for SEM, but there was a PhD student needing to conduct these experiments on the properties of other sand and another reason is that these experiments are just the additional test in order to understand more about the fill materials.

❖ ***Scanning electron microscope (SEM)***

A scanning electron microscope (SEM) is one of electron microscope types which simply image a sample by scanning it with a high-energy beam of electrons in a raster scan pattern. The electrons can interact with the atoms that make up the sample producing signals that contain information about the sample's surface topography, composition (Wikipedia, 2010). For the purpose of this research study, SEM is conducted in order to illustrate the shape of the sand particles which is presented in the next chapter.

CHAPTER IV

RESEARCH RESULTS

4.1 Introduction

The research results which are shown in this chapter have been divided into three main categories respectively. The first part illustrates all the result about three-dimensional modeling which includes solid modeling, cross-section views subsurface of Phnom Penh subsoil for the whole area as well as by each district. In addition to the first part, there are also some more results regarding statistical analysis of geotechnical properties of Phnom Penh subsoil such as physical and geotechnical properties. Finally, the last part of this chapter concludes with some result of physical properties of Mekong River sand.

4.2 Three-dimensional geological modeling of Phnom Penh city

4.2.1 Dang Kao district

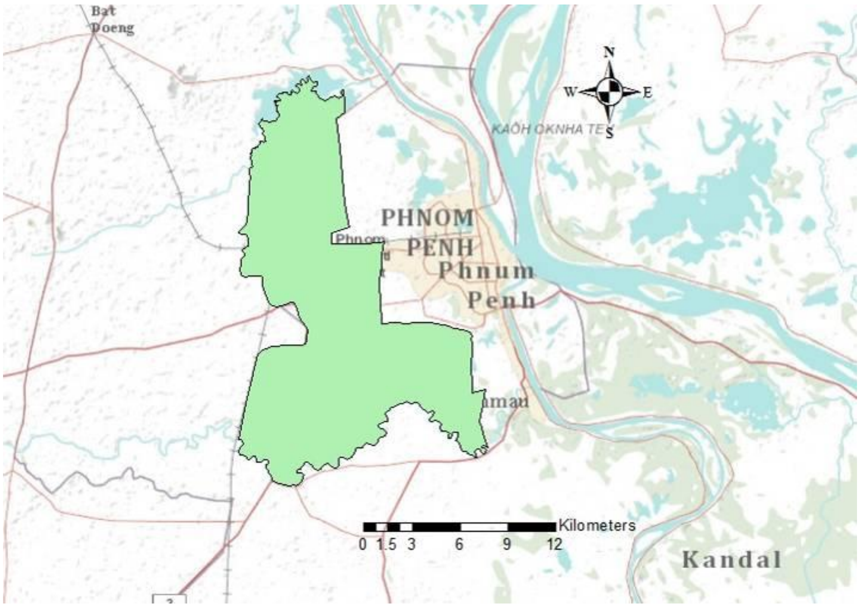


Figure 4.1 Dangkao District areas

Dangkao District is a district in the western part of Phnom Penh Municipality, Cambodia as shown in figure 4.1. It is the largest district of Phnom Penh. The district is subdivided into 15 arrondissements and 14 groups. The district has an area of 340

184,643 m^2. According to Phnom Pend Municipality, it has a population of 257, 724. Consequently, because Dangkao district is quite far from business area as well as the lack of soil boring log data, there was few gathering soil boring loges, which does not cover the area.

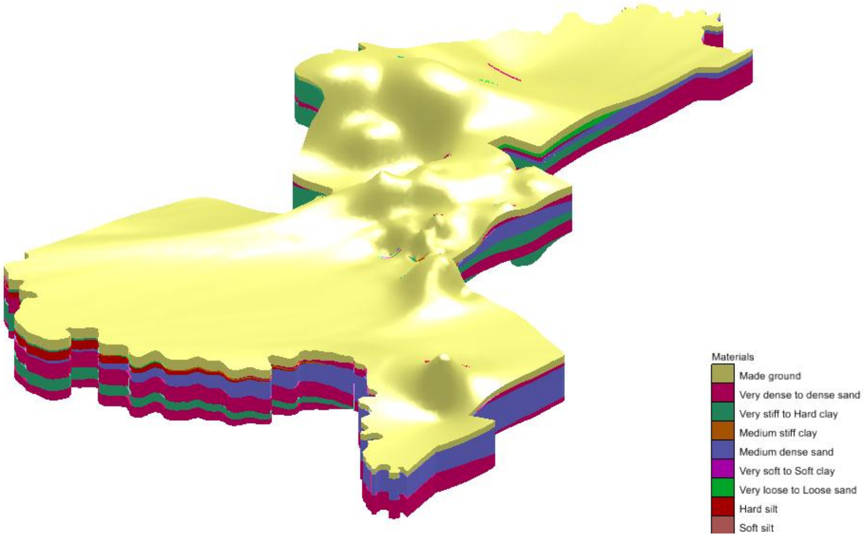


Figure 4.2 Solid model of Dangkao district in oblique view

Figure 4.2 (a) shows the solid model of Dangkao district in oblique view which is built from soil boring log data. Importantly, cross-section of this area is also cut in anywhere inside the solid boundary in order to interpret the variation of subsurface level which presents in figure 4.2 (b).

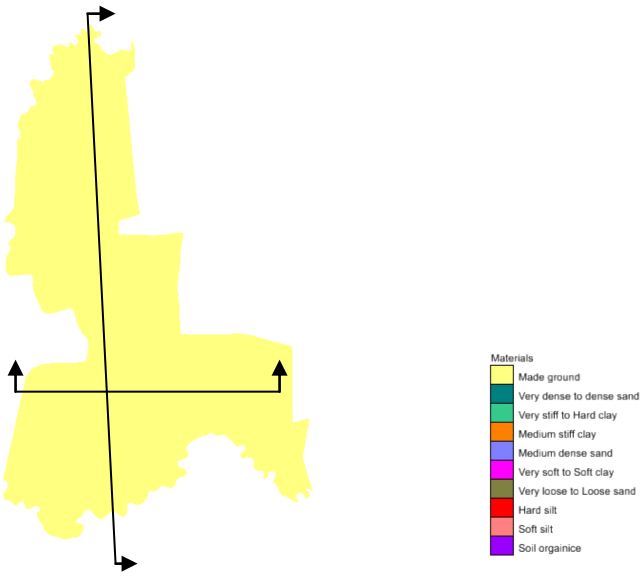


Figure 4.2 (b) Solid model of Dangkao district in plan view

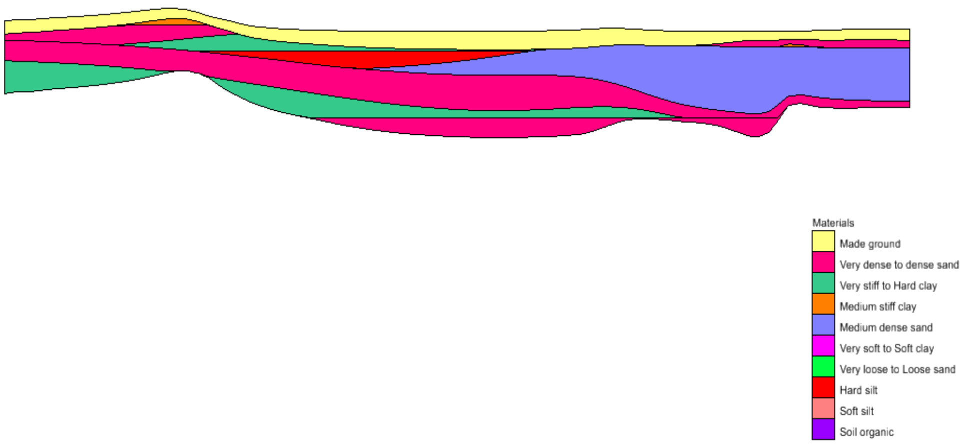


Figure 4.3 (a) West to East cross section subsoil profile of Dangkoa district

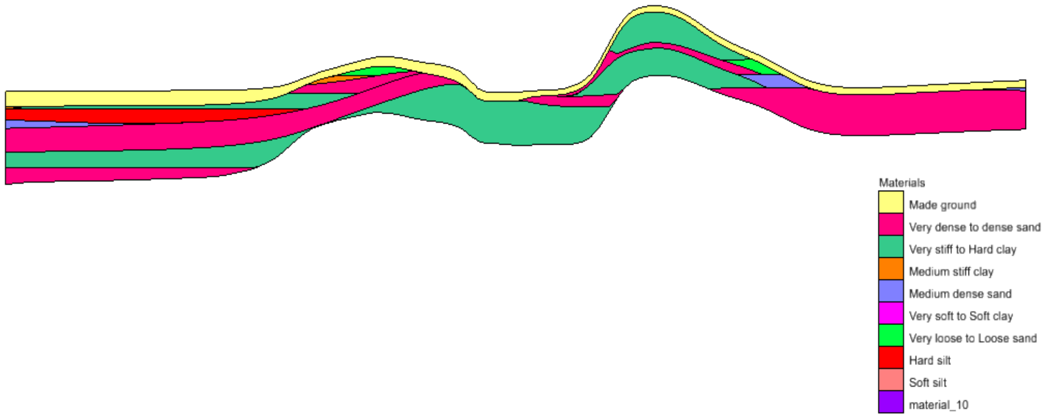


Figure 4.3 (b) North to South cross section subsoil profile of Dangkoa district

As presented in figure 4.3 (a) and (b), made ground is covered over the areas of cross-section view from North to South (N-S) and West to East (W-E) of Dangkao district. It is followed by very stiff to stiff clay, medium dense sand and hard silt from N-S view. On the other side of view, from W-E, underneath the made ground, it is also covered by very dense to dense sand, very stiff to stiff clay, hard silt and medium dense sand. Very dense to dense sand seems to appear as the third layer of both cross-section view following by very stiff to stiff clay one again. Because this cross-section is cut about 15 meters depth, it is viewed that the last layer of Dangkao district is very dense to dense sand.

4.2.2 Daun Penh District

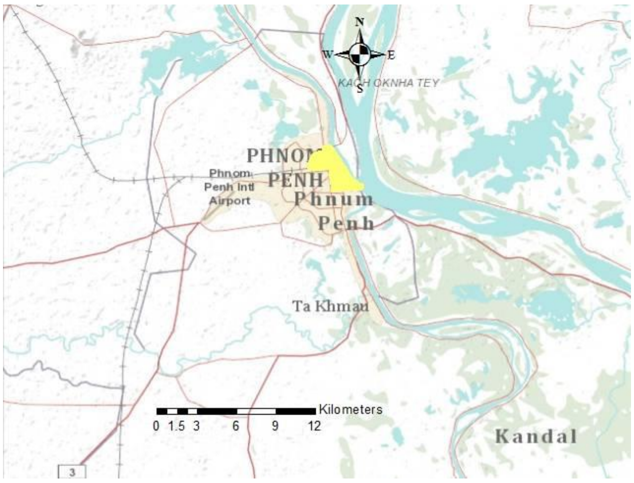


Figure 4.4 Daun Penh District areas

Daun Penh as shown in figure 4.4 is a major district in Phnom Penh, Cambodia. Many major business buildings of Phnom Penh city are located in this district. The district has an area of 7,412,767 m^2 with population of 126,550 and population density of 17,479 person/km^2. This district is the commercial hub of Phnom Penh, marked by Phsar Thom Thmei market with its unique art deco architecture and several major roads which emanate from and pass near the market under French Protectorates. The district is subdivided into 11 arrondissements and 134 groups.

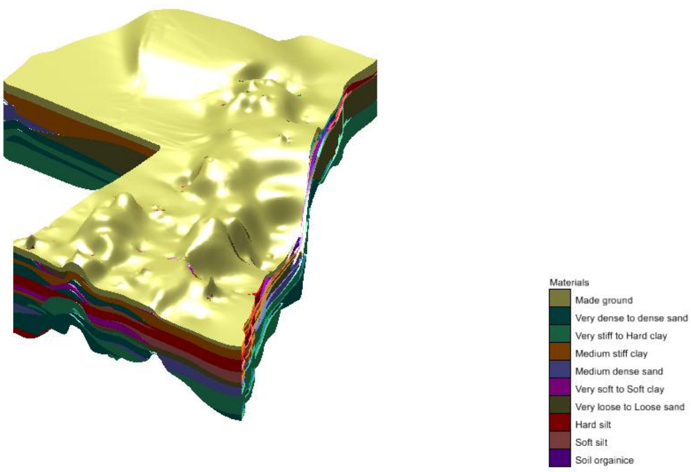


Figure 4.5 (a) Solid model of Daun Penh District in oblique view

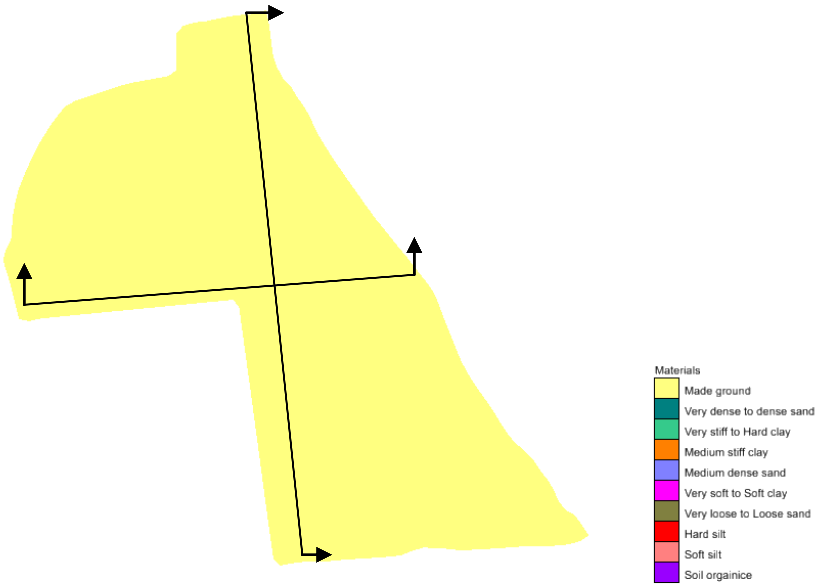


Figure 4.5 (b) Solid model of Daun Penh District in plan view

Three-dimensional geological modeling of Daun Penh district is built according to the geology information as well as soil boring logs gathered around the area as shown in figure 4.5 (a). Cross-section is cut according to the plan view as shown in figure 4.5 (b). Because Daun Penh district is located at the commercial zone, soil investigation has been performed in depth layer which is about 40 meters.

It is concluded from figure 4.6 (a) and (b) that the cross-section from north to south view of Doun Penh District seems to be complicated. There are several thin layers over the area. Made ground still takes place on the top of the surface.

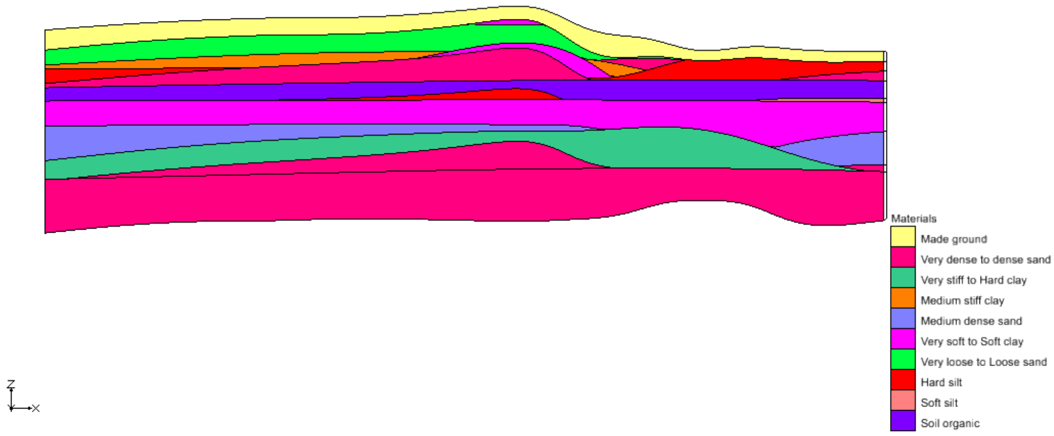


Figure 4.6 (a) West to East cross section subsoil profile of Daun Penh district

In West to East (W-E) cross-section as shown in figure 4.6 (a), below the made ground, a layer of very loose to loose sand is presented, but in some places, hard silt also appeared. There is a layer of very dense to dense sand above the soil organic. After the soil organic, very soft to soft clay is also presented as thick layer above the medium dense sand. Followed by the layer of very stiff to stiff clay, there is a very thick layer of very dense to dense sand as the bottom part of the cross-section.

North to South (N-S) cross-section presented in figure 4.6 (b), underneath the made ground is followed by the thin layer of very loose to loose sand and/or medium stiff clay. Underneath this layer, very dense and dense sand is also appearing below somewhere with organic soil. Furthermore, once again, very loose to loose sand is presented at the same depth as very soft to soft clay. Medium stiff sand is presented below the very loose to loose sand above very stiff to stiff layer. Finally, Daun Penh cross-section view from north to south ends up with layer of very dense to dense sand.

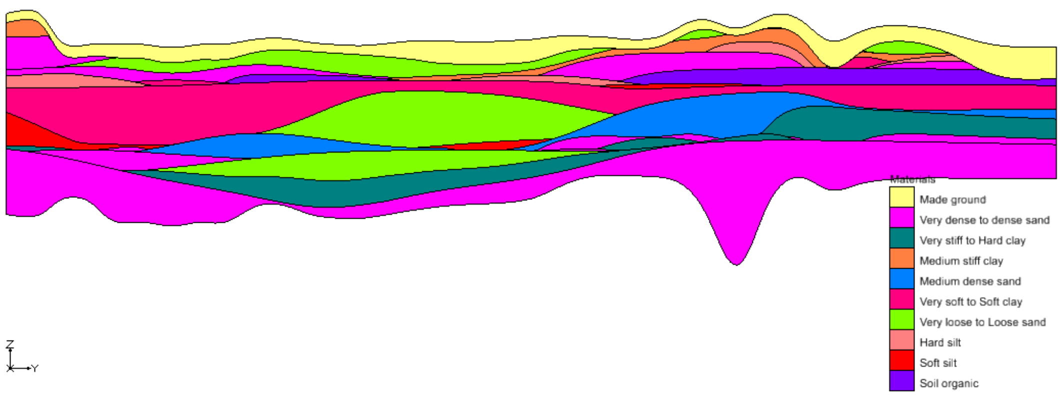


Figure 4.6 (b) North to South cross section subsoil profile of Daun Penh dirtict

4.2.3 Mean Chey District

Mean Chey District is located in the southeastern part of Phnom Penh, Cambodia illustrated in figure 4.7. The district is subdivided into 8 arrondissements and 30 groups. The district has an area of 44,000,448 m^2. According to the Phnom Penh Municipality, it had a population of 327,801 with population density of 2,951 person/ km^2.

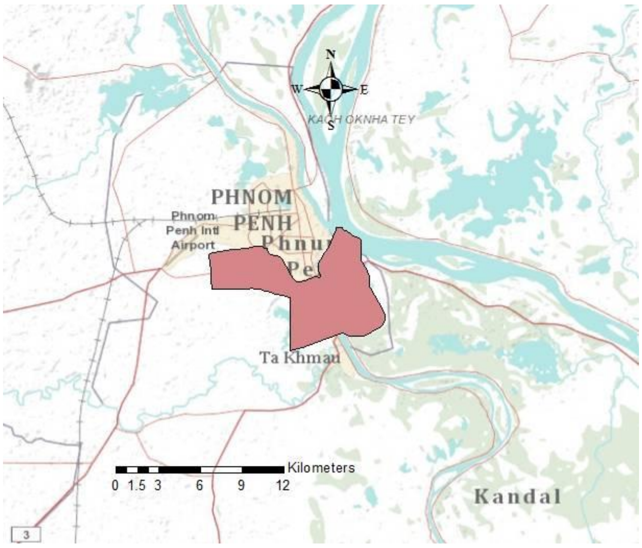


Figure 4.7 Mean Chey District areas

Because Bassac River is located in Mean Chey district, the solid modeling is divided into two solids with the left and the right hand side of the Bassac river in oblique view as presented in figure 4.8 (a). Consequently, it is view that made ground is the top surface of this solid modeling.

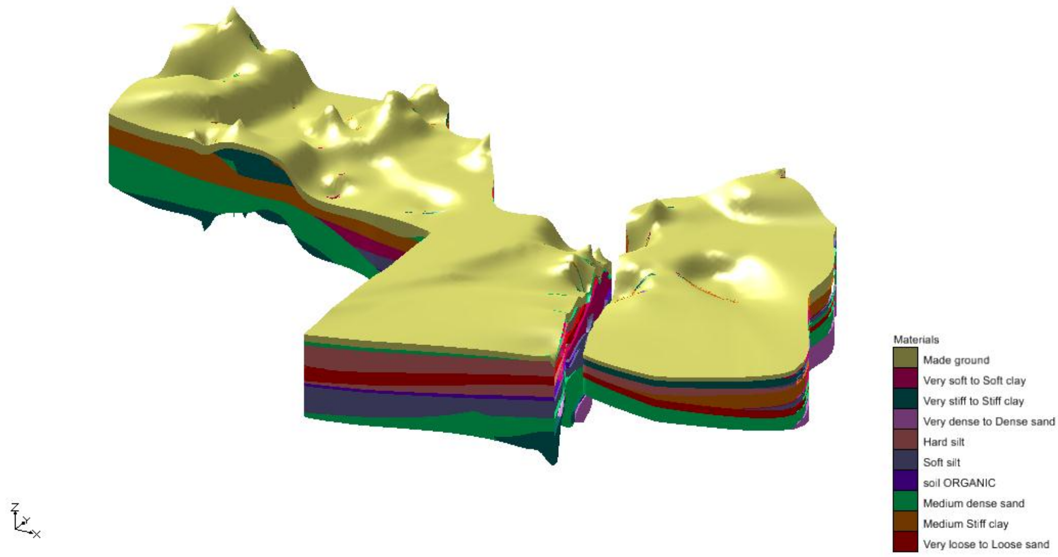


Figure 4.8 (a) Solid model of Mean Chey District in oblique view

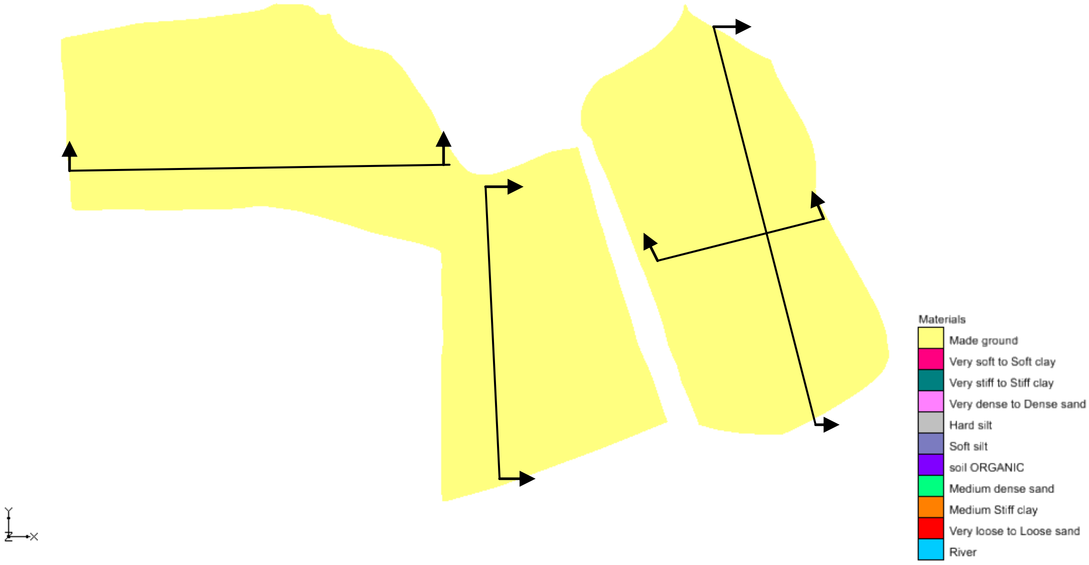


Figure 4.8 (b) Solid model of Mean Chey District in plan view

- ***Mean Chey 1***

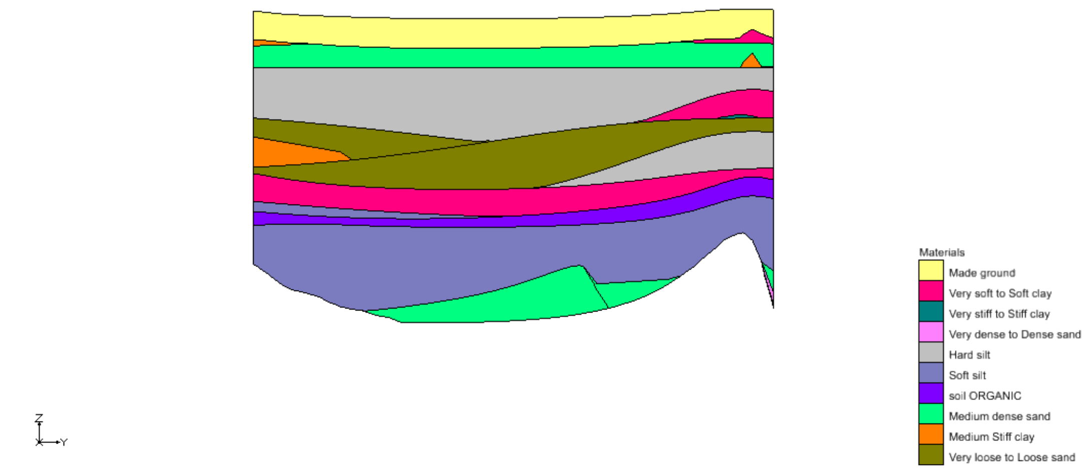


Figure 4.9 (a) West to East cross section subsoil profile of Mean Chey 1

On the left hand side of Bassac river, called "Mean Chey 1". by cutting cross-section according to figure 4.8 (b), cross-section of Mean Chey district on the right hand sand of Bassac River from the west to east view is shown in figure 4.9 (a) and (b). Medium dense sand is addressed followed by a layer of hard silt and/or medium stiff clay. The layering is continued by very loose to loose sand above very stiff to stiff clay layer. There is a thick layer of soft silt below very loose to loose sand layer and it is followed by organic soil. Once again, medium dense sand seems the last layer for Mean Chey cross-section from north to south.

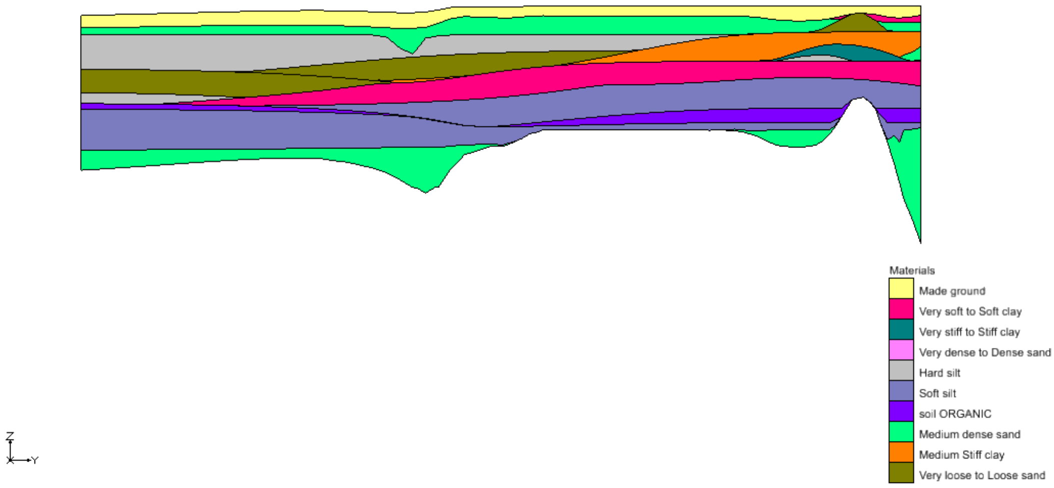


Figure 4.9 (b) North to South cross section subsoil profile of Mean Chey 1

- ***Mean Chey 2***

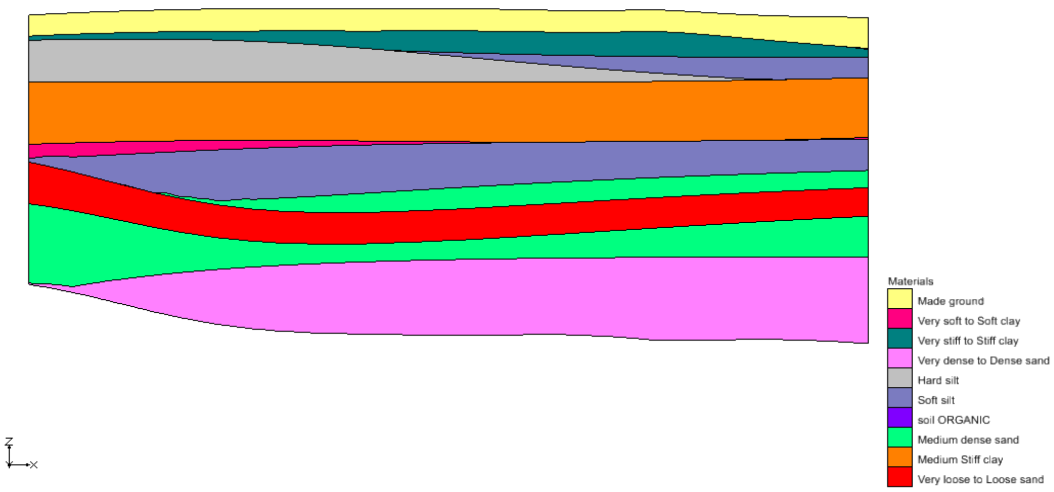


Figure 4.10 (a) West to East cross section subsoil profile of Mean Chey 2

Mean Chey 2 is located at the right hand side of Bassac River which is next to Kandal province. The whole area is cover by the made ground as the top surface presented in figure 4.10 (a) and (b), and it is followed by very stiff to stiff clay and/or very loose to loose sand. The second layer is hard silt above medium stiff clay. A layer of soft silt is already above a layer of medium stiff clay. Soft silt appears above medium stiff sand. Continuously, very loose to loose sand is a layer in the middle of medium dense sand. Finally, it ends with very dense to dense sand.

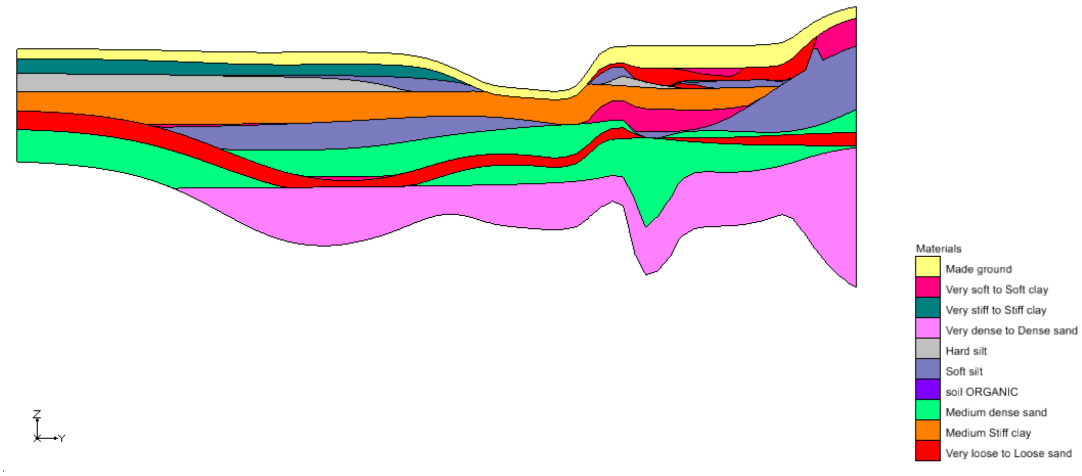


Figure 4.10 (b) North to South cross section subsoil profile of Mean Chey 2

4.2.4 Chamkar mon District

Figure 4.11 Chamkar Mon District areas

Chamkar Mon District is the southernmost district in central Phnom Penh illustrated in figure 4.11, Cambodia. The district is subdivided into 12 arrondissements and 9 groups. This district has an area of 10,788,213 m^2. According to Phnom Penh municipality, it has a population of 182,004 with population density of 17,468 person/ km^2. The name was also Romanized as Chamkar Mon in accordance with the Romanization system used in Cambodia during the 1950s and 1960s (Molyvann, 2003). Subsurface modeling of Chamkar Mon district is addressed in oblique view in figure 4.12 (a) and in plan view in figure 4.12 (b).

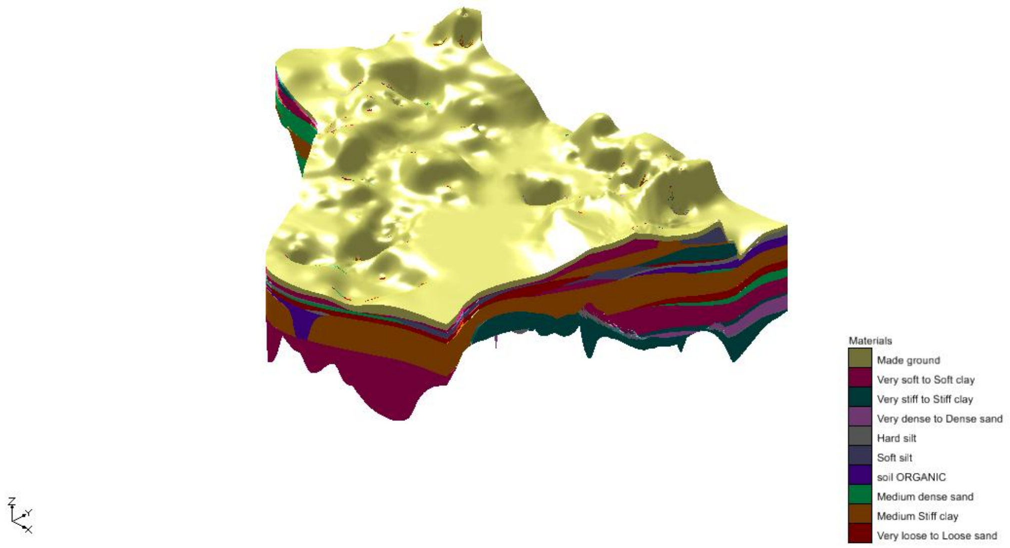


Figure 4.12 (a) Solid models of Chamkar Mon District in oblique view

There are many thin layers of cross-section view both West to East (W-E) and North to South view (N-S) view. This is because information from boring log report includes soil layer where the depth is less than 1 meter.

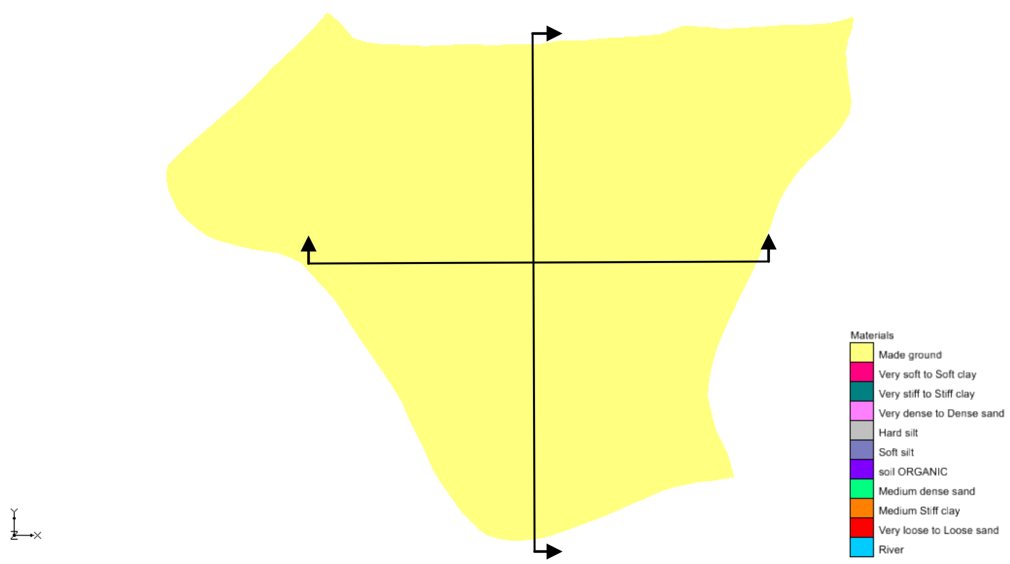


Figure 4.12 (b) Solid models of Chamkar Mon District in plan view

From figure 4.13 (a), very loose to loose sand seems to be the second layer of Chamka Mon subsurface modeling which is followed by very soft to soft clay and/or medium stiff clay from West to East (W-E) view above medium dense sand and/or very loose to loose sand. There is also a thick layer of soft silt underneath the very loose to loose sand followed by very soft to soft clay. The last thick layer of this cross-section is medium dense sand once again which is followed by very thin layer of very dense to dense sand and very stiff to hard clay.

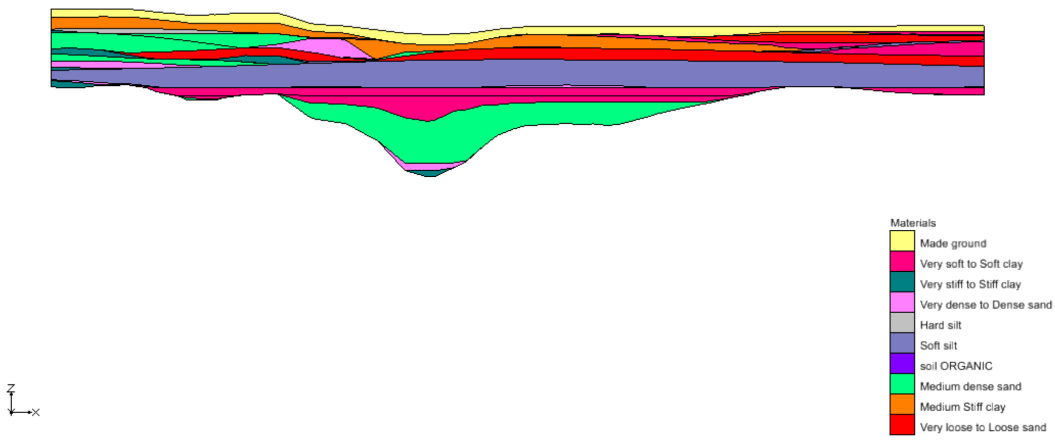


Figure 4.13 (a) West to East cross section subsoil profile of Chamkar Mon districts

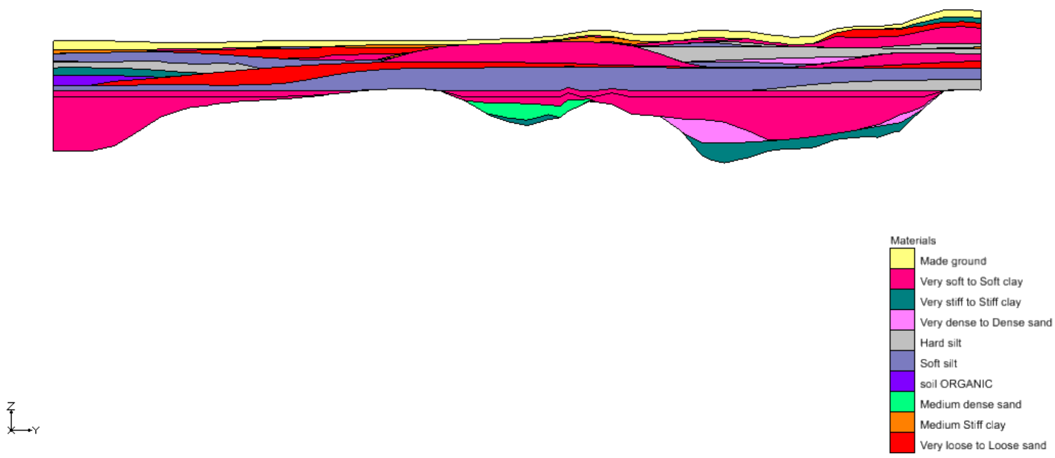


Figure 4.13 (b) North to South cross section subsoil profile of Chamkar Mon districts

The North to South (N-S) cross-section view is presented in figure 4.13 (b). Under made ground layer, soft silt, very loose to loose sand, and very soft to soft clay are addressed above hard silt and very loose to loose sand one again. There is a thick layer of soft silt. Below this soft silt layer, very soft to soft clay seems to be present again with thick layer above some thin layer of medium dense sand, and very dense to dense sand. This cross-section ends up with very stiff to stiff clay layer.

4.2.5 Ressei Keo District

Figure 4.14 Ressei Kao District areas

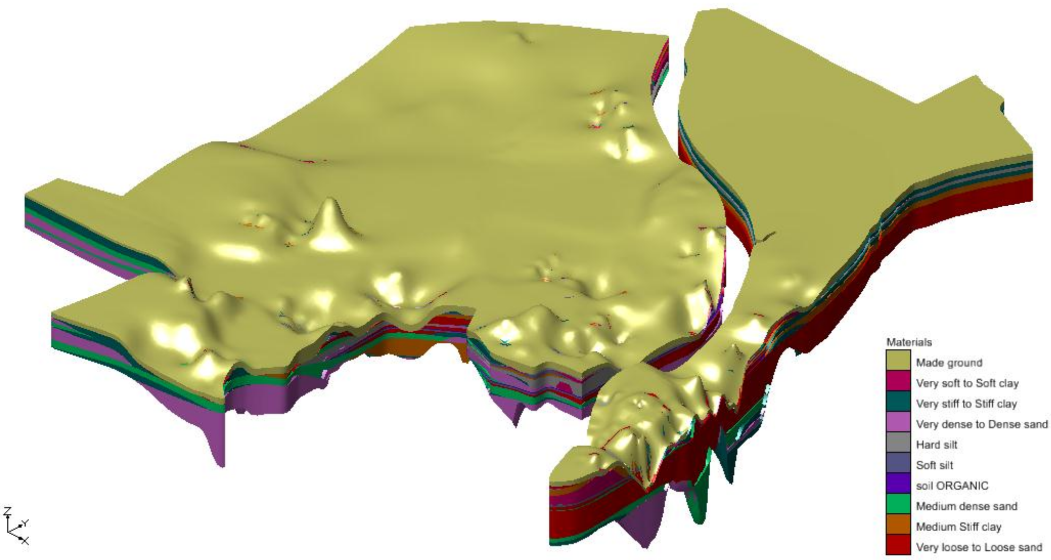


Figure 4.15 (a) Solid models of Ressei Kao District in oblique view

Russei Keo is a district in the municipality of Phnom Penh, Cambodia. This district consists of the northern and northwestern outskirts of the main city of Phnom Penh, stretching from the Dangkor District in the west to the Tonle Sap River in the east (Molyvann, 2003) as shown in figure 4.14. It is the second-largest district of Phnom Penh. According to Phnom Penh Municipality, Cambodia, it covers an area of 63,948,255 m^2 with the total population 196,684 and population density of 1,827 person/ km^2.

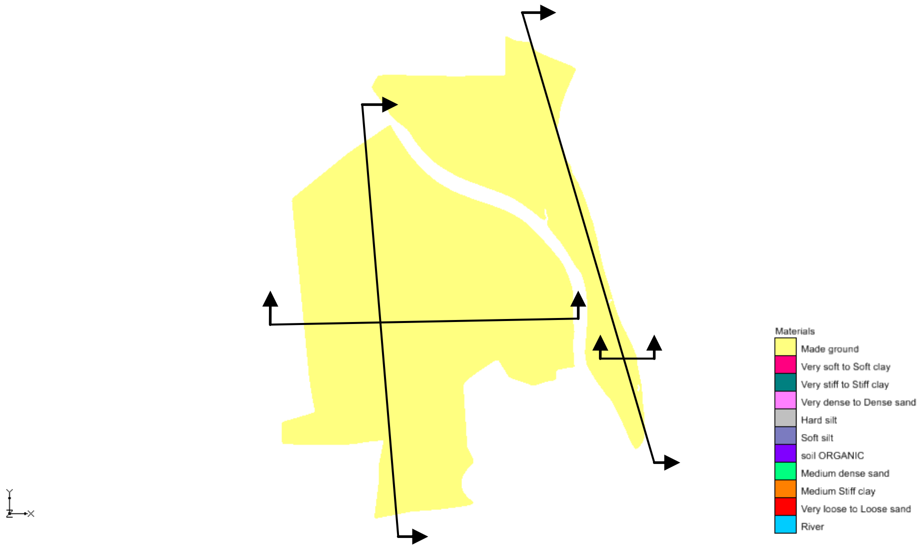


Figure 4.15 (b) Solid models of Ressei Kao District in plan view

- ***Ressei Kao 1***

The area at the left hand side of Tonle Sab is named Ressei Kao 1 illustrated in figure 4.15 (a) and (b). The cross-section is cut according to figure 4.17 (b) and presented in detail in figure 4.16 (a) and (b). From these two cross-section views, a very thick layer of very soft to soft clay and/or medium stiff clay is demonstrated. Another thick layer of medium dense sand also appears at the same bottom level of soft silt. Very loose to loose sand is also present below very soft to soft clay and/or soft silt. The last layer of Ressei Kao cross-section is very dense to dense sand. From the northern part of Ressei Kao 1 cross-section, There are many fluctuating layers of very stiff to stiff clay, medium dense sand and very dense to dense sand respectively.

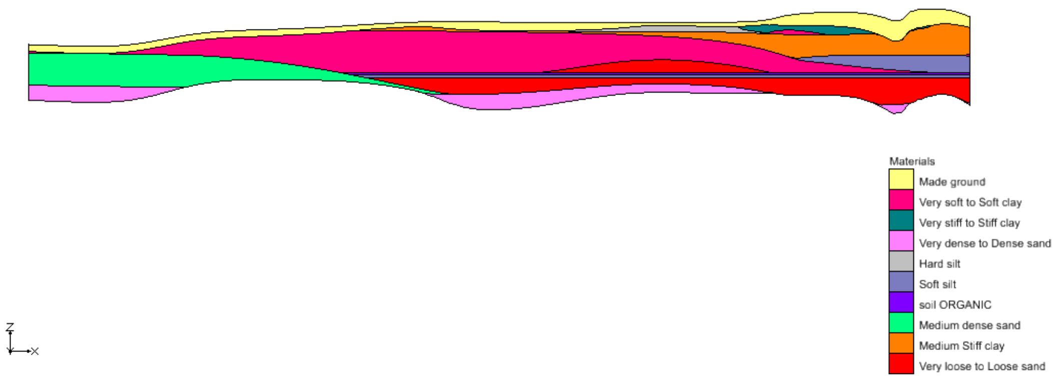


Figure 4.16 (a) West to East cross section subsoil profile of Ressei Kao1 districts

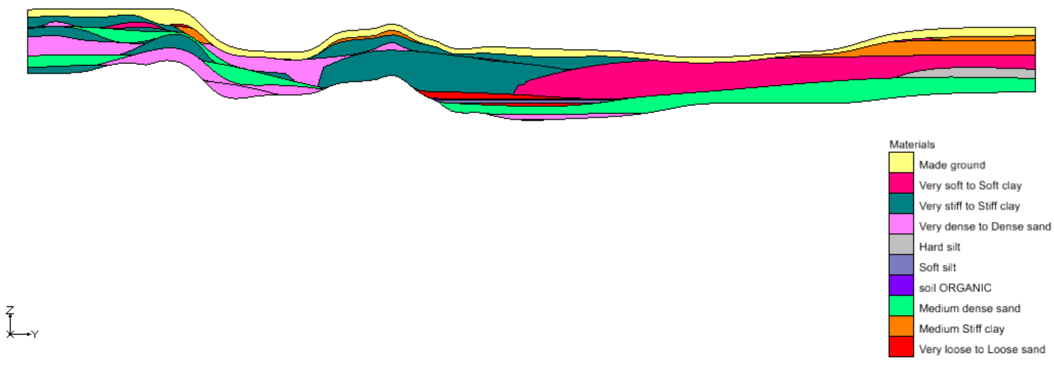


Figure 4.16 (b) North to South cross section subsoil profile of Ressei Kao1 districts

- ***Ressei Kao 2***

The other side of Tonle Sab is addressed as Ressei Kao 2. There is a little soil boring log information of this area because it is quite far from the commercial zone. As shown in figure 4.17 (a) and (b), underneath the made ground, hard silt layer is presented above very soft to soft clay. Organic soil is demonstrated below very soft to soft clay and above a very thick layer of very loose to loose sand. There is a thick layer of medium dense sand and/or very stiff to stiff clay above very dense to dense sand. It is noticed that at the southern part of this area, there is very little available data so that it is very constant according to interpolation method.

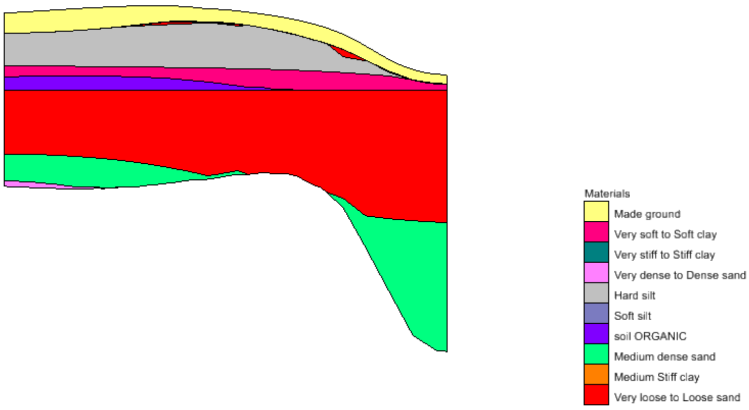


Figure 4.17 (a) West to East cross section subsoil profile of Ressei Kao 2

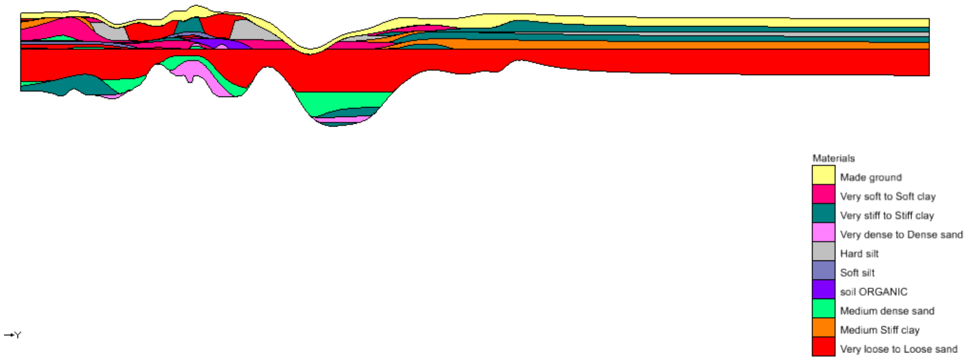


Figure 4.17 (b) North to South cross section subsoil profile of Ressei Kao 2

4.2.6 Prampi Makara District

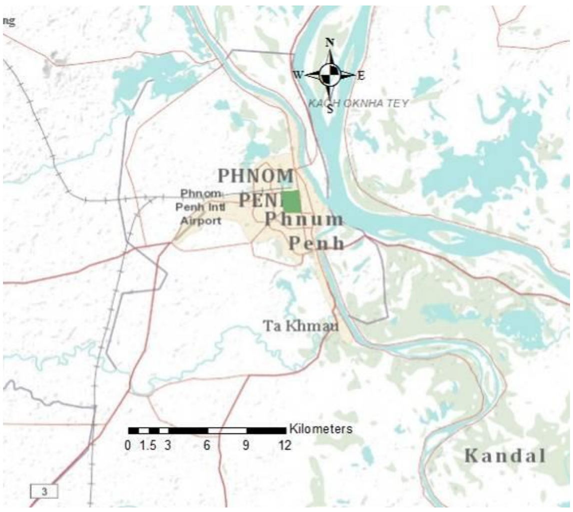


Figure 4.18 Prampi Makara District areas

Prampi Makara District is the smallest district in Phnom Penh, Cambodia illustrated in figure 4.18. The district is subdivided into 8 arrondissements and 33 groups. The district has an area of 2,228,027 m². According to the Phnom Penh Municipality, it has a population of 91,895 with population density of 44,395 person/ km^2.

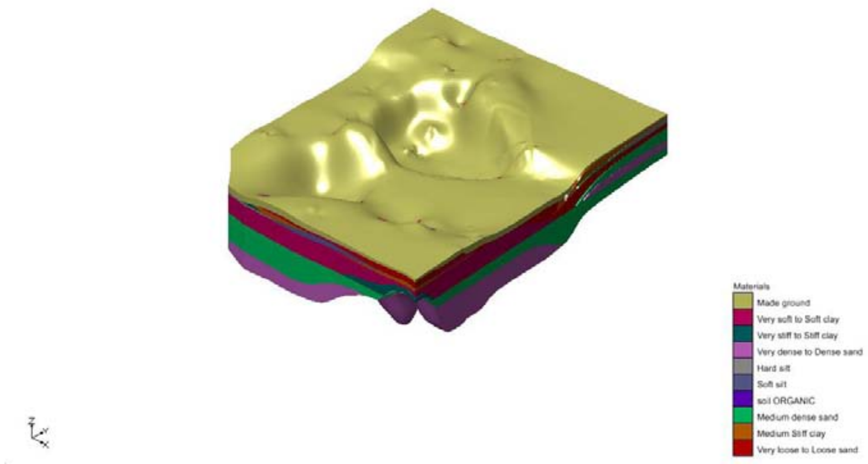


Figure 4.19 (a) Solid models of Prampi Makara District in oblique view

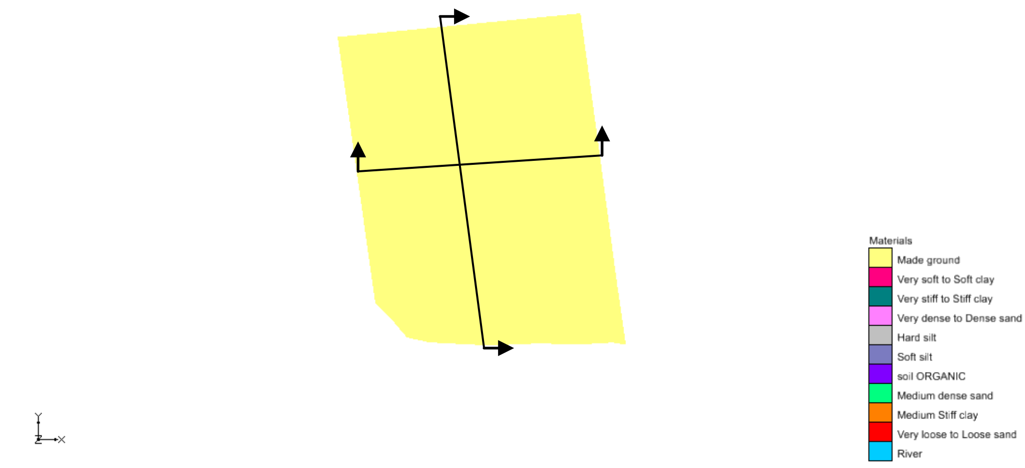


Figure 4.19 (b) Solid models of Prampi Makara District in plan view

The solid view both in oblique and plan view are presented in figure 4.19 (a) and (b). Cross-section is cut from West to East (W-E) and North to South (N-S) as shown in figure 4.20 (a) and (b). Very thin layer of hard silt, very stiff to stiff clay and medium stiff clay can be described as the second layer of Prampi Makara subsoil profile followed by another layer of very soft to soft clay and/or very loose to loose sand. Underneath the very soft to soft clay, a layer of medium stiff clay which is above another layer of very soft to soft clay also appears. A very thick layer of medium dense sand is occupied below the made ground or a layer below very loose to loose sand and very soft to soft clay. Very dense to dense sand is presented as the end layer of Prampi Makara subsoil profile.

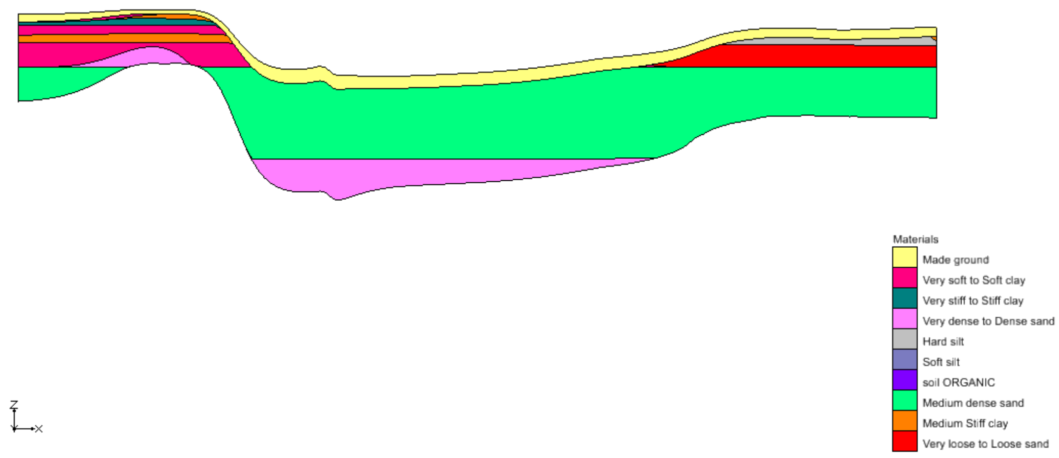


Figure 4.20 (a) West to East cross section subsoil profile of Prampi Makara district

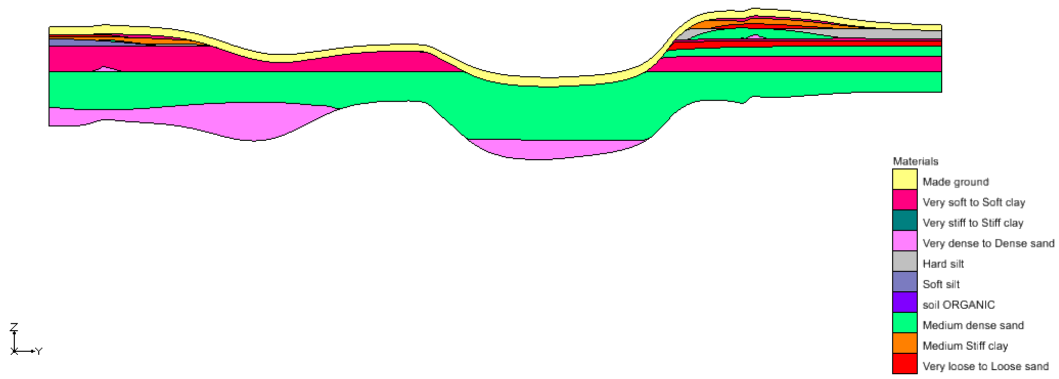


Figure 4.20 (b) North to south cross section subsoil profile of Prampi Makara district

4.2.7 Toul Kork district

Tuol Kork is well-known for the large villas in its northern part of the district of Phnom Penh city presented in figure 4.21. This district is subdivided into 10 arrondisements and 143 groups. Subsoil modeling is also demonstrated in three-dimensional view in figure 4.22 (a) and in plan view in figure 4.22 (b).

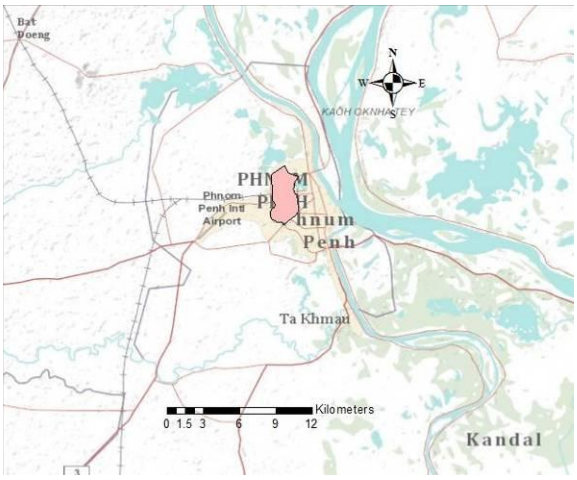


Figure 4.23 Toul Kork District areas

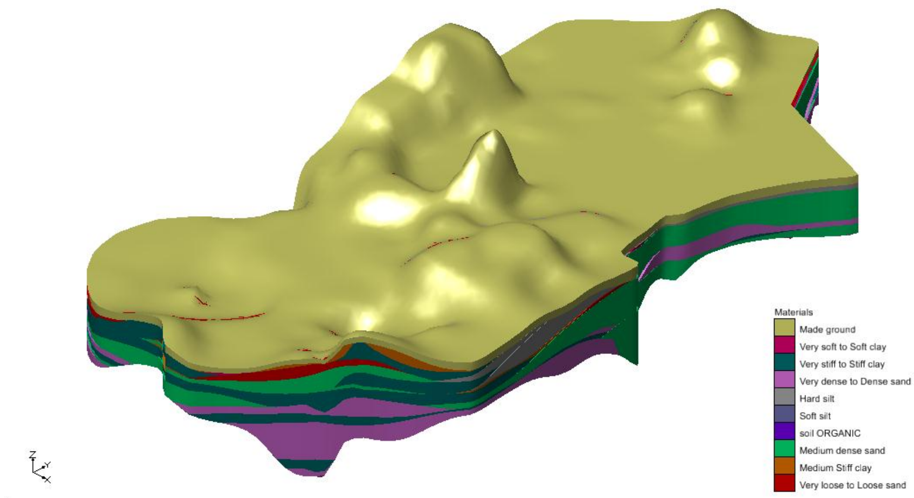


Figure 4.22 (a) Solid models of Toul Kork District in oblique view

Figure 4.22 (b) Solid models of Toul Kork District in plan view

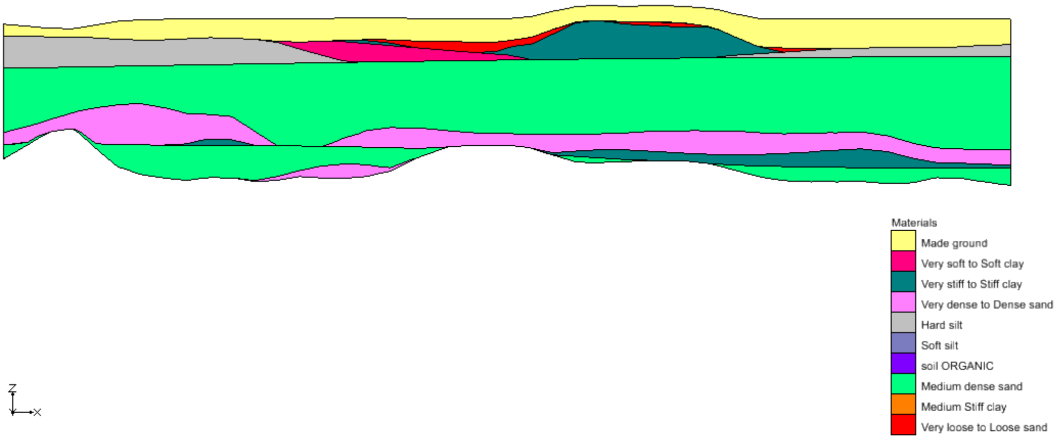


Figure 4.23 (a) West to East cross section subsoil profile of Toul Kork district

Figure 4.23 (a) shows the cross-section view from West to East (W-E) of Toul Kork district. It is noticed that there is not much fluctuating layer in this cross-section. Below the made ground, hard silt, very soft to soft clay and very stiff to stiff clay are demonstrated as the second layer which is followed by a very thick layer of medium dense sand. A layer of very dense to dense sand is also represented as another continuous layer above medium dense sand one again and/or very stiff to stiff clay. There is layer of very dense to dense sand and medium dense sand again at the bottom layer of this cross-section view.

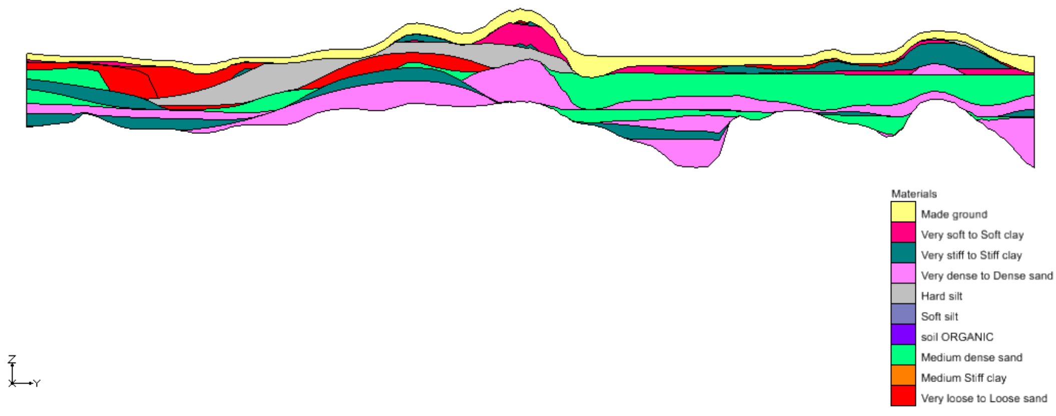


Figure 4.23 (b) North to South cross section subsoil profile of Toul Kork districts

North to South (N-S) cross-section as shown in figure 2.23 (b) is very varied from one layer to another layer. Very soft to soft clay, very loose to loose sand and very stiff to stiff clay takes place as the layer below the made ground layer. The following layer is hard silt and medium dense sand above very dense sand to dense in somehow very stiff to stiff clay also appears above another layer of very dense to dense sand. The next layer below very dense to dense sand is very stiff to stiff clay. The bottom layer of N-S cross-section is very dense to dense sand.

4.2.8 River modeling

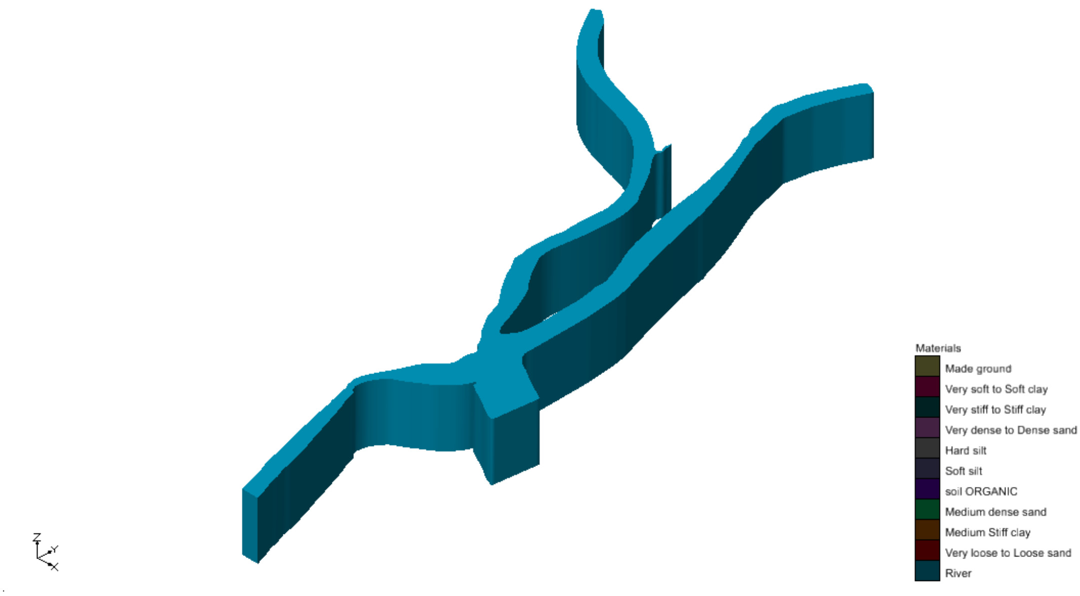


Figure 4.24 Solid models of river modeling in oblique view

Because Phnom Penh is located at the confluence of three rivers, river modeling needs to take into account for Phnom Penh modeling. Importantly, this research study is focused on only subsoil modeling which does not include much about the river's data. Also, there is no available data regarding the depth of the river during rainy and dry season. As a result, the elevation of rivers is just supposed about 30 meter below the ground level to fulfill with Phnom Penh modeling which is shown in figure 4.24.

4.2.9 Phnom Penh subsoil modeling

Area and location of Phnom Penh city show in figure 2.25. Figure 4.26 (a) and (b) show the solid model for the whole of Phnom Penh city which is divided into four main solids in oblique and plan view. The location of cross-sections from West to East (W-E) and North to South (N-S) are demonstrated in the next figure.

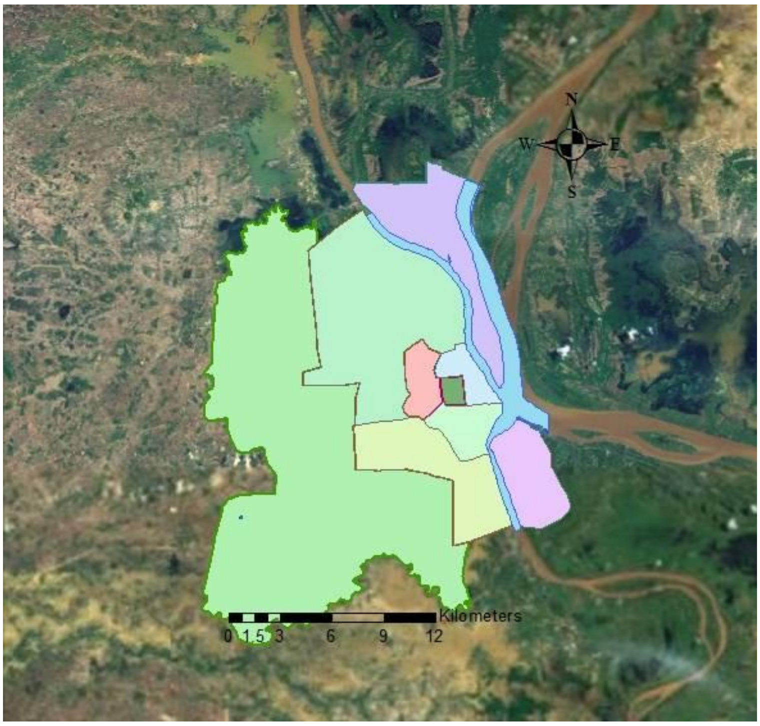


Figure 4.25 Phnom Penh city areas

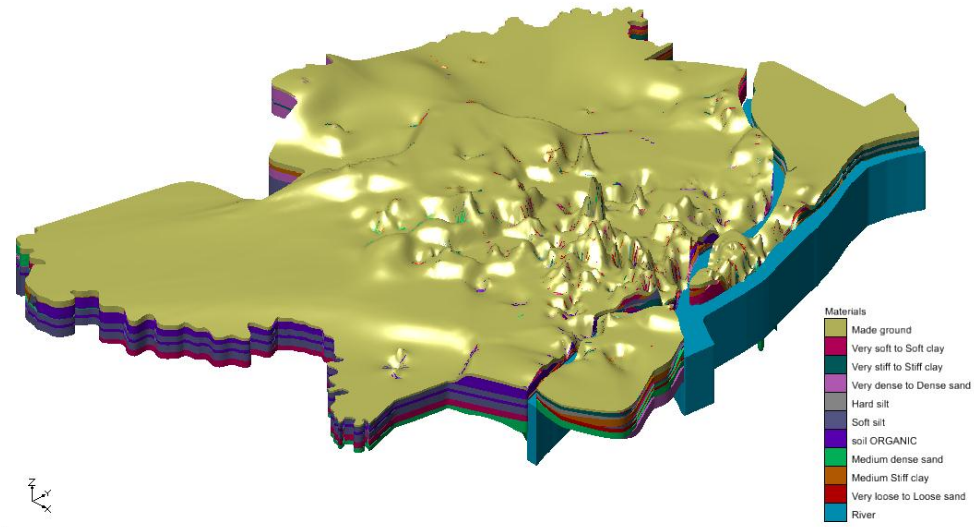


Figure 4.26 (a) Solid models of Phnom Penh city in oblique view

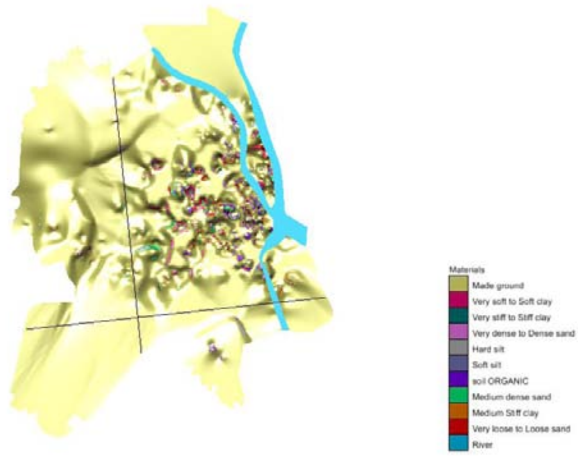


Figure 4.26 (b) Solid models of Phnom Penh city in plan view

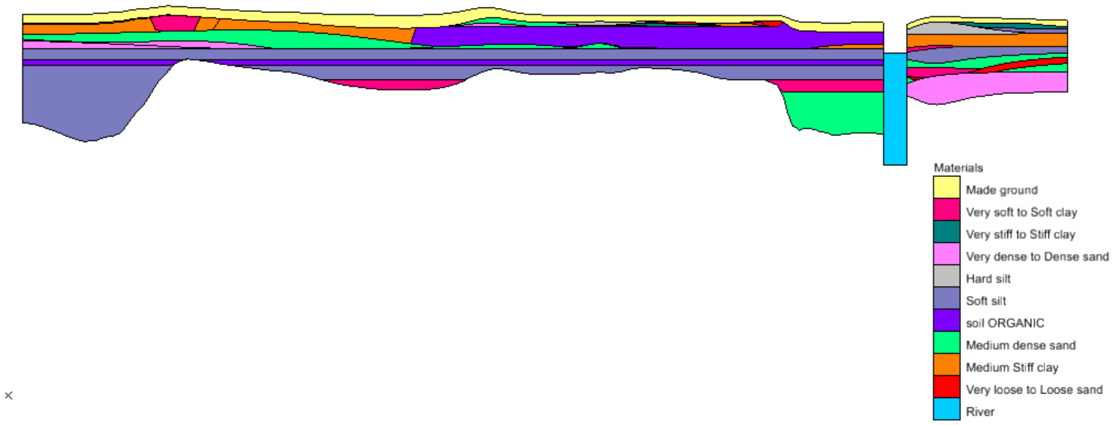


Figure 4.27 (a) West to East cross section subsoil profile of Phnom Penh city

From the location of the West to East view shown in figure 4.27 (a), cross-section is separated by Bassac River at the southern part of Phnom Penh city. The area is cover by the made ground and it is followed by medium stiff clay and/or organic soil. Following this layer, medium dense sand is present above a thin layer of very dense to dense sand. There is a constant layer of soft silt which is also followed by organic soil once again. Underneath the organic soil, a layer of soft silt also appears followed by very soft to soft clay. On the other side of Bassac River, the layer below soft clay is medium dense sand which is followed by very soft to soft clay and very loose to loose sand. The last layer of this cross-section at the right hand side of Bassac River is medium dense sand and at the right hand side of Bassac River is very dense to dense sand.

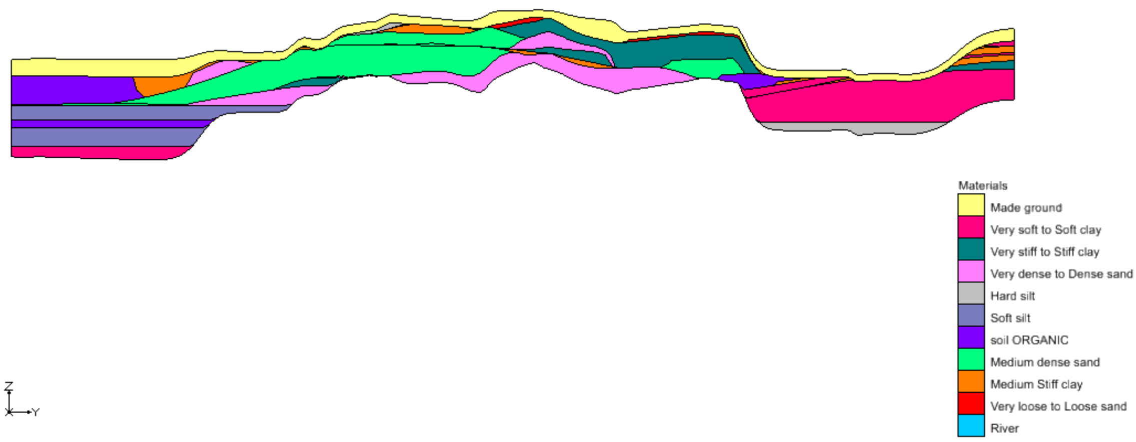


Figure 4.27 (b) North to South cross section subsoil profile of Phnom Penh city

Another view of the cross-section of Phnom Penh city is North to South view which is shown in figure 4.27 (b). According to the illustration, the top layer of this cross-section is made ground which is followed by thick layer of very stiff to stiff clay, medium dense sand and organic soil. There are also several thin layers of very soft to soft clay and medium stiff clay appearing as a layer below the made ground. Very dense to dense sand is layer below medium dense sand in the middle part of the cross-section. On the other hand, at the western part of cross-section, soft silt is a layer below the soil organic which is followed by soft silt one again. This part ends up with very soft to soft clay. Furthermore, on the eastern part of the cross-section, a very thick layer of very soft to soft clay appears at the bottom layer below very stiff to stiff clay which ends up with a thin layer of hard silt.

4.3 Statistical analysis of Phnom Penh subsoils

In many circumstances, preliminary or conceptual design decision requires adequate subsoil data particularly during the very initial stage of project development. Geotechnical data has been collected from 1200 boring log reports over the area of Phnom Penh city as shown in figure 4.28. Geotechnical boreholes were homogenized and archived in GIS geo-database. These data have been analyzed from the existing soil boring log reports from several sites covering seven districts in Phnom Penh city. Presently, the subsurface geology of Phnom Penh is not yet well understood due to its complex combination of soil and rock components. The subsoil of Phnom Penh mainly results from river deposition and its sediments can be divided into made ground, clay, silt, sand and organic material.

Interpreted geological and geotechnical data of the subsoil of Phnom Penh city were collected from public administrations and private companies. The data was classified and filtered according to specific criteria before being archived in the geo-database, i.e., selecting boreholes with reliable location, detailed descriptions as well as field and laboratory geotechnical tests. Therefore, the following results present a summary of typical geological conditions and their geotechnical parameters for each district of Phnom Penh city.

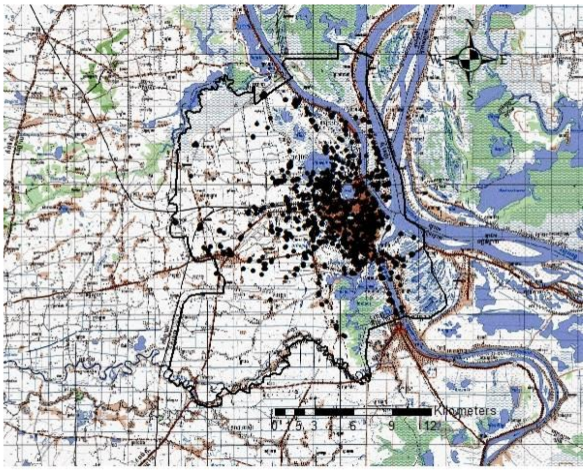


Figure 4.28 Schematic map of the study area with the location of the boreholes

4.3.1 Cross-section and properties of Phnom Penh subsoil

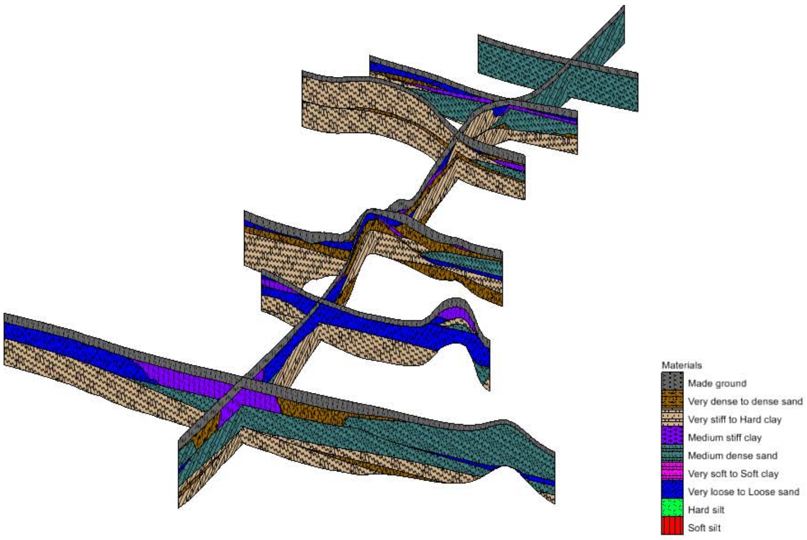


Figure 4.29 Cross-section view of Dangkao district

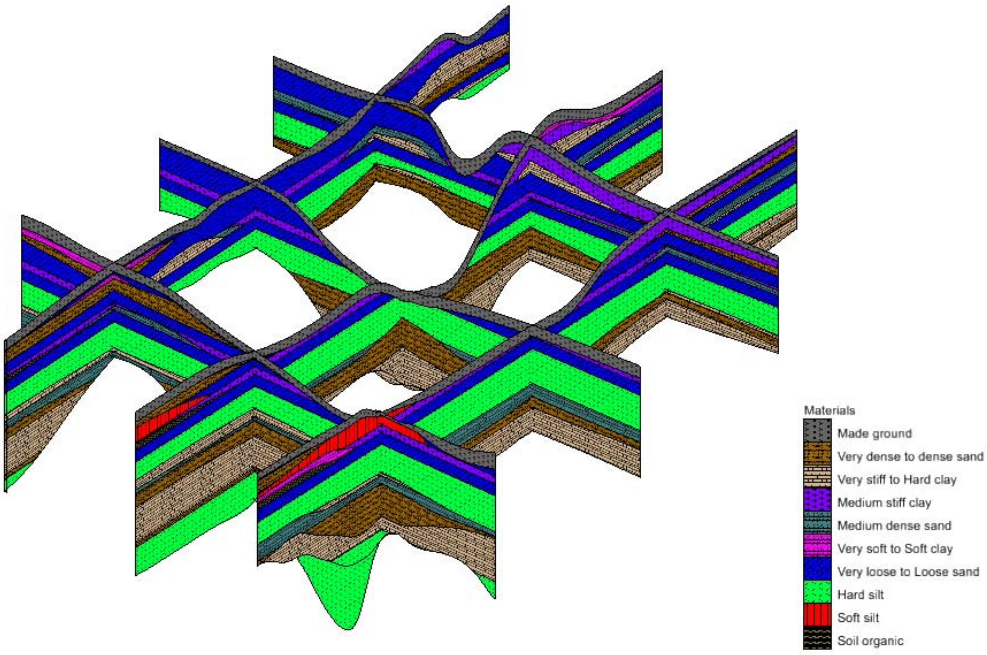


Figure 4.30 Cross-section view of Prampi Makara district

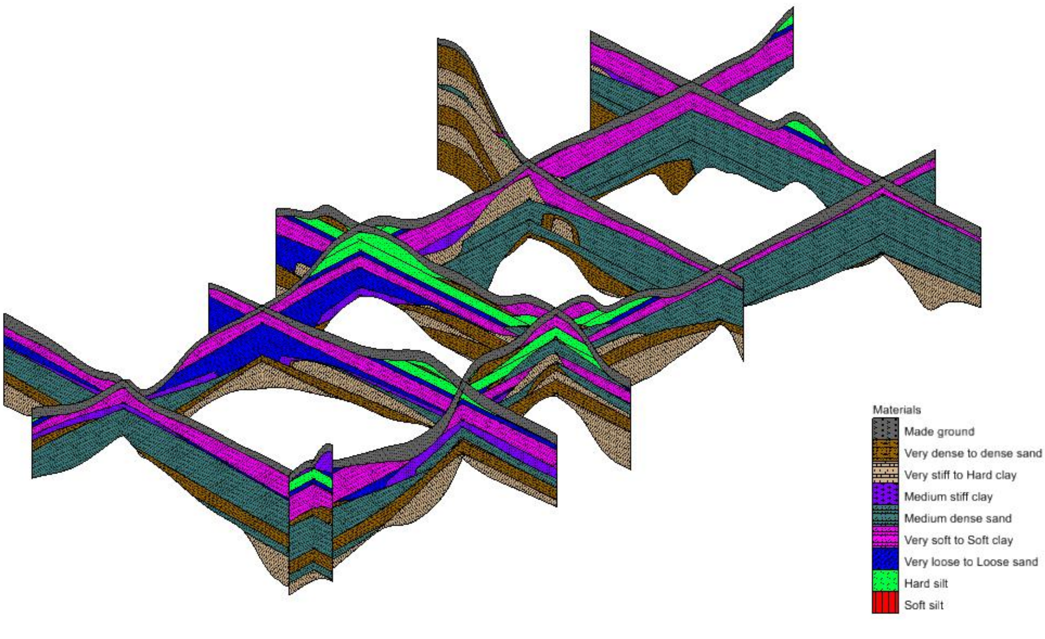


Figure 4.31 Cross-section view of Toul Kork district

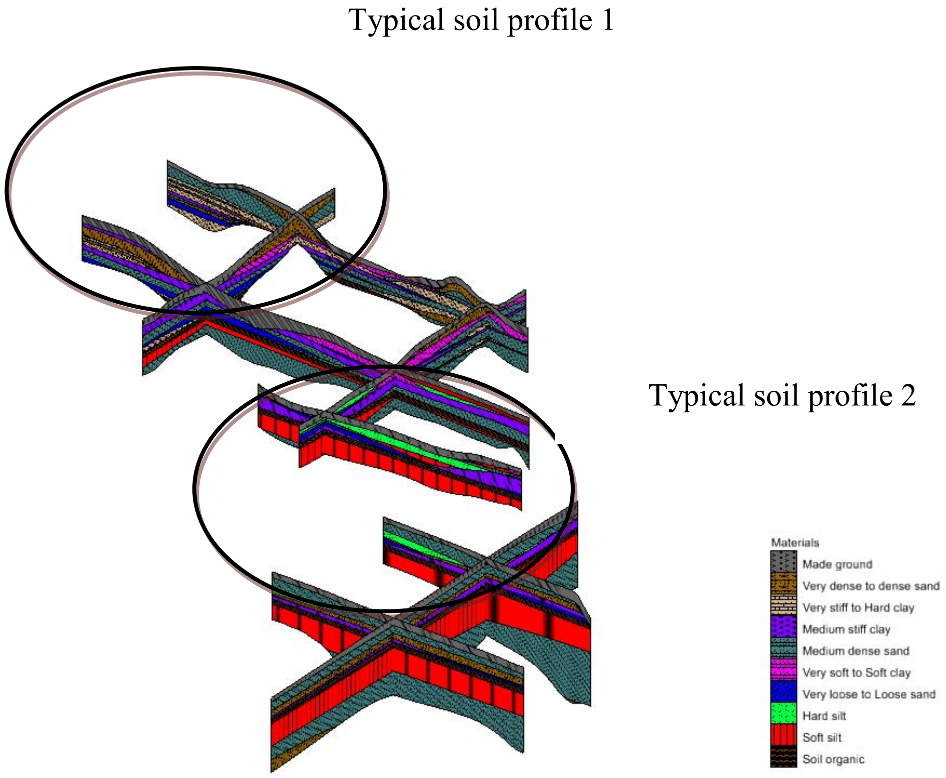


Figure 4.32 Cross-section view Mean Chey district

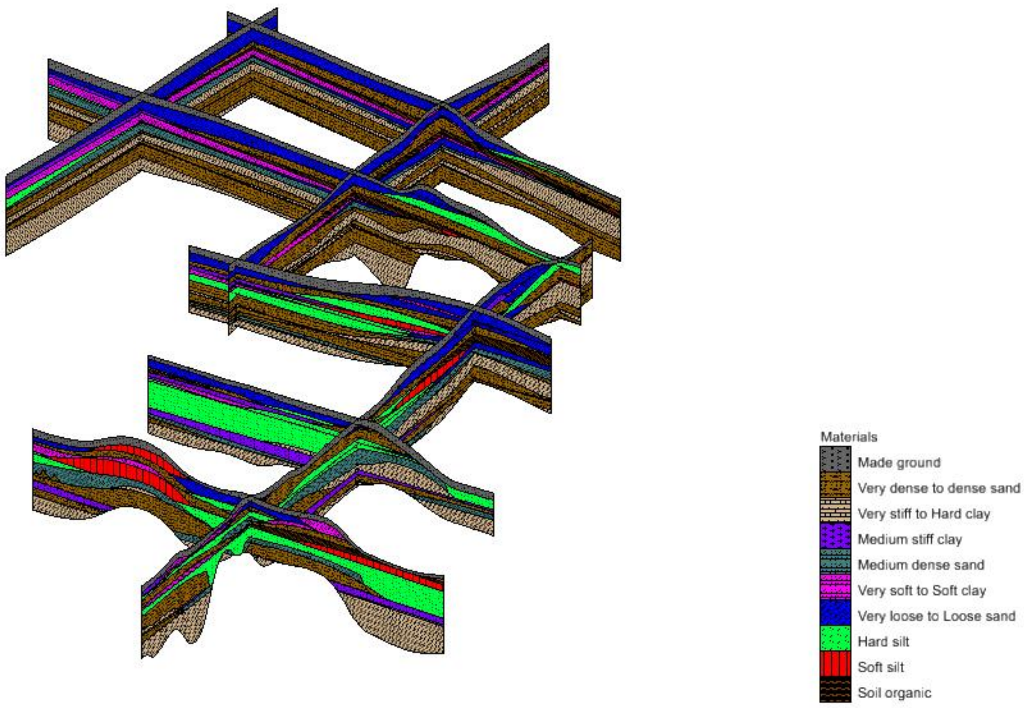


Figure 4.33 Cross-section view Daun Penh district

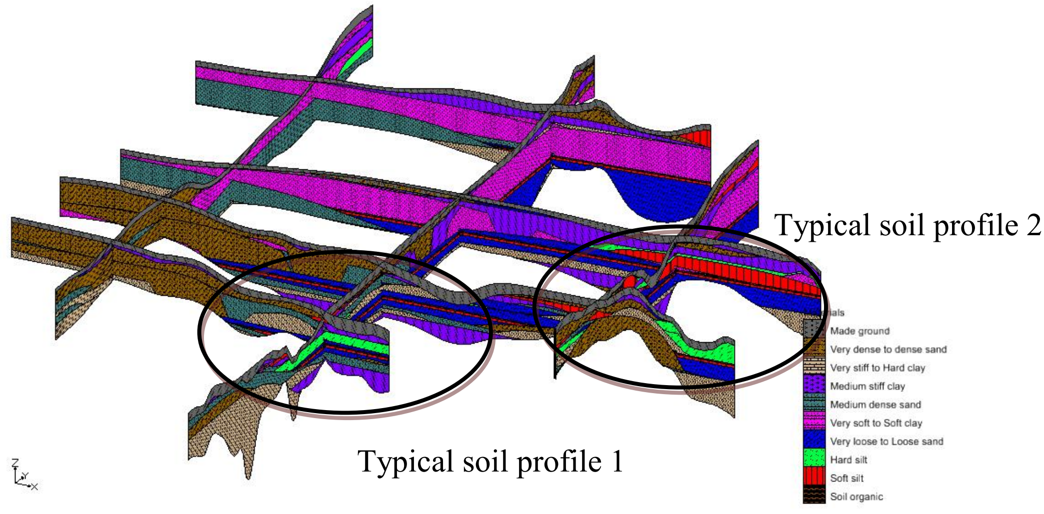


Figure 4.34 Cross-section view of Ressei Kao district

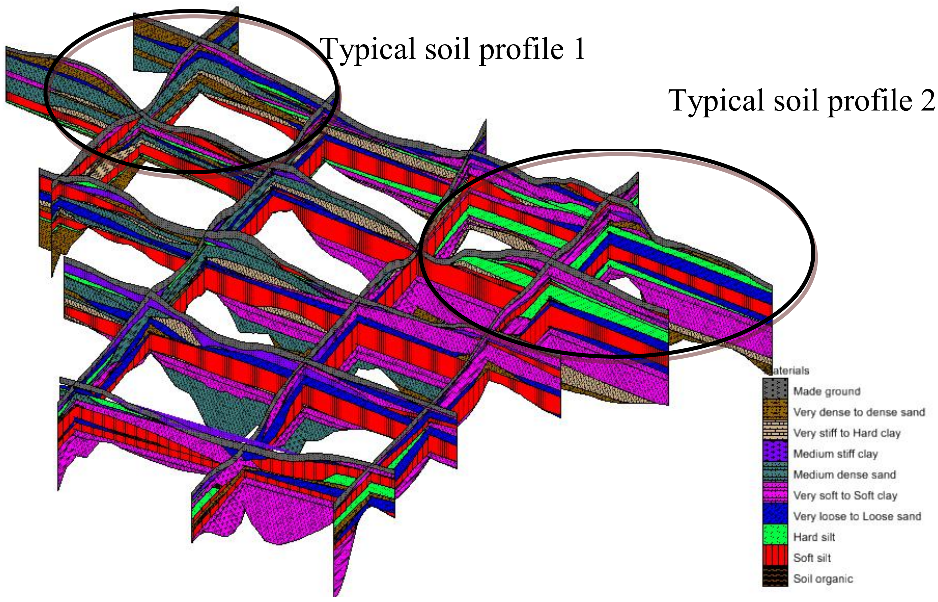


Figure 4.35 Cross-section view of Chamkar Mon district

Figure 4.29 to 4.35 presents the cross-section views of each district respectively Dangkao, Russei Kao, Prampi Makara, Toul Kok, Mean Chey, Daun Penh and Chamkar Morn districts, respectively. As noticed that, in once district, there might be several type of typical soil profiles which are marked by circle and the result of statistical analysis will be show in tables below.

Statistical analysis performs according to the result of three-dimensional modeling which are shown in figure 4.29 to 4.35 for each district. Once typical soil profile is considered, physical and engineering properties of each soil types at the same depth of typical soil layer are uploaded. Statistical parameters such as minimum, maximum, mean, standard deviation and sampling number are determined in order to demonstrate the subsoil condition of Phnom Penh city.

Table 4.1 Physical properties of typical soil profile of Dangkao district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION		
				w_n	LL	PL	PI	LI	γ_{wet}	γ_{dry}	M&C	S	G
m				%	%	%	-	-	kN/m³	kN/m³	%	%	%
0-1.5	8.73	Made ground	-	-	-	-	-	-	-	-	-	-	-
1.5-2.5		Very loose to loose sand	Min	8.51	13.15	10.61	2.04	<0	17.00	14.44	8.46	49.61	-
			Max	31.54	45.72	24.08	21.64	0.48	20.00	18.43	63.59	91.54	-
			Mean	15.10	26.17	15.77	9.55	0.07	19.00	16.12	35.50	64.57	-
			SD	4.31	8.18	3.50	5.45	0.25	0.66	0.78	10.69	9.89	
			N0	51									
2.5-4.5		Medium stiff clay	Min	10.70	20.90	6.20	5.71	<0	18.50	14.93	25.28	0.00	-
			Max	27.25	58.31	40.82	32.28	19.29	20.10	17.50	100.00	49.89	-
			Mean	19.94	31.24	20.38	13.05	0.21	19.50	16.34	71.47	25.28	-
			SD	4.57	8.06	5.49	6.86	5.36	0.44	0.74	17.57	14.99	-
			N0	39									
4.5-6.5		Medium dense sand	Min	8.05	10.06	10.99	1.25	<0	19.00	15.35	8.06	45.94	-
			Max	27.05	59.92	31.31	37.03	15.11	20.00	18.05	87.41	91.95	-
			Mean	14.15	32.76	16.89	15.73	0.08	19.50	17.05	30.91	70.11	-
			SD	3.34	11.53	3.98	8.49	5.65	0.36	0.52	16.09	11.08	-
			N0	80									
6.5-11		Very dense to dense sand	Min	10.01	12.42	10.81	6.26	<0	19.00	16.80	14.13	29.47	-
			Max	18.41	85.73	29.45	62.84	-	21.00	18.92	78.92	85.87	-
			Mean	12.46	41.19	19.89	20.11	-	20.00	17.70	28.53	71.77	-
			SD	1.88	12.52	2.81	11.08	-	0.32	0.41	9.96	9.43	-
			N0	80									
11.0-15		Very stiff to stiff clay	Min	7.23	19.54	11.65	2.27	<0	18.20	15.69	32.00	0.00	-
			Max	25.79	63.67	27.20	36.99	0.63	21.80	19.47	100.00	68.00	-
			Mean	16.22	37.11	19.25	16.10	0.11	20.00	17.23	62.15	37.85	-
			SD	3.83	9.21	3.59	7.09	0.17	0.46	0.73	17.12	17.12	-
			N0	78									

Notes: w_n = Natural Water Content, LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, LI = Liquidity Index, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number, M&C= Silt and Clay, S= Sand, G=Gravel

Table 4.2 Geotechnical properties of typical soil profile of Dangkao district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	SHEAR STRENGTH					SPECIFIC GRAVITY	VOID RATIO	Young's modulus	**SPT**
				Direct Shear		Unconfined compression	Field vane test	Pocket penetration				
				c	ϕ	$q_u/2$	s_u	s_u	G_s	e	E	N-Value
m				kN/m^2	Degree	kPa	kPa	kPa			kPa	blows
0-1.5	8.73	Made ground	-	-	-	-	-	-	-	-	-	-
1.5-2.5		Very loose to loose sand	Min	0.00	27.00	-	-	-	2.70	0.47	2400	1.00
			Max	0.00	30.00	-	-	-	2.70	0.87	21000	13.00
			Mean	0.00	28.00	-	-	-	2.70	0.67	10000	8.00
			SD	0.00	1.17	-	-	-	-	0.08	3076	3.85
			N0	51								
2.5-4.5		Medium stiff clay	Min	6.00	13.00	66.00	57.00	50.00	2.70	0.54	8500	3.00
			Max	38.00	30.30	110.00	160.00	100.00	2.70	0.81	18000	13.00
			Mean	6.00	21.65	79.00	75.00	60.00	2.70	0.65	13000	8.00
			SD	18.48	12.23	13.80	23.64	20.37	0.00	0.08	2247	2.28
			N0	39								
4.5-6.5		Medium dense sand	Min	0.00	30.00	-	-	-	2.70	0.50	14000	9.00
			Max	21.00	35.20	-	-	-	2.70	0.76	22000	30.00
			Mean	0.00	32.00	-	-	-	2.70	0.58	17000	18.00
			SD	4.58	1.11	-	-	-	-	0.05	2010	5.20
			N0	80								
6.5-11		Very dense to dense sand	Min	-	35.00	-	-	-	2.70	0.43	23000	21.00
			Max	-	42.00	-	-	-	2.70	0.61	72500	140.00
			Mean	-	40.00	-	-	-	2.70	0.53	32500	47.50
			SD	-	2.31	-	-	-	0.00	0.04	10792	25.69
			N0	80								
11.0-15		Very stiff to stiff clay	Min	27.00	23.00	123.00	105.00	96.00	2.70	0.39	17000	10.00
			Max	41.00	40.00	530.50	300.00	350.00	2.70	0.72	50000	111.00
			Mean	36.00	26.00	189.35	150.00	200.00	2.70	0.57	32000	22.00
			SD	7.09	7.63	99.09	46.92	71.47	-	0.06	11269	17.62
			N0	78								

Notes: UC = Unconfined Compressive test, DSB = Direct Shear Box, FV = Field Vane test, SPT = Standard Penetration test, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number

Table 4.3 Physical properties of typical soil profile of Prampi Makara district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION		
				w_n	LL	PL	PI	LI	γ_{wet}	γ_{dry}	M&C	S	G
m				%	%	%	-	-	kN/m^3	kN/m^3	%	%	%
0-1.5	2.09	Made ground	-	-	-	-	-	-	-	-	-	-	-
1.5-6.5		Very loose to loose sand	Min	12.24	16.71	12.50	1.19	<0	18.00	14.15	10.10	47.31	-
			Max	27.19	34.08	20.58	14.63	2.04	19.50	16.69	52.70	89.90	-
			Mean	20.35	22.04	15.35	6.33	0.82	19.00	15.63	29.69	70.31	-
			SD	4.01	4.83	2.47	3.96	0.81	0.49	0.72	12.03	12.03	-
			N0	30									
6.5-8.5		Medium stiff clay	Min	16.05	26.31	15.38	5.59	<0	18.70	14.51	51.26	0.00	-
			Max	32.12	49.94	28.25	21.69	0.57	20.10	17.08	100.00	48.74	-
			Mean	23.38	35.40	21.68	17.44	0.21	19.20	15.58	82.63	17.37	-
			SD	3.84	6.92	3.49	5.18	0.16	0.50	0.74	16.54	16.54	-
			N0	30									
8.5-12		Very loose to loose sand	Min	16.71	15.04	12.27	0.86	1.04	17.00	13.97	6.58	24.50	-
			Max	29.96	32.44	22.63	15.48	1.99	19.50	16.46	75.51	93.42	-
			Mean	21.70	24.10	16.12	7.95	1.86	19.00	15.41	32.70	67.30	-
			SD	3.93	5.50	3.25	4.43	0.52	0.57	0.63	15.26	15.26	-
			N0	30									
12-16.5		Hard silt	Min	13.50	0.05	13.46	2.90	<0	18.50	13.73	51.73	0.00	-
			Max	34.72	59.69	33.74	29.17	2.85	20.00	17.23	100.00	48.27	-
			Mean	23.04	41.84	27.99	14.87	0.41	20.00	16.12	64.64	35.37	-
			SD	4.83	13.33	5.44	6.42	0.94	0.44	0.83	16.22	16.22	-
			N0	30									
16.5-20		Medium dense sand	Min	11.12	16.26	11.96	0.95	<0	19.00	15.47	5.03	0.00	-
			Max	25.84	51.52	28.59	22.93	3.86	20.00	17.55	100.00	94.97	-
			Mean	17.50	23.88	15.79	7.34	0.60	19.50	16.39	22.17	77.84	-
			SD	3.42	6.10	2.80	4.55	1.29	0.32	0.55	14.64	14.64	-
			N0	74									
20-23		Very dense to dense sand	Min	7.80	19.14	0.00	0.00	<0	19.50	16.13	0.00	0.00	-
			Max	23.96	63.81	27.71	36.09	1.31	20.00	18.55	48.22	92.01	-
			Mean	13.08	35.32	18.31	16.31	0.05	20.00	17.68	29.65	69.30	-
			SD	2.90	8.61	4.11	7.51	0.48	0.10	0.46	9.63	13.90	-
			N0	80									
23-35		Very stiff to stiff clay	Min	11.90	15.52	9.49	3.67	<0	19.30	15.04	23.36	0.00	-
			Max	28.98	52.97	28.59	31.71	1.39	20.00	17.87	100.00	76.65	-
			Mean	18.70	36.51	20.17	15.78	0.20	20.00	16.72	68.42	31.58	-
			SD	4.37	9.09	4.29	6.30	0.24	0.18	0.67	18.56	18.56	-
			N0	80									

Notes: w_n = Natural Water Content, LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, LI = Liquidity Index, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number, M&C= Silt and Clay, S= Sand, G=Gravel

Table 4.4 Geotechnical properties of typical soil profile of Prampi Makara district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	SHEAR STRENGTH: Direct Shear		Unconfined compression	Field vane test	Pocket penetration	SPECIFIC GRAVITY	VOID RATIO	Young's modulus	SPT
				c	ϕ	$q_u/2$	s_u	s_u	G_s	e	E	N-Value
m				kN/m^2	Degree	kPa	kPa	kPa			kPa	blows
0-1.5		Made ground	-	-	-	-	-	-	-	-	-	-
1.5-6.5		Very loose to loose sand	Min	-	26.00	-	-	-	2.70	0.62	4000	2.00
			Max	-	31.00	-	-	-	2.70	0.91	15000	14.00
			Mean	-	29.00	-	-	-	2.70	0.73	12250	10.00
			SD	-	1.20	-	-	-	-	0.08	2421	3.68
			N0	30								
6.5-8.5		Medium stiff clay	Min	-	-	68.00	40.00	80.00	2.70	0.58	9000	6.00
			Max	-	-	97.30	110.00	110.00	2.70	0.86	18000	15.00
			Mean	-	-	83.60	70.00	87.50	2.70	0.73	13000	10.00
			SD	-	-	9.98	15.07	12.91	0.00	0.08	2072	2.74
			N0	30								
8.5-12		Very loose to loose sand	Min	-	25.00	-	-	-	2.70	0.64	5000	1.00
			Max	-	31.00	-	-	-	2.70	0.93	16000	14.00
			Mean	-	29.00	-	-	-	2.70	0.75	12000	8.00
			SD	-	1.40	-	-	-	-	0.07	2452	4.08
			N0	30								
12-16.5	2.09	Hard silt	Min	27.00	15.00	50.70	50.00	100.00	2.70	0.57	8900	7.00
			Max	40.00	75.00	209.00	300.00	250.00	2.70	0.97	50000	97.00
			Mean	33.00	20.50	77.40	107.50	157.50	2.70	0.68	22000	15.50
			SD	5.18	17.87	63.35	73.34	60.20	-	0.09	12147	20.85
			N0	30								
16.5-20		Medium dense sand	Min	-	30.40	-	-	-	2.70	0.54	13000	11.00
			Max	-	36.00	-	-	-	2.70	0.75	22500	34.00
			Mean	-	33.00	-	-	-	2.70	0.65	19000	22.00
			SD	-	1.14	-	-	-	-	0.05	2199	5.23
			N0	74								
20-23		Very dense to dense sand	Min	-	34.00	-	-	-	2.70	0.46	21000	27.00
			Max	-	42.00	-	-	-	2.70	0.67	55000	124.00
			Mean	-	41.00	-	-	-	2.70	0.53	44500	72.00
			SD	-	2.35	-	-	-	-	0.04	9625	28.14
			N0	80								
23-35		Very stiff to stiff clay	Min	24.00	10.00	61.00	10.00	-	2.70	0.51	14000	6.00
			Max	50.00	40.00	394.00	362.00	-	2.70	0.80	70000	118.00
			Mean	25.00	34.50	151.00	160.00	-	2.70	0.61	33000	31.00
			SD	14.73	11.75	81.47	83.25	-	-	0.07	13912	23.87
			N0	80								

Notes: UC = Unconfined Compressive test, DSB = Direct Shear Box, FV = Field Vane test, SPT = Standard Penetration test, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number

Table 4.5 Physical properties of typical soil profile 1 of Mean Chey district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION		
				w_n	LL	PL	PI	LI	γ_{wet}	γ_{dry}	M&C	S	G
m				%	%	%	-	-	kN/m³	kN/m³	%	%	%
0-1.5		Made ground	-	-	-	-	-	-	-	-	-	-	-
1.5-3		Very dense to dense sand	Min	9.18	15.12	10.99	3.19	<0	20.00	16.39	5.32	54.68	-
			Max	22.01	43.58	21.31	22.85	0.78	21.00	18.62	45.33	94.68	-
			Mean	12.94	27.86	17.26	10.04	0.32	20.00	17.71	26.09	73.91	-
			SD	3.66	7.69	2.62	5.63	0.25	0.13	0.57	9.52	9.52	-
			N0	55									
3-5.5		Medium dense sand	Min	11.82	21.95	14.26	4.97	<0	18.50	14.83	3.89	50.99	-
			Max	27.87	39.79	24.44	16.23	0.81	20.00	17.44	49.02	96.12	-
			Mean	20.01	28.80	17.65	11.87	0.45	19.50	16.25	13.55	86.45	-
			SD	3.51	6.88	3.50	4.49	0.51	0.28	0.60	10.64	10.91	-
			N0	49									
5.5-7		Very soft to soft clay	Min	20.40	24.65	7.36	4.31	<0	18.00	11.72	64.22	0.00	-
			Max	53.65	61.37	30.66	44.34	3.64	19.50	15.29	100.00	35.78	-
			Mean	33.54	33.20	22.84	10.80	0.92	18.00	13.89	100.00	0.00	-
			SD	7.33	9.16	4.07	7.69	0.67	0.41	0.90	10.80	10.80	-
			N0	44									
7-11		Very stiff to stiff clay	Min	10.34	17.01	12.00	5.01	<0	18.30	14.05	8.26	0.00	-
			Max	33.81	60.68	28.11	36.68	1.04	21.60	19.03	100.00	91.74	-
			Mean	21.51	37.65	20.59	17.27	0.13	20.00	16.45	100.00	0.00	-
			SD	4.29	9.39	3.30	7.05	0.19	0.56	0.93	20.47	20.47	-
			N0	55									
11-12		Medium stiff clay	Min	14.03	20.82	13.04	2.63	<0	19.00	13.37	50.67	0.00	-
			Max	42.15	76.11	32.21	52.39	1.46	19.50	16.66	100.00	49.33	-
			Mean	25.66	36.92	21.26	13.98	0.22	19.00	15.16	100.00	0.00	-
			SD	6.13	11.86	4.66	9.33	0.34	0.20	0.74	18.68	18.68	-
	4.3		N0	30									
12-15		Medium dense sand	Min	7.46	20.47	15.86	2.78	<0	19.00	15.37	5.93	24.63	-
			Max	25.08	40.62	19.67	21.36	0.97	20.00	17.69	75.37	94.07	-
			Mean	17.65	25.89	17.15	9.38	-	19.50	16.44	21.76	78.24	-
			SD	3.68	6.68	1.55	6.74	-	0.37	0.53	13.74	13.74	-
			N0	31									
15-16.5		Very loose to loose sand	Min	16.78	19.14	7.55	4.84	0.36	18.00	13.97	2.32	29.19	-
			Max	29.23	41.86	19.51	34.31	1.41	19.00	15.70	70.82	97.68	-
			Mean	23.74	24.19	15.72	6.65	0.69	18.50	14.88	29.26	70.75	-
			SD	3.18	6.75	3.42	9.25	0.39	0.44	0.45	13.80	13.80	-
			N0	30									
16.5-18.5		Very stiff to stiff clay	Min	11.99	22.68	14.95	1.41	<0	19.00	14.65	50.11	0.00	-
			Max	35.79	63.50	29.00	35.69	1.26	22.20	18.92	100.00	49.89	-
			Mean	19.93	37.27	20.42	17.50	0.12	20.00	16.79	100.00	0.00	-
			SD	4.68	9.87	3.94	6.77	0.25	0.63	0.81	15.72	15.72	-
			N0	56									
18.5.20		Very dense to dense sand	Min	6.91	22.67	13.08	6.59	<0	19.50	15.70	6.52	55.24	-
			Max	27.35	54.95	24.28	33.33	0.05	21.00	18.33	44.77	93.49	-
			Mean	15.56	36.16	18.92	17.74	0.03	20.00	17.35	21.62	78.38	-
			SD	5.29	7.22	2.65	5.82	0.03	0.21	0.75	8.56	8.56	-
			N0	50									
20-25		Medium dense sand	Min	7.36	20.28	10.22	3.88	0.04	19.00	14.73	11.73	50.01	-
			Max	29.00	43.47	20.35	23.12	0.19	19.50	17.70	49.99	88.27	-
			Mean	14.96	32.29	17.07	15.22	0.14	19.50	16.96	24.93	75.07	-
			SD	6.63	5.97	2.41	5.62	0.06	0.25	1.00	10.00	10.00	-
			N0	32									

Table 4.6 Geotechnical properties of typical soil profile 1 of Mean Chey district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	SHEAR STRENGTH					SPECIFIC GRAVITY	VOID RATIO	Young's modulus	SPT
				Direct Shear		Unconfined compression	Field vane test	Pocket penetration				
				c	ϕ	$q_u/2$	s_u	s_u	G_s	e	E	N-Value
m				kN/m^2	Degree.	kPa	kPa	kPa			kPa	blows
0-1.5		Made ground	-	-	-	-	-	-	-	-	-	-
1.5-3		Very dense to dense sand	Min	-	33.00	-	-	-	2.70	0.45	19500	24
			Max	-	42.00	-	-	-	2.70	0.65	55000	120
			Mean	-	39.00	-	-	-	2.70	0.52	30000	46
			SD	-	2.47	-	-	-	-	0.05	9809	20
			N0	55								
3-5.5		Medium dense sand	Min	-	30.00	-	-	-	2.70	0.55	13500	11
			Max	-	35.00	-	-	-	2.70	0.82	21500	37
			Mean	-	32.50	-	-	-	2.70	0.66	18000	21
			SD	-	1.17	-	-	-	-	0.06	2236	5
			N0	49								
5.5-7		Very soft to soft clay	Min	-	-	-	6.00	17.00	2.70	0.77	2000	1
			Max	-	-	-	70.00	60.00	2.70	1.30	40000	9
			Mean	-	-	-	15.00	25.00	2.70	0.94	3250	4
			SD	-	-	-	20.34	18.58	-	0.13	6352	2
			N0	44								
7-11		Very stiff to stiff clay	Min	29.00	18.00	85.10	40.00	100.00	2.70	0.42	7000	6
			Max	88.00	42.00	276.00	260.00	300.00	2.70	0.92	46000	70
			Mean	50.00	24.00	158.50	145.20	200.00	2.70	0.64	28000	25
			SD	24.64	8.98	58.11	64.20	51.57	-	0.09	9035	13
			N0	55								
11-12		Medium stiff clay	Min	-	-	49.00	40.00	40.00	2.70	0.62	9000	5
			Max	-	-	87.00	90.00	160.00	2.70	1.02	17500	14
			Mean	-	-	72.00	67.50	75.00	2.70	0.78	13000	9
			SD	-	-	17.68	15.59	26.29	-	0.09	2706	2
	4.3		N0	30								
12-15		Medium dense sand	Min	-	31.00	-	-	-	2.70	0.53	15000	14
			Max	-	36.10	-	-	-	2.70	0.76	22500	34
			Mean	-	33.00	-	-	-	2.70	0.64	19000	23
			SD	-	1.50	-	-	-	-	0.05	2291	6
			N0	31								
15-16.5		Very loose to loose sand	Min	-	27.00	-	-	-	2.70	0.72	7500	1
			Max	-	31.00	-	-	-	2.70	0.93	14500	14
			Mean	-	29.00	-	-	-	2.70	0.81	11000	8
			SD	-	1.15	-	-	-	-	0.05	1824	3
			N0	30								
16.5-18.5		Very stiff to stiff clay	Min	-	-	66.50	120.00	79.20	2.70	0.43	14000	10
			Max	-	-	290.90	200.00	275.00	2.70	0.84	50000	43
			Mean	-	-	174.15	200.00	160.00	2.70	0.61	29000	23
			SD	-	-	59.66	46.19	54.93	-	0.08	7545	8
			N0	56								
18.5.20		Very dense to dense sand	Min	-	35.00	-	-	-	2.70	0.47	22000	27
			Max	-	42.00	-	-	-	2.70	0.72	70000	126
			Mean	-	37.00	-	-	-	2.70	0.56	25000	42
			SD	-	2.36	-	-	-	-	0.07	9282	22
			N0	50								
20-25		Medium dense sand	Min	-	31.00	-	-	-	2.70	0.53	14000	12
			Max	-	35.00	-	-	-	2.70	0.83	21500	33
			Mean	-	33.00	-	-	-	2.70	0.59	18500	21
			SD	-	1.24	-	-	-	-	0.10	1972	5
			N0	32								

Table 4.7 Physical properties of typical soil profile 2 of Mean Chey district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION		
				w_n	LL	PL	PI	LI	γ_{wet}	γ_{dry}	M&C	S	G
m				%	%	%	-	-	kN/m^3	kN/m^3	%	%	%
0-2.5	6.84	Made ground	-	-	-	-	-	-	-	-	-	-	-
2.5-5.5		Hard silt	Min	20.89	25.97	19.66	5.71	<0	18.50	13.64	64.13	0.00	-
			Max	35.60	70.25	37.06	35.92	1.20	21.00	17.37	100.00	35.87	-
			Mean	30.39	47.88	29.16	17.99	0.14	19.50	15.27	100.00	0.00	-
			SD	4.38	9.66	3.32	6.58	0.26	0.63	0.92	10.71	10.71	-
			N0	34									
5.5-7		Very loose to loose sand	Min	13.02	19.45	15.30	0.81	0.72	18.00	14.31	6.05	24.50	-
			Max	30.52	42.65	24.29	19.36	0.72	19.50	16.81	75.50	93.95	-
			Mean	22.34	26.17	18.30	8.94	0.72	19.00	15.53	25.62	74.39	-
			SD	4.89	6.42	3.04	5.88	-	0.47	0.69	14.19	14.22	-
			N0	33									
7.00-11		Medium stiff clay	Min	16.05	27.68	16.86	8.93	<0	18.90	14.64	49.35	0.00	-
			Max	30.58	55.58	27.09	28.49	0.75	20.00	16.80	100.00	50.66	-
			Mean	25.25	38.06	21.49	16.99	0.24	19.00	15.41	100.00	0.00	-
			SD	3.94	7.24	2.97	4.78	0.21	0.35	0.63	17.45	17.45	-
			N0	31									
11-12.5		Organic soil	Min	4.00	38.95	24.86	10.31	0.39	16.00	8.05	100.00	0.00	-
			Max	98.72	87.06	51.14	35.91	4.63	18.00	10.63	100.00	0.00	-
			Mean	71.27	55.57	36.34	17.87	1.73	16.00	9.26	100.00	0.00	-
			SD	20.15	10.42	6.92	5.38	0.97	0.57	0.79	0.00	0.00	-
			N0	27									
12.5-17.5		Soft silt	Min	18.43	18.56	16.13	1.65	<0	18.00	10.74	51.88	0.00	-
			Max	67.63	58.37	34.27	25.07	5.04	19.50	16.46	100.00	48.13	-
			Mean	40.62	36.48	25.61	10.31	1.33	18.00	12.70	100.00	0.00	-
			SD	11.19	10.55	4.50	6.30	1.05	0.38	1.29	14.42	14.42	-
			N0	35									

Notes: w_n = Natural Water Content, LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, LI = Liquidity Index, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number, M&C= Silt and Clay, S= Sand, G=Gravel

Table 4.8 Geotechnical properties of typical soil profile 2 of Mean Chey district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	SHEAR STRENGTH					SPECIFIC GRAVITY	VOID RATIO	Young's modulus	SPT
				Direct Shear		Unconfined compression	Field vane test	Pocket penetration				
				c	ϕ	$q_u/2$	s_u	s_u	G_s	e	E	N-Value
m				kN/m^2	Degree.	kPa	kPa	kPa			kPa	blows
0-2.5	6.84	Made ground	-	-	-	-	-	-	-	-	-	-
2.5-5.5		Hard silt	Min	25.00	10.00	55.80	50.00	70.00	2.70	0.55	11000	6
			Max	32.00	21.00	227.40	200.00	280.00	2.70	0.98	89000	68
			Mean	26.00	16.00	101.95	110.00	130.00	2.70	0.77	21500	16
			SD	3.79	5.51	44.15	36.92	57.45	-	0.11	14774	13
			N0	34								
5.5-7		Very loose to loose sand	Min	-	27.00	-	-	-	2.70	0.61	8000	3
			Max	-	30.00	-	-	-	2.70	0.89	15000	15
			Mean	-	29.00	-	-	-	2.70	0.74	12000	11
			SD	-	1.10	-	-	-	-	0.08	2169	4
			N0	33								
7.00-11		Medium stiff clay	Min	4.00	13.00	40.80	40.00	50.00	2.70	0.61	7000	5
			Max	49.00	21.00	89.00	113.00	150.00	2.70	0.84	26000	13
			Mean	23.00	19.50	56.75	77.00	77.50	2.70	0.75	14000	9
			SD	19.35	3.77	22.05	17.86	25.14	-	0.07	3559	2
			N0	31								
11-12.5		Organic soil	Min	-	-	-	9.00	20.00	2.70	1.54	2000	2
			Max	-	-	-	50.00	70.00	2.70	2.35	2000	12
			Mean	-	-	-	30.00	35.00	2.70	1.92	2000	4
			SD	-	-	-	14.65	21.60	-	0.25	-	3
			N0	30								
12.5-17.5		Soft silt	Min	-	-	-	5.00	50.00	2.70	0.64	2000	1
			Max	-	-	-	50.00	50.00	2.70	1.51	90000	11
			Mean	-	-	-	10.50	50.00	2.70	1.13	2000	3
			SD	-	-	-	10.89	-	-	0.20	14913	3
			N0	35								

Notes: UC = Unconfined Compressive test, DSB = Direct Shear Box, FV = Field Vane test, SPT = Standard Penetration test, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number

Table 4.9 Physical properties of typical soil profile 1 of Ressei Kao district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION		
				w_n	LL	PL	PI	LI	γ_{wet}	γ_{dry}	M&C	S	G
m				%	%	%	-	-	kN/m^3	kN/m^3	%	%	%
0-2		Made ground	-	-	-	-	-	-	-	-	-	-	-
2.00-5.00		Very dense to dense sand	Min	8.42	9.60	11.34	0.97	<0	19.50	15.67	6.93	23.02	59.01
			Max	30.00	57.88	31.69	39.25	12.01	20.00	20.00	49.37	93.07	76.98
			Mean	14.78	27.78	16.91	12.42	1.22	20.00	17.52	23.49	75.76	71.45
			SD	4.99	10.85	3.54	8.74	3.99	0.11	0.88	9.31	14.40	9.20
			N0	52									
5.00-8.00		Medium dense sand	Min	11.83	15.84	13.01	1.26	<0	19.00	14.74	6.35	48.44	-
			Max	32.32	39.37	22.60	21.83	0.74	20.00	17.44	51.56	93.65	-
			Mean	18.24	23.04	16.68	6.09	0.23	19.50	16.34	23.41	76.59	-
			SD	3.70	5.70	2.06	5.11	0.22	0.34	0.58	10.28	10.28	-
			N0	32									
8.00-13.00		Very stiff to stiff clay	Min	1.90	20.14	13.78	3.46	<0	18.50	14.17	29.66	0.00	-
			Max	33.22	62.91	33.75	47.40	0.89	20.00	17.79	100.00	70.35	-
	4.05		Mean	21.95	38.20	20.36	18.09	0.20	20.00	16.38	84.19	15.81	-
			SD	5.21	10.42	4.55	7.67	0.21	0.34	0.83	19.42	19.42	-
			N0	80									
13.00-18.00		Very dense to dense sand	Min	-	34.00	-	-	-	2.70	0.48	22000	29	-
			Max	-	42.00	-	-	-	2.70	0.69	50000	88	-
			Mean	-	38.00	-	-	-	2.70	0.54	31000	46	-
			SD	-	2.10	-	-	-	-	0.05	9453	15	-
			N0	55									
18.00-23		Very stiff to stiff clay	Min	10.96	1.00	14.00	5.42	<0	18.80	14.46	51.50	0.00	-
			Max	37.33	57.22	29.06	30.82	2.43	20.80	18.02	100.00	48.50	-
			Mean	21.29	41.06	21.84	17.65	0.14	20.00	16.45	91.18	8.83	-
			SD	4.77	9.35	3.45	5.63	0.47	0.25	0.72	15.63	15.63	-
			N0	70									

Notes: w_n = Natural Water Content, LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, LI = Liquidity Index, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number, M&C= Silt and Clay, S= Sand, G=Gravel

Table 4.10 Geotechnical properties of typical soil profile 1 of Ressei Kao district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	SHEAR STRENGTH					SPECIFIC GRAVITY	VOID RATIO	Young's modulus	**SPT**
				Direct Shear		Unconfined compression	Field vane test	Pocket penetration				
				c	ϕ	$q_u/2$	s_u	s_u	G_s	e	E	N-Value
m				kN/m²	Degree.	kPa	kPa	kPa			kPa	blows
0-2	4.05	Made ground	-	-	-	-	-	-	-	-	-	-
2.00-5.00		Very dense to dense sand	Min	-	34.00	-	-	-	2.70	0.48	22000	29
			Max	-	42.00	-	-	-	2.70	0.69	50000	88
			Mean	-	38.00	-	-	-	2.70	0.54	31000	46
			SD	-	2.10	-	-	-	-	0.05	9453	15
			N0	52								
5.00-8.00		Medium dense sand	Min	-	30.00	-	-	-	2.70	0.55	12500	10
			Max	-	37.00	-	-	-	2.70	0.83	22000	31
			Mean	-	32.00	-	-	-	2.70	0.65	17000	20
			SD	-	1.31	-	-	-	-	0.06	2325	5
			N0	32								
8.00-13.00		Very stiff to stiff clay	Min	28.00	20.00	57.00	40.00	100.00	2.70	0.52	14000	9
			Max	28.00	42.00	649.00	300.00	200.00	2.70	0.91	50000	115
			Mean	28.00	40.00	150.00	150.00	136.00	2.70	0.65	30000	26
			SD	-	12.17	95.98	62.13	36.53	-	0.09	10405	18
			N0	80								
13.00-18.00		Very dense to dense sand	Min	-	35.00	-	-	-	2.70	0.47	9230	31
			Max	-	42.00	-	-	-	2.70	0.72	65000	115
			Mean	-	38.00	-	-	-	2.70	0.55	28000	44
			SD	-	2.03	-	-	-	-	0.05	12439	23
			N0	55								
18.00-23		Very stiff to stiff clay	Min	43.00	20.00	56.00	60.00	110.00	2.70	0.50	10000	8
			Max	43.00	20.00	293.00	300.00	280.00	2.70	0.87	75000	121
			Mean	43.00	20.00	159.00	150.00	205.00	2.70	0.64	28000	29
			SD	-	-	61.10	73.35	49.61	-	0.08	13861	21
			N0	70								

Notes: UC = Unconfined Compressive test, DSB = Direct Shear Box, FV = Field Vane test, SPT = Standard Penetration test, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number

Table 4.11 Physical properties of typical soil profile 2 of Ressei Kao district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION		
				w_n	LL	PL	PI	LI	γ_{wet}	γ_{dry}	M&C	S	G
m				%	%	%	-	-	kN/m^3	kN/m^3	%	%	%
0-2	5.89	Made ground	-	-	-	-	-	-	-	-	-	-	-
2.00-4.00		Medium stiff clay	Min	12.18	19.20	12.41	2.63	<0	19.00	14.41	22.25	0.00	-
			Max	31.83	57.43	27.01	32.99	1.46	20.00	17.27	100.00	77.75	-
			Mean	23.49	38.86	21.10	18.05	0.17	19.00	15.53	97.46	2.54	-
			SD	5.19	8.68	3.42	6.58	0.29	0.36	0.71	23.72	23.72	-
			N0	40									
4.00-12		Very soft to soft clay	Min	24.29	25.63	19.25	4.79	0.31	18.00	10.98	72.71	0.00	-
			Max	63.92	48.45	30.59	19.28	3.40	19.70	15.29	100.00	27.30	-
			Mean	32.45	34.36	23.02	10.64	1.24	18.00	13.65	94.07	5.93	-
			SD	8.26	5.06	2.91	3.42	0.80	0.45	1.00	9.79	9.79	-
			N0	32									
12.00-13.5		Hard silt	Min	16.70	19.25	12.79	0.59	<0	18.00	13.22	50.84	0.00	-
			Max	43.69	58.04	32.37	27.19	0.96	20.00	17.14	100.00	49.17	-
			Mean	26.79	47.67	28.63	18.16	0.39	19.50	15.43	100.00	0.00	-
			SD	6.19	12.90	6.09	7.48	0.35	0.55	1.03	18.82	18.82	-
			N0	32									
13.5-15.5		Very loose to loose sand	Min	11.52	15.77	9.44	3.49	<0	18.00	13.35	4.97	50.14	-
			Max	36.01	43.42	22.37	23.64	0.97	20.00	17.04	49.86	95.04	-
			Mean	22.31	25.21	17.47	7.54	0.81	18.75	15.18	22.09	77.91	-
			SD	7.26	9.35	4.68	6.82	0.33	0.55	0.92	13.51	13.51	-
			N0	30									
15.5-17.00		Soft silt	Min	25.68	21.16	18.32	1.09	<0	18.00	10.68	55.05	0.00	-
			Max	68.60	54.15	39.59	23.94	8.23	20.00	15.06	100.00	44.95	-
			Mean	38.11	36.46	25.03	10.48	1.25	18.00	13.11	100.00	0.00	-
			SD	9.32	8.39	4.76	4.63	1.41	0.41	1.06	15.84	15.96	-
			N0	50									
17.00-19.00		Very loose to loose sand	Min	11.84	14.96	13.88	0.92	-	18.00	13.88	4.69	46.33	-
			Max	31.58	46.59	27.52	29.01	-	20.00	16.36	53.66	95.31	-
			Mean	20.04	29.38	19.03	10.01	-	18.50	15.70	22.60	77.41	-
			SD	5.14	9.21	3.49	8.23	-	0.55	0.64	14.53	14.78	-
			N0	36									
19.00-21.5		Medium dense sand	Min	9.02	17.26	10.74	-1.23	<0	19.00	15.48	10.67	50.48	-
			Max	26.63	50.91	22.19	32.52	4.41	20.00	18.06	49.52	89.34	-
			Mean	14.22	28.59	16.42	13.52	0.21	19.50	16.94	33.93	66.07	-
			SD	3.73	9.16	2.97	7.45	1.65	0.35	0.58	10.20	10.20	-
			N0	47									
21.5-25.5		Medium stiff clay	Min	13.30	26.19	14.33	0.87	<0	19.00	13.67	58.52	0.00	-
			Max	42.69	51.59	28.44	27.73	1.14	20.00	17.28	100.00	41.48	-
			Mean	23.55	36.27	21.47	16.66	0.27	19.50	15.74	76.02	22.72	-
			SD	5.46	7.46	3.47	5.46	0.28	0.33	0.73	13.66	13.90	-
			N0	41									

Notes: w_n = Natural Water Content, LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, LI = Liquidity Index, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number, M&C= Silt and Clay, S= Sand, G=Gravel

Table 4.12 Geotechnical properties of typical soil profile 2 of Ressei Kao district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	SHEAR STRENGTH					SPECIFIC GRAVITY	VOID RATIO	Young's modulus	**SPT**
				Direct Shear		Unconfined compression	Field vane test	Pocket penetration				
				c	ϕ	$q_u/2$	s_u	s_u	G_s	e	E	N-Value
m				kN/m^2	Degree.	kPa	kPa	kPa			kPa	blows
0-2		Made ground	-	-	-	-	-	-	-	-	-	-
2.00-4.00		Medium stiff clay	Min	-	-	49.00	40.00	54.00	2.70	0.56	7000	5
			Max	-	-	150.00	115.00	110.00	2.70	0.87	20000	28
			Mean	-	-	89.00	82.50	80.00	2.70	0.74	14500	9
			SD	-	-	32.42	18.60	15.60	-	0.08	2779	5
			N0	40								
4.00-12		Very soft to soft clay	Min	-	-	-	6.00	30.00	2.70	0.76	2000	1
			Max	-	-	-	50.00	60.00	2.70	1.46	10000	10
			Mean	-	-	-	15.00	41.00	2.70	0.98	2000	4
			SD	-	-	-	12.54	14.47	-	0.15	2457	2
			N0	32								
12.00-13.5		Hard silt	Min	23.00	10.00	35.20	22.00	80.00	2.70	0.57	5500	5
			Max	30.00	35.00	189.00	300.00	290.00	2.70	1.04	47000	54
			Mean	27.00	19.00	113.75	132.50	150.00	2.70	0.75	20000	18
			SD	3.51	10.90	40.07	70.36	63.34	-	0.12	9388	13
			N0	32								
13.5-15.5		Very loose to loose sand	Min	-	27.00	-	-	-	2.70	0.58	7500	1
			Max	-	30.00	-	-	-	2.70	1.02	15000	13
			Mean	-	28.00	-	-	-	2.70	0.78	11500	7
			SD	-	1.05	-	-	-	-	0.11	2130	4
	5.89		N0	30								
15.5-17.00		Soft silt	Min	-	-	77.00	6.00	-	2.70	0.79	1964	1
			Max	-	-	77.00	130.00	-	2.70	1.53	23000	19
			Mean	-	-	77.00	13.00	-	2.70	1.06	2000	4
			SD	-	-	-	24.25	-	-	0.17	3900	3
			N0	50								
17.00-19.00		Very loose to loose sand	Min	-	27.00	-	-	-	2.70	0.65	7500	2
			Max	-	31.00	-	-	-	2.70	0.94	17000	90
			Mean	-	28.00	-	-	-	2.70	0.71	10000	9
			SD	-	1.15	-	-	-	-	0.07	2255	16
			N0	36								
19.00-21.5		Medium dense sand	Min	-	31.00	-	-	-	2.70	0.50	14000	13
			Max	-	38.00	-	-	-	2.70	0.74	29000	43
			Mean	-	32.88	-	-	-	2.70	0.59	18500	21
			SD	-	1.32	-	-	-	-	0.06	2570	5
			N0	47								
21.5-25.5		Medium stiff clay	Min	-	-	61.00	30.00	60.00	2.70	0.56	7500	6
			Max	-	-	106.00	150.00	125.00	2.70	0.98	26000	15
			Mean	-	-	76.00	72.00	78.00	2.70	0.71	13000	10
			SD	-	-	18.29	25.13	20.56	-	0.08	3656	2
			N0	41								

Notes: UC = Unconfined Compressive test, DSB = Direct Shear Box, FV = Field Vane test, SPT = Standard Penetration test, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number

Table 4.13 Physical properties of typical soil profile 1 of Chamkar Mon district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION		
				w_n	LL	PL	PI	LI	γ_{wet}	γ_{dry}	M&C	S	G
m				%	%	%	-	-	kN/m³	kN/m³	%	%	%
0-1.5		Made ground	-	-	-	-	-	-	-	-	-	-	-
			Min	8.42	17.70	11.34	0.97	<0	19.50	15.67	6.93	50.64	-
			Max	25.21	57.88	21.52	39.25	1.86	20.00	18.21	49.37	93.07	-
1.5-5.00		Very dense to dense sand	Mean	14.92	27.52	16.50	11.75	0.23	20.00	17.41	24.00	76.00	-
			SD	3.94	9.85	2.48	8.60	0.69	0.10	0.59	9.25	9.27	-
			N0	50									
			Min	13.51	17.75	14.95	0.98	<0	17.00	13.76	11.36	27.42	-
			Max	31.96	54.02	22.85	31.17	1.78	19.50	18.00	57.65	88.64	-
5.00-7.00		Very loose to loose sand	Mean	21.73	21.93	17.00	4.84	0.70	18.50	15.26	22.36	76.51	-
			SD	4.28	9.05	2.15	7.46	0.51	0.53	0.83	11.58	13.34	-
			N0	44									
			Min	11.83	18.78	13.75	2.30	<0	19.00	14.74	6.35	48.44	-
			Max	32.32	39.37	22.60	21.83	0.74	20.00	17.44	51.56	93.65	-
7.00-10.5		Medium dense sand	Mean	18.60	23.18	17.13	6.36	0.24	19.50	16.39	25.34	74.66	-
			SD	3.85	5.99	2.13	5.39	0.23	0.36	0.62	10.97	10.97	-
			N0	48									
			Min	1.90	20.14	13.78	3.46	<0	18.50	14.17	29.66	0.00	-
			Max	33.22	62.91	33.75	47.40	0.89	20.00	17.79	100.00	70.35	-
10.5-13.5	2.65	Very stiff to stiff clay	Mean	22.08	37.48	20.40	17.64	0.20	20.00	16.37	83.33	16.67	-
			SD	5.35	10.22	4.55	7.55	0.21	0.35	0.84	19.12	19.12	-
			N0	77									
			Min	9.19	18.08	13.00	3.30	<0	19.50	15.69	8.52	54.81	-
			Max	27.51	53.28	24.83	28.81	0.51	20.00	18.32	45.19	91.48	-
13.5-16.5		Very dense to dense sand	Mean	13.60	29.89	17.88	12.19	0.42	20.00	17.61	27.68	72.33	-
			SD	3.81	8.32	3.12	5.77	0.11	0.07	0.58	7.93	7.93	-
			N0	51									
			Min	12.34	15.84	13.01	1.26	<0	19.00	15.14	4.99	55.11	-
			Max	25.92	46.83	29.24	17.59	0.46	20.00	17.36	44.89	95.02	-
16.5-19		Medium dense sand	Mean	17.87	24.08	16.59	7.56	0.28	19.50	16.38	19.55	80.46	-
			SD	6.31	8.74	5.27	5.52	0.21	2.79	2.36	11.11	14.73	-
			N0	41									
			Min	25.68	21.16	18.32	1.09	<0	18.00	10.68	55.05	0.00	-
			Max	68.60	54.15	39.59	23.94	8.23	19.00	15.06	100.00	44.95	-
19-23		Soft silt	Mean	39.59	37.22	25.31	11.70	1.20	18.00	12.88	100.00	0.00	-
			SD	10.23	8.37	4.69	4.72	1.44	0.35	1.12	16.24	16.43	-
			N0	35									

Notes: w_n = Natural Water Content, LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, LI = Liquidity Index, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number, M&C= Silt and Clay, S= Sand, G=Gravel

Table 4.14 Geotechnical properties of typical soil profile 1 of Chamkar Mon district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	SHEAR STRENGTH: Direct Shear		SHEAR STRENGTH: Unconfined compression	SHEAR STRENGTH: Field vane test	SHEAR STRENGTH: Pocket penetration	SPECIFIC GRAVITY	VOID RATIO	Young's modulus	**SPT**
				c	ϕ	$q_u/2$	s_u	s_u	G_s	e	E	N-Value
m				kN/m^2	Degree.	kPa	kPa	kPa			kPa	blows
0-1.5	2.65	Made ground	-	-	-	-	-	-	-	-	-	-
1.5-5.00		Very dense to dense sand	Min	-	34.00	-	-	-	2.70	0.48	22000	30
			Max	-	42.00	-	-	-	2.70	0.72	50000	88
			Mean	-	38.00	-	-	-	2.70	0.55	31000	46
			SD	-	2.15	-	-	-	-	0.05	9189	14
			N0	50								
5.00-7.00		Very loose to loose sand	Min	-	27.00	27.00	14.00	-	2.70	0.61	7500	1
			Max	-	31.00	27.00	25.00	-	2.70	0.96	15500	16
			Mean	-	29.00	27.00	19.50	-	2.70	0.78	11500	8
			SD	-	1.12	-	7.78	-	-	0.08	1941	4
			N0	44								
7.00-10.5		Medium dense sand	Min	-	31.00	-	-	-	2.70	0.55	13500	12
			Max	-	37.00	-	-	-	2.70	0.83	22000	29
			Mean	-	32.00	-	-	-	2.70	0.65	17500	20
			SD	-	1.37	-	-	-	-	0.06	2181	5
			N0	48								
10.5-13.5		Very stiff to stiff clay	Min	-	-	57.00	40.00	100.00	2.70	0.52	14000	9
			Max	-	-	649.00	300.00	200.00	2.70	0.91	50000	115
			Mean	-	-	129.00	150.00	136.00	2.70	0.65	28000	24
			SD	-	-	98.47	61.25	36.53	-	0.09	10818	20
			N0	77								
13.5-16.5		Very dense to dense sand	Min	-	35.00	-	-	-	2.70	0.47	20000	31
			Max	-	42.00	-	-	-	2.70	0.72	65000	115
			Mean	-	38.00	-	-	-	2.70	0.53	28000	44
			SD	-	1.97	-	-	-	-	0.05	12248	24
			N0	51								
16.5-19		Medium dense sand	Min	-	30.00	-	-	-	2.70	0.56	12500	10
			Max	-	34.00	-	-	-	2.70	0.78	21000	31
			Mean	-	32.00	-	-	-	2.70	0.65	17000	20
			SD	-	5.35	-	-	-	-	0.11	3207	6
			N0	41								
19-23		Soft silt	Min	-	-	77.00	6.00	-	2.70	0.79	2000	1
			Max	-	-	77.00	100.00	-	2.70	1.53	13000	19
			Mean	-	-	77.00	10.00	-	2.70	1.10	2000	3
			SD	-	-	-	20.25	-	-	0.18	2860	3
			N0	35								

Notes: UC = Unconfined Compressive test, DSB = Direct Shear Box, FV = Field Vane test, SPT = Standard Penetration test, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number

Table 4.15 Physical properties of typical soil profile 2 of Chamkar Mon district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION		
				w_n	LL	PL	PI	LI	γ_{wet}	γ_{dry}	M&C	S	G
m				%	%	%	-	-	kN/m^3	kN/m^3	%	%	%
0-1.5		Made ground	-	-	-	-	-	-	-	-	-	-	-
1.5-5.5		Very soft to soft clay	Min	20.99	25.63	16.45	4.79	0.08	18.00	10.98	72.71	0.00	-
			Max	63.92	48.45	30.59	19.28	3.40	19.70	15.45	100.00	27.30	-
			Mean	31.44	33.99	22.02	11.64	0.76	18.50	14.10	100.00	0.00	-
			SD	8.78	5.08	3.06	3.54	0.79	0.48	1.08	9.21	9.21	-
			N0	35									
5.5-7.5		Hard silt	Min	16.70	19.25	12.79	0.59	<0	18.00	13.22	50.84	0.00	-
			Max	43.69	58.09	32.37	27.36	0.96	21.50	18.01	100.00	49.17	-
			Mean	27.07	48.68	28.98	18.74	0.39	19.45	15.21	100.00	0.00	-
			SD	6.21	13.70	6.33	8.01	0.33	0.65	1.09	19.22	19.22	-
			N0	30									
7.5-10.5		Very loose to loose sand	Min	13.66	18.24	12.82	2.05	<0	18.00	14.43	11.80	55.59	-
			Max	27.06	56.23	28.20	28.03	1.44	20.00	17.49	44.41	88.21	-
			Mean	19.15	24.32	16.13	7.33	0.36	18.50	15.61	25.46	74.55	-
			SD	3.10	8.79	3.55	5.96	0.51	0.55	0.75	9.97	9.97	-
			N0	41									
10.5-14		Soft silt	Min	26.05	22.51	18.98	1.04	<0	17.70	10.98	55.45	0.00	-
			Max	63.93	57.44	38.87	26.46	4.37	20.00	14.93	100.00	44.55	-
			Mean	37.08	36.18	26.13	9.83	0.74	18.00	13.51	80.19	19.82	-
			SD	7.23	9.05	4.47	5.64	1.14	0.39	0.98	13.63	13.64	-
	2.04		N0	46									
14.17		Hard silt	Min	12.09	17.00	15.17	0.74	<0	19.00	13.68	48.00	0.00	-
			Max	42.52	59.67	34.74	27.84	0.83	20.00	17.66	100.00	52.00	-
			Mean	25.42	45.31	28.51	17.35	0.13	19.80	15.83	68.47	31.54	-
			SD	6.14	12.39	5.20	8.19	0.31	0.39	0.96	18.04	19.03	-
			N0	30									
17-22		Very soft to soft clay	Min	18.91	23.37	16.36	4.99	<0	18.00	12.76	59.29	13.64	-
			Max	47.30	42.66	26.14	18.14	2.54	19.90	16.31	86.36	40.72	-
			Mean	28.10	31.41	21.85	10.02	0.55	18.00	14.80	76.98	23.02	-
			SD	6.11	5.22	2.31	3.57	0.53	0.53	1.03	8.64	8.64	-
			N0	40									
22-24.5		Very stiff to stiff clay	Min	10.96	1.00	14.00	5.42	<0	18.80	14.46	51.25	0.00	-
			Max	37.33	58.58	29.06	31.53	2.43	20.80	18.02	100.00	48.76	-
			Mean	21.36	41.51	21.97	17.45	0.15	20.00	16.43	92.40	7.60	-
			SD	4.60	9.72	3.58	6.04	0.44	0.29	0.71	16.22	16.22	-
			N0	77									
24.5-28		Very dense to dense sand	Min	8.56	26.00	15.37	10.11	<0	19.50	15.54	4.94	51.91	-
			Max	28.71	52.82	27.24	31.25	-	20.00	18.30	48.10	95.06	-
			Mean	13.75	37.33	19.85	17.70	-	20.00	17.58	24.46	75.54	-
			SD	4.64	6.47	3.02	5.25	-	0.10	0.67	11.84	11.82	-
			N0	54									

Notes: w_n = Natural Water Content, LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, LI = Liquidity Index, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number, M&C= Silt and Clay, S= Sand, G=Gravel

Table 4.16 Geotechnical properties of typical soil profile 2 of Chamkar Mon district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	SHEAR STRENGTH					SPECIFIC GRAVITY	VOID RATIO	Young's modulus	SPT
				Direct Shear		Unconfined compression	Field vane test	Pocket penetration				
				c	ϕ	$q_u/2$	s_u	s_u	G_s	e	E	N-Value
m				kN/m^2	Degree.	kPa	kPa	kPa			kPa	blows
0-1.5		Made ground	-	-	-	-	-	-	-	-	-	-
1.5-5.5		Very soft to soft clay	Min	-	-	-	6.00	30.00	2.70	0.75	2000	1
			Max	-	-	-	58.00	60.00	2.70	1.46	10000	10
			Mean	-	-	-	20.00	41.00	2.70	0.91	4400	4
			SD	-	-	-	13.95	14.47	-	0.16	2581	2
			N0	35								
5.5-7.5		Hard silt	Min	23.00	10.00	35.20	22.00	75.00	2.70	0.50	5500	5
			Max	30.00	35.00	189.00	300.00	290.00	2.70	1.04	47000	54
			Mean	27.00	19.00	117.50	122.50	107.50	2.70	0.77	18000	16
			SD	3.51	10.90	43.86	70.43	65.64	-	0.12	8988	14
			N0	30								
7.5-10.5		Very loose to loose sand	Min	-	27.00	-	-	-	2.70	0.54	8000	3
			Max	-	32.00	-	-	-	2.70	0.87	17500	20
			Mean	-	28.00	-	-	-	2.70	0.73	11500	8
			SD	-	1.21	-	-	-	-	0.08	1925	4
			N0	41								
10.5-14		Soft silt	Min	-	-	35.00	5.00	25.00	2.70	0.81	1964	1
			Max	-	-	39.00	130.00	25.00	2.70	1.46	23000	8
			Mean	-	-	37.00	10.00	25.00	2.70	0.99	2000	3
			SD	-	-	2.83	23.56	-	-	0.15	3899	2
	2.04		N0	46								
14.17		Hard silt	Min	-	30.00	48.00	70.00	100.00	2.69	0.53	10000	6
			Max	-	36.00	227.00	298.00	100.00	2.70	0.97	40000	67
			Mean	-	30.00	126.00	135.00	100.00	2.70	0.71	18500	16
			SD	-	2.61	59.56	54.61	-	-	0.11	8240	14
			N0	30								
17-22		Very soft to soft clay	Min	-	-	-	5.00	-	2.70	0.61	2000	1
			Max	-	-	-	68.00	-	2.70	1.12	12000	9
			Mean	-	-	-	18.00	-	2.70	0.82	2000	4
			SD	-	-	-	17.53	-	-	0.15	2924	2
			N0	40								
22-24.5		Very stiff to stiff clay	Min	-	-	-	60.00	100.00	2.70	0.50	10000	8
			Max	-	-	-	300.00	280.00	2.70	0.87	75000	121
			Mean	-	-	-	170.00	200.00	2.70	0.64	28500	28
			SD	-	-	-	72.37	53.29	-	0.07	13109	21
			N0	77								
24.5-28		Very dense to dense sand	Min	-	34.00	-	-	-	2.70	0.48	22000	27
			Max	-	42.00	-	-	-	2.70	0.74	50000	86
			Mean	-	39.00	-	-	-	2.70	0.54	31000	45
			SD	-	2.64	-	-	-	-	0.06	7780	15
			N0	54								

Notes: UC = Unconfined Compressive test, DSB = Direct Shear Box, FV = Field Vane test, SPT = Standard Penetration test, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number

Table 4.17 Physical properties of typical soil profile Daun Penh district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION		
				w_n	LL	PL	PI	LI	γ_{wet}	γ_{dry}	M&C	S	G
m				%	%	%	-	-	kN/m³	kN/m³	%	%	%
0-1.5		Made ground	-	-	-	-	-	-	-	-	-	-	-
1.5-6.5		Very loose to loose sand	Min	15.11	17.06	14.11	1.53	<0	17.00	13.29	2.63	32.61	-
			Max	35.40	29.20	20.42	9.61	0.68	20.00	16.94	67.39	97.38	-
			Mean	23.12	24.53	15.64	7.55	0.42	18.00	15.04	28.00	72.01	-
			SD	5.32	3.77	2.05	2.80	0.15	0.61	0.87	15.76	15.76	-
			N0	36									
6.5-8.5		Very dense to dense sand	Min	9.17	16.53	11.55	0.53	<0	19.00	15.17	8.74	50.99	-
			Max	28.54	50.86	23.14	31.66	0.63	21.00	18.32	49.01	91.26	-
			Mean	13.97	33.86	17.41	15.72	0.22	20.00	17.66	24.66	75.34	-
			SD	3.66	8.14	2.54	6.57	0.21	0.26	0.61	9.25	9.25	-
			N0	50									
8.5-11.5		Organic soil	Min	22.30	34.10	23.58	1.57	<0	13.00	7.71	53.22	0.00	-
			Max	95.67	70.37	49.11	26.57	3.49	18.00	14.72	100.00	46.78	-
			Mean	60.68	53.51	36.67	16.91	1.45	16.00	8.69	100.00	0.00	-
			SD	19.01	10.33	7.05	5.35	0.98	0.80	2.00	12.97	12.97	-
			N0	29									
11.5-13.5		Very soft to soft clay	Min	11.70	25.02	17.21	5.28	<0	18.00	12.66	25.94	0.00	-
			Max	42.18	46.95	26.25	22.44	2.02	19.50	17.01	100.00	74.07	-
			Mean	28.62	33.12	21.24	11.14	0.59	18.50	14.38	100.00	0.00	-
			SD	6.11	5.57	2.18	4.32	0.45	0.48	0.91	16.46	16.54	-
			N0	45									
13.5-16		Medium dense sand	Min	10.15	14.64	12.36	0.62	<0	16.00	14.84	5.96	52.03	-
			Max	73.87	52.33	36.03	23.47	0.50	20.00	18.15	47.97	94.04	-
			Mean	17.60	23.21	16.35	8.43	0.13	19.50	16.56	26.74	73.26	-
			SD	9.68	9.25	4.99	5.92	0.22	0.62	0.72	11.52	11.52	-
	2.97		N0	42									
16.00-18.00		Hard silt	Min	11.70	33.79	17.38	8.46	<0	18.00	10.18	25.94	0.00	-
			Max	76.82	61.82	32.97	30.49	2.98	21.00	17.23	100.00	74.07	-
			Mean	28.00	46.37	29.07	17.65	0.21	19.50	15.16	100.00	0.00	-
			SD	9.53	6.86	2.93	5.54	0.71	0.57	1.18	16.66	16.66	-
			N0	42									
18.00-21.00		Very dense to dense sand	Min	7.10	20.33	11.44	6.15	<0	19.50	16.74	14.37	53.43	-
			Max	19.50	77.48	29.65	47.83	-	29.00	26.82	46.58	85.64	-
			Mean	11.60	35.97	18.57	18.04	-	20.00	17.85	25.18	74.82	-
			SD	2.46	12.35	4.21	9.36	-	1.30	1.35	8.21	8.21	-
			N0	50									
21-23.5		Very stiff to stiff clay	Min	10.68	15.20	14.33	0.87	<0	18.70	14.40	37.65	0.00	-
			Max	33.11	65.08	31.47	38.02	0.66	21.10	18.07	100.00	62.35	-
			Mean	20.03	41.73	22.62	18.78	0.15	20.00	16.72	78.52	21.49	-
			SD	5.22	10.19	3.65	7.48	0.18	0.53	0.94	17.54	17.54	-
			N0	60									
23.5-29		Very dense to dense sand	Min	8.01	15.94	9.79	2.25	<0	19.50	16.24	15.31	26.85	-
			Max	23.17	77.67	28.10	53.74	1.29	21.00	19.05	73.15	84.70	-
			Mean	12.27	40.49	18.57	20.41	0.10	20.00	18.05	30.09	69.91	-
			SD	3.06	15.39	4.05	13.13	0.69	0.53	0.74	10.72	10.72	-
			N0	56									
29-35		Very stiff to stiff clay	Min	13.16	18.27	11.63	5.27	<0	18.00	14.85	50.98	0.00	-
			Max	31.28	96.94	30.07	39.42	0.95	21.40	17.71	100.00	49.03	-
			Mean	20.61	43.32	21.71	21.52	0.10	20.00	16.70	88.97	11.04	-
			SD	3.98	12.10	3.98	7.04	0.20	0.49	0.68	17.00	17.00	-
			N0	53									

Table 4.18 Geotechnical properties of typical soil profile of Daun Penh district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	SHEAR STRENGTH: Direct Shear		SHEAR STRENGTH: Unconfined compression	SHEAR STRENGTH: Field vane test	SHEAR STRENGTH: Pocket penetration	SPECIFIC GRAVITY	VOID RATIO	Young's modulus	SPT
				c	ϕ	$q_u/2$	s_u	s_u	G_s	e	E	N-Value
m				kN/m^2	Degree.	kPa	kPa	kPa			kPa	blows
0-1.5	2.97	Made ground	-	-	-	-	-	-	-	-	-	-
1.5-6.5		Very loose to loose sand	Min	-	26.00	-	15.00	-	2.70	0.59	4000	1
			Max	-	30.00	-	35.00	-	2.70	1.03	14000	14
			Mean	-	28.00	-	25.00	-	2.70	0.79	10000	6
			SD	-	1.24	-	14.14	-	-	0.10	2233	4
			N0	36								
6.5-8.5		Very dense to dense sand	Min	-	35.00	-	38.00	-	2.70	0.47	6700	6
			Max	-	42.00	-	38.00	-	2.70	0.78	50000	92
			Mean	-	40.00	-	38.00	-	2.70	0.53	35000	54
			SD	-	2.36	-	-	-	-	0.06	9970	19
			N0	50								
8.5-11.5		Organic soil	Min	-	-	-	10.00	38.00	2.70	0.83	2000	3
			Max	-	-	-	85.00	45.50	2.70	2.50	8000	14
			Mean	-	-	-	30.00	41.75	2.70	2.11	2000	5
			SD	-	-	-	22.28	5.30	-	0.51	1200	3
			N0	29								
11.5-13.5		Very soft to soft clay	Min	-	-	-	6.00	10.00	2.70	0.59	2000	2
			Max	-	-	-	70.00	70.00	2.70	1.13	17000	19
			Mean	-	-	-	30.00	40.00	2.70	0.88	6000	5
			SD	-	-	-	15.61	18.80	-	0.12	3507	3
			N0	45								
13.5-16		Medium dense sand	Min	-	31.00	-	-	-	2.70	0.49	2000	8
			Max	-	40.00	-	-	-	2.70	0.82	44000	82
			Mean	-	32.00	-	-	-	2.70	0.63	18000	21
			SD	-	1.51	-	-	-	-	0.07	5073	11
			N0	42								
16.00-18.00		Hard silt	Min	-	-	42.60	70.00	60.00	2.70	0.57	2000	8
			Max	-	-	295.60	220.00	250.00	2.70	1.65	43000	40
			Mean	-	-	120.00	150.00	130.00	2.70	0.78	20000	17
			SD	-	-	61.59	46.35	51.26	-	0.17	7642	7
			N0	42								
18.00-21.00		Very dense to dense sand	Min	-	35.00	-	-	-	2.70	0.01	24500	29
			Max	-	42.00	-	-	-	2.70	0.61	50000	99
			Mean	-	41.00	-	-	-	2.70	0.51	34000	53
			SD	-	2.63	-	-	-	0.00	0.08	6764	17
			N0	50								
21-23.5		Very stiff to stiff clay	Min	-	-	74.00	90.00	80.00	2.70	0.49	16000	11
			Max	-	-	315.00	300.00	300.00	2.70	0.87	75000	88
			Mean	-	-	145.00	150.00	200.00	2.70	0.61	35000	31
			SD	-	-	70.78	74.35	67.16	-	0.10	17842	21
			N0	60								
23.5-29		Very dense to dense sand	Min	-	35.00	-	-	-	2.70	0.42	23000	32
			Max	-	43.62	-	-	-	2.70	0.66	390000	168
			Mean	-	39.25	-	-	-	2.70	0.50	39000	54
			SD	-	2.46	-	-	-	-	0.06	48398	26
			N0	56								
29-35		Very stiff to stiff clay	Min	-	-	82.10	45.00	100.00	2.70	0.52	8000	11
			Max	-	-	267.00	300.00	300.00	2.70	0.82	50000	64
			Mean	-	-	137.40	175.00	180.00	2.70	0.62	35000	31
			SD	-	-	55.39	71.04	43.74	-	0.07	11058	14
			N0	53								

Table 4.19 Physical properties of typical soil profile Toul Kork district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	WATER CONTENT	ATTEBERG LIMIT		PLASTIC INDEX	LIQUITY INDEX	UNIT WEIGTH OF SOIL		PARTICAL SIZE DISTRIBUTION		
				w_n	LL	PL	PI	LI	γ_{wet}	γ_{dry}	M&C	S	G
m				%	%	%	-	-	kN/m^3	kN/m^3	%	%	%
0-2	5.42	Made ground	-	-	-	-	-	-	-	-	-	-	-
2-6.5		Hard silt	Min	12.61	16.52	12.15	4.22	<0	19.00	14.48	52.71	0.00	-
			Max	31.19	58.04	30.84	27.19	0.77	20.50	17.76	100.00	0.00	-
			Mean	22.72	41.24	26.83	14.61	0.33	20.00	16.24	100.00	0.00	-
			SD	4.50	11.40	5.87	6.22	0.38	0.37	0.74	17.33	17.33	-
			N0	31									
6.5-9.5		Medium dense sand	Min	10.13	15.60	9.52	0.81	<0	18.50	15.46	11.74	50.56	-
			Max	26.52	57.43	28.09	33.22	0.36	20.00	17.84	49.44	88.26	-
			Mean	14.85	26.53	15.49	10.64	0.08	19.25	16.79	32.91	67.20	-
			SD	3.40	10.03	4.00	7.46	0.10	0.40	0.53	8.46	8.48	-
			N0	60									
9.5-13.5		Very soft to soft clay	Min	14.21	21.09	12.08	6.33	<0	18.00	13.00	53.31	0.00	-
			Max	38.51	48.55	27.02	27.63	1.96	20.00	16.93	100.00	47.78	-
			Mean	22.19	37.10	20.06	16.56	0.15	19.00	15.65	83.51	16.49	-
			SD	5.77	6.06	3.12	4.80	0.44	0.52	0.89	18.54	18.62	-
			N0	30									
13.5-17.5		Very loose to loose sand	Min	9.40	13.28	10.61	1.31	<0	18.00	14.73	14.77	47.57	-
			Max	26.85	45.72	24.08	23.97	3.04	20.00	18.09	52.43	85.23	-
			Mean	17.20	23.48	15.73	7.12	0.69	18.50	15.93	39.58	60.43	-
			SD	4.34	7.56	3.47	5.32	0.86	0.51	0.74	10.42	10.42	-
			N0	38									
17.5-20.5		Very dense to dense sand	Min	9.25	21.79	12.50	8.28	<0	19.00	16.19	13.48	0.00	-
			Max	21.68	52.02	26.54	28.83	0.50	21.30	18.46	100.00	86.53	-
			Mean	12.30	37.57	18.67	18.39	0.40	20.00	17.66	31.72	68.28	-
			SD	2.64	7.86	3.40	5.34	0.22	0.31	0.44	12.40	12.40	-
			N0	66									
20.5-22.5		very stiff to stiff clay	Min	10.44	19.95	11.36	6.66	<0	19.00	15.35	49.54	0.00	-
			Max	30.25	70.05	30.52	42.56	0.44	20.00	17.95	100.00	50.47	-
			Mean	18.24	36.67	19.52	17.97	0.18	20.00	16.87	74.05	25.96	-
			SD	4.33	12.31	4.35	8.89	0.12	0.20	0.61	17.03	17.17	-
			N0	55									
22.5-26		Very dense to dense sand	Min	6.72	18.90	12.10	6.81	<0	19.50	17.08	16.97	52.85	-
			Max	17.13	53.83	25.23	35.60	0.23	21.00	19.03	47.16	83.04	-
			Mean	12.28	38.52	19.09	18.50	0.23	20.00	17.73	28.50	71.50	-
			SD	1.82	8.03	3.14	5.97	-	0.25	0.36	7.25	7.25	-
			N0	75									
26-35		very stiff to stiff clay	Min	11.37	21.44	12.08	6.97	<0	19.00	14.44	50.87	0.00	-
			Max	31.62	72.87	31.61	41.26	0.50	21.70	19.12	100.00	49.13	-
			Mean	19.98	37.89	20.30	18.31	0.12	20.00	16.70	82.51	17.49	-
			SD	4.10	10.12	4.07	6.96	0.13	0.45	0.74	18.09	18.07	-
			N0	69									

Notes: w_n = Natural Water Content, LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, LI = Liquidity Index, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number, M&C= Silt and Clay, S= Sand, G=Gravel

Table 4.20 Geotechnical properties of typical soil profile Toul Kork district

DEPTH	GROUND WATER LEVEL	SOIL DESCRIPTION	STATISTICAL PARAMETERS	SHEAR STRENGTH: Direct Shear		Unconfined compression	Field vane test	Pocket penetration	SPECIFIC GRAVITY	VOID RATIO	Young's modulus	**SPT**
				c	ϕ	$q_u/2$	s_u	s_u	G_s	e	E	N-Value
m				kN/m²	Degree.	kPa	kPa	kPa			kPa	blows
0-2		Made ground	-	-	-	-	-	-	-	-	-	-
2-6.5		Hard silt	Min	19.00	15.00	100.00	70.00	62.00	2.70	0.52	11000	5
			Max	42.00	25.00	243.00	300.00	215.00	2.70	0.86	60000	57
			Mean	37.00	19.00	166.00	132.00	150.00	2.70	0.66	26000	18
			SD	9.92	4.60	46.80	73.50	50.16	-	0.08	11138	12
			N0	31								
6.5-9.5		Medium dense sand	Min	-	30.91	-	-	-	2.70	0.51	2000	15
			Max	-	35.00	-	-	-	2.70	0.75	21500	28
			Mean	-	32.00	-	-	-	2.70	0.61	17000	20
			SD	-	1.06	-	-	-	-	0.05	3059	4
			N0	60								
9.5-13.5		Very soft to soft clay	Min	-	-	-	10.00	15.00	2.70	0.59	2000	3
			Max	-	-	-	65.00	75.00	2.70	1.08	14000	16
			Mean	-	-	-	27.00	40.00	2.70	0.73	6800	6
			SD	-	-	-	16.70	14.64	-	0.11	2887	3
			N0	30								
13.5-17.5		Very loose to loose sand	Min	-	26.00	-	-	-	2.70	0.49	5000	1
			Max	-	30.00	-	-	-	2.70	0.83	20000	17
			Mean	-	29.00	-	-	-	2.70	0.69	12000	9
			SD	-	1.17	-	-	-	-	0.08	2565	4
	5.42		N0	38								
17.5-20.5		Very dense to dense sand	Min	-	34.00	111.60	-	125.00	2.70	0.46	19000	12
			Max	-	42.00	461.40	-	125.00	2.70	0.64	50000	108
			Mean	-	40.00	286.50	-	125.00	2.70	0.53	32000	47
			SD	-	2.48	247.35	-	-	-	0.04	9471	20
			N0	66								
20.5-22.5		very stiff to stiff clay	Min	-	-	-	55.00	200.00	2.70	0.50	14000	10
			Max	-	-	-	300.00	270.00	2.70	0.76	50000	77
			Mean	-	-	-	127.50	235.00	2.70	0.60	26000	20
			SD	-	-	-	69.98	49.50	-	0.06	12028	16
			N0	55								
22.5-26		Very dense to dense sand	Min	-	35.00	-	-	-	2.70	0.42	20000	32
			Max	-	42.45	-	-	-	2.70	0.58	50000	138
			Mean	-	42.00	-	-	-	2.70	0.52	34500	58
			SD	-	2.35	-	-	-	-	0.03	8133	24
			N0	75								
26-35		very stiff to stiff clay	Min	-	-	70.40	80.00	55.00	2.70	0.41	9800	5
			Max	-	-	335.00	300.00	280.00	2.70	0.87	50000	65
			Mean	-	-	146.80	205.00	150.00	2.70	0.62	27000	20
			SD	-	-	59.18	77.54	52.58	-	0.07	11483	14
			N0	69								

Notes: UC = Unconfined Compressive test, DSB = Direct Shear Box, FV = Field Vane test, SPT = Standard Penetration test, Min= Minimum value, Max= Maximum value, SD= Standard Deviation, N0= Sampling number

Table 4.1 to 4.20 present the representative of subsoil physical and geotechnical properties of Dangkao, Prampi Makara, Mean Chey, Russei Kao, Chamkar Morn, and Daun Penh and Toul Kork districts, respectively. According to the cross-section as well as the boring logs, typical soil profile can be judged directly. It can be concluded that the subsoil conditions in Phnom Penh city is very varied from place to place. Soil properties of the downtown area have usually been investigated profound depth. It is because of an increase of construction activities, especially high-rise building in this areas. On the other hand, there are only several villas (low-rise building) constructed around suburb area. The soil investigation has been therefore observed up to 15 m for the purpose of shallow foundation.

There are two types of properties, physical and engineering properties, which are conducted for Phnom Penh subsoil. Both properties are carefully performed by geotechnical engineers at site investigation and laboratory. Statistical parameters were determined such as minimum, maximum, Mean, standard deviation and sampling number.

4.3.2 Analysis of Geotechnical properties

The spatial distribution of geotechnical properties in natural soil is difficult to deterministically predict, especially when sampling interests a very scarce portion of the total volume of soil (Jones et al., 2002; Parsons and Frost, 2002). Probabilistic methods, used along with conventional geotechnical applications, allow for quantifying uncertainty in assessing hazard mitigation measures and in designing projects to compensate for risks (Lacasse and Nadim, 1996). The collected soil data including soil classification, field tests and laboratory tests have been well-documented according to US standard (Hunt, 2005). The various laboratory test were performed generally according to the procedure specified by American Society for Testing and Material (ASTM, 1979)

Classification and Index properties: Basic soil properties and indices were performed according to ASTM standard in the laboratory. The percentages of gravel, sand, silt and clay particles from the sieve analysis; and Atterberg limits and indices of each soil layer are standard performed as reported in Table 4.1 to 4.20 for each districts of Phnom Penh.

Field testing results: With adequate selection of field test, proper control over the procedures adopted and careful extraction of undisturbed samples, the in-situ tests aim to provide the information on behavior of the subsoil. They are considered to be a preferred means of strength characterization such as SPT and FV. The values of SPT N-Values are shown against depth in Table 4.1 to 4.20.

Strength Properties: Direct shear Box (DSB) is chosen to determine the shear strength of soil in Phnom Penh city. This is because it is a conventional method which easy to understand and reliable. As shown in Table from 4.1 to 4.20, the values of cohesion and friction angle are not however to evaluate in some depth especially in clay layers.

Stiffness and compressibility: The compressibility of Phnom Penh subsoil can be roughly determined by oedometer test. An undisturbed sample should respond to more reliable results. However, according to the time consuming of consolidation test, some empirical estimates are useful to estimate the stiffness or compressibility. The Young's modulus as shown in this study is converted from the corrected SPT N-value.

Because of the limitation of laboratory test of geotechnical engineering section in Cambodia, some experiments are not able to conduct. That is why some parameter values are missed from the table above. As the result, statistical analysis could not be performed for some properties. Furthermore, assumption of some value is raised in order to fulfill which the standard of soil investigation. For example, the value of specific gravity (Gs) is the same even in different type of soil.

4.4 Properties of Mekong River sand Index properties

4.4.1 Physical properties

Table 4.21 Physical properties of Mekong River sand

Sample	Cu	Cc	Gs	e_{min}	e_{max}	USCS Symbol
	Coefficient of uniformity	Coefficient of curvature	Specific gravity			
S1	2.62	0.62	2.64	0.510	0.828	SP
S2	2.32	1.4	2.67	N/A	N/A	SP

Remarks: N/A= not available

Note: Particle size analysis conducted following ASTM D422, Gs determined by ASTM D854, and Unified Soil Classification System (USCS) determined by ASTM D2487.

Table 4.21 demonstrates the physical properties of Mekong River sand which is mainly used for construction sector such as house construction and road construction. Mekong River sand is the most popular fill material for any construction purpose.

4.4.2 Scanning Electron Microscope (SEM)

- ***Sample 1 (S1)***

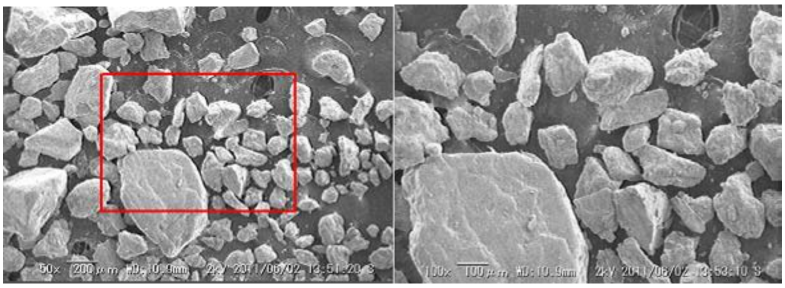


Figure 4.36 SEM of Sampling 1

The sand particles of sampling 1 which is taken from Mekong River sand as shown in figure 4.36 captured by SEM are blocky, mostly elongate conchoidal fractures, showing broken surfaces and rough with v-shaped depression developed on flat surfaces.

- ***Sample 2 (S1)***

Figure 4.37 shows the sand particles of Mekong River sand which was taken at the bottom of riverbank captured by SEM. These sand particles are blocky, longitudinal shape, partially fractures on the top surface.

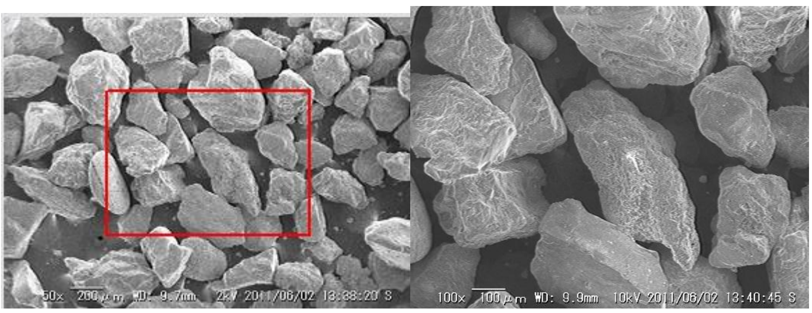


Figure 4.37 SEM of Sampling 2

CHAPTER V
RESEARCH DISCUSSION AND CONCLUSIONS

This final chapter will firstly discuss about research result. There are three main parts of this chapter namely three-dimensional geological modeling of Phnom Penh city, statistical analysis of geotechnical properties of Phnom Penh subsoil and the properties of Mekong river sand. Next implication will be focused on the conclusion as well as the limitation of this research study. In addition, possibly future research will be included in this chapter.

5.1 Three-dimensional geological modeling of Phnom Penh city

In this study, a methodology to generate different types of accessible geological information (boreholes, outcrop, cross-section, geological map, solid face) in a 3D geological model is presented. Moreover, this methodology is based on structuring and storing in digital formats the various data of different type of soil. Solids were created from interpolating borehole data and TINs.

The reliable and usable data are then validated and selected for the 3D geological model. According to the obtained information, the accuracy of the model strongly depends on the amount of data available, its nature and quality and its dispersion over the area of study. Importantly, some hypotheses have been raised in order to construct a model of the geological surface. This means that the computational ability and its illustration can complement to the model to be simple and it is easy to understand, and reasonable. In addition, human knowledge and reflection can also supplement to help the modeling more reliable.

Three-dimensional structures such as stratigrapgic horizons are very difficult since the concept of input required the clear data that is not easy to obtain in practice. To make model accurate, many manual corrections and human judgments are required in order to produce a better result in complex setting. It is because the geological model is a knowledge-based model required a lot of experience from expertise and the efficiency of their interaction.

As a result of the solid model and the cross-section in chapter 4, there are many soil layers which appeared. This is because data from soil boring log also counts a very thin layer of each soil type. Importantly, this three-dimensional geological modeling mainly depends on interpolation method which is not exactly the same as the reality of subsoil condition. This modeling is then created by ignoring surface. It is also assumed the constant depth of the river at 30 meters below sand because this research is focused on subsoil modeling and there is no reliable data regarding the river information in Phnom Penh city.

5.2 Geotechnical properties of Phnom Penh subsoil

A thorough study has been carried out to compile numerous geotechnical data in order to establish correlations between some important engineering parameters. Several kinds of field and laboratory tests have been conducted for subsoil investigation around Phnom Penh city by one well-known company called Research and Design Enterprise (RDE) carrying out the ground investigation for almost 20 years. Soil boring logs have been gathered from each district in order to determine the representative subsoil properties including physical and geotechnical properties using a static analysis. The Standard Penetration test (SPT) and Field Vane test (FVT) are two typical field tests presented in this study; on the other hand, there are several laboratory tests have been performed based on ASTM standard such as Atterberg limits, Particle size distribution, Void ratio, Specific gravity Unit weight, direct shear box (DSB) test, Unconfined compressive (UC) test and Oedometer test. All typical values from field and laboratory tests are summarized in the Table 4.1 to 4.20 in chapter 4.

On the other hand, statistical analysis is performed according to the cross-section of three-dimensional geological modeling of Phnom Penh subsoil so the typical soil profile is depended on the processing of solid. As mentioned earlier that there is a limitation of borehole’s number which is affected to the result of the geotechnical properties of Phnom Penh subsoil.

5.3 Properties of Mekong River sand

There are just some laboratory experiments further conducted for Mekong River sand. The purpose of conducting these is to understand about the most typical fill material in Phnom Penh city for embankment and road construction. According to geological history around 100 years ago, the Phnom Penh area was low land which was usually flooded every year. Thus, the government decided to high-elevate with filled material from neighbouring area. Therefore, Mekong River sand was one of the fill materials during that operation.

5.4 Contribute of research

This research aims to understand more about subsoil condition of Phnom Penh city. The limited number of researchers has been conducted research regarding about geological and geotechnical condition of Phnom Penh city so far. This research study is the first research which tried to gather soil boring logs over the Phnom Penh city and the result of this research will keep as the main information of subsoil condition of Phnom Penh city. The fundamental knowledge of Phnom Penh subsoil as presented in this study will contribute in particular to the development of infrastructure in Phnom Penh City and to the Cambodian geologists in general for their further references.

5.5 Limitation and direction for future research

The results of subsoil modeling presented in the study should be viewed as a preliminary work due to the limited number of soil boring log used at 1200 boreholes which is not spread over the area of study yet.

There are two types of error which are counted for this study. These types of error are from human error and systematic error. Human error can be defined as the error which is created by human, engineer over the complexity of the input data obtained from the file. It is very difficult for engineer to judge exactly correct on what they cannot see underground about geological condition because ground condition is very varied from one place to another and one layer to another. On the other hand, systematic error is referred to the nature of the research program and process which is used as a tool to develop subsurface modeling. Beside these, the simple linear interpolation method might not be appropriately used in complex ground circumstance. Horizon to solid tool is mainly depending on the interpolation which absolutely can't be the same as the reality.

For future research, more numbers of borehole gatherings should be well-collected over Phnom Penh city. It is also very important to understand about the variation of the river as well as the ground water condition because subsoil condition of Phnom Penh is mainly from river deposit. The determination of the distribution from one borehole to another should be raised in order to know the accuracy of the solid model. Moreover, the thin layers should not be considered because these layers may come from the error of site investigation or judgments of geological and geotechnical engineers. Most importantly, the value of accuracy of the models should be determined in order to make model more reliable. Lastly, the statistical analyses of geotechnical properties need to be improved by some other methods because in this study, the analysis depends on the three-dimensional geological modeling which is already simplified.

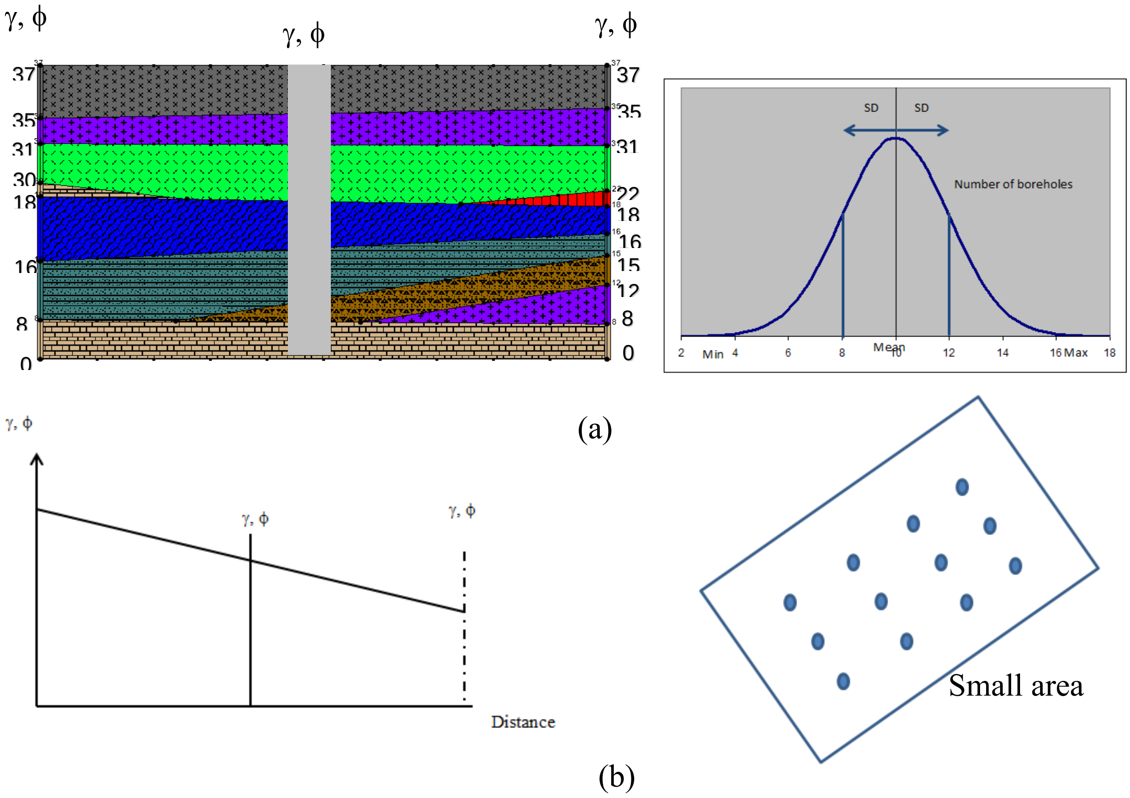


Figure 5.1 Comparison between statistical analysis in this research and the interpolation of soil properties (a) statistical analysis in this research (b) the interpolation of soil properties

In addition to this research study, a related topic which also interested for the future research is the interpolation of soil properties. Figure 5.1 is an explanation between statistical analysis in this research and the interpolation of soil properties. For this research, the user can understand about the statistical value such as minimum, maximum, mean, standard deviation and sampling number. These values will aim to understand the geotechnical properties of Phnom Penh subsoils as the primary idea. In this research 1200 boreholes were uploaded over Phnom Penh city to provide a better understanding of geotechnical properties by running statistical value in each case more than 30 sampling number. On the other hand, soil interpolation is also a good topic for geotechnical engineering, but to achieve this, the quality of data is very important and it might not work well with a large area like Phnom Penh city.

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