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Reconstructing sedimentary environments of MR1 core and investigating facies' geotechnical properties through the piezocone penetration test in the Late Pleistocene-Holocene periods in the Mekong River Delta

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Abstract. The aim of the study was to reconstruct sedimentary environments of the MR1 core and investigate geotechnical properties of sedimentary facies through the piezocone penetration test (CPTU). A core at the Vinhlong province, Mekong River Delta (MRD), sufficiently presented the Holocene facies of the area. Eight facies were identified based upon sedimentary properties. Characteristics of the units showed development of sedimentary facies. Each sedimentary facies was formed under different environment.

Each sedimentary facies presents CPTU results differently. A facies has various sedimentary structures and materials such as the estuarine channel, estuarine marine, and delta front mouth bar facies; values of cone resistance, q_t, sleeve friction, f_s, and pore water pressure, u_2, in its CPTU results will increase highly, vary largely, and present in saw-tooth shape in the overall plot of them as a function of depth. A facies' sedimentary property is highly homogeneous such as the marsh, bay, and prodelta facies; its values of q_t, f_s, and u_2 increase almost linearly with depth.

Keywords: Vinhlong; Late Pleistocene-Holocene; MRD; facies' geotechnical properties; CPTU.

1. Introduction

The late Pleistocene-Holocene sediments in the MRD that has accumulated consist of several sedimentary facies, each of which was formed in a different sedimentary environment and has typical sedimentary structures and materials, and undergone complex changes [1,2]. The geotechnical properties in the MRD curious trends [3]. The sediments, sedimentary structures, and the post-depositional processes affect the geotechnical properties [4,5]. Therefore, studying sedimentary environment change was conducted and the first step using the CPTU test investigated the geotechnical properties of the sedimentary facies.

2. Materials and Methods

The investigation was conducted in Vinhlong province, MRD (Fig. 1). The borehole (designated MR1) was located at

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latitude 10° 14' 2" N, longitude 105° 59' 8" E at an altitude of +2 m and reached to a depth of -46.05 m. Carbon isotope (^{14}C) dating, grain size, sedimentary structures were analyzed. CPTU test was used as a field test, designated CPTU1, was conducted to a depth of -47.8 m. Soil-behavior-type classification of the Vinhlong site was performed using the CPTU results [6,7]. A distance of the MR1 borehole and position of the CPTU1 test is 2m.

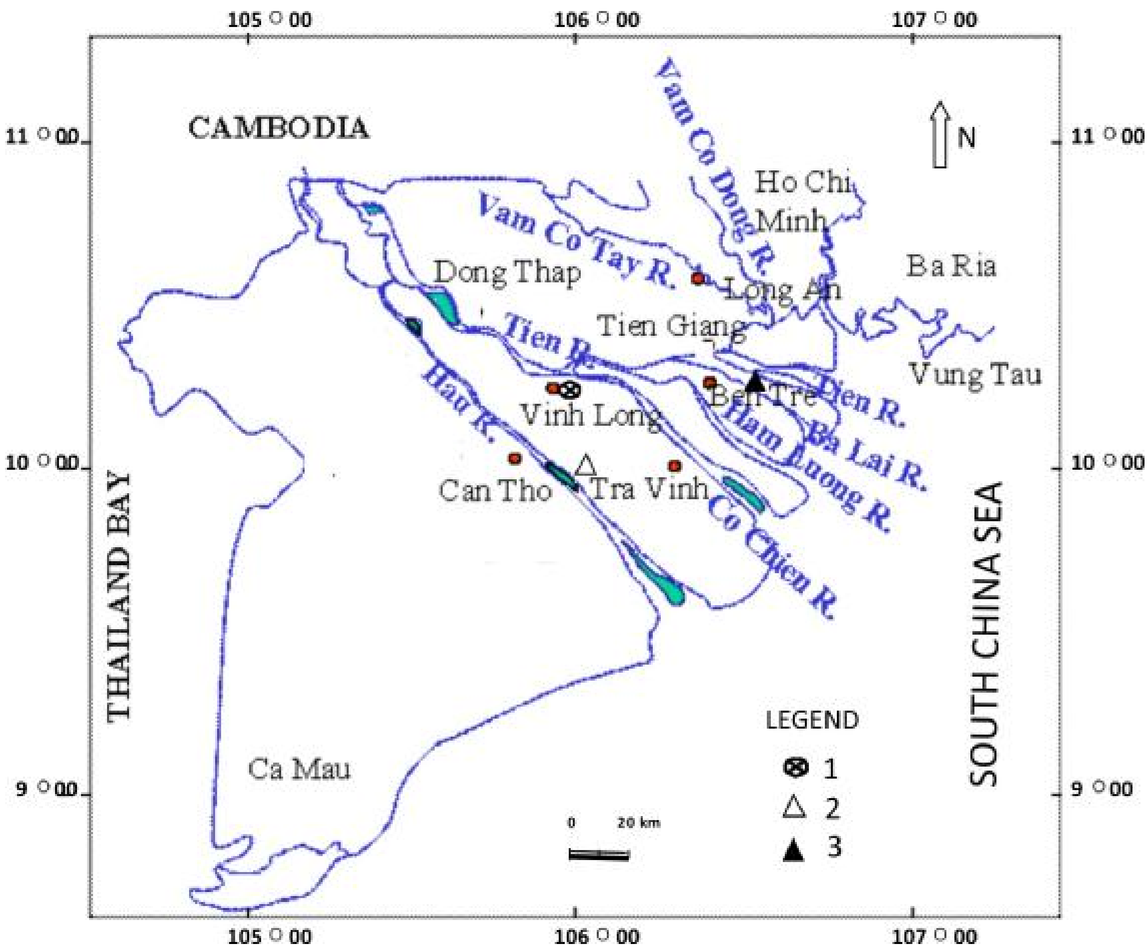

Fig. 1. Location of the MR1 (1), VL1 (2), and BT2 (3) boreholes [1, 2, and 8].

3. Results

3.1. Lithostratigraphy

Based on the sedimentary properties, the sediments of the MR1 core can be divided into eight lithostratigraphic units, the depositional facies can then be inferred (Fig. 2), presented below in ascending order.

1) Unit 1 (-46.05 to -41.5 m below present sea level)

This unit consists of darkish and greenish-gray silty clay to clayey silt and discontinuous fine sand laminae of 2 mm thick; it contains scattered laterite (5-10 mm in diameter) and angular quartz (maximum 15 mm in length) pebbles (Fig. 3A). Parallel and lenticular beddings are common. The plant fragments and plentiful organic materials were found at a depth of -44 to -41.35 m.

2) Unit 2 (-41.5 to -27.8 m)

This unit consists of two parts. The lower part is characterized by inter-bedded, brownish-gray silty clay and clayey to sandy silt. Faint bedding exists in the brownish-gray silt (Fig. 3B). The upper part of unit 2 contains discontinuous parallel laminae, wavy, flaser, parallel and lenticular bedding, humus, bioturbation, calcareous concretions, and mollusca. Mica flakes are scattered throughout the unit.

3) Unit 3 (-27.8 to -25 m)

This unit is divided into two parts. The lower part, from -27.8 to -26.4 m, consists of intercalated darkish gray silty sand to medium sand and clayey silt to silty clay, coarsening upward succession. The upper part, from -26.4 to -25 m, consists of greenish-gray silty sand and greenish-gray clayey silt. In general, the unit is characterized by parallel laminae, wavy bedding, lenticular bedding (Fig. 3C), and flaser bedding characterize the unit. The shell fragments and humus are scattered throughout the unit.

4) Unit 4 (-25 to -22.0 m)

This unit consists of darkish-gray clayey silt in the lower part and greenish-gray clayey silt and silty clay mud with discontinuous, very thin sandy bedding in the upper part (Fig. 3D). The grain distribution shows a fining-upward succession. Humus matter, mica flakes, shell fragments, and calcareous incipient are scattered throughout the unit. The facies is high homogeneity.

5) Unit 5 (-22.0 to -18.5 m)

This unit is divided into two parts. The lower part, from -22 m to -20 m, includes gray silty clay and very fine sand coarsening upward. The sediments commonly present interbedded greenish-gray clayey silt and silty clay and discontinuous parallel laminated mud. The upper part of the unit contains parallel laminated sandy mud (Fig. 3E). In general, mica flakes, calcareous nodules and calcareous incipient are scattered throughout the unit (Fig. 3E).

6) Unit 6 (-18.5 to -5.5 m)

The unit contains an intercalated greenish-gray clay and silt, greenish-gray sandy silt and fine to coarse sand in a coarsening-upward succession. It is inhomogeneous, with several sandy layers of various thicknesses, some of the sandy layers are relatively thick (Fig. 3F). In general, medium to coarse sands are common soil types of the unit (Fig. 2). Parallel laminae, lenticular, flaser and wavy bedding, and fine to coarse sand with parallel clayey laminae are also common. Burrow, bioturbation, plant fragments and mica flakes are scattered throughout the unit.

7) Unit 7 (-5.5 to -1.5 m)

The unit consists of laminated greenish- and darkish-gray clayey silt, sandy silt and very fine to medium sand and shows parallel laminae, discontinuous parallel laminae, lenticular and wavy bedding. The deposits from –2.4 to –3 m consist of intercalated sand and mud. Humus matter, bioturbation and burrow (Fig. 3G) are also present in this unit.

8) Unit 8 (-1.5 to +1 m)

The unit contains greenish-darkish gray mud with small yellowish-greenish spots from -1.5 to +0.5 m. The greenish- and darkish-gray medium to fine sandy mud are from +0.5 to +1.0 m and rich in organic materials.

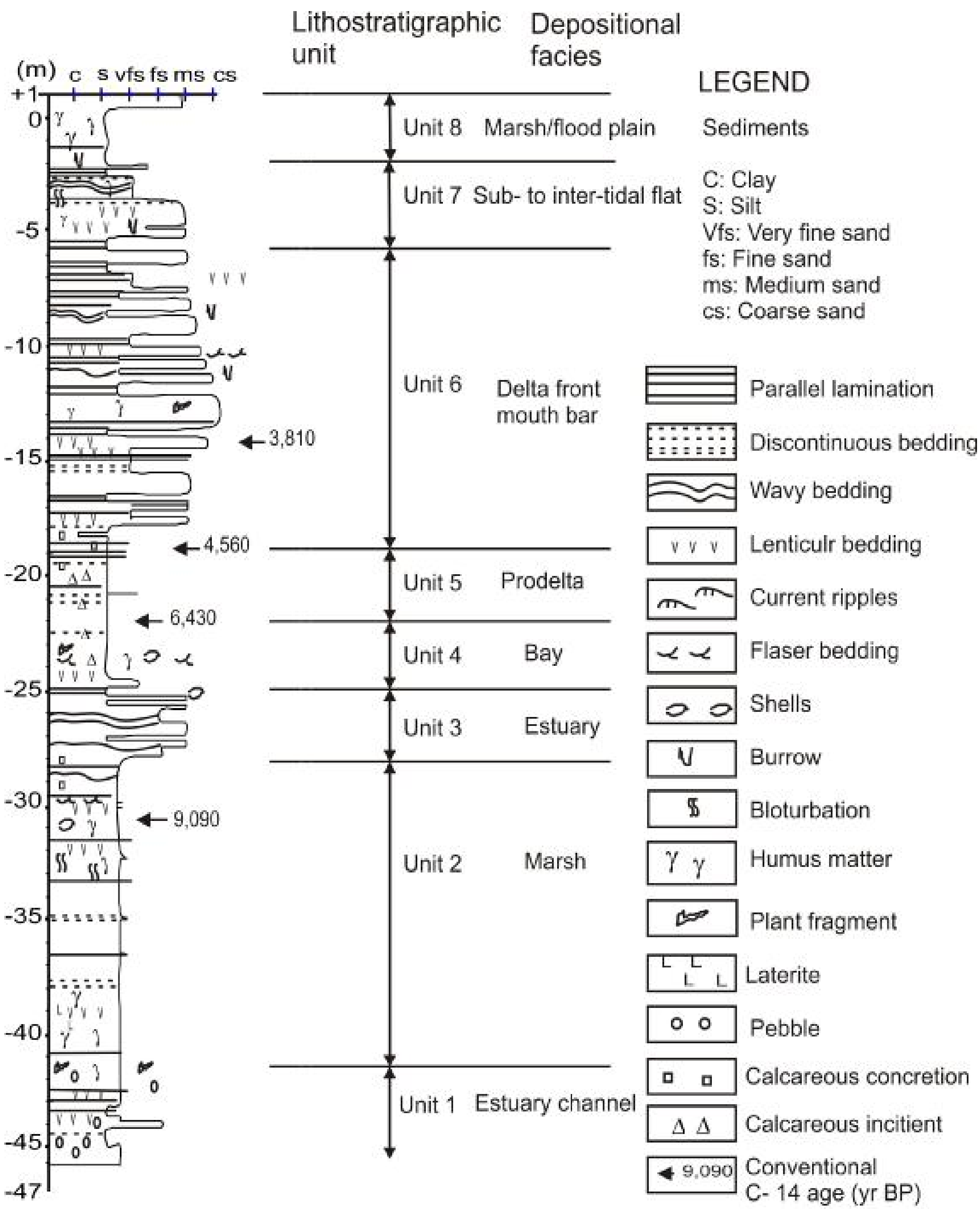

Fig. 2. Geological column of the MR1 core and its correlation with lithostratigraphic units.

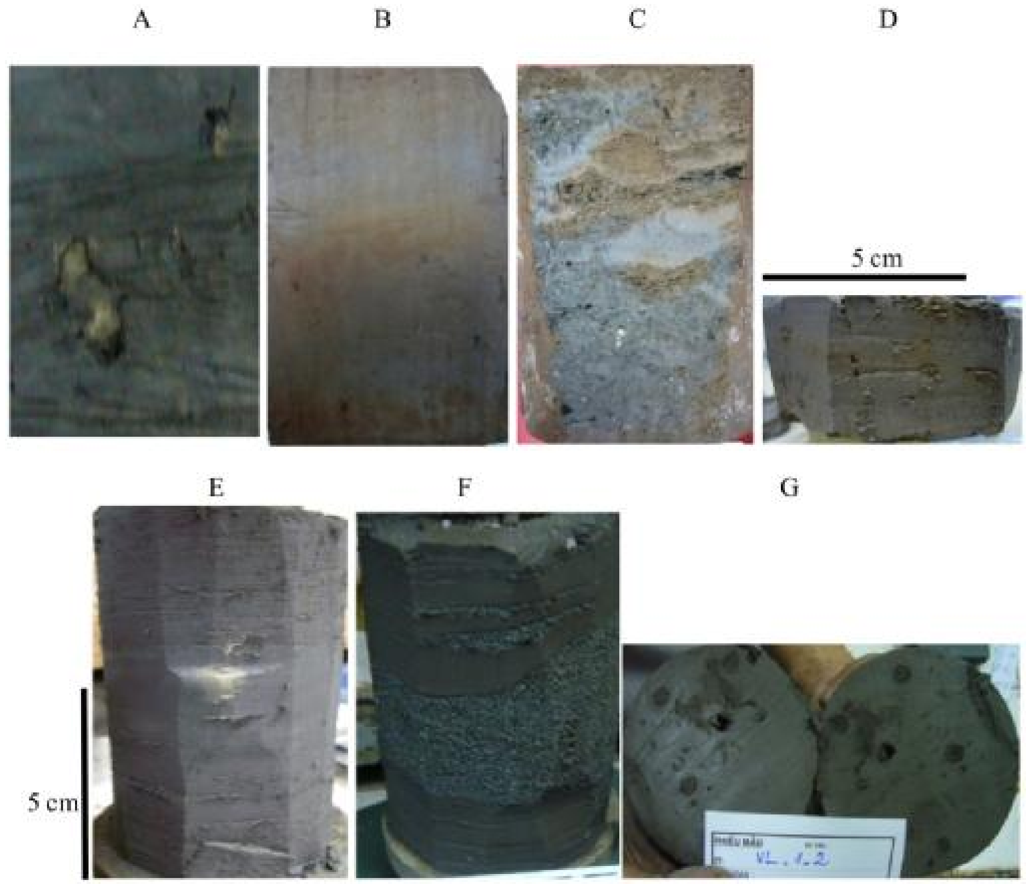

Fig. 3. Selected photographs of sedimentary structures of the MR1 core. A) (at depth -44.5 m) angular quartz pebbles; clay mass. B) (-34.9 m) Faint bedding exists in the brownish-gray silt. C) (-25.08 m) lenticular bedding. D) (-22.08 m) discontinuous, very thin sandy bedding. E) (-19.54 m) parallel laminated sandy mud, calcareous nodules. F) (-10 m) sandy layers with various thicknesses. G) (-2.4 m) burrow.

3.2. Inferred depositional facies

In a similar fashion as was conducted by Ta et al. [1,2,8], the MR1 core was carefully studied and divided into eight facies, as described below.

3.2.1. Estuarine/tidal channel sandy silty clay facies

This facies is located at the lowest part of the MR1 core and corresponds to Unit 1. The lithofacies are characterized by silty clay bearing scattered quartz pebbles and laterite pebbles and by mixing of the humus matter with clay and silt. These characteristics indicate that the sediments were deposited under dynamic hydrological conditions such as might be caused by the presence of an estuarine channel or a tidal river.

3.2.2. Salt marsh facies

The lithostratigraphic characteristics of Unit 2 show fining upwards succession represented by interbedded, brownish-gray sandy silt and clayey silt, together with faint laminae in the lower part and discontinuous parallel laminae, flaser and lenticular bedding in the upper part. These features indicate that the sediments were deposited under relatively quiet hydrological conditions so that concretions of soft calcareous material produced calcareous nodules in the sandy and clayey silts. From this information, it can be inferred that the marsh facies correspond to lithostratigraphic Unit 2. Shell fossils such as mollusca are found at -32.5 m indicate a marine-brackish water habitat. The sediment deposited in a muddy tidal flat/salt marsh environment from the upper part of this salt marsh facies at -30.75 m is dated at 9,090 ± 40 ^{14}C yr BP (Table 1).

Table 1. ^{14}C datings from the MR1 core

Depth (m)	Materials	Delta ^{13}C (permil)	Conventional ^{14}C age (yr BP)	Calibrated age (cal yr BP)	1 sigma	Lab. Code No.
-14	Organic	-25.5	3810 ± 40	4230/4200/4160	4250-4150	BETA-239789
-18.5	Organic	-26	4560 ± 40	5280/5130/5070	5170-5130	BETA-268599
-21.95	Organic	-25.4	6430 ± 40	7410/7390/7370/7360/7330	7420-7310	BETA-254198
-30.75	Organic	-27	9090 ± 40	10240	10250-10220	BETA-239788

BETA-: ^{14}C dating in Beta Analytic.

3.2.3. Estuarine marine sand and sandy silt facies

This facies corresponds to lithostratigraphic Unit 3. The textural characteristics and the presence of mollusca_indicate that sand and sandy silt were deposited in an estuarine environment. The characteristics of this facies indicate a transgressive lag deposit or estuarine channel deposit affected by strong tidal currents.

3.2.4. Open bay mud facies

This facies coincides with Unit 4 and consists of dark gray silty clay, clayey silt in the lower part and homogenous greenish-gray mud in the upper part. The grain size distribution shows a fining upward pattern and the mud content is the highest among all the facies, over 90%. Shell fragments, organic materials and incipient nodules are scattered throughout this facies. Sets of interbedded gray clay (25-55 mm) and dark clay (2-5 mm) can be clearly seen in its lowest part. Some sets of faintly parallel laminae are also seen that their formation might be caused by seasonal fluctuations in suspended sediment load or variations of the amount and kinds of supplied organic materials, or, alternatively, by tidal influences.

3.2.5. Pro-delta mud facies

This facies coincides with Unit 5 and consists of an coarsening-upward succession from dark gray silty clay to very fine sand. Sediments commonly appear as structureless massive mud. Interbedded greenish-gray silt (25-30 mm) and silty clay (2-5 mm) exist in the lower part; they are dated at 6,430 ± 40 ^{14}C yr BP at -21.95 m (Table 1). In the upper part, discontinuous parallel laminae contain very fine sand seams. Calcareous concretions are common and calcareous nodules appear. There are significant variations in the lithology and sedimentary structures of this layer; these could be caused by the effects of higher sediment supply and/or more active hydrodynamics. The pro-delta facies ended at 4,560 ± 40 ^{14}C yr BP at -18.5 m (Table 1).

3.2.6. Delta front: mouth bar sand, silty sand facies

This facies coincides with Unit 6 and represents a normal upward succession of intercalated greenish-gray silt, greenish-gray sandy silt and coarse sand. Parallel laminae, lenticular bedding, wavy bedding and flaser bedding are common. Mica flakes are scattered throughout the facies. Several sedimentary structures may indicate strong hydrodynamic conditions mainly resulting from tidal currents and flooding causing high depositional rates. It is inferred that the sedimentary process occurred in a river-mouth environment that formed a silty sand mouth bar in the delta front. The measured ^{14}C age at -14 m is $3{,}810 \pm 40$ ^{14}C yr BP (Table 1).

3.2.7. Sub- to inter-tidal flat sandy silt facies

This facies coincides with Unit 7 and consists of intercalated darkish-gray sandy silt layers and gray sand. Wavy bedding and parallel laminae, as well as lenticular bedding and discontinuous parallel laminae, can be seen. The deposits from -2.4 to -3 m consist of interbedded sand and mud which resemble tidal rhythmites.

3.2.8. Flood plain/marsh facies

This facies coincides with Unit 8. The unit was formed very close to the ground surface. Sediments are mud, riches in organic matters. The presence of alternating fine sandy mud layers shows that this facies was formed by flooding. These features indicate a depositional environment in the marsh or flood plain.

3.3. Results of CPTU tests

Measured quantities the CPTU1 named cone resistance, q_t, sleeve friction, f_s, and pore water pressure measured behind the cone tip, u_2, are shown in Fig. 4 together with the columnar section of MR1 core. All of these values show an increasing trend with depth. The sudden increases in q_t and f_s with a corresponding drop in u_2 indicate the presence of a sand layer or of intermediate soils with high permeability (i.e., cohesionless soil). As the cone penetrates into cohesionless soil, the pore water pressure immediately dissipates and reduces to the hydrostatic water pressure, u_0. The value of pore water pressure drops further, becoming lower than u_0 when the cone encounters a pure sand soil. This observation helps us to identify the different types of cohesionless soils quickly and easily. The alternating of cohesionless and cohesive soil layers results in a saw-tooth shape in the overall plot of q_t, f_s and u_2 as a function of depth. The change in the amplitude of the saw-tooth depends on the arrangement of the soil layers and the mixed levels of sand, silt and clay soils. If the thickness of the cohesionless or cohesive soil layer is large, the fluctuation in amplitude will also be large, and the said layers are inhomogeneous. In the cohesive soil layers with homogeneous material properties, q_t, f_s and u_2 are all rather constant and change very little with depth (Fig. 4). A typical soil profile can be estimated by soil-behavior-type classification using the following normalized values [6, 7]:

Normalized cone resistance:

$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \tag{1}$$

Normalized friction ratio:

$$F_R = \frac{f_s}{q_t - \sigma_{vo}} \times 100\% \tag{2}$$

Normalized pressure ratio:

$$B_q = \frac{u - u_o}{q_t - \sigma_{vo}} \tag{3}$$

where σ_{v0} and σ'_{v0} are total and effective vertical stress.

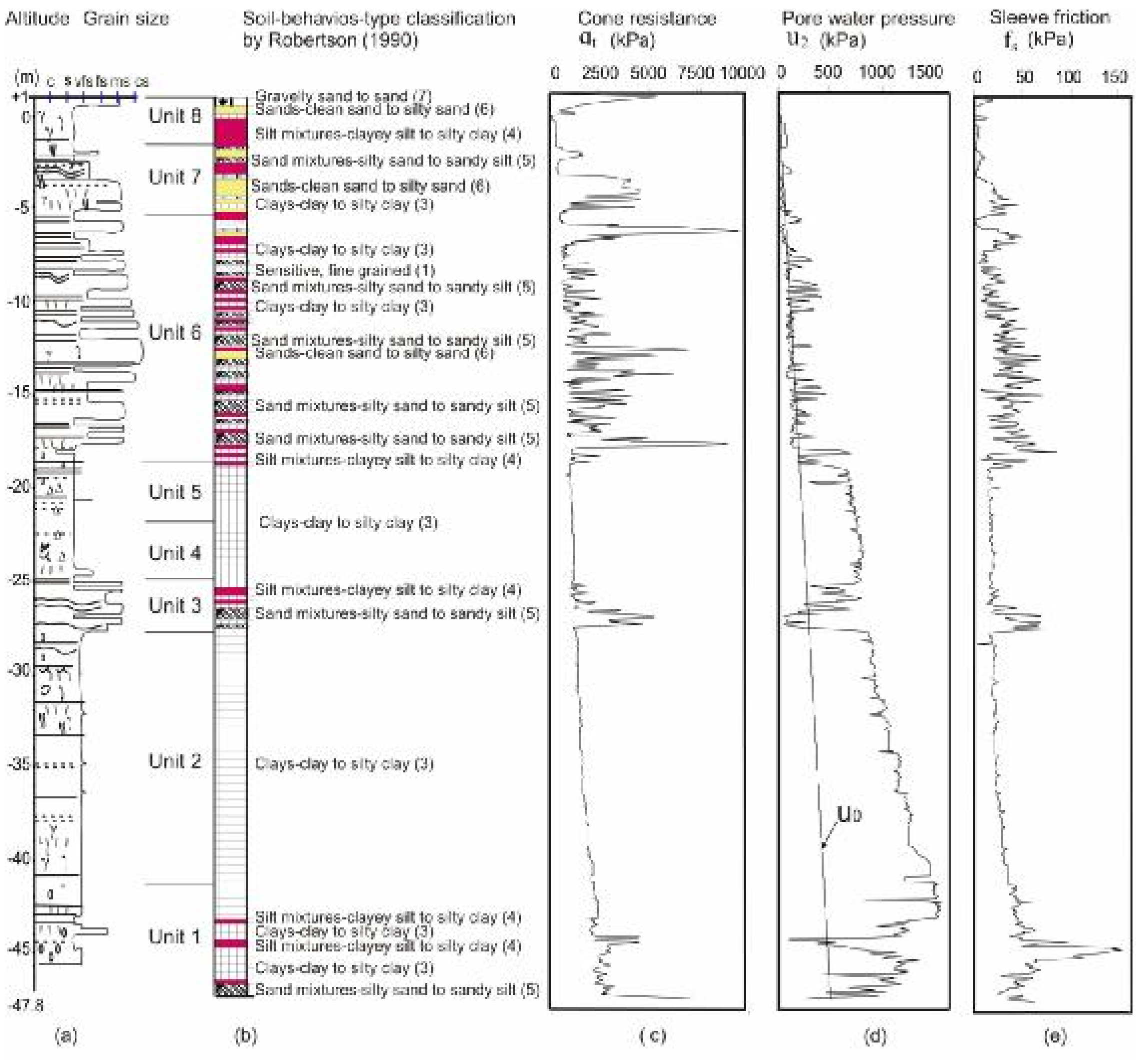

Fig. 4. Columnar section of the MR1 core and results of the CPTU1 test.

4. Discussion

4.1. Sedimentary facies changes

The estuarine channel facies were certainly formed older than 9,090 yr BP. The laterite pebbles are splintered and perfectly round shape. These characteristics are reliable indicators of their origin. These laterite pebbles were formed in the late Pleistocene undifferentiated sediments, which were affected by high hydrodynamic activity. They then moved above the estuarine channel sediments. These facts indicate that the estuarine channel sediment facies unconformably overlay the Late Pleistocene undifferentiated sediments.

Sediment supply may be so plentiful in this specific type of environment.

MR1 core data were compared with data from the BT2 core [1, 8] in the incised valley and with data from the VL1 core [2] in the interfluvial zone (Fig. 1). Estuarine channel sediment was found in the MR1 core at a depth of -41.5 m and in the BT2 core at a depth of -62.3 m. In the VL1 core, the sediments began in an open bay environment. It is likely that the MR1 core was located in the incised valley where an estuarine channel environment was developed. The marsh facies, in which sediments were found mollusca, were clearly influenced by marine factors. The formation of salt marsh silty clay and clayey silt facies was characterized by faint laminae indicative of tidal influences. The thickness of the marsh facies is 13.7 m and it is found at -27.8 m; in comparison, the thickness and vertical location of the marsh facies in the BT2 core are 7.8 m and -54.50 m, respectively (Table 2).

The marsh facies in the MR1 core is considerably thicker than that in the BT2 core. In the MR1 core, the estuarine marine sandy facies is 2.8 m thick and is found at -25.0 m. It is characterized by tidal laminae and layers with abundant mollusca, both of which are reliable indicators of an estuarine environment. In comparison with the BT2 core, the estuarine marine facies and the open bay facies are thinner than the marsh of MR1.

Table 2. Thickness and depth of facies appearance in the MR1 core and BT2 [1, 8] and VL1 cores [2]

Core	Estuary channel	Marsh	Estuary	Bay	Pro-delta	Delta front	Sub-to intertidal flat	Marsh /flood plain	Facies
MR1	-41.5	-27.8	-25	-22	-18.5	-5.5	-1.5	1	Depth of appearance (m)
	>4.5	*13.7*	*2.8*	*3*	*3.5*	*13*	*4*	*2.5*	*Thickness of facies (m)*
BT-2	-62.3	-54.5	-35.95	-20	-17	-8	-2	2	Depth of appearance (m)
	6.7	*7.8*	*18.55*	*15.95*	*3*	*9*	*6*	*4*	*Thickness of facies (m)*
VL-1	none	none	none	-24.5	-14.5	-4.5	0	2	Depth of appearance (m)
				11	*10*	*10*	*4.5*	*2*	*Thickness of facies (m)*

A coarsening-upward succession began in the pro-delta and was gradually created. The pro-delta contained very fine and fine sand laminae. The pro-delta is 3.5 m thick in the MR1 core. In comparison with the pro-delta in the VL1 core, which is 10 m thick, the pro-delta in MR1 is so thin. The coarsening-upward succession can be seen most clearly in the delta front with the coarse sand. The delta front facies is particularly attractive and can be considered one of the unique characteristics of the MR1 core. The sediments are sand and silty sand. The coarse sandy layers are so abundant that their thicknesses increase from 1-2 mm to 1.3 m. The thick coarse sandy layers contain parallel silty clay laminae. In comparison, the materials in the delta front facies of the VL1 core are the more commonly found sandy and silty clay. The delta front-mouth bar sand and silty sand facies of MR1, 13 m thick, is slightly thicker than that of the delta front in the VL1 core. On the other hand, the sub- to inter-tidal flat sandy silt facies of MR1 is thinner than that of the BT2 core (Table 2). The flood plain/marsh facies includes a long-continued accumulation of silty and clayey mud, with medium-fine sandy mud located in the upper part of the MR1 core; the thickness of this layer is relatively small in comparison with that of the BT2 core (Table 2).

4.2. Late Pleistocene-Holocene development of the delta

In southeast Asia at the Last Glacial Maximum, the last lowstand of sea level was about -120 m at approximately 18,000-20,000 yr BP [9]. The fall in sea level led to the lowering of the base level of the river, resulting in an incised valley. The MR1 core was within this incised valley system. Following the last glacial stage, sea level rose rapidly and simultaneously created an estuarine channel environment. This was an early stage of sea level rise at the site of the MR1 core and caused the formation of an estuarine channel. The river channel shifted and received lag deposits predominantly consisting of gravel, laterite pebbles and rich organic material, and the river mouth shifted gradually landwards. The rapid transgression led to speedy horizontal translation of the shoreline that reached several tens of meters per year in southeast Asia [9]. The shoreline in the MRD site was probably created in the incised valleys; it formed a huge marsh environment from which the MR1 core was obtained. It can be inferred that the sea level was about -30.75 m at about 9,090 $\pm$ 40 yr BP. In the BT2 core [1, 8], the lowest part of the salt marsh facies (-60.87 m) yielded an age of 11,340 $\pm$ 115 yr BP. From these data, it can be estimated that a salt marsh environment existed in the region between 11,500-9,000 yr BP. Subsequently, sea level increased, and the transgression advanced landward, resulting in the simultaneous formation of an estuarine marine environment and an open bay environment with fining upwards succession. The rate of transgression for the MR1 core site was so rapid that it was converted into an open bay facies. The sedimentary succession indicates that a maximum transgression, dated at 6,430 yr BP, occurred at this open bay facies. These data coincide with the maximum Holocene transgression at around 6,000 yr BP, showing that the marine area occupied the delta except for some upland in the northern part of the island in the MRD [9]. A marine transgression succession, incised-valley fill sediments including salt marsh, estuarine marine, and open bay mud sediments might have occurred during the 11,500-6,400 yr BP based on ages of 11,340 $\pm$ 115 yr BP at -60.87 m in the BT2 core site and 6,430 yr BP at -21.95 m in the MR1 core site.

Subsequently, a regression caused by the combined effects of sea level fall and high sediment supply occurred. The marine regression began and the pro-delta mud facies appeared and developed with a depositional rate of 1.84 mm/yr, estimated from ^{14}C dating at the depths of -21.95 m and -18.5 m (Table 1). The regression continued to occur. Between 4,560 yr BP at -18.5 m and 3810 yr BP at -14 m, the sand and silty sand mouth bar appeared and developed with a depositional rate of 6 mm/yr, higher than the rate of deposition of the pro-delta facies. The topographies rapidly settled at -5.5 m at the end of the delta front. The delta front silty sand facies, around 3,810 yr BP at -14 m, are consistent with the unconfirmed coastlines in the idealized model of coastal evolution during 4,500-3,000 yr BP [9]. These data coincide with the evidence for coastal evolution in the marine regression during the 4,000-3,000 yr BP relative to the positions of the MR1 and VL1 cores (Fig. 1). A regressive stage in this MR1 core is suggested by the fact that subaqueous delta plain sediments occurred. Its age is estimated to be 6,400-2,400 ^{14}C yr BP.

After 2,400 yr BP, a sub- to inter-tidal flat sedimentary environment occurred and the sea level lowered completely. The marine regression was completed and resulted in the sub- to inter-tidal flat sandy silt facies formation was at about -1.5 m altitude.

The last phase is the development of the flood plain/marsh environments. After the marine regression was completed, the topography of the MRD_was not entirely a flat terrain, and marshes appeared. During the flood season, the Mekong River system has no sufficient capacity to discharge a large amount of floodwater, causing overland flows along the banks and interior fields. Flood basins are low-lying areas and received these sedimentary materials. The flood basins of the Mekong River system lie relatively parallel to the river and cover an extremely large area 100 km wide and 150 km long [9]. The MR1 core site lies in this area, specifically between the Tien and Hau Rivers (Fig. 1). The long-continued accumulation of silts and clays that settled from over-bank flows after periods of extremely high hydrodynamic activity during the flood seasons, and the sediment is coarse grain. A medium-fine sand layer was formed at the top of the MR1 core, while a flood plain/marsh facies was formed at the upper part of the MR1 core and was obtained at +1.0 m altitude.

4.3. Geotechnical characteristics of sedimentary facies and correlation

4.3.1. Transgressive incised-valley fill sediments

4.3.1.1. Estuarine channel/tidal river sandy silt facies (Unit 1)

The results of CPTU1 on the facies showed that the soil-behavior-types vary and that their formed sequences are similar to sedimentary structures (Figs. 4a and 4b). The soil-behavior-types in the range of -47.8 to -47 m were of cohesionless soil. The soil-behavior-types in the range of -47 to -44 m were of cohesion soil (clays), the clays were formed rather early under a large effective overburden pressure. The results also showed that the soil layer is overconsolidated. In the range of -44 to -41.35 m, the soil-behavior-types are normally consolidated to overconsolidated clays (clay to silty clay). The facies' q_t, f_s, and u_2 increased highly and changed largely in range of 2000 to 7000kPa, 25 to 150kPa, and 90 to 1500kPa, respectively.

4.3.1.2. Salt marsh facies (Unit 2)

The CPTU1 results of this facies show that the common soil-behavior-type is normally clays (clay to silty clay) (Fig. 4b). This indicates highly homogeneous structure and material. q_t, u_2, and f_s all increase linearly with depth (Fig. 4), q_t, f_s, and u_2 in range of 1000 to 2200kPa, 15 to 35kPa, and 550 to 1460kPa, respectively. A few small changes in q_t, f_s, and u_2 showed interbedded, faint laminae and discontinuous parallel laminae. These are all features of the marsh facies.

4.3.1.3. Estuarine marine sand and sandy silt facies (Unit 3)

The CPTU1 results of this facies from -27.8 to -26.4 m revealed that q_t increased well beyond the usual increase with depth (Fig. 4c). Soil-behavior-types are clay to silty clay and silty sand to sandy silt. At the upper part of this facies, from -26.4 to – 25 m, q_t and f_s are smaller than those of the lower facies. Soil-behavior-types are most likely clay to silty clay and clayey silt to silty clay (Fig. 4b). These correlate with the sedimentary properties of the facies. In general, q_t, f_s , and u_2 changed largely in the range of 1000 to 5000kPa, 15 to 70kPa, and 60 to 800kPa, respectively; show saw-tooth variations with rather large amplitudes (Fig. 4). These are all features of the estuarine marine facies.

4.3.1.4. Open bay mud facies (Unit 4)

The CPTU1 results of this facies show that q_t, u_2, and f_s in the range of 1120 to 1200kPa, 700 to 800kPa, and 10 to 20, respectively, all increase linearly with depth (Fig. 4), indicating a main soil-behavior-type of normally consolidated clay to silty clay. They show high homogeneity levels.

4.3.2. Regressive deltaic sediments

4.3.2.1. Pro-delta mud facies (Unit 5)

The CPTU1 results were divided into two parts (Figs. 4). The lower part, from -22 to -20 m, revealed that q_t, f_s, and u_2 are rather constant with depth and that the soil-behavior-type is only normally consolidated clay to silty clay. However, the upper part shows small variations in these values, with characteristics correlative with the sedimentary properties at the end; the soil-behavior-types are normally consolidated clay to silty clay with intercalated silt mixtures (Fig. 4b). In general, q_t, f_s, and u_2 is in the range of 900 to 1200kPa, 10 to 55kPa, and 200 to 800kPa, respectively. This differs from pro-delta mud facies and areas below open bay mud facies.

4.3.2.2. Delta front-mouth bar sand, silty sand facies (Unit 6)

In the CPTU1 results of this facies, q_t, f_s, and u_2 in the range of 500 to 9100kPa, 1 to 70kPa, and 25 to 410kPa, respectively, show saw-tooth graphs with large variations. In general, soil-behavior-type mainly tends to be cohesionless soils but plentiful (Fig. 4b). It presents characteristics of delta front-mouth bar sand, silty facies.

4.3.2.3. Sub- to inter-tidal flat sandy silt facies (Unit 7)

The results of CPTU1 of this facies showed that q_t, f_s , and u_2 in the range of 250 to 4600kPa, 2 to 45kPa, and -50 to 130kPa, respectively, have saw-tooth graphs with large amplitudes. The soil-behavior-types classification varies; especially, the clean sand to silty sand layers appear many times and are rather thick in comparison with other facies (Figs. 4b) and their formatted sequence is approximate to the sedimentary structure with intercalated sandy and silty mud.

4.3.2.4. Flood plain/marsh facies (Unit 8)

The CPTU1 results showed that the main soil-behavior-type is slightly sensitive to sensitive clayey silt to silty clay, approximating silty clay and clayey silt mud in its sedimentary properties (Figs. 4b). At a depth of +0.5 to +1 m, soil-behavior-types are gravelly sand to sand and clean sand to silty sand, corresponding to the fine-medium sand mud formed by the flood. The sequence of the mechanical behavior observed by CPTU is correlative with the sedimentary properties.

5. Conclusions

- The MR1 core site was formed in an incised valley and composed of two sedimentary successions: (1) transgressive incised-valley fill sediments, which include estuarine channel, salt marsh, estuarine marine and open bay mud facies; (2) Regressive deltaic sediments deposited between 6,400-2,400 yr BP, which include pro-delta, delta front-mouth bar, sub- to inter-tidal flat, and flood plain/marsh facies.

- The results indicate that each sedimentary facies presents the typical sequences of the geotechnical properties through the CPTU test.

+ The estuarine channel facies, which was formed under strong hydrodynamic conditions, includes several sedimentary structures and materials; it experienced post-depositional processes resulting in geotechnical properties related to slightly overconsolidated to overconsolidated conditions. q_t, f_s, and u_2 increase highly and change largely in range of 2000 to 7000kPa, 25 to 150kPa, and 90 to 1500kPa, respectively. These are also the same as those of the estuarine marine facies, but q_t, f_s, and u_2 are lower than and in range of 1000 to 5000kPa, 15 to 70kPa, and 60 to 800kPa, respectively because the estuarine marine facies is so younger than the estuarine channel facies.

+ The delta front-mouth bar sand and silty sand facies, which was formed under strong hydrodynamic conditions, has several sedimentary structures and materials. Values of CPTU vary very largely, q_t, f_s, u_2 in the range of 500 to 9100kPa, 1 to 70kPa, and 25 to 410kPa, respectively. Values of q_t are greater than those of the estuarine channel and estuarine marine facies because materials of the delta front mouth bar facies are common sand with great thickness. The overall plot are in saw-tooth shape with large amplitudes.

+ The marsh, bay, and pro-delta facies, which were formed under low hydrodynamic conditions, contain fine-grained mud with faint, discontinuous laminae. Their sedimentary properties are all highly homogeneous and their q_t, f_s, and u_2 increase linearly with depth.

- It needs to study additional lab tests in the geotechnical properties for clear awareness about the consolidation level and clay minerals of each facies.

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