

GEOLOGICAL AND GEOTECHNICAL PROPERTIES OF MEKONG DELTA CLAY AS COMPARISON WITH BANGKOK CLAY

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ABSTRACT: Mekong Delta Clay and Bangkok Clay, the uppermost soil layers, were reviewed from soil formation, landforms, and geotechnical properties. This paper studied and compared the geological and geotechnical properties of Mekong Delta Clay and Bangkok Clay using secondary data from 20 boreholes in the Mekong Delta and more than 4,000 boreholes in Bangkok Clay. Data validation was examined for data normalization, possible, and statistical ranges. Some engineering properties are correlated to physical properties. The landforms of the Mekong Delta are classified into three types: back swamp/swamp, mangrove marsh, and sand dune close to the coastal zone. While Chao Phraya Delta mainly consists of marine deposits associated with an alluvial river fan at the edge. The results showed that Mekong Delta Clay's and Bangkok Clay's thicknesses were 4–22 and 3–30 m, respectively. Mekong Delta Clay contained silt-sized particles, whereas Bangkok Clay contained clay-sized particles predominantly. Physical properties indicated, for example, that Mekong Delta Clay had less plasticity ($PI = 19.95\%$) than Bangkok Clay ($PI = 42.26\%$). The overconsolidation ratio (OCR) of Mekong Delta Clay was normally consolidated to moderately overconsolidated clay ($OCR = 1.04\text{--}7.99$), while OCR of Bangkok Clay was classified as normally consolidated to lightly overconsolidated ($OCR = 0.83\text{--}2.92$). In addition, the compression index (C_c) showed that Mekong Delta Clay ($C_c = 0.04\text{--}0.36$) had much lower compressibility than Bangkok Clay ($C_c = 0.51\text{--}1.54$). These data will further serve as essential indexes for the Mekong Delta's sustainable development.

Keywords: Mekong Delta Clay, Bangkok Clay, Soil Formation, Landform, Geotechnical Properties

1. INTRODUCTION

The Mekong Delta in Vietnam and the Chao Phraya Delta in Thailand are Southeast Asia's first and third largest delta plains, respectively [1, 2]. Currently, these two delta areas are the locations of the major cities of both countries, where infrastructure and buildings are continuously being constructed. With urbanization and thriving economic expansion on these plains, geotechnical information is in high demand. Therefore, in recent years, some research has been conducted to evaluate Mekong Delta Clay's and Bangkok Clay's characteristics. As a result, several relationships between the physical and engineering properties of soils have been proposed for geotechnical design. However, only a few have studied the behaviors related to the landform, especially in Mekong Delta.

The previous studies on Chao Phraya Delta (known as Bangkok Clay) can be summarized into three research periods. Before 2000, the studies involved the soft clay sediment processes and properties of the lower Chao Phraya River Basin [3, 4]. Borehole investigations were gradually collected, interpreted, analyzed, and published in a geotechnical database from 2000 to 2010 [5-7]. Until 2010, Mairaing and Amonkul [8] collected data for more than 4000 boreholes. The study classified soft Bangkok Clay zoning from strongest (zones A, B, and C) to weakest (zones D, E, and F) from the edge into

the inner part. Zones A, B, and C were formed mainly by alluvial deposits, whereas marine deposits formed zones D, E, and F. Some applications for pile foundations, highway, and embankment designs were given in this study. It has been widely used for preliminary planning and design for many projects. Research in this area is still ongoing for soil formation related to the geotechnical properties of Bangkok Clay. From 2010 to the present, many studies have been added to the geotechnical database and applications on pile foundations, highways, and land subsidence [9-11].

The research on Mekong Delta Clay before 2007 also showed soft clay delta sediment combined with coastal evolution sediment and coastal evolution. These results indicated that the soft soil was widely distributed into many landforms [12, 13]. Subsequently, from 2007–2016, some research was carried out [14, 15] on soft soil's geotechnical properties and composition in the coastal part of the Mekong Delta. Up to now, Ngoc [16, 17] shows that soft clay in Mekong Delta has high compression indices with a high void ratio and low bearing capacity. In addition, most works of the literature showed that different soil-forming environments, such as soil origin, transportation, and sedimentation process, influenced the geotechnical properties of soil. Therefore, this study is focused on the interpretation of soil engineering properties related to landforms.

The objectives of the research are as follows: 1) correlate the soil's physical properties to engineering properties, 2) relate those properties to landforms, and 3) comparison between the properties of Bangkok clay to Mekong Delta clay. This study emphasizes the very soft clay, which is the problematic soil layer in both areas. Some applications on highway embankments and soil improvement in Mekong Delta are corroborated. This study intends to be the preliminary data for the Mekong Delta's sustainable development [16, 17].

2. RESEARCH SIGNIFICANCE

Viet Nam has launched its Mekong Delta Regional Master Plan for 2021-2030. By 2030, the region will have 830 km. of a highway, 4,000 km. of the national road, four airports, and 39 ports. The advanced knowledge of the geotechnical properties in the areas will be crucial for planning and designing every infrastructure in the future. Assessing the relationship between soil-forming processes and landforms with the geotechnical properties allows engineers and planners to estimate the soil condition in areas lacking information. This study can give the idea for planning the detailed investigation. In the future, it can lead to a geotechnical database for the region.

3. BACKGROUND OF STUDY AREA

3.1 Mekong Delta, Vietnam

The Mekong Delta (Fig.1) is roughly a triangular region bordered by Phnom Penh, Cambodia, the mouth of Saigon River in Ho Chi Minh City, and Ca Mau Cape in Ca Mau Peninsula's south [12, 18]. Estimates of the delta area range from 62,520 km² to 93,781 km² [12, 18]. The morphology has two parts: an upper delta plain dominated by fluvial processes and a lower delta plain influenced mainly by marine processes [12, 18].

The upper delta plain is occupied mainly by the back swamp, swamp, and floodplain [18]. Back swamp and swamp environments occur in depressions where flood basins are low and wet, allowing a community of sedges and reeds to develop (high-flood zone) [12]. In the lower delta plain, the rows of sand dunes trend northeast to southwest (Fig.1). Beach ridges align in Eastern Coastal Area, with the dunes paralleling the coastline. The Ca Mau Peninsula is characterized in low areas by a mangrove marsh and a large mangrove forest more than 90 km long and 25 km wide [18].

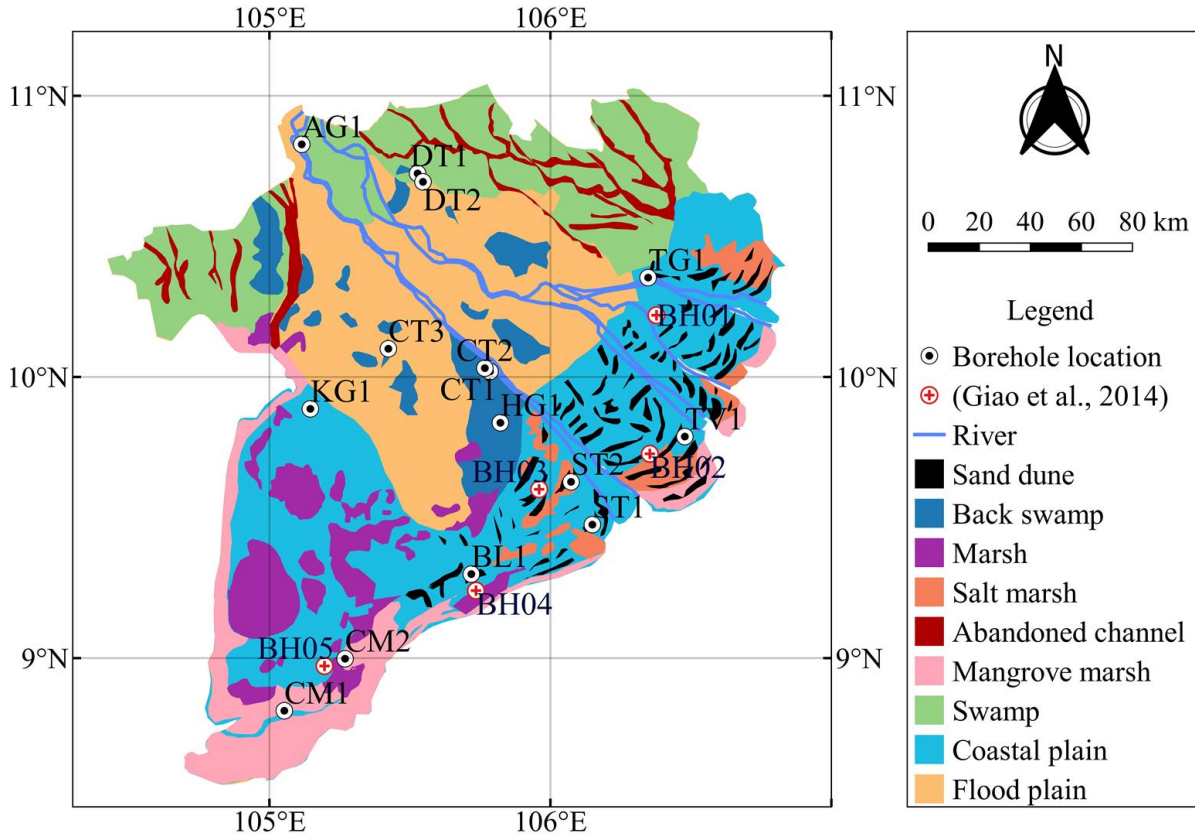


Fig.1 Landforms and borehole locations in Mekong Delta, Vietnam (modified from [18])

3.2 Chao Phraya Delta

The Chao Phraya Delta, covering 10,400 km² [1], is bounded on the west by the Tanaosri mountain ranges and the east by the Petchabun mountain ranges on the western edge of the Khorat Plateau. The eastern and western margins of the plain area are surrounded by mountain ranges with terraces and alluvial fans. The gentle slope of the plain ranges from 1.0 to 2.5 m/km [4]. The related sediments consist of deltaic deposits, marine deposits, intertidal and shallow infralittoral sand, and mud. The recent alluvial deposits of rivers testify to the sea transgression cycle [4] (Fig.2).

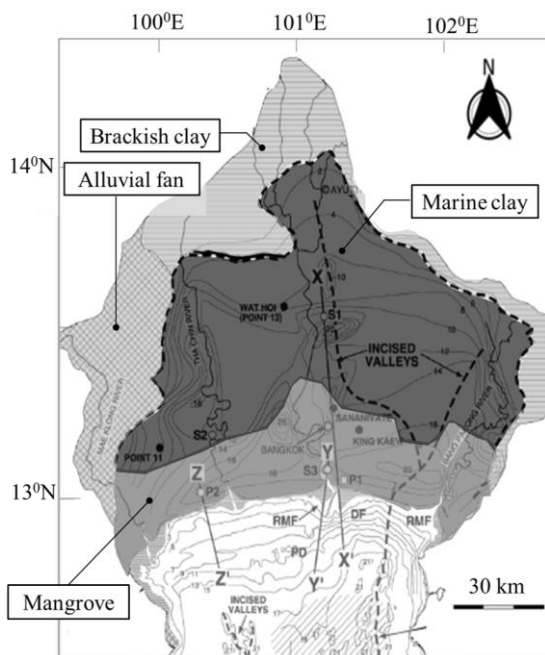


Fig.2 Geomorphology and sediment distribution of Chao Phraya Delta (modified from [1]).

3.3 Evolution of Delta in Quaternary Period

The critical factors influencing delta evolution and sedimentation in the Quaternary are the rising sea level in the Late Pleistocene to Holocene after post-glacial marine transgression in the two deltas [4, 18]. The evolution of the deltas reflects Holocene sea-level changes [2] (Fig.3,4), with an aggradation system that developed during the slow rise of the sea level from 8,000 to 6,000 years ago and a progradation system developed 6,000 years ago when sea level had nearly stabilized.

3.3.1 Sea-level related geological formation

The delta evolution in the Chao Phraya and Mekong deltas depended on sea level fluctuations (Fig.3a,4). During the late Pleistocene and early Holocene, the sea level fluctuated from -120 to +4 m

(Fig.3b), making it comparable to the present mean sea level. During this time, the deltaic sequence comprised Bangkok Clay between the alluvial, tidal flat, and brackish areas, extending northerly to Ayutthaya (Fig.2).

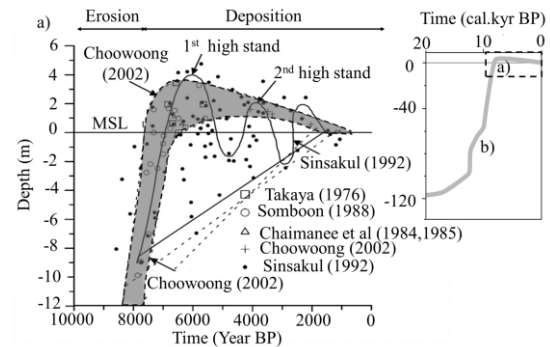


Fig.3 Sea-level curves for Thailand to present from 8,000 years ago, a) and for Sunda Shelf, b) from 20,000 years ago (modified from [19, 20]).

During the same period, the northern part of the Mekong delta's shoreline prograde during the mid-Holocene Sea level rising about 5,000 to 6,000 years ago (Fig.4). After the sea level started going down, the delta area started to explore more and forming present Mekong Delta.

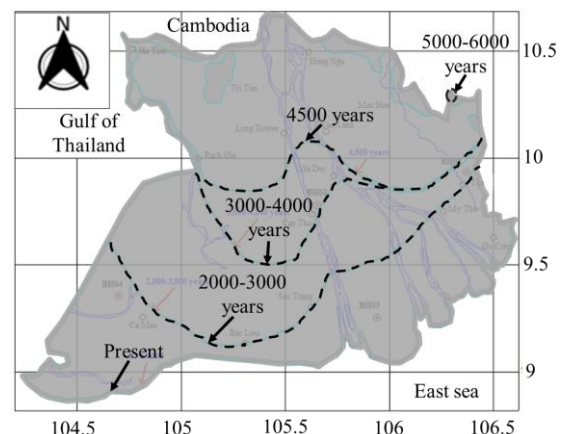


Fig.4 Shoreline migration of Mekong Delta from around 6,000 years ago to the present (modified from [12]).

3.3.2 Soil formation process

The characteristics of the soil formation process on the two deltas are shown in Table 1. Before around 10,000 years ago, it was called the "Erosion period." Soil material was produced by physical and chemical weathering and erosion due to rainfall and runoff from mainly basement rocks [4, 12]. These initial development periods of the deltas occurred about 8,000–6,000 years ago, primarily controlled by the declining rate of the Holocene sea-level rise,

namely the “Deposition period.” Sediment supply from rivers surpassed the accommodation created by the sea-level rise. About ten times the water discharge from the Mekong River compared to the Chao Phraya River resulted in about 15 times the sediment transport in the Mekong River, leading to the progradation rate for the Mekong Delta being relatively faster than for the Chao Phraya Delta. Because of hydro-isostatic effects, tectonic uplift or subsidence, and sediment compaction, the deltas responded differently to the relative sea-level changes [4, 18].

Tide-dominated activity influenced Chao Phraya Delta. Sediment materials reflect deltaic and shallow marine environments corresponding to Bangkok Clay. Progradation rate of Mekong Delta decreased rapidly from 3,000 years ago from 17–40 m/yr to 8–20 m/yr due to Mekong Delta's regressive deltaic system that was divided into two phases: a tide-dominated delta that formed about 6,000 years ago and a tide and wave-dominated delta that evolved about 3,000 years ago. The coarser grain was deposited upstream from the coast.

Table 1 Characteristics of soil formation process Chao Phraya Delta and Mekong Delta.

Delta Characteristic	Chao Phraya Delta, Thailand	Mekong Delta, Vietnam		References
Classification of delta	Tide dominated	Tide dominated	Tide-wave dominated	[4, 12, 16, 20]
Formation time	8,000–6,000 yr ago	Before 3,000 yr ago	After 3,000 yr ago	[4, 12, 16, 20]
Stratigraphic sequences	Top Bangkok Clay of Holocene Epoch, and	Top Mekong Delta Clay of Holocene Epoch: Holocene aquifer (0–49 m): Holocene, and		[4, 12, 18, 21]
Major river	Eight Aquifers (600 m) in Pleistocene Epoch Chao Phraya River	Pleistocene Sediments (31–193 m): Upper Pleistocene, Middle Pleistocene, Lower Pleistocene. Mekong River		[2, 22]
Water discharge	Greater than 1,500 m ³ /s	14,900 m ³ /s		[2, 22]
Annual sediment discharge	11 million t/yr	160 million t/yr		[1, 4, 12, 18]
Mean tidal-wave influences	Tidal: 1.2 m Mixed semidiurnal tide Low-energy environment	Tidal: 2.5 ± 0.1 m Mixed-energy (tide-wave dominated) Mean wave height: 0.9 m		[1, 4, 12, 18]
Grain size	1–22% sand content	2–30% sand content	30–90% sand content	[1, 4, 12, 18]
Typical facie association	Prodelta Delta-front Tidal flat	Prodelta Delta-front Tidal flat	Delta-front Subtidal flat Beach-ridge	[1, 4, 12, 18]
Sedimentary structure	Parallel lamination, lenticular.	Parallel lamination, lenticular.	Lenticular and flasher bedding, wave-ripple lamination	[1, 4, 12, 18]
Progradation rate (excluding erosion)	1.6–28.9 m/yr (last 2,000 yr)	17–40 m/yr	8–20 m/yr	[1, 4, 12, 18]

3.4 Previous Study of Bangkok Clay

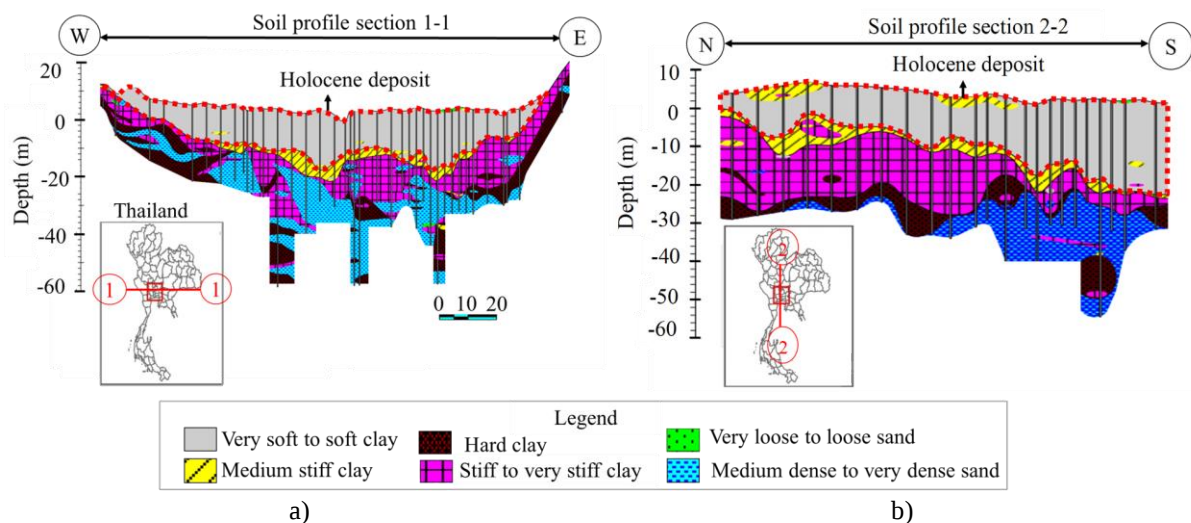


Fig.5 Typical soil profile of Bangkok Clay (modified from [8]), a) Soil profile in west-east direction, b) Soil profile in north-south direction.

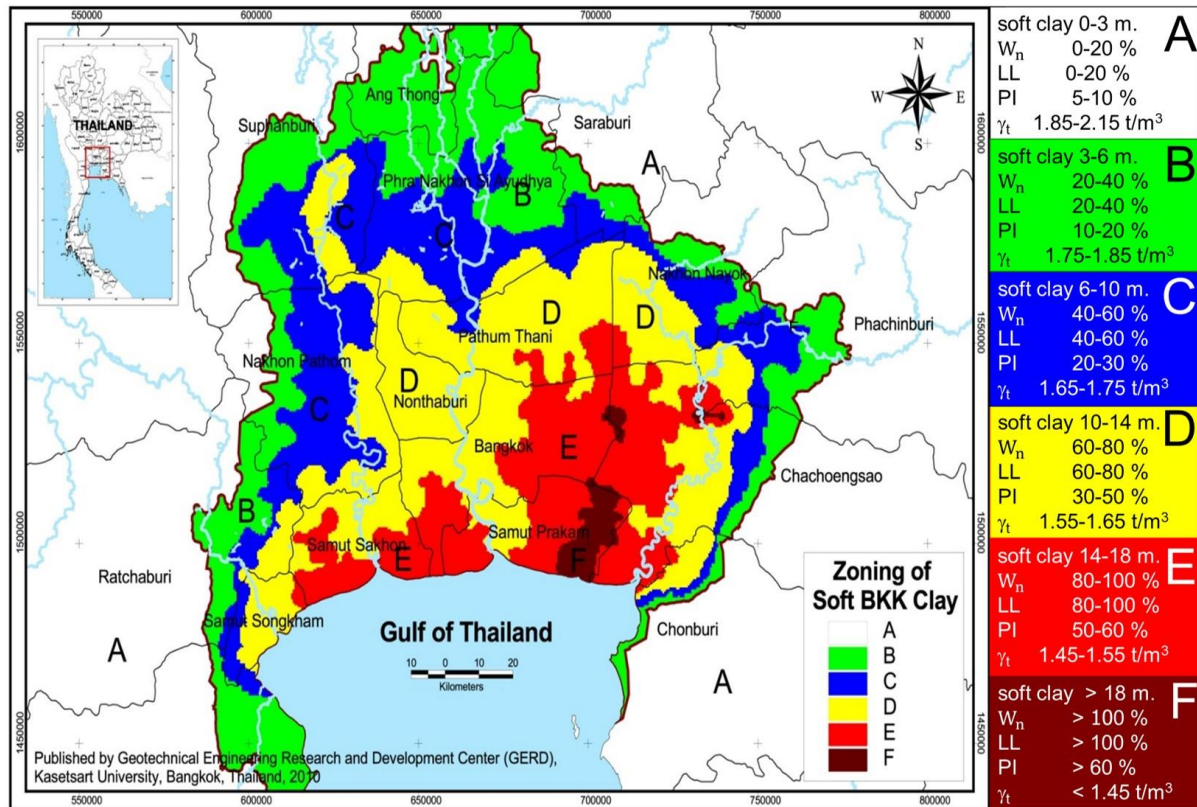


Fig.6 Zoning of Soft Bangkok Clay (modified from [8]).

As shown in Fig.5, the typical soil profile of Bangkok Clay from the surface consists of: 1) top crust of 1–3 m; 2) very soft to soft clay of 10–20 m; 3) medium stiff clay of 26 m; 4) stiff to very stiff clay of 2–6 m; 5) medium dense sand of 2–6 m; and 6) dense to very dense sand of 0–6 m. The surface has a very soft to soft clay layer from the ground with an average depth of approximately 12 m. There is a general depth of very soft to soft clay (about 15.24 m) in the middle of the basin, with about 18–25 m depth located between the Chao Phraya River and Bang Pakong. The area with the most significant depth (25–28 m) is in Samut Prakan province.

Mairaing and Amonkul [8] divided Bangkok Clay into six zones depending on thickness, water content, Atterberg limits, and total unit weight of Bangkok Clay at each location, as shown in Fig.6. These classifications are from the strongest to weakest: Zone A, Zone B, Zone C (edge), and Zone D, Zone E, Zone F (inner part).

4. METHODOLOGY

The research workflow is given in Fig.7. This research aimed to assess the soil formation processes, typical landforms, and soil physical and engineering properties of both delta areas.

4.1 Literature Review

The background of the study area of two deltas was reviewed based on documentary research. First, general information about Mekong Delta and Chao Phraya Delta was collated. Next, delta evolution was assessed in the Quaternary period, consisting of sea-level-related geological formation and soil formation processes. Finally, existing publications of Bangkok Clay were reviewed.

4.2 Data Collection

Data collection for geological-geotechnical engineering properties comprised of three primary sources of secondary data: (1) investigated data were collected from Construction Laboratory No. LAS-XD 1078 of The South Mekong verifying construction consultants and investment company limited, Cantho, Vietnam; (2) academic publications, such as journals and proceedings; and (3) existing soil data from Engineering Soil Database System – Kasetsart University (ESDS-KU) [23].

4.3 Data Processing

4.3.1 Raw data

Raw data was collected from soil boring log reports. The selection of boreholes was based on specific criteria such as reliable location, detailed descriptions, and geotechnical tests (in the field and

laboratory). The soil samples are tested in the laboratory according to ASTM standards.

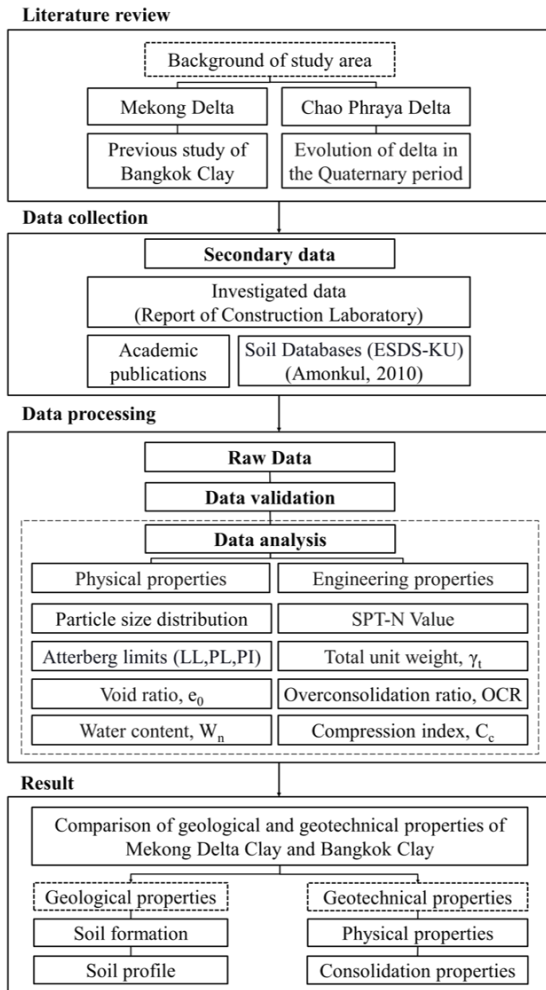


Fig.7 Research workflow.

4.3.2 Data validation

This step intends to check the raw data's relevance, accuracy, and quality before use. The following steps include:

Firstly, the data collected from different sources were checked by data normalization based on the X-bar statistic. Next, these data were normalized by checking the mean of samples.

Secondly, methods of data screening by the statistical analysis were used. First, data screening was done using typical ranges (possible maximum and minimum values). The typical data range was obtained from the study of soil properties in references [8, 14].

Finally, a limit of two standard deviations (Mean $\pm$ 2SD) was applied to identify and remove outliers from the data sample based on a confidence interval at the 95% confidence level according to the proposal by Wang [24].

4.3.3 Data analysis

4.3.3.1 Generating soil profile in Mekong Delta

Subsequently, landform and soil profiles were investigated in detail based on SPT-N value. The boreholes from soil report data and Giao, P.H [14] are shown in Fig.8. The soil profile focused on the soft clay layer's depth, thickness, and properties. In addition, the soft clay formation in the two data.

4.3.3.2 Comparison of geotechnical properties

This study compared the physical and geotechnical properties of Mekong Delta Clay and Bangkok Clay. The physical properties used to assess initial soil behavior were: particle size distribution, plasticity chart, water content, and Atterberg limit. Geotechnical properties focused on consolidation parameters. The overconsolidation ratio (OCR) determines the stress history related to soil formation. In addition, a compression index was used to assess settlement problems.

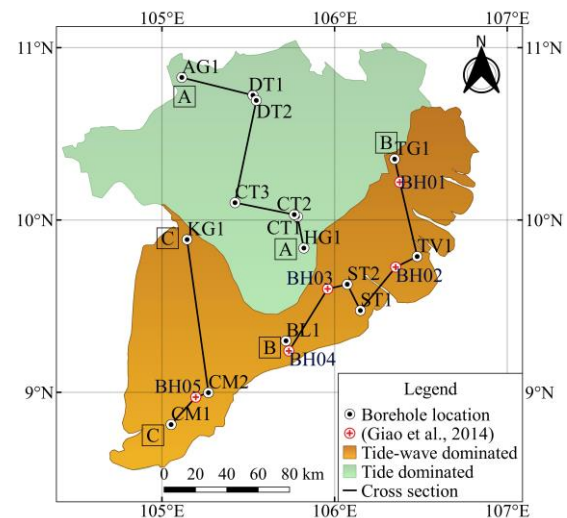


Fig.8 Borehole locations in Mekong Delta.

5. RESULTS AND DISCUSSION

5.1 Soil Profile of Landforms in Mekong Delta

This study used 15 boreholes from investigated data and five boreholes from Giao, P.H [14] to generate soil profiles based on landforms (Fig.1) and the boundary of the delta (Fig.8). The results showed that very soft to soft clay could be found on top of the layer in every section. The different characteristics of the Mekong Delta are that the layers are beneath a soft clay layer. The results of soil profiles are shown in Fig. 9–11.

Section A-A represents the back swamp/swamp environments (Fig.9). This section was associated with the floodplain delta (fluvial processes). The soil profile showed very soft to soft clay from the surface to about -14 m with a thickness of 8–14 m. These

layers were transported and sediment along the Mekong River. Underneath the very soft to soft clay, the layer is stiff to very stiff clay interbedded with medium dense sand, which was found at a depth of -8 m to -45 m.

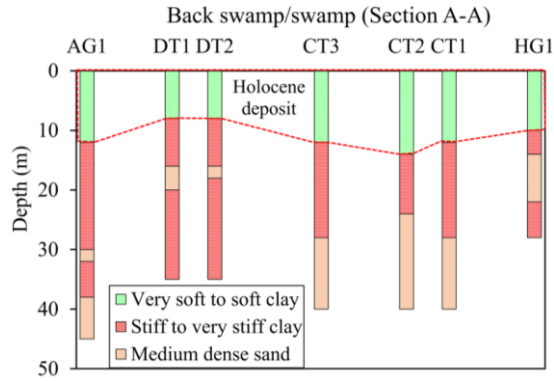


Fig.9 Soil profile of back swamp/swamp landform.

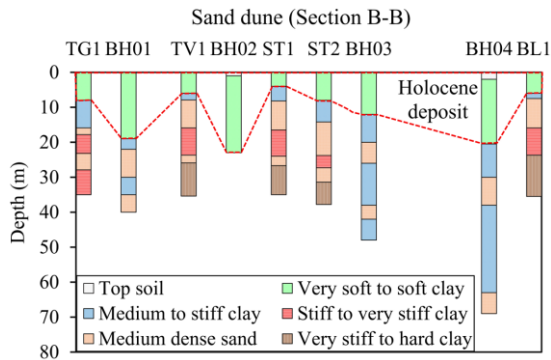


Fig.10 Soil profile of sand dune landform.

Section B-B represents sand dune deposition (Fig.10). This area was affected mainly by coastal activities, resulting in more complex soil layers. First, a coastal wave was noticed where more sand layers had formed into sand dunes. Then, during the rainy season, the thin layer of clay was covered by flooding. As a result, the upper layer was very soft to soft clay from the surface to about -22 m (with the thickness ranging from 4 m to 22 m). These layers were formed from Mekong River and Dong Nai River materials and tributaries. Beneath the very soft to soft clay, there was a layer of medium to stiff clay with intercalations of stiff to very stiff clay, very stiff to hard clay, and medium dense sand. It was found at a depth of -4 m to -68 m.

Section C-C represents a mangrove marsh (Fig.11). Mangrove marsh is coastal wetlands found in the southern part of the Ca Mau Peninsula and mainly behind tidal flats. Therefore, this landform was mainly tide-dominated. It was characterized by shrubs, mangrove trees, and other plants growing in brackish to saline tidal waters. Mangrove fine roots are an essential contributor to sediment accumulation of soft

clay. Consequently, there was a thicker layer of very soft clay in these landforms than in other landforms. Very soft to soft clay was found from the surface to approximately -18.5 m with a thickness of 6–18.5 m. Beneath these layers, there was medium to stiff clay with intercalations of stiff to very stiff clay, very stiff clay to hard clay, and medium dense sand. It was found at a depth from -6 m to -48 m.

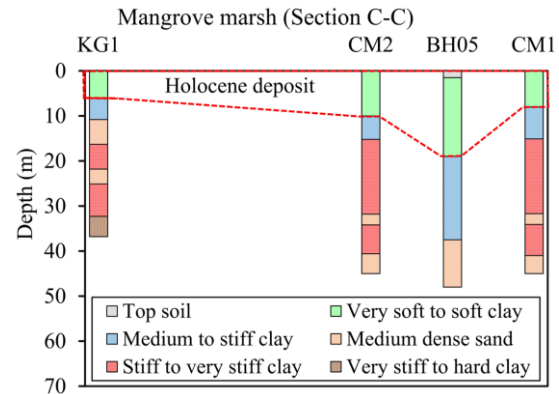


Fig.11 Soil profile of mangrove marsh landform.

As mentioned above, Mekong Delta Clay was mainly deposited in a deltaic environment where the Mekong River joined the South China Sea. The thickness of the very soft to soft clay of the Mekong Delta Clay varied between 4 and 22 m. This thickness changes markedly, not just along the shoreline but also across the Mekong Delta. On the Chao Phraya Delta, very soft to soft Bangkok Clay was deposited in a tidal flat and tide-dominated environment. The thickness of Bangkok Clay in the Chao Phraya Delta varied between 3 and 30 m (Fig.5). The deepest Bangkok Clay occurred in the basin center and at a shallower depth toward the plain margins.

5.2 Comparison of Geotechnical Properties in Soft Clay of Each Landform

The geotechnical properties in each landform were compared. The plasticity chart is illustrated in Fig.12. According to “The Unified Soil Classification System (USCS),” soil materials of the back swamp/swamp landform ($LL = 40.25\text{--}49.52\%$) and sand dune landform ($LL = 28.13\text{--}49.54\%$) had primarily low plasticity, whereas the mangrove marsh landform had low to high plasticity ($LL = 35.43\text{--}55.42\%$). As a result, Mekong Delta Clay was inferred to be relatively low to high plasticity and mainly silty clay (CL).

The particle size distribution is shown in Table 2. Mangrove marsh had a clay content of about 47.36–68.23%, higher than the back swamp/swamp (34.68–59.67%) and sand dune landforms (22.26–49.31%)

because the root system of the mangrove marsh accumulated more soft clay than the other landforms.

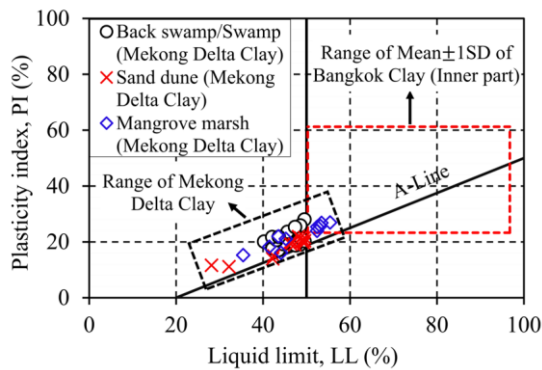


Fig.12 Plasticity chart of Mekong Delta Clay and Bangkok Clay.

Other physical properties in each landform are illustrated in Fig.15. The properties of the back swamp/swamp landform differed from the other landforms. Due to high floods, sediment originated from the Mekong River and clay minerals [6]. The water content and plasticity index were greater than the other landforms by about 47.52–97.39% and 17.08–28%, respectively. The total unit weight was about 1.44–1.68 t/m³. In addition, the compressibility was higher than for the other landforms in terms of void ratio ($e_0 = 1.35$ –2.66) and compression index ($C_c = 0.16$ –0.36) (Fig.14).

(coastal process), whose soil properties had less plasticity (11.14–26.97%) and water content (23.30–76.10%) than those in the back swamp/swamp landform but the total unit weight (1.60–1.81 t/m³) of soil was more than for the mangrove marsh landform. Nevertheless, the LL and PL of these landforms were not substantially different. In addition, as mentioned in Section 3.4, soft clay in the inner part of Bangkok Clay was weaker than soft clay on the outer edge. The reason is that sediments on the edge are mostly alluvial deposits, whereas sediments on the inner part are mostly marine deposits.

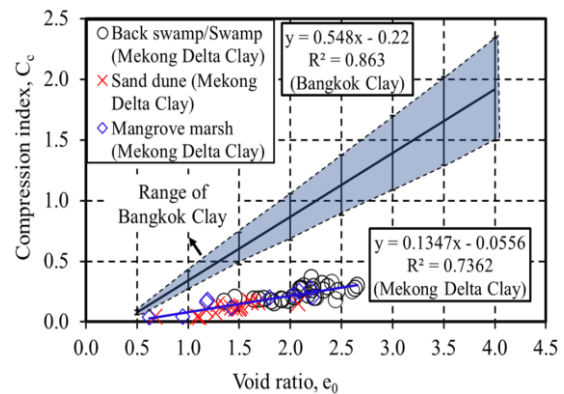


Fig.14 Correlation between the compression index and void ratio of Bangkok Clay [23] and Mekong Delta Clay.

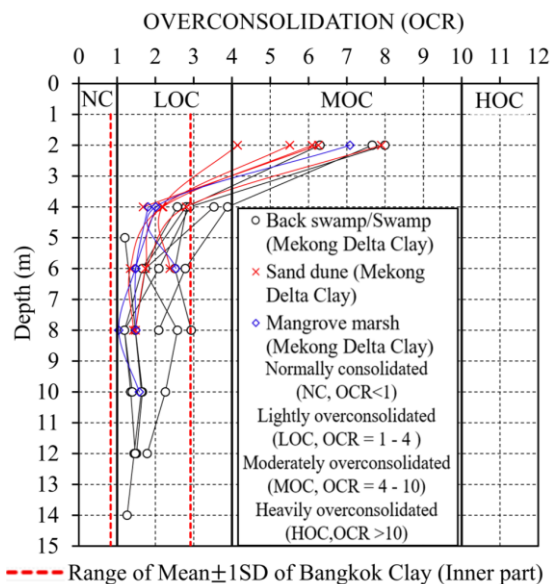


Fig.13 OCR versus depth of Mekong Delta Clay and Bangkok Clay, classification by Kulhawy [25].

As a result, for the Mekong Delta, the geotechnical properties of soft clay were identified in the sand dune, and mangrove marsh landforms

The overconsolidation ratio (OCR) of the Mekong Delta Clay changed with depth but was never less than 1 (Fig.13). The OCR values decreased as the depth increased and could be divided into three parts: 1) above -4 m, where the OCR was defined as moderately overconsolidated clay (MOC); 2) -4 m to -10 m, defined as lightly overconsolidated clay (LOC); and 3) the OCR decreased substantially in the back swamp/swamp landform, where it was greater than for the other landforms and nearly equal to 1 (NC).

5.3 Comparison of Geotechnical Properties of Mekong Delta Clay and Bangkok Clay

A summary of the geotechnical properties of Mekong Delta Clay and Bangkok Clay is shown in Table 2. This study conducted a statistical evaluation of the geotechnical properties of the inner part of Bangkok Clay from Mairaing and Amonkul [8] because these geotechnical properties in the inner part more closely represent Bangkok Clay properties than do the edge properties.

Based on statistical, 68% of the data was within one standard deviation of mean value (Mean $\pm$ 1SD) proposed for geotechnical properties of the inner part of Bangkok Clay, as shown in Fig.12 to 15. These results were compared with Mekong Delta Clay.

Table 2 shows that the mean value for the clay content in the Mekong Delta was lower than for Bangkok Clay. However, the mean value of silt and sand content was higher. Furthermore, according to Fig.15, the value of LL for Mekong Delta Clay varied between 28.13% and 55.42%, and the mean value was 45.95%. On the other hand, the value of LL for Bangkok Clay varied between 50.27% and 96.77%, and the mean value was 73.52%. Thus, Mekong Delta Clay consists of mainly low plasticity soil and can be classified as silty clay (CL). On the other hand, Bangkok Clay was mainly high-plasticity soil and can be classified as a high-plasticity silt clay (CH). These

results indicated that Mekong Delta Clay had less compressibility and plasticity than Bangkok Clay.

The plasticity chart in Fig.12 shows that the range of Mekong Delta Clay (black frame) was lower than for Bangkok Clay (red frame) because of faster flow of the Mekong River compared to Chao Phraya River. According to Hjulstrom diagram theory [26], a greater velocity often produces coarser sediments and vice versa. As a result, Mekong Delta Clay had more silt-sized particles than clay-sized particles (Table 2). In addition, the plasticity of Mekong Delta Clay was lower than that of Bangkok Clay.

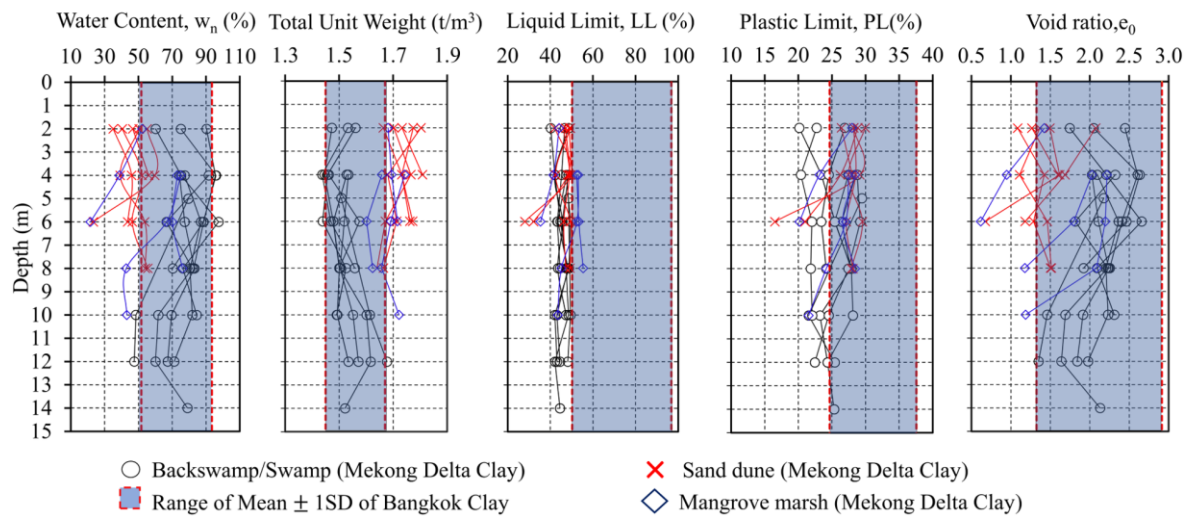


Fig.15 Physical properties of Mekong Delta Clay and Bangkok Clay.

Table 2 Summary of physical and geotechnical properties of Mekong Delta Clay and Bangkok Clay.

Soil property	Mekong Delta Clay			Bangkok Clay					
	Back swamp/ Swamp	Sand dune	Mangrove marsh	Inner part					
				Mean	Data	Mean ± 1SD	SD	Mean	Data
Physical property									
Clay (%)	34.68–59.67	22.26–49.31	47.36–68.23	46.77	58	–	–	≈60 ^a	–
Silt (%)	15.45–59.99	25.27–42.84	12.87–39.10	34.00	58	–	–	≈20 ^a	–
Sand (%)	3.23–32.77	8.91–47.53	2.45–22.40	14.60	58	–	–	≈5 ^a	–
W _n (%)	47.52–97.39	23.30–59.69	21.54–76.10	65.24	58	51.70–93.44	20.87	72.57	15,783
LL (%)	40.25–49.52	28.13–49.54	35.43–55.42	45.95	58	50.27–96.77	23.25	73.52	10,322
PL (%)	20.38–29.45	16.51–29.96	20.15–28.45	25.72	58	24.67–37.55	6.44	31.11	10,270
PI (%)	17.08–28.00	11.14–21.90	15.27–26.97	19.95	58	23.29–61.23	18.97	42.26	10,377
γ _t (t/m³)	1.44–1.68	1.64–1.81	1.60–1.74	1.61	58	1.45–1.67	0.11	1.56	13,742
e ₀	1.35–2.66	0.68–2.07	0.62–2.22	1.82	58	1.33–2.91	0.79	2.12	487
Geotechnical property									
C _c	0.16–0.36	0.04–0.18	0.04–0.27	0.19	58	0.51–1.54	0.52	1.03	487
OCR	1.19–7.99	1.33–7.90	1.04–7.08	2.67	58	0.83–2.91	1.04	1.87	487

Note: SD, Standard deviation; ^a Ohtsubo et al. (2000)[27]

Of the physical properties analyzed, the mean water content value of Mekong Delta Clay (W_n = 65.24%) was lower than for Bangkok Clay (W_n = 72.57%), resulting in the mean total unit weight of Mekong Delta Clay (γ_t = 1.61 t/m³) being higher than for Bangkok Clay (γ_t = 1.56 t/m³).

A comparison of the OCR values versus the depth of the Mekong Delta is shown in Fig.13 and Table 2. Mekong Delta Clay was inferred to be relatively normally consolidated to moderately overconsolidated (OCR = 1.04 – 7.99) with a mean value of 2.67. The reasons for the overconsolidation of Mekong Delta Clay were sediment cementation, the aging process, and the rapid drop in the

groundwater table. On the other hand, Bangkok Clay was classified as normally consolidated to lightly overconsolidated ($OCR = 0.83\text{--}2.92$) with a mean value of 1.87 because the desiccated crust due to evaporation had changed its characteristics in the environment of the Chao Phraya Delta.

The correlation between the compression index and void ratio of Bangkok Clay and Mekong Delta Clay is illustrated in Fig.14. The void ratio of Mekong Delta Clay values varied between 0.62 and 2.66, and the mean value was 1.82. On the other hand, the void ratio Bangkok Clay values varied between 1.33 and 2.91, and the mean was 2.12. Consequently, the compression index of Mekong Delta Clay was in the range $C_c = 0.04\text{--}0.36$, with a mean value of 0.19. This was much less than for the Bangkok Clay range of $C_c = 0.51\text{--}1.54$, with a mean value of 1.03. The high clay content, liquid limit, and plasticity index resulted in the high compressibility of Bangkok Clay.

6. CONCLUSIONS

The main conclusions are:

(1) Mekong Delta Clay and Bangkok Clay were formed by river-transported sediments interacting with sea-level fluctuations between 8,000 and 6,000 years ago. The typical soil profile of Mekong Delta and Bangkok Clay was very soft to soft clay on top of the layer. The different characteristics of Mekong Delta and Bangkok Clay are that the layers are beneath the soft clay layer, and their formation is dependent on the effect of their origin.

(2) The thickness of very soft to soft clay at Mekong Delta varied between 4 and 22 m. This thickness varied considerably, not just along the shoreline but also across Mekong Delta. On Chao Phraya Delta, very soft to soft clay was deposited in a tidal flat and tide-dominated environment. The thickness varied between 3 and 30 m. The deepest Bangkok Clay was in basin center, with a shallower depth towards plain margins.

(3) Mekong Delta Clay was relatively low in the liquid limit (CL). However, mangrove marsh landform was CH due to influence of root system in accumulating soft clay, so particle size of clay content was more significant than for the other landform. But the back swamp/swamp landform had more scatter data for water content ($W_n = 47.52\text{--}97.39\%$), plasticity index ($PI = 17.08\text{--}28\%$), and compression index ($C_c = 0.16\text{--}0.36$) than the other landforms.

(4) Mekong Delta Clay consisted predominantly of silt-sized particles, whereas Bangkok Clay was predominantly clay-sized. The reason is that faster flow of Mekong River is larger than Chao Phraya River. The mean values of the physical properties indicated that Mekong Delta Clay ($PI = 19.95\%$) had less plasticity than Bangkok Clay ($PI = 42.26\%$).

(5) Mekong Delta Clay was considered relatively normally consolidated to moderately overconsolidated ($OCR = 1.04\text{--}7.99$). Bangkok Clay was classified as normally consolidated to lightly overconsolidated ($OCR = 0.83\text{--}2.92$). A correlation between the compression index and void ratio of Bangkok Clay values varied between 1.33 and 2.91, while for the Mekong Delta Clay values, the correlation varied between 0.62 and 2.66. The compression index for Mekong Delta Clay was $C_c = 0.04\text{--}0.36$. This result was much lower than Bangkok Clay, which was in the $C_c = 0.51\text{--}1.54$. The high clay content, liquid limit, and plasticity index meant that Bangkok Clay had high compressibility. These data will further serve as essential indexes for the Mekong Delta's sustainable development.

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