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Influence of sedimentary environment on geotechnical properties and consolidation characteristics of Mekong Delta late Pleistocene-Holocene sediments

by
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A dissertation submitted in partial fulfillment of the requirements for the degree
of
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ABSTRACT

The aim of the study was to characterize a variety of microstructure development-levels and geotechnical properties of the Mekong Delta (MD) late Pleistocene-Holocene sediments. The thesis furthermore studies the influences of sedimentary environment and conditions on the geotechnical properties and the influences of delta formation mechanisms on the geotechnical property sequences of the successions of the sedimentary facies and relationship between the sedimentary geology and geotechnical properties. The survey is associated the geotechnical engineering and the sedimentary geology of the late Pleistocene-Holocene sediments at five sites and also the undifferentiated Pleistocene sediments. Cross-sections rebuilt in the delta progradation-direction between the Mekong and Bassac rivers represent the complicated stratigraphy.

The microstructure development-level of the argillaceous soil of each sedimentary facies is interpreted by a combination of the sediment formation mechanism, consolidated properties, ^{14}C age, and analysis on the petrography-images in thin section (PTS) and Scanning electron micrograph (SEM) images. The MD late Pleistocene-Holocene sediments can be divided into three main broad cases, namely the surface sediment facies and the deep sediment facies with microstructure development-levels being very high to high, the shallow sediment facies with microstructure development-levels being medium to low. The microstructure development-levels could suggest how to choose a coefficient “k-value” for estimating yield stress ratio, OCR, using the normalized resistance obtained from the piezocone penetration tests (CPTU). The OCR of the all sediments facies change with depth but not less than 1. The post depositional processes significantly influenced the microstructure development, particularly the dehydrating and oxidizing processes, affecting k-value.

In general, the contents of clay minerals decrease in order from the illite, kaolinite, chlorite, to smectite by the characteristic of material source of the Mekong River. The illite content tends to decrease in the delta progradation-direction, while the smectite content tends to increase. The characteristics of the clay minerals made the high microstructure development and plasticity, which slightly increase with the reduction of illite content. The cross-sections sufficiently represented by ten successive sedimentary facies of the area were identified based upon the sedimentary properties. The characteristics of the unit showed development of sedimentary facies. Each sedimentary facies was formed under a different environment and revealed typical

geotechnical properties. Estuarine channel, estuarine marine, delta front, and sub- to inter-tidal flat facies were produced under strong hydrodynamic conditions. The sediments were from clay to coarse sand and even pebbles, and the sedimentary structures are plentiful. Strengths of the sedimentary facies vary significantly, which can be captured by CPTU, but not by standard penetration test (SPT). The normalized values obtained from CPTU in these facies show saw-tooth graphs with large variations. The soil-behavior-types determined from the normalized values are plentiful from cohesionless to cohesive soils. On the other hand, marsh, bay, pro-delta and march/flood plain facies, which were made under low hydrodynamic conditions, they had simple and homogenous sedimentary properties. The sediments are commonly silt and clay. Strengths of these sedimentary facies increased linearly with depth, the normalized values were all rather constant with depth and their soil behavior-types are only clays derived from CPTU results. It could be said that these particular sedimentary conditions in the MD late Pleistocene-Holocene sediments can be reasonably estimated by CPTU test. The cross-section displays the successions of the sedimentary facies which were created in the all delta formation mechanisms including the tide-dominated delta with significant fluvial activity and material source, the tide-dominated delta, the tide- and wave-dominated delta, and the tide- and wave-dominated delta with strongly dominated by the waves (coast). Each succession of sedimentary facies was formed under a different delta formation mechanism and revealed a typical geotechnical property sequence. The particular trend of the mechanical behavior of the sedimentary succession can be reasonably inferred from the delta formation mechanism.

Six typical soil structure types were established based on the thickness and arrangement of the soil layers of the surface, shallow, and deep sediment facies. Considering the typical geotechnical properties of the dominant sediment facies of each structure type, potential or critical geotechnical problems are identified. Furthermore taking the current practice of geotechnical investigation in Vietnam into account, rational investigation procedures are proposed, including critical geotechnical conditions, which should be obtained with reasonable accuracy by the investigation to avoid the potential geotechnical problems in the infrastructure construction in the MD.

Organization of the dissertation

This dissertation is fallen into 7 chapters. **Chapter 1** with title is “**Introduction**”. This chapter briefly presented:

- Literature review and background of research, the specific geotechnical problems of MD
- Methods and results of researches on the post-glacial argillaceous sediments in MD and in other deltas in the world.
- Motivation of the research
- Objectives of the research

Chapter 2 is titled “**Sedimentary geology of Mekong River Delta**”. This chapter describes about:

- General geological structure of MRD
- Geological history in the formation of MRD late Pleistocene-Holocene sediments
- Changes in sea-level, sedimentary environment, progradation, sedimentary geology
- Delta formation mechanisms and their characteristics, Holocene delta evolution and depositional model of the MRD, comprising with other deltas about sedimentary geology.

Chapter 3 is titled “**Research strategy – study sites and methodology**”. This chapter describes about:

- Methods of the research
- Introduction and summary of investigation
- Soil investigation program including investigation sites, boring and sampling, in situ and lab geotechnical tests
- Geological investigation: carbon isotope age, minerals, and image analyses.

Chapter 4 is “**Results of sedimentary geology and geotechnical properties**”. This chapter presents about:

- Results of sedimentary geology, and stratigraphy and sedimentary environments of cores in this study and of reference cores
- Sedimentary facies changes and late Pleistocene-Holocene development of the delta

- Results of geotechnical properties and characteristics of geotechnical properties

Chapter 5 is titled “**Influence of sedimentary environment on geotechnical properties and consolidation characteristics**”. This chapter gives:

- Relation between the sedimentary facies and geotechnical properties
- Influence of sedimentary environment and condition on geotechnical properties
- Results of consolidation tests
- Characteristics of consolidation of sedimentary facies
- Levels of consolidation of the late Pleistocene-Holocene sediments and discussing about how to choose values of k for estimating OCR from CPTU test.

Chapter 6 is titled “**Consideration of soil structure and soil characterization for the infrastructure construction in MRD**”. This chapter presents about:

- Soil structure models
- Advantages and disadvantages for the infrastructure construction in MRD
- Difficulty in soil characterization of MRD; a rational investigation procedure for the late Pleistocene-Holocene sediments
- Comparison with other deltas about geotechnical properties.

And final **Chapter 7** with title is “**Conclusions and recommendations**” presents the all conclusions of this study about:

- Influence of sedimentary environment on geotechnical properties
- Delta formation mechanism influence geotechnical property sequence
- Characteristics of consolidation
- Soil structure mode and advantage and disadvantage for infrastructure construction
- Rational investigation procedure

*** Recommendations for future study.**

CONTENTS

Title page	i
Acknowledgement	ii
Abstract	iii
Organization of the dissertation	v
Contents	vii
List of figures	xii
List of tables	xxv
Notations	xxvii
CHAPTER 1. INTRODUCTION	1
1.1. Literature review and general background	1
1.1.1. Physical Geography	1
1.1.2. Goods and traffic	4
1.1.3. Geotechnical problems in Mekong Delta	6
1.1.4. Problem of geotechnical properties in Mekong Delta	11
1.2. Motivation of the research	17
1.3. Objectives of the research	18
CHAPTER 2. SEDIMENTARY GEOLOGY OF MEKONG RIVER DELTA	19
2.1. General geological structure of MRD	19
2.2. Geological history in the formation of Mekong Delta	19
latest Pleistocene-Holocene sediments	
2.2.1. Changes in sea-level and stages of development of Mekong Delta	19
2.2.2. Late Pleistocene-Holocene sediments	24
2.3. Delta formation mechanisms and their characteristics in	27
Mekong delta and other deltas	
2.3.1. Delta formation mechanisms and their characteristics in Mekong delta	27
2.3.2. Comparison with other deltas	33
2.4. Summary	35

CHAPTER 3. RESEARCH STRATEGY-STUDY SITES AND METHODOLOGY 38

3.1. Methodology	38
3.2. Introduction and summary of investigation	38
3.3. Soil investigation program	39
3.3.1. Investigation sites	39
3.3.2. Boring and sampling, and geological investigations	44
3.3.3. In situ tests	45
3.3.3.1. Plan layouts of each investigation site and instruments	45
3.3.3.2. Methods for analyzing in-situ test results	50
3.3.3.2.1. Piezo-cone penetrometer tests, CPTU	50
3.3.3.2.2. Standard penetration test, SPT	53
3.3.4. Laboratory geotechnical tests	54
3.3.4.1. Basic geotechnical properties	54
3.3.4.2. One-dimensional consolidation tests	54
3.3.5. Carbon isotope age, and clay minerals, and chemical analyses	55
3.3.6. Image analyses	56
3.4. Summary	56

CHAPTER 4. INVESTIGATION RESULTS ON SEDIMENTARY GEOLOGY 59 AND GEOTECHNICAL PROPERTIES

4.1. Introduction	59
4.2. Sedimentary geology results	60
4.2.1. Lithostratigraphy and inferred depositional facies of Vinhlong core	60
4.2.2. Lithostratigraphy and inferred depositional facies of Caolanh core	66
4.3. Stratigraphy and sedimentary environments of reference cores	71
4.3.1. Lithostratigraphy and depositional facies of BT1 core	71
4.3.2. Lithostratigraphy and depositional facies of BT2 core	73
4.3.3. Lithostratigraphy and depositional facies of BT3 core	77
4.4. Sedimentary facies changes and late Pleistocene-Holocene development of the delta	78
4.4.1. Transgressive marine stage	79

4.4.2. Regressive marine stage	83
4.5. Changes in sedimentary structures and materials of MRD late Pleistocene-Holocene sediments	85
4.5.1. Transgressive incised-valley-filling sediments	85
4.5.2. Regressive Holocene delta sediments	86
4.6. In-situ geotechnical test results	91
4.6.1. Vinhlong site	91
4.6.2. Caolanh site	102
4.6.3. Bentre-1 site	107
4.6.4. Bentre-2 site	113
4.6.5. Bentre-3 site	123
4.7. Lab geotechnical test results	131
4.7.1. Vinhlong core	131
4.7.2. Caolanh core	137
4.8. Characteristics of geotechnical properties of MRD	143
4.9. Summary of chapter 4	145
4.9.1. Sedimentary geology	145
4.9.2. Geotechnical properties	147
 CHAPTER 5. INFLUENCE OF SEDIMENTARY ENVIRONMENT ON GEOTECHNICAL PROPERTIES AND CONSOLIDATION CHARACTERISTICS	 149
5.1. Introduction	149
5.2. Relationship between the sedimentary facies and geotechnical properties	150
5.2.1. Transgressive incised-valley fill sediments	150
5.2.1.1. Estuarine channel facies (Sublayer 1 of VLM1 core)	150
5.2.1.2. Salt marsh facies (Sublayer 2 of VLM1 core)	151
5.2.1.3. Marsh/tidal flat facies (Sublayer 1 of CLM1 core)	151
5.2.1.4. Estuarine marine facies (Sublayer 3 of VLM1 core)	155
5.2.1.5. Sub- to inter-tidal flat facies (Sublayer 2 of CLM1 core)	155
5.2.1.6. Open bay mud facies (Sublayer 4 of VLM1 core, Sublayer 1 of BT2 core)	156
5.2.2. Regressive Holocene delta sediments	156

5.2.2.1. Pro-delta mud facies, and prodelta/bay facies (Sublayer 5 of VLM1 core, Sublayer 3 of CLM1 core, Sublayer 2 of BT2 core, Sublayer 1 of BT3)	156
5.2.2.2. Delta front facies (Sublayer 4 of CLM1 core, Sublayer 6 of VLM1 core, Sublayer 1 of BT1, Sublayer 3 of BT2 core, Sublayer 2 of BT3 core)	158
5.2.2.3. Intertidal flat facies (Sublayer 5 of CLM1 core)	161
5.2.2.4. Sub- to inter-tidal flat sandy silt facies (Sublayer 7 of VLM1 core, Sublayer 2 of BT1 core, Sublayer 4 of BT2 core, Sublayer 3 of BT3 core)	162
5.2.2.5. Flood plain facies (Sublayer 6 of CLM1 core, sublayer 8 of VLM1 core, sublayer 3 of BT1 core)	163
5.2.2.6. Sand dune facies (Sublayer 5 of BT2 core, Sublayer 4 of BT3 core)	164
5.2.2.7. Natural levee facies (Sublayer 7 of CLM1 core)	164
5.2.3. Relationship between the delta formation mechanism and geotechnical property sequence	167
5.2.4. Undifferentiated Pleistocene sediment-basement	170
5.3. Conclusions about influence of sedimentary environment on geotechnical properties from upper to lower Mekong Delta	171
5.4. Consolidation characteristics	174
5.4.1. Results of consolidation tests	174
5.4.1.1. Vinhlong site	174
5.4.1.2. Caolanh site	181
5.4.1.3. Void index	186
5.4.1.4. Swelling sensitivity	188
5.4.1.5. Coefficients of consolidation	189
5.4.1.6. Overconsolidation ratio	193
5.4.2. Development level of microstructure	195
5.4.2.1. Surface sediment facies	198
5.4.2.2. Shallow sediment facies	209
5.4.2.3. Deep sediment facies	213
5.5. Conclusions about consolidation characteristics	219

CHAPTER 6.	CONSIDERATION OF SOIL STRUCTURE AND SOIL CHARACTERIZATION FOR THE INFRASTRUCTURE CONSTRUCTION IN MD	222
6.1. Introduction		222
6.2. Soil structure models, and their advantages and disadvantages for highway and railway construction		223
6.2.1. Soil structure models		223
6.2.2. Advantages and disadvantages for highway and railway		227
6.3. Difficulty in soil characterization of MRD		231
6.3.1. Sensitivity of MRD soils		231
6.3.2. Influence of alternation-sand-seams		236
6.4. Poor geotechnical investigation practice		237
6.5. Rational investigation procedure		242
6.6. Comparison with other deltas about geotechnical properties		242
6.7. Conclusion of chapter 6		249
CHAPTER 7.	CONCLUSIONS AND RECOMMENDATIONS	252
7.1. Conclusions		252
7.1.1. Influence of sedimentary environment on geotechnical properties		252
7.1.2. Influence of delta formation mechanism on geotechnical property sequence		254
7.1.3. Characteristics of consolidation		254
7.1.4. Soil structure models and advantage and disadvantage for infrastructure construction		256
7.1.5. Rational investigation procedure		257
7.2. Recommendations for future study		257
REFERENCES		259

LIST OF FIGURES

Fig.1.1. Location of the MRD and administrative map in MRD simplified after Ma et al. (2003).	2
Fig. 1.2. Distribution of flooded area in the MRD (Nguyen et al., 2002).	3
Fig. 1.3. Diagram of each way type and length total of road traffic situation in the MRD (Vietnam road traffic general directorate, 2013).	6
Fig. 1.4. Breakdown of viaduct span of Cantho Bridge in MRD on Sep. 26 th , 2007	7
Fig. 1.5. (a) Two collapsed viaduct spans. (b) Supports of 2 viaduct spans, permanent piers (P13, P14, & P15) & temporary supports (T13, T14). (c) Soil profiles at the site.	8
Fig. 1.6 . (a) Settlement of approach of bridge in Dongthap MRD; (b) Settlement of approach of Vanthanh Bridge made house be declinational and damaged in district 1 Hochiminh city	9
Fig. 1.7. (a) Even settlement at two heads of immoderate plate of Vanthanh Bridge in district 1 (b) Approach and immoderate plate of bridge in district 8 Hochiminh City suddenly settled and completely damaged	10
Fig. 1.8. Contiguous zone of bridge propped by piles and embankment building in Dongthap province MRD	10
Fig. 1.9. Diagram of operating process of immoderate structure	11
Fig. 1.10. Limit of even settlement according to horizontal (Briaud, J. L., 1997)	11
Fig. 1.11.1. Soil stratigraphy of some boreholes in Mekong delta (Bui, 2003).	12
Fig. 1.11.2. Overconsolidation ratios versus depth (Man, 2003).	12
Fig. 1.12.1. Values of OCR from one borehole at the Camau site calculated by different methods versus depth (Nguyen and Giao, 2005).	13
Fig. 1.12.2. (a) The e-logp curves on the samples from the first soft clay layer and (b) Those on the samples from the second hard clay at the Camau site (Nguyen and Giao, 2005).	14
Fig. 1.13.1. Values of C_{C1} , C_{C2} , C_{C1}/C_{C2} , p'_y , and OCR from the CRS with depth for JFP and Shelby samples on the Cantho clay by Takemura et al. (2007).	15
Fig. 1.13.2. Relationship between $\Delta e/e_0$ and $p'_y/p'_{y-JFP\&CRS}$ with the criteria on sample quality of soft clay OCR less than 2 by Lunne et al. (1997) was found out by Takemura et al. (2007).	16

Fig. 2.1. Diagram of general geological stratum of the MRD	20
Fig. 2.2. Environmental sedimentary map of the Mekong River Delta (Nguyen et al., 2000) and location of the BT2 core site (Ta et al., 2001, 2002a).	21
Fig. 2.3. Age-depth curves at the BT2 core site (Ta et al., 2002a). (A) sea-level curve for the last 15 kyrs of MRD by Nguyen et al. (2000); (B) sea-level curve for the last 20 kyrs of the Sunda Shelf by Hanebuth et al. (2000).	22
Fig. 2.4. Progradation of Mekong Delta (Nguyen et al., 2000).	23
Fig. 2.5. Vestiges of wave-erosion on limestone cliffs at $z = +3.3$ m and $+4.5$ m in Hatien, MRD.	24
Fig. 2.6. Location of incised-valley zone and map by Nguyen et al., 2010.	26
Fig. 2.7. Map showing the location of major deltas (Hori and Saito, 2003). After Hori and Saito (2003). The Arno Delta added into the map.	27
Fig. 2.8. A classification of deltas in terms of fluvial, wave and tide influence (Hori and Saito, 2003).	28
Fig. 2.9. Mean wave height versus mean tidal range for major large-river deltas. (Hori and Saito, 2003).	29
Fig. 2.10. Basic environments of deltas (Hori and Saito, 2003). (a) Tide-dominated delta, (b) Fluvial-dominated delta.	29
Fig. 2.11. Components of deltas based on morphology and sedimentary environment. (a) Gilbert-type delta, (b) Tide-dominated delta, (c) Fluvial-dominated delta (Hori and Saito, 2003).	30
Fig. 2.12. Schematic depositional models of tide-dominated delta (a) and tide- and wave-dominated delta (b) (Ta et al, 2005).	31
Fig. 2.13. Two models of schematic facies-succession for the tide-dominated delta (a) and tide- and wave-dominated delta (b) (Ta et al., 2002).	32
Fig. 3.1. Plan layout of the investigation sites. Investigation sites: Caolanh (CLM1), Vinhlong (VLM1), Bentre-1 (BT1), Bentre-2 (BT2), and Bentre-3 (BT3) in this study, and Cantho (CTM1) and Tanan (TAS1) sites of Takemura et al. (2007). On the sedimentary map of Mekong River Delta (Ta et al. 2005).	40
Fig. 3.2. Location of CLM1, VLM1, BT1, BT2, and BT3 investigation sites in this study, and CTM1 and TAS1 sites of Takemura et al. (2007) on administrative	42

map of MRD simplified after Ma et al. (2003).	
Fig. 3.3.1. Plan layout of CLM1 borehole, CPTU1-CL, and SPT-CL tests at the Caolanh (CLM1) site in Fig. 3.2.	42
Fig. 3.3.2. Plan layout of VLM1 borehole, CPTU1-VL, CPTU2-VL, and SPT-VL tests at the Vinhlong (VLM1) site in Fig. 3.2.	43
Fig. 3.3.3. Plan layout of CPTU1-BT1 and SPT-BT1 tests near borehole BT1 (Ta et al., 2001) at Bentre-1 (BT1) site in Fig. 3.2.	43
Fig. 3.3.4. Plan layout of CPTU1-BT2, CPTU2-BT2, CPTU3-BT2, and SPT-BT2 tests near borehole BT2 (Ta et al., 2001) at Bentre-2 (BT2) site in Fig. 3.2.	43
Fig. 3.3.5. Plan layout of CPTU1-BT3 and SPT-BT3 tests near borehole BT3 (Ta et al., 2001) at Bentre-3 (BT3) site in Fig. 3.2.	44
Fig. 3.4. Hydraulic type thin-walled tube sampler with a fixed piston.	45
Fig. 3.5. For an example: boring and sampling were conducted at Vinhlong site in Vinhlong province, MRD.	48
Fig. 3.6. Piezo-cone penetrometer (CPTU), (a) details of CPTU, (b) cone tip, (c) penetrating rods.	48
Fig. 3.7. CPTU test was conducting at Vinhlong site in Vinhlong province MRD.	49
Fig. 3.8. Cleaning sand and remainder soil fragment and checking the depth before conducting SPT test at Vinhlong site in Vinhlong province MRD.	49
Fig. 3.9. Chart of Q_t of F_R for determining soil behaviors types proposed by Robertson (1990).	52
Fig. 4.1. Geological column of the VLM1 core and its correlation with lithostratigraphic units.	61
Fig. 4.2. Selected photographs of sedimentary structures from the VLM1 core:	64
Fig. 4.3. Geological column of the CLM1 core and its correlation with lithostratigraphic units.	67
Fig. 4.4. Selected photographs of sedimentary structures from the CLM1 core:	68
Fig. 4.5. Geological column of the BT1 core and its correlation with lithostratigraphic units (Ta et al. 2002a, and 2002b).	72
Fig. 4.6. Geological column of the BT2 core and its correlation with lithostratigraphic units (Ta et al. 2001).	76
Fig. 4.7. Geological column of the BT3 core and its correlation with	78

lithostratigraphic units (Ta et al. 2002a and 2002b).	
Fig. 4.8 Sedimentary cross-section is rebuilt to base on the sedimentary results of the CLM1 and VLM1 cores combined with three reference cores (Ta et al., 2001, 2002a, and 2002b).	81
Fig. 4.9. Investigative core sites: CLM1, VLM1 in this study. Core sites: BT1, BT2, BT3, DT1, VL1, TC1, TV1, VC1, CD1, GC1, and CM1(Ta et al., 2005 and Nguyen et al., 2004). TAS1 and CTM1 core sites (Takemura et al., 2007). Plan layout of core sites of a soil structure model with cross sections IB, MN, and QP. Sedimentary map of Mekong River Delta (Ta et al., 2005).	89
Fig. 4.10. Results of the <i>in situ</i> tests at the Vinhlong site: From SPT-VL: (a) N value. From CPTU1-VL: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , in addition, requisite time, t_{50} , for dissipating 50% of pore water pressure, and values of c_v and c_h calculated from t_{50} at the each depth, (f) sublayers divided based on the results of CPTU1-VL and SPT-VL.	92
Fig. 4.11. Results of the CPTU2-VL at the Vinhlong site: (a) soil-behavior-type classification by Q_t and F_R , (b)– (d) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , of CPTU2-VL compared with those of CPTU1-VL.	93
Fig. 4.12. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU1-VL and CPTU2-VL at the Vinhlong site.	93
Fig. 4.13. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained by CPTU1-VL at Vinhlong site: (a) Sublayers 1, 2, 3, 6, 7, and 8; (b) Sublayers 4 and 5.	94
Fig. 4.14. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU2-VL at the Vinhlong site: Sublayers 5 to 8.	95
Fig. 4.15. Undrained shear strengths vs. depth obtained from CPTU1-VL and CPTU2-VL at the Vinhlong site.	96
Fig. 4.16.1. Results of pore water pressure-dissipation test at -7.91 m during CPTU1-VL at the Vinhlong site.	97
Fig. 4.16.2. Results of pore water pressure-dissipation test at -13.5 m during CPTU1-VL at the Vinhlong site.	98

Fig. 4.16.3. Results of pore water pressure-dissipation test at -19.49 m during CPTU1-VL at the Vinhlong site.	99
Fig. 4.17. Results of the <i>in situ</i> tests at the Caolanh site: From SPT-CL: (a) N value. From CPTU1-CL: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , in addition, requisite time, t_{50} , for dissipating 50% of pore water pressure, and values of c_v and c_h calculated from t_{50} at the each depth, (f) sublayers divided based on the results of CPTU1-CL and SPT-CL.	102
Fig. 4.18. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU1-CL at the Caolanh site.	103
Fig. 4.19. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU1-CL at the Caolanh site: Sublayers 1 to 7.	103
Fig. 4.20. Undrained shear strengths vs. depth obtained from CPTU1-CL at the Caolanh site.	104
Fig. 4.21. Results of pore water pressure-dissipation test at -8.33 m during CPTU1-CL at the Caolanh site.	105
Fig. 4.22. Results of the <i>in situ</i> tests at the Bentre-1 site: From SPT-BT1: (a) N value. From CPTU1-BT1: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , in addition, values of t_{50} is requisite time for dissipating 50% of pore water pressure, values of c_v and c_h were calculated at the each depth, (f) sublayers divided based on the results of CPTU1-BT1 and SPT-BT1.	108
Fig. 4.23. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU1-BT1 at the Bentre-1 site.	109
Fig. 4.24. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU1-BT1 at the Bentre-1 site: Sublayers 1 to 3.	109
Fig. 4.25. Undrained shear strengths vs. depth obtained from CPTU1-BT1 at the Bentre-1 site.	110
Fig. 4.26.1. Results of pore water pressure-dissipation test at -2.88 m during CPTU1-BT1 at the Bentre-1 site.	111
Fig. 4.26.2. Results of pore water pressure-dissipation test at -7.31 m during	112

CPTU1-BT1 at the Bentre-1 site.	
Fig. 4.27.1. Results of the <i>in situ</i> tests at the Bentre-2 site: From SPT-BT2:	114
(a) N value. From CPTU1-BT2: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , (f) sublayers divided based on the results of CPTU1-BT2 and SPT-BT2.	
Fig. 4.27.2. Results of the <i>in situ</i> tests at the Bentre-2 site: From SPT-BT2 test:	115
(a) N value. From CPTU2-BT2 test: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , (f) sublayers divided based on the results of CPTU2-BT2 and SPT-BT2.	
Fig. 4.27.3. Results of the <i>in situ</i> tests at the Bentre-2 site: From SPT-BT2:	116
(a) N value. From CPTU3-BT2: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , (f) sublayers divided based on the results of CPTU3-BT2 and SPT-BT2.	
Fig. 4.28.1. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU1-BT2 at the Bentre-2 site.	117
Fig. 4.28.2. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU1-BT2 at the Bentre-2 site: Sublayers 1 to 5.	117
Fig. 4.29.1. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU2-BT2 at the Bentre-2 site.	118
Fig. 4.29.2. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU2-BT2 at the Bentre-2 site: Sublayers 1 to 5.	118
Fig. 4.30.1. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU3-BT2 at the Bentre-2 site.	119
Fig. 4.30.2. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU3-BT2 at the Bentre-2 site: Sublayers 1 to 5.	119
Fig. 4.31. Undrained shear strengths vs. depth obtained from CPTU1-BT2,	120

CPTU2-BT2, and CPTU3-BT2 at the Bentre-2 site.	
Fig. 4.32. Results of the <i>in situ</i> tests at the Bentre-3 site: From SPT-BT3:	124
(a) N value. From CPTU1-BT3: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , in addition, values of t_{50} is requisite time for dissipating 50% of pore water pressure, values of c_v and c_h were calculated at the each depth in (d), (f) sublayers divided based on the results of CPTU1-BT3 and SPT-BT3.	
Fig. 4.33.1. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU1-BT3 at the Bentre-3 site.	125
Fig. 4.33.2. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU1-BT3 at the Bentre-3 site: Sublayers 1 to 4.	125
Fig. 4.34. Undrained shear strengths vs. depth obtained from CPTU1-BT3 at the Bentre-3 site.	126
Fig. 4.35.1. Results of pore water pressure-dissipation test at -6.48 m during CPTU1-BT3 at the Bentre-3 site.	127
Fig. 4.35.2. Results of pore water pressure-dissipation test at -12.1 m during CPTU1-BT3 at the Bentre-3 site.	128
Fig. 4.35.3. Results of pore water pressure-dissipation test at -15 m during CPTU1-BT3 at the Bentre-3 site.	129
Fig. 4.36. Summary of lab test results of the VLM1 core: (a) Sublayers divided by the lab geotechnical test results, (b) Description of the material, (c) Grain size distribution, (d) Saturated unit weight γ_{sat} and specific gravity G_s , (e) Natural water content w_n , plastic limit w_p , liquid limit w_L , (f) Liquidity index LI, (g) Compression strength for undisturbed sample q_u , (h) Sensitivity, ration of compression strength for undisturbed sample q_u to remold sample q_{ru} , (i) Yield stress from IL oedometer test σ'_{y-IL} and CRS test σ'_{y-CRS} , with vertical effective overburden stress σ'_{v0} , (j) Average coefficients of consolidation from in-situ vertical stress/vertical effective overburden stress σ'_{v0} to yield stress from IL oedometer test σ'_{y-IL} or CRS test σ'_{y-CRS} .	133

Fig. 4.37. Plasticity chart of cohesive soils of the VLM1 core and Tanan and Cantho cores (Takemura et al., 2007): (a) deeper deposits from Sublayer 1 to sublayer 4 and (b) shallower deposits from sublayer 5 to sublayer 8.	134
Fig. 4.38.1. Axial stress and strain curves of UC tests from -4 m to -16.5 m of VLM1 core.	135
Fig. 4.38.2. Axial stress and strain curves of UC tests from -18.9 m to -29.95 m of VLM1 core.	135
Fig. 4.38.3. Axial stress and strain curves of UC tests from -32.74 m to -37.55 m of VLM1 core.	136
Fig. 4.38.4. Axial stress and strain curves of UC tests from -38.2 m to -48 m of VLM1 core.	136
Fig. 4.39. Changes of void ratio due to recompression to the effective overburden stress from oedometer tests on Vinhlong and Caolanh cohesive specimens.	139
Fig. 4.40. Summary of lab test results of Caolanh site: (a) Geological column of the CLM1 core, (b) Description of the materials, (c) Grain size distribution, (d) Saturated unit weight γ_{sat} and specific gravity G_s , (e) Natural water content w_n , plastic limit w_p , liquid limit w_L , (f) Liquidity index LI, (g) Compression strength for undisturbed sample q_u , (h) Sensitivity, ratio of compression strength for undisturbed sample q_u to remold sample q_{ru} , (i) Yield stress from IL oedometer test σ'_{y-IL} and CRS test σ'_{y-CRS} , with vertical effective overburden stress σ'_{v0} , (j) Average coefficients of consolidation (C_v) from in-situ vertical stress/vertical effective overburden stress σ'_{v0} to yield stress from IL oedometer test σ'_{y-IL} or CRS test σ'_{y-CRS} .	140
Fig. 4.41. Plasticity chart of deposits in the CLM1 core at Caolanh site; Tanan and Cantho cores (Takemura et al., 2007).	141
Fig. 4.42.1. Axial stress and strain curves of UC tests from +0.83 m to -1.85 m of CLM1 cores.	142
Fig. 4.42.2. Axial stress and strain curves of UC tests from -4.06 m to -24.85 m of CLM1 cores.	142
Fig. 5.1. General soil profile consists of investigation sites: (1) Caolanh,	153

(2) Vinhlong, (3) Bentre-1, (4) Bentre-2, (5) Bentre-3;	
Fig. 5.2. General profile of investigation sites: (1) Caolanh,	154
(2) Vinhlong, (3) Bentre-1, (4) Bentre-2, (5) Bentre-3; each investigation site displays about: (a) Values of the normalized cone resistance, Q_t , (b) Sleeve friction, F_R , and (c) Pore water pressure, B_q , obtained from the CPTU tests.	
Fig. 5.3. Plasticity chart of deposits of the CLM1 core, VLM1 (Truong et al., 2011), and TAS1 and CTM1 (Takemura et al., 2007) cores.	169
Fig. 5.4.1a. Curves of $e\text{-log}\sigma'_v$ on sediment specimens from -41.52 to -32.64 m.	175
Fig. 5.4.1b. c_v vs. vertical effective stress on sediment specimens from -41.52 to -32.64 m.	175
Fig. 5.4.2a. Curves of $e\text{-log}\sigma'_v$ on sediment specimens from -32.61 to -30.81 m.	176
Fig. 5.4.2b. c_v vs. vertical effective stress on sediment specimens from -32.61 to -30.81 m.	176
Fig. 5.4.3a. Curves of $e\text{-log}\sigma'_v$ on sediment specimens from -30.5 to -22.12 m.	177
Fig. 5.4.3b. c_v vs. vertical effective stress on sediment specimens from -30.5 to -22.12 m.	177
Fig. 5.4.4a. Curves of $e\text{-log}\sigma'_v$ on sediment specimens from -14.5 to -9.62 m.	178
Fig. 5.4.4b. c_v vs. vertical effective stress on sediment specimens from -14.5 to -9.62 m.	178
Fig. 5.4.5a. Curves of $e\text{-log}\sigma'_v$ on sediment specimens from -9.59 to -6.38 m.	179
Fig. 5.4.5b. c_v vs. vertical effective stress on sediment specimens from -9.59 to -6.38 m.	179
Fig. 5.4.6a. Curves of $e\text{-log}\sigma'_v$ on sediment specimens from -6.38 to -1.42 m.	180
Fig. 5.4.6b. c_v vs. vertical effective stress on sediment specimens from -6.38 to -1.42 m.	180
Fig. 5.4. Curves of $e\text{-log}\sigma'_v$ of loading & unloading stages, & c_v vs. vertical effective stress from IL & CRS tests on undisturbed and reconstituted cohesive soil specimens of Vinhlong core.	180
Fig. 5.5. Coefficients c_v vs. vertical effective stress on type 4, silt mixtures-clayey silt to silty clay (Robertson, 1990) at $z = -7.91$ m by IL & CPTU tests at Vinhlong site.	181
Fig. 5.6.1a. Curves of $e\text{-log}\sigma'_v$ on sediment specimens from -27.55 to -22.9 m.	182
Fig. 5.6.1b. c_v vs. vertical effective stress on sediment specimens from -27.55 to -22.9 m.	182
Fig. 5.6.2a. Curves of $e\text{-log}\sigma'_v$ on sediment specimens from -7.5 to -1.45 m.	183
Fig. 5.6.2b. c_v vs. vertical effective stress on sediment specimens from -7.5 to -7.45 m.	183
Fig. 5.6.3a. Curves of $e\text{-log}\sigma'_v$ on sediment specimens from -1.78 to -1.68 m.	184

Fig. 5.6.3b. c_v vs. vertical effective stress on sediment specimens from -1.78 to -1.68 m.	184
Fig. 5.6.4a. Curves of $e\text{-log}\sigma'_v$ on sediment specimens from 0.25 to 0.98 m.	185
Fig. 5.6.4b. c_v vs. vertical effective stress on sediment specimens from 0.25 to 0.98 m.	185
Fig. 5.6. Curves of $e\text{-log}\sigma'_v$ of loading & unloading stages, & c_v vs. vertical effective stress from IL& CRS tests on undisturbed and reconstituted cohesive soil specimens of Caolanh core.	185
Fig. 5.7. Coefficients c_v vs. vertical effective stress on type 3, Clays-clay to silty clay (Robertson, 1990) at $z = -8.33$ m by IL & CPTU tests at Caolanh site.	186
Fig. 5.8. Relationship between void indices I_{vo} and effective overburden stress σ'_{vo} on the Caolanh, Vinhlong cohesive soils, Cantho and Tanan cohesive soils (Takemura et al., 2007).	188
Fig. 5.9. OCRs by IL, CRS, and CPTU with values of k being 0.2, 0.3, 0.4, and 0.5, and normalized cone resistance, Q_t on the cohesive soil at Caolanh site.	193
Fig. 5.10. OCRs by IL, CRS, and CPTU with values of k being 0.2, 0.3, 0.4, and 0.5, and normalized cone resistance, Q_t on the cohesive soil at Vinhlong site.	194
Fig. 5.11.1. Values of OCRs with depth from IL, CRS and CPTU tests for the cohesive soils at Caolanh, Vinhlong, and Bentre-1 sites.	196
Fig. 5.11.2. Values of OCRs with depth from CPTU tests for the cohesive soils at Bentre-2, Bentre-3 sites.	197
Fig. 5.12. Simplified geotechnical profile with three main broad soil layers on the plan layout of the core sites in Fig. 3.1.	201
Fig. 5.13. Selected petrography-images in thin sections of Caolanh core: a , & b) clay-specimens in the natural levee facies, iron and calcium cements significantly joined in bond. Large angular quartz fragments (Q) obtained 0.35 mm length and distributed chaotically and plentifully; Q were completely enclosed by iron oxide. Density of space pores is so small. Sizes of space pores are general small through blue color. Other images of Vinhlong core: c & d) in the delta front, Q with even sizes, and organic materials are plentiful with general greenish gray and black joining in bond, e_0 increased highly; e & f) in the delta front, contiguous zone between sandy and clayey parts; g & h) in prodelta, clayey seams plainly divided, e_0 decreased. i , j & k) in marsh, clayey seams and hydromica sticks arranged clearly parallel together, the matrix between the sand grains contains	203

opaque iron oxide and calcites, e_0 significantly decreased; **l & m**) in marsh, calcite, iron compound and diatoms are plentiful, but e_0 unusually increase; **n, o**) in estuary channel, iron cements and pyrites and calcites abundantly crystallized, e_0 and size of e_0 decreased, well compacted.

Fig. 5.14. Selected SEM images of Caolanh core: **a**) in natural levee $z = 0.28\text{m}$, 205
clay-minerals arranged chaotically, clay particles aggregated and generally bond well, sizes and density of space pores are so small; **b**) in flood $z = -4.81\text{m}$, clay-minerals arranged chaotically, clay particles aggregated, sizes of space pores are greater than those of the natural levee sediment. Cantho core: **c**) in delta front at $z = -11.1\text{m}$ (Takemura et al., 2007), salt flocculation and large space pore, clay particles weakly bond. Vinhlong core: **d**) in prodelta $z = -21.01\text{m}$, clays arrange in parallel seams; **e, f, & g**) in prodelta $z = -21.01\text{m}$, shapes of the diatoms are petri dish and tubular, pyrites crystallized in space pore of the petri dish diatom, the matrix of fine clay-particles around the diatoms is not well compacted. Cantho site: **h**) in open bay $z = -20.1\text{m}$ (Takemura et al., 2007), pyrite-sizes are greater than those of delta front sediment and more plentiful than, petri dish diatom fragments. Vinhlong core: **i, j & k**) in marsh $z = -30.45\text{m}$, clays clearly arranged in seams, pyrites plentifully crystallized, sizes of space pore decreased; **l, m & n**) in marsh $z = -37.3\text{m}$, clays so clearly arranged parallel, tubular diatoms are extremely plentiful, the matrix around the tubular diatoms is quite compacted, but the clear open cycles of the tubular diatoms are large with $10\text{ }\mu\text{m}$ in diameter and $150\text{ }\mu\text{m}$ on the exposed surface; **o**) in estuary channel $z = -45.75\text{m}$, clays with large sizes arranged parallel, sizes of space pore decreased, and well compacted.

Fig. 5.15. Comparison of curves of $e\text{-log } \sigma'_v$ given by IL and CRS tests on 206
undisturbed cohesive soil specimens of natural levee facies ($z = 0.98\text{ m}$, 0.93 m , & 0.3m) with those of flood plain facies ($z = -1.68\text{ m}$, -1.73 m , & -1.78 m) of CLM1 core.

Fig. 5.16. S-shape of $e\text{-log } \sigma'_v$ curves from the IL and CRS tests with characteristic 210
of curve of clay in the flocculent structure at $z = -9.76\text{ m}$, -9.74 m , -9.59 m , and -6.35 m of VLM1 core.

Fig. 5.17. Observed cross section of test specimens for oedometer and CRS tests. 211

Fig. 5.18. SEMs of Osaka Bay clay: **a**) Marine clay $z = -144.1\text{ m}$, petri dish diatom 215

contains some framboidal pyrite particles and compacted aggregates; **b)** Marine clay $z = -162.2$ m, framboidal pyrites particles increase in amount and size, the pore spaces and shape of diatoms have changed; **c)** Marine clay $z = -164.4$ m, diatom fills with framboidal pyrite particles and aggregated structure; **d)** Marine clay $z = -274.8$ m, compacted microfabric with clay particles moulding microfossil elements, tubular diatom; **e)** Marine clay $z = -383.7$ m, petri dish diatom cover about 1/3 of the exposed surface, no pyrite filling the pore space, clay matrix is so compressed and pore space has vanished, shape and pore space of petri dish have been changing; **f)** Diluvial clay $z = -181.4$ m, shape and pore space of petri dish diatom have been changing, no pyrite filling the pore space, clay matrix is so compressed and pore space has vanished, and abundant microfossil fragments, oriented, reported by Tanaka et al. (1999) and Locat et al. (2001).

Fig. 5.19. Compression curves, $e - \log \sigma'_v$ relationship, and yield stresses (P'_c) obtained 216
from IL loading oedometer tests and CRS tests for cohesive soils of case 3 of
VLM1 core contained microfossils and high organic material, data of
Osaka Bay cohesive soils (Tanaka et al., 1999).

Fig. 6.1. Generally preliminary soil structure model with three main broad soil layers 226
based on geotechnical and sedimentary properties of core sites (simplified after
Truong et al., 2011; Ta et al., 2005 and Nguyen et al., 2004; Takemura et al., 2007).
The plan layout of the core sites in the model is in Fig. 4.9.

Fig. 6.2. Six typical soil structure types base on the thickness and arrangement of 227
three main broad layers.

Fig. 6.3. Sensitivity, ration of compression strength for undisturbed sample, 232
 q_u , to remold sample, q_{ru} , on the Vinhlong core according to the
classification of Rosenqvist (1953).

Fig. 6.4. Sensitivity, ration of compression strength for undisturbed sample, q_u , 232
to remold sample, q_{ru} , on the Caolanh core according to the classification of
Rosenqvist (1953).

Fig. 6.5. Sample quality in terms of (1) failure strains, ε_f , (2) secant moduli divided by the 233
undrained shear strength, $E_{50}/(q_u/2)$, from UC tests, and (3) $\Delta e/e_0$ from IL tests on
Vinhlong core.

- Fig. 6.6.** Sample quality in terms of (1) failure strains, ε_f , (2) secant moduli divided by the undrained shear strength, $E_{50}/(q_u/2)$, from UC tests, and (3) $\Delta e/e_0$ from IL tests on Caolanh core. 233
- Fig. 6.7.** Comparisons of undrained shear strength obtained from CPTU with those by UC tests at Caolanh site. 234
- Fig. 6.8.** Comparisons of undrained shear strength obtained from CPTU with those by UC tests at Vinhlong site. 235
- Fig. 6.9.1.** Cumulative log-time/deformation curves for all stages from IL test of typical clay specimen at – 7.8 m Vinhlong core. 240
- Fig. 6.9.2.** Square-root-time/deformation curves for all stages from IL test of typical clay specimen at – 7.8 m Vinhlong core. 241

LIST OF TABLES

Table 1.1. Parameters of the flood areas in MRD (Nguyen et al., 20002).	3
Table 1.2. Comparing transport of passengers and goods in MRD with all the Vietnam country in 2009 (Vietnam Traffic-Transport Development and Strategy Institute, 2013).	4
Table 1.3. Road traffic situation in MRD (Vietnam road traffic general directorate, 2013).	6
Table 2.1. Delta areas of selected major river systems, suspended load, water discharge, drainage area. After Hori and Saito (2003). The Arno Delta added into the list.	28
Table 2.2. Characteristics of the tide-dominated delta and the tide- and wave-dominated Delta in MRD from the sea-level highstand to present sea level, 8,000-0.0 yr BP (Ta et al., 2005 and Nguyen et al., 2000).	33
Table 3.1. List of the site information, boreholes, and in-situ tests in this study and reference data.	41
Table 4.1. Results of clay mineral content analysis of argillaceous sediments of the facies from Vinhlong core.	62
Table 4.2. List of ^{14}C ages from the VLM1 core.	62
Table 4.3. List of ^{14}C ages from the CLM1 core.	69
Table 4.4. Results of clay mineral content analysis of argillaceous sediments of the facies from Caolanh core.	69
Table 4.5. Comparison of thickness, altitude of appearance of sedimentary facies, ^{14}C age, and altitude difference between maximum and minimum appearances of the VLM1 and CLM1 cores with BT1, BT2, BT3, VL1, and DT1 cores (Ta et al., 2002a, 2002b, 2001, and Nguyen et al., 2010).	82
Table 4.6. Information of sediment facies of core sites in this study and collected core sites (Ta et al., 2001; 2002a; 2005; and Nguyen et al., 2005).	90
Table 5.1a. Exchangeable-ion content in the argillaceous sediments from the CLM1 and VLM1 cores.	166
Table 5.1b. Total ion content in the argillaceous sediments from the CLM1 and VLM1 cores.	167
Table 5.2. Void indices, I_{vo} , in situ void ratio, e_o , and void ratios, e^*_{100} , e^*_{1000} , at vertical stresses 100 kPa and 1000 kPa on $e\text{-log}\sigma'_v$ of remold specimens, of cohesive soils of Caolanh and Vinhlong cores	187

Table 5.3. Swell sensitivities, C_s^*/C_s , yield stress ratio, OCR, virgin compression index, C_c , from IL tests and Atterberg limits of facies' argillaceous sediments of the CLM1 and VLM1 cores.	190
Table 5.4. Values of coefficients of consolidation in direction: vertical, c_v , and horizontal, c_h , from CPTU and IL at the sites.	191
Table 5.5. Values of k and OCR values by the CPTU at the Caolanh, Vinhlong, Bentre-1, Bentre-2, and Bentre-3 sites.	202
Table 5.6. To interpret development-levels of microstructure of facies' argillaceous sediments based on a combination of the consolidated properties, ^{14}C age, and analysis on PTS and SEM in Figs. 4.6, and 4.7 of CLM1, VLM1, and CTM1a cores. Values of k suggested for calculating OCR from CPTU test.	207
Table 5.7. Summary of clay mineral content analysis of argillaceous sediments of Vinhlong and Caolanh cores.	218
Table 6.1. Summary the typical geotechnical properties of each facies.	224
Table 6.2. Amount of sediment facies, thicknesses of late Pleistocene-Holocene sediments, top facies, and appearance-depth of undifferent Pleistocene sediments in each type of geotechnical structure and typical core site; Levels of advantage and disadvantage of them for construction of structures.	228
Table 6.3. Summary the typical consolidation properties of each facies at Vinhlong site.	230
Table 6.4. To summarize the geotechnical data of the MRD, Mississippi (Paul, 2005), and Arno deltas (Giovanni et al., 2012).	244

NOTATIONS

A	Sea-level curve for the last 15 kyrs of MRD
B	Sea-level curve for the last 20 kyrs of the Sunda Shelf
BP	Before present
B_q	Normalized pressure ratio
BT1	Bentre-1 site in the Bentre province of the MRD
BT2	Bentre-2 site in the Bentre province of the MRD
BT3	Bentre-3 site in the Bentre province of the MRD
c	Clay
C_c	Compression index
c_c	Consolidated cohesion
C_c^*	Compression index from 1000 to 100 kPa
C_{c1}	Maximum compression index at consolidation stress $\sigma'_v = 1,000 \text{ kPa}$
C_{c2}	Compression index at consolidation stress $\sigma'_v = 1,000 \text{ kPa}$
CE	Extremely high plastic clay
CH	High plastic clay
c_h	Coefficients of consolidation in horizontal direction
CI	Medium plastic clay
CL	Low plastic clay
CLM1	Caolanh site in the Caolanh province, Mekong River Delta
CPTU	Piezo-cone penetrometer test
CPTU1-BT1	The piezo-cone penetrometer test at the Bentre-1 site
CPTU1-BT2	The first piezo-cone penetrometer test at the Bentre-2 site
CPTU2-BT2	The second piezo-cone penetrometer test at the Bentre-2 site
CPTU3-BT2	The third piezo-cone penetrometer test at the Bentre-2 site
CPTU1-BT3	The piezo-cone penetrometer test at the Bentre-3 site
CPTU1-CL	Piezo-cone penetrometer test at the Caolanh site
CPTU1-VL	The first piezo-cone penetrometer test at the Vinhlong site
CPTU2-VL	The second piezo-cone penetrometer test at the Vinhlong site
CRS	Constant rate of strain consolidation test
cs	Coarse sand
C_s	Undisturbed swelling index

C_s^*	Intrinsic swelling index
C_s^*/C_s	Swell sensitivity
CV	Very high plastic clay
c_v	Coefficient of consolidation in vertical direction
^{14}C	Carbon isotope ages
C_α	Coefficient of secondary compression
e	Void ratio
e_0	In situ void ratio, effective overburden stress
e_{100}^*	Void ratios of the intrinsic compression curve at $\sigma_v' = 100$ kPa
e_{1000}^*	Void ratios of the intrinsic compression curve at $\sigma_v' = 1000$ kPa
F_R	Normalized friction ratio
fs	Fine sand
f_s	Sleeve friction
G_s	Specific gravity
H_{av}	Mean specimen height during the load increment, measured in mm
ICL	Intrinsic compression line
IL	Incremental loading oedometer test
I_{vo}	Void indices
k	Constant for estimating OCR from CPTU results, values from 0.2 to 0.5
k_h	Coefficient of permeability in horizontal direction
k_v	Coefficient of permeability in vertical direction
k_h/k_v	Possible field values for soft clays
LGM	Last glacial maximum
LI	Liquidity index
ME	Extremely high plastic silt
MH	High plastic silt
MI	Medium plastic silt
ML	Low plastic silt
MRD	Mekong River Delta
MD	Mekong Delta
ms	Medium sand
MV	Very high plastic silt

N	Value in the SPT results is the blow count for the standard penetration going into the ground 30 cm
OCR	Overconsolidation ratios/yield stress ratio
PI	Plasticity index
PN	Polar nicol of the microscope
P_y'	Preconsolidation pressure/yield stress
PTS	Petrography-images in thin sections
$p'_{y-JFP \& CRS}$	Yield stress from CRS and sampling with Japanese type thin-walled tube sampler with fixed piston
Q	Quartz fragments
q_u	Unconfined compressive strength on undisturbed soils and remolded soil, q_{ur}
q_{ur}	Unconfined compressive strength on remolded soil
q_t	Cone resistance
Q_t	Normalized cone resistance
s	Silt
SCL	Sedimentation compression line
SEM	Scanning electron micrographs
SPT-BT1	Standard Penetration test at the Bentre-1 site
SPT-BT2	Standard Penetration test at the Bentre-2 site
SPT-BT3	Standard Penetration test at the Bentre-3 site
SPT-CL	Standard Penetration test at the Caolanh site
SPT-VL	Standard Penetration test at the Vinhlong site
SPT	Standard Penetration Test
S_t	Sensitivity
t_{50}	Requisite time for dissipating 50% of pore water pressure
U	Degree of dissipation
UC	Unconfined compression test
u_i	Pore pressure at start of dissipation test
USL	Undisturbed swelling line
u_t	Pore pressure at time t
$u_{t=50}$	pore pressure corresponding to the degree of dissipation by 50 percent
u_0	Hydrostatic water pressure/Equilibrium in situ pore pressure
u_2	Pore water pressure was measured behind the cone tip

vfs	Very fine sand
VLM1	Vinhlong site in the Vinhlong province at center of the MRD
VPI	Analysis Lab Center, Vietnam Petroleum Institute
w_n	Natural water content
w_p	Plastic limit
w_L	Liquid limit
XN	Crossed nicol of the microscope
yr	Year
z	Depth
γ	Unit weight
γ_{sat}	Saturation unit weight
σ'_v	Preconsolidation pressure/yield stress
σ'_{y-IL}	Vertical yield stresses were estimated from the IL results
σ'_{y-CRS}	Vertical yield stresses were estimated from the CRS results
σ_{v0}	Total vertical stress
σ'_{v0}	Vertical effective overburden stress
σ'_{vy}	Vertical yield stress
$\sigma'_{vy}/\sigma'_{v0}$	Overconsolidation ratios or yield stress ratio
Δe	Void ratio decrease
$\Delta \sigma$	Increase of total stress
Δu_2	Maximum excess hydrostatic pressure
Σ_w	Viscid cohesion

CHAPTER 1

INTRODUCTION

1.1. Literature review and general background

1.1.1. Physical Geography

The Mekong River Delta (MRD) is the largest delta in Vietnam, is located in southern Vietnam between $8^{\circ} 30'$ and $11^{\circ} 00'N$ and $104^{\circ} 30'$ and $106^{\circ} 50'E$ (Figure. 1.1). The area that belongs to Vietnam is $52,100 \text{ km}^2$. The MRD was divided into two broad parts. The first part is influenced by flood from the Mekong river system and called the upper part or the flood-area or the upper delta plain (Fig. 1.2). The second is influenced by tidal regimes from the seas and called the lower part or the lower delta plain (Fig. 1.2).

Distribution of flood-area with different flooded-water-levels in the upper part of the MRD is shown in Fig. 1.2 (Nguyen and Tran, 2002). The distributions of flooded-area with different flood-water-levels and of population in each corresponding flooded-area were distributed into four grades. Their parameters in the four grades are shown in Table 1.1 (Nguyen and Tran, 2002). About 50% of the MRD region has been flooded annually and more than 30% of the region has been inundated over 2 meters deep (Nguyen and Tran, 2002).

The MRD has been being influenced by two different tidal regimes. A semi-diurnal tide has amplitude of 2.5-3.8 m in the South China Sea and a diurnal tide has amplitude of 0.5-1.0 m in the Gulf of Thailand (Gagliano and McIntire, 1968; Wolanski et al., 1996). In the lower delta plain of the MRD, the marine influence reaches 80 to 100 km inland via the river systems (Gagliano and McIntire, 1968). Under the influence of these tidal regimes of the South China Sea and Gulf of Thailand, salty water intrudes into the river systems of almost the lower delta plain of the MRD. The river flow in the dry season is strongly reduced, so the salty water will intrude strongly and far into inland. The altitude of the crest of tide is normally +1.3 to +1.35 m in comparison with the average present sea level(a.p.s.l.). The altitude of the maximum crest of tide was about +1.975 m in comparison with the a.p.s.l. in 1993 and 1998 (Tran, D. K., 2009).



Mekong River Delta

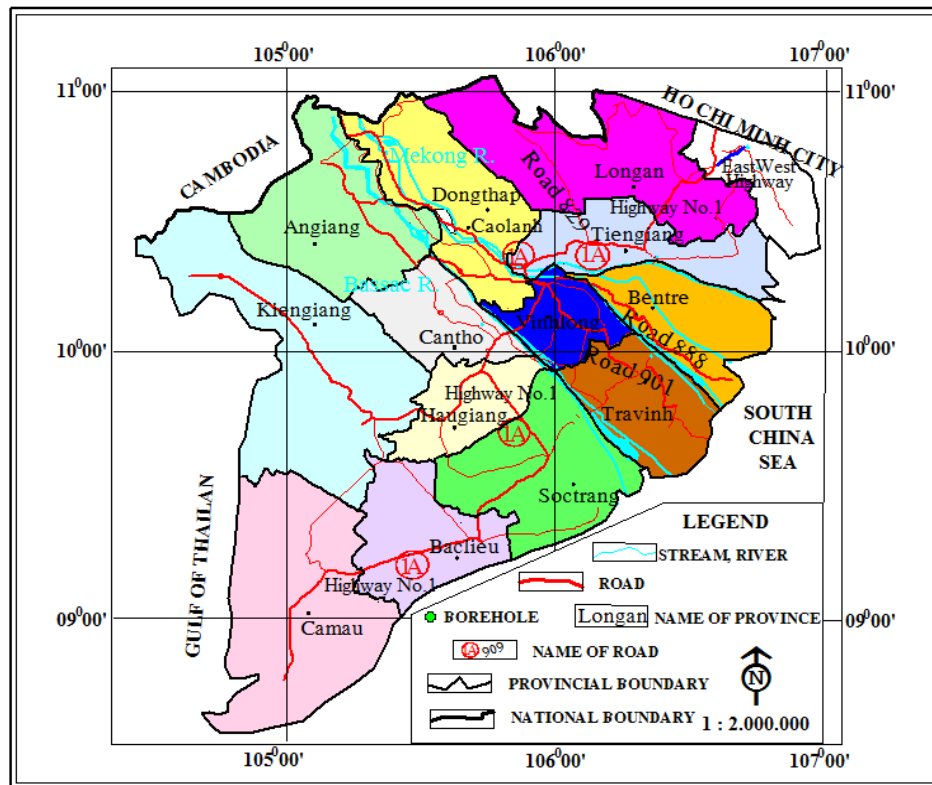


Fig.1.1. Location of the MRD and administrative map in MRD simplified after Ma et al. (2003).

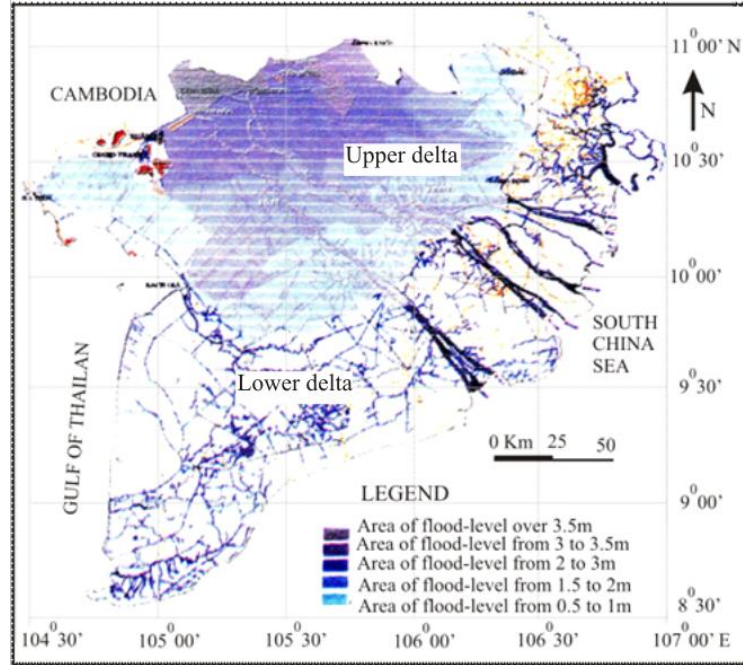


Fig. 1.2. Distribution of flooded area in the MRD (Nguyen and Tran, 2002).

Table 1.1. Parameters of the flood areas in MRD (Nguyen and Tran, 2002).

Altitudes of flood-water-level	Corresponding area was flooded	In comparison with the total flood-area	Population in corresponding flood-area	In comparison with the total population
(m)	(km ²)	(%)	(people)	(%)
more than 3	2,641.0	13.5	1,371,740	15.2
from 2 to 3	3,145.4	16.1	818,616	9.6
from 1 to 2	7,482.5	37.3	2,829,964	31.8
less than 1	6,487.0	33.1	3,954,833	43.4
Total	19,755.9	100.0	8,975,153	100.0

The climate in the MRD is humid tropical and dominated by a monsoon. The rainy season lasts six months - from May to November, and the dry season lasts from December to April of next year. The mean annual rainfall is 1,700 mm in the delta and reaches more than 2,000 mm along the Gulf of Thailand. Annually, the temperature is relatively uniform with an average of 27-30⁰ C and annual evaporation is 1020-1204 mm.

1.1.2. Goods and traffic

The population is about 17.4 million (Vietnamese statistical general directorate, 2011). The MRD plays an important role in supplying foods for Vietnam with 18.5 million tons of rice per year, 233,500 tons of aquatic fish products, and many types of tropical-fruits (Nguyen, N. T., 1990).

We will consider transports of passengers and goods in 2009 in the MRD that was reported by Vietnam Traffic-Transport Development and Strategy Institute (2013). Transport of passengers in the MRD in comparison with those in all the Vietnam country in 2009 is rather large, 29.5%, and transport of goods is 11.6% (Tab. 1.2). Transport of passengers by the road traffic system in the MRD in comparison with those in all the Vietnam country is 25.5% (Tab. 1.2). Transport of passengers by the road traffic system in comparison with the other transport types in the MRD is so large, 79.1%, and of goods is 34.2% (Tab. 1.2). We realize the road traffic needed in the MRD is so high.

Table 1.2. Comparing transport of passengers and goods in MRD with all the Vietnam country in 2009 (Vietnam Traffic-Transport Development and Strategy Institute, 2013)

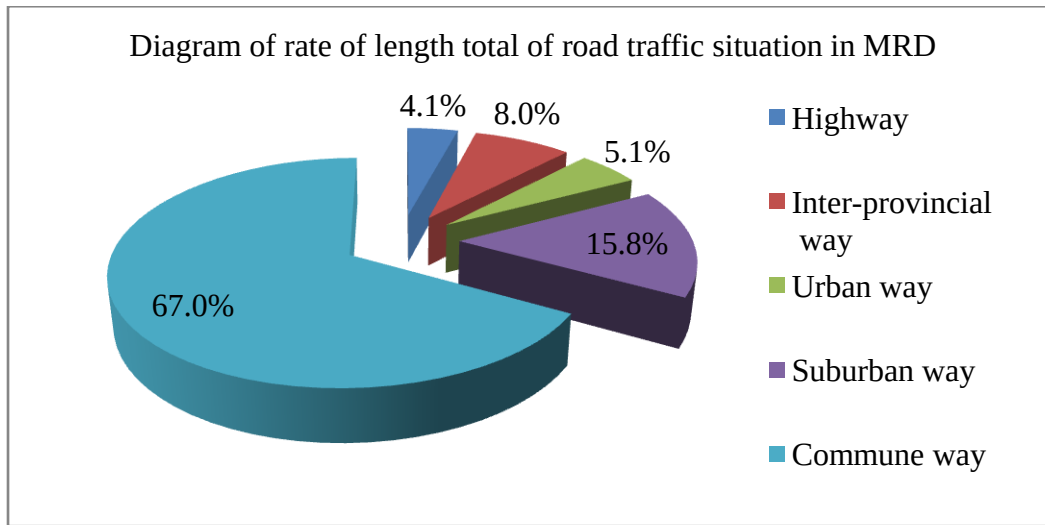
Transport types	Unit	MRD	All the Vietnam country	MRD/All the Vietnam country,%	Transport Type/MRD,%
Transport of passenger	million person	585.08	1,982.10	29.5	
Road traffic	as above	463.00	1,818.70	25.5	79.1
Waterway	as above	121.40	148.20	81.9	20.7
Seaway	as above	0.13	4.50	2.9	0.02
Airway	as above	0.55	10.70	5.1	0.1
Transport of goods	million tons	80.51	691.74	11.6	
Road traffic	as above	27.50	494.60	5.6	34.2
Waterway	as above	47.40	135.70	34.9	58.9
Seaway	as above	no	61.30		
Airway	as above	0.01	0.14	7.1	0.01

But the infrastructure is still behind the times, especially in the traffic system. We are going to refer to the quality of the traffic system in the MRD. For the highway reaches, mostly the levels III and IV with two lanes, the surfaces of the highways are asphaltic (Vietnamese traffic technical standard has 5 levels from I to V, the level I is highest). The good exploitation of the highway is 94.78 % (Tab. 1.3) (Vietnam Traffic-Transport Development and Strategy Institute, 2013). The inter-provincial way reaches the levels III and IV; a few inter-provincial ways are level V, with one lane. And the good exploitation situation of the inter-provincial ways is only 56.29 % (Tab. 1.3). Finally there are the suburban and commune ways. The good exploitation situation of the suburban and commune ways are too low, from 32 to 38 % (Tab. 1.3). The surfaces of the suburban and commune ways are only soil. Densities of way types are mostly low; especially densities of highways, inter-provincial ways, and urban ways in comparison with the area of the MRD and less than 0.086 (Table 1.3). The rate of the highway length and way length total is very low, 4.1%; the rate of the inter-provincial way length and way length total is 8.0%; and the rate of the urban way length and way length total is also very low, 5.1% (Fig. 1.3). There are not enough bridges (Vietnam Traffic-Transport Development and Strategy Institute, 2013).

The soil ground in MRD is generally soft and there are many large waterways. Many dikes and traffic systems have been and are being constructed; some of them are under difficult circumstances crossing the waterways. Especially in the upper delta plain of the MRD they have been damaged by flooding every year. Generally, the dikes and traffic systems in the MRD need to be developed. The traffic system is the most important infrastructure for the MRD development projects (Vietnam Traffic-Transport Development and Strategy Institute, 2013). In the flood area, the dike systems need to prevent and control the flooding. In the lower delta plain, the dike systems need to prevent the intrusion of salt water. In the MRD the dikes and waterways are normally combined together. The topography of the MRD is fairly flat; the average altitude is +1 in comparison with the a.p.s.l. Therefore, the height of the embankments in the MRD is commonly high, from 2.0 m to 5.0 m.

Table 1.3. Road traffic situation in MRD (Vietnam road traffic general directorate, 2013).

Way types	Total of good & bad ways, km	Good way, km	Bad way, km	Density (Good & bad ways length total/area), km/km ²	Rate (Good way/total of good & bad ways), %
Highway	1,784.67	1,691.45	93.23	0.044	94.78
Inter-provincial way	3,450.32	1,942.08	1,508.24	0.085	56.29
Urban way	2,211.39	1,728.80	482.59	0.055	78.18
Suburban way	6,801.68	2,602.79	4,198.89	0.168	38.27
Commune way	28,875.52	9,312.05	19,563.47	0.712	32.25
Total	43,123.58	17,277.17	25,846.42	1.064	40.06

**Fig. 1.3.** Diagram of each way type and length total of road traffic situation in the MRD (Vietnam road traffic general directorate, 2013).

1.1.3. Geotechnical problems in Mekong Delta (MD)

In the past to present many geotechnical problems have been happening for bridges and roads in the MD and Hochiminh City. They can be divided into two general cases: (1) excessive settlements, e.s., uneven settlements between approach and bridge abutment, (2) failures of geotechnical structures constructed on soft soils such as:

(1) The collapse of two viaduct spans of the Cantho Bridge construction site in the MD on Sep. 26th, 2007 is the most serious in the construction of bridges and roads in Vietnam (Fig. 1.4 and 1.5a). The parameters of the two damaged viaduct spans are 80 m in length, 24 m in width, and from 35 to 40 m in height (Fig. 1.5b). Sixty-four workers lost their lives and over 180 were injured in this collapse. And the collapse of the partially built bridge delayed its opening for 2 years. The result of an investigation about geotechnical engineering, construction, and structure during eight months after the collapse by Vietnamese Ministry of Construction and Japanese experts reported that the causes were an excessive and uneven settlement of temporary piles (Nguyen, H. Q., 2008). The excessive settlement was due to the insufficient length of the pile. The length was designed based on the soil data at the bore hole a little far from the site. From the reinvestigated soil data, the depth of the soft clay layer was found to be underestimated and the pile end did not reach the sand layer (Fig. 1.5c). For this reason, the weight of the floor-beam concentrated on the T13 and T14, special T13; and the equilibrium was lost and collapsed (Fig. 1.5b). The strange changes in geotechnical properties of layers in small distance that the principles of geotechnical engineering investigation of the AASHTO standard couldn't realize them. What is the root cause of the strange changes in geotechnical properties?



Fig. 1.4. Location of collapsed viaduct spans at Cantho Bridge construction site on Sep. 26, 2007.

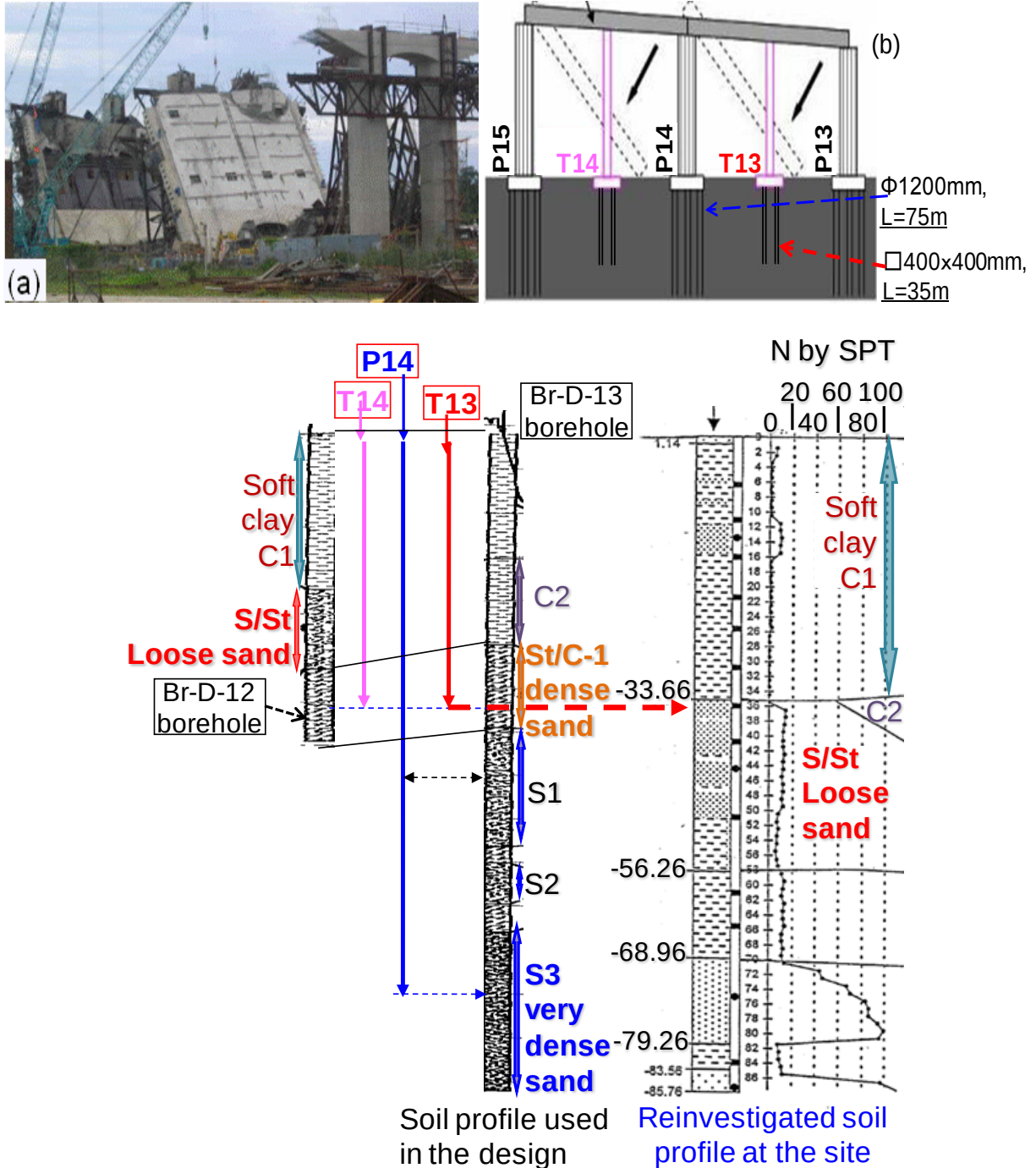


Fig. 1.5. (a) Two collapsed viaduct spans. (b) Supports of 2 viaduct spans, permanent piers (P13, P14, & P15) & temporary supports (T13, T14). (c) Soil profiles at the site.

(2) The settlements of approaches with large values are common in the MD; and then, excessive and uneven settlements between the approaches and spans supported by piles happened (Fig. 1.6a). The settlements and collapses of the approaches of the bridges also occur in Hochiminh City, Vietnam. The approach of the Vanthanh Bridge in district 1 Hochiminh city

Vietnam happened in 2002; simultaneously, they also made the houses along it settle and damage (Fig. 1.6b).

We consider a contiguous zone between bridge and embankment in building stage in Dongthap province MD (Fig. 1.8). And an immoderate plate is between the bridge and road (Fig.1.9). One head of immoderate plate is put on the abutment propped by piles and the other is put on the beam propped by the embankment. In the operating process, one head of immoderate plate will settle according to the abutment and the other will settle according to the embankment. As a result, two uneven points at two heads of immoderate plate will form and develop (Fig. 1.7a and 1.9). When the settlement of approach significantly increases, then two uneven points at two heads of immoderate plate will be very different (Fig. 1.7a and 1.9). Briaud, J. L. (1997) suggested that if a slope (S/L with S : settlement value and L : length unit) overcomes $1/200$ (Fig. 1.10), then it will bring about danger for transport and humans or further lead a damage of the structure. For an example, the approach and immoderate plate of the bridge in district 8 Hochiminh City suddenly settled and completely damaged in 2000 (Fig. 1.7b).



Fig. 1.6 . (a) Settlement of approach of bridge in Dongthap MRD; (b) Settlement of approach of Vanthanh Bridge made house be declinational and damaged in district 1 Hochiminh city.



Fig. 1.7. (a) Even settlement at two heads of immoderate plate of Vanthanh Bridge in district 1 (b) Approach and immoderate plate of bridge in district 8 Hochiminh City suddenly collapsed and completely damaged.



Fig. 1.8. Contiguous zone of bridge propped by piles and embankment building in Dongthap province MD.

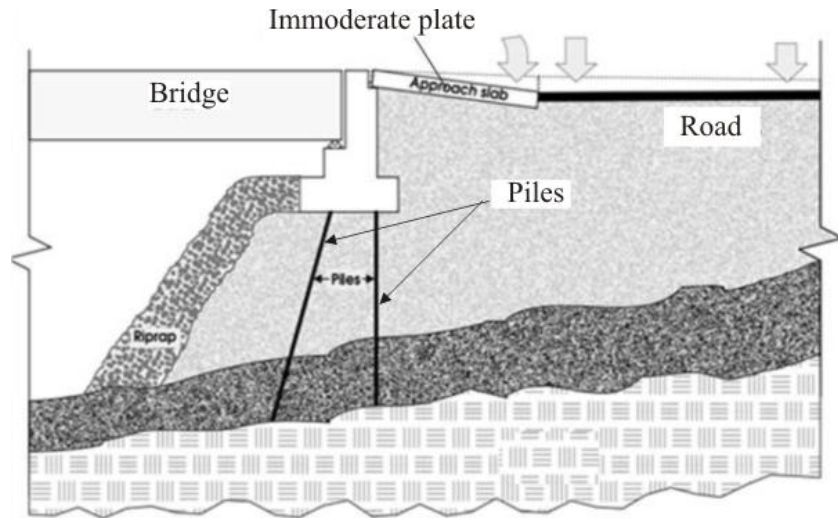


Fig. 1.9. Diagram of operating process of immoderate structure.

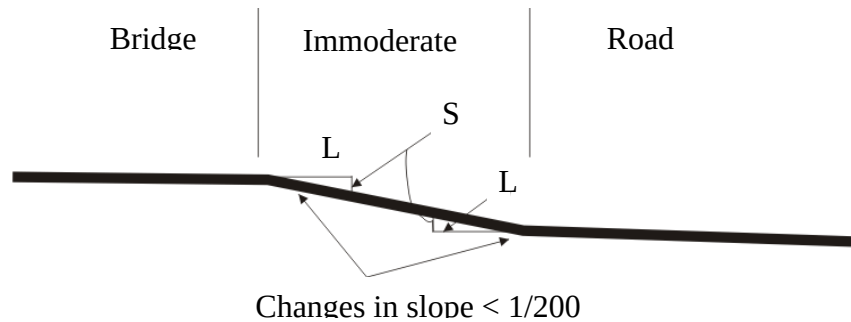


Fig. 1.10. Limit of even settlement according to horizontal (Briaud, J. L., 1997).

1.1.4. Problem of geotechnical properties in Mekong Delta

There are many researches about the specific geotechnical problems of Vietnam in general and MD in particular. Consolidation properties of sediments of the MD reported in the geotechnical investigations. Man (2003) reported the overconsolidation ratio (OCR) decrease with depth of some soil stratigraphies at many places in the MD (Fig. 1.11.1); OCR are mostly less than one from 12 downward to 40 m in depth in the results of soil investigation from Vietnamese companies (Fig. 1.11.2). The low sample quality was a cause of the strange mechanical properties suggested by Man (2003).

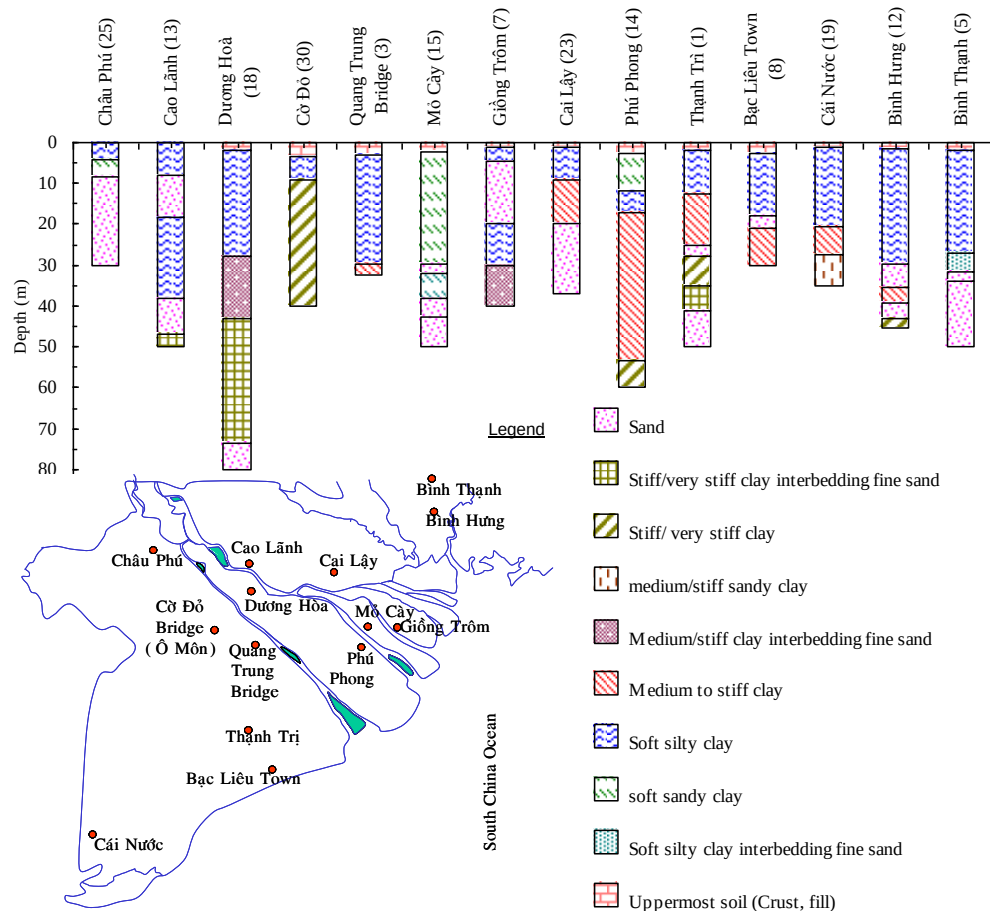


Fig. 1.11.1. Soil stratigraphy of some boreholes in Mekong delta (Man, 2003).

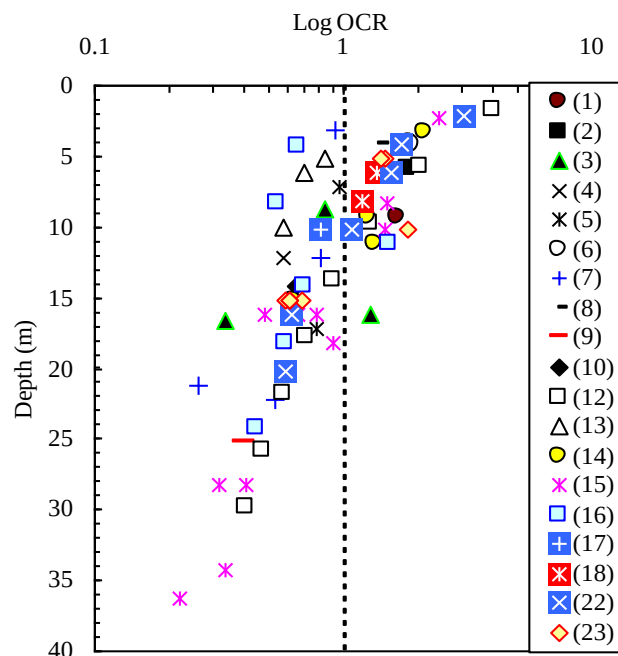


Fig. 1.11.2. Overconsolidation ratios versus depth (Man, 2003).

In contrast, Nguyen and Giao (2005) found at Camau province (Fig. 1.1) upper clay layer from the surface to about 17 m in depth was normally consolidated (very soft to soft clay) with the grayish black, organic, but, and then completely shift to overconsolidated claylayer (hard clay) in the lower part from 17 downward to 60 m in depth with the grayish blue, yellow, brownish red. Their values of OCR from one borehole at the Camau site calculated by different methods are shown in Fig. 1.12.1. He indicated the strange characteristics of the e-logp curves from one borehole at the Camau site. Namely, the e-logp curves on the samples from the first soft clay layer the change of void ratio is significant and the breakdown points could be observed quite well (Fig. 1.12.2a). In contrast, those of the samples from the second hard clay the curves are more rounded and the breakdown points could not be identified well (Fig. 1.12.2b).

Nguyen and Giao (2005) also reviewed ten methods to determine preconsolidation pressure; and fell into three groups including void ratio-applied stresses, constrained modulus-applied stresses, and strain energy-applied stress relationship on the clay samples at the Camau site. But, the results determined from these ten methods could not indicate clear causes about strange changes.

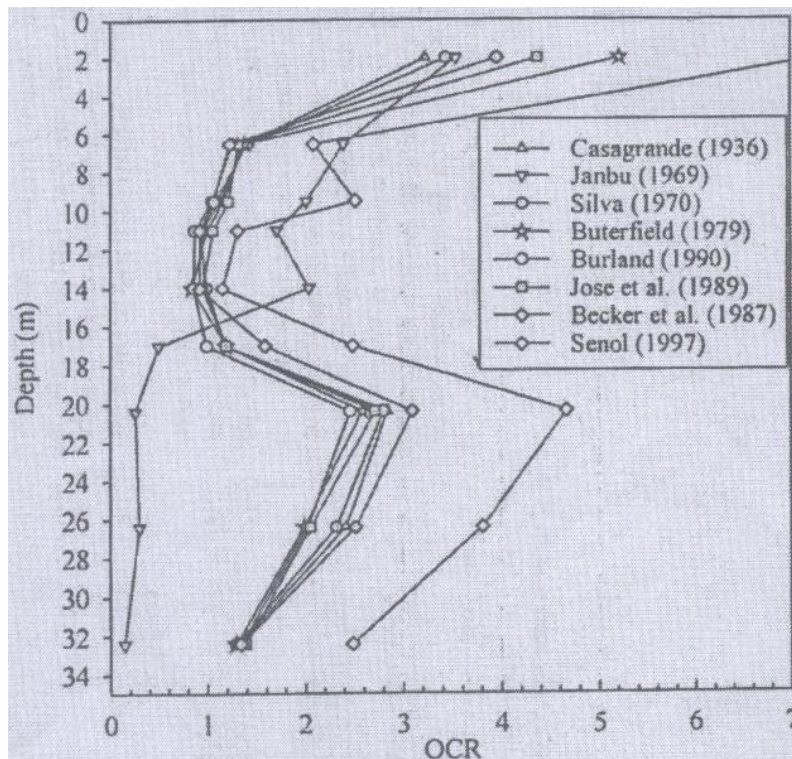


Fig. 1.12.1. Values of OCR from one borehole at the Camau site calculated by different methods versus depth (Nguyen and Giao, 2005).

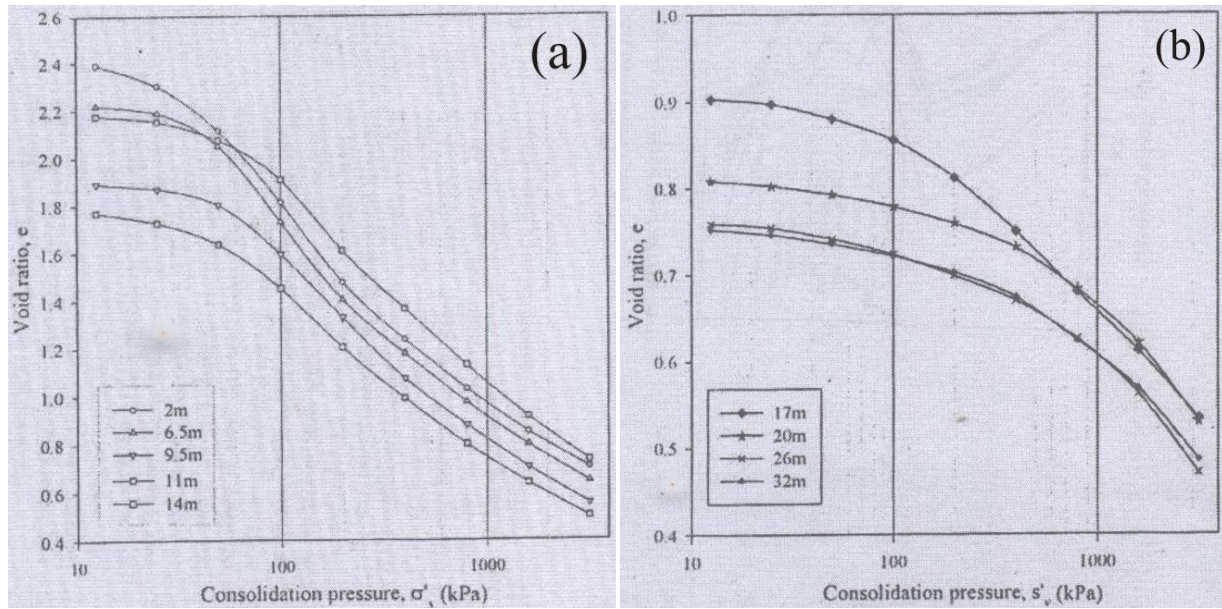


Fig. 1.12.2. (a) The e-logp curves on the samples from the first soft clay layer and **(b)** Those on the samples from the second hard clay at the Camau site (Nguyen and Giao, 2005).

Takemura et al. (2007) researched characterization of soft clay in Cantho city of the MRD sediments, Tanan-Longan city of the Saigon River sediments, and Haiphong City in the Red River and MRD deltas sediments of Vietnam (Fig. 1.1). From their researches recommended using the thin-walled tube sampler with fixed piston for the high quality samples rather than Shelby open sampler which is commonly used in Vietnam. He studied on these high quality samples and indicated the level of microstructure-development of the Cantho clay being very high based on the results of the constant rate of strain consolidation tests (CRS), despite very recent deposition about 6,000 BP. Namely, the C_{C1}/C_{C2} ratios were so large, more than 6 (C_{C1} is the maximum compression index and C_{C2} is the compression index at consolidation stress $\sigma'_v = 1,000 \text{ kPa}$) and the OCR ratios were more than 1 as show in Fig. 1.13.1 (Takemura et al., 2007). Simultaneously, using the yield stresses, P'_y , yield stress ratios, OCR, obtained from the CRS, which is reliable and always more than those from the oedometer test, the better quality of the samples obtained from Japanese fixed piston type thin wall (JFP) sampler were shown in Figs. 1.13.1c and 1.13.1d.

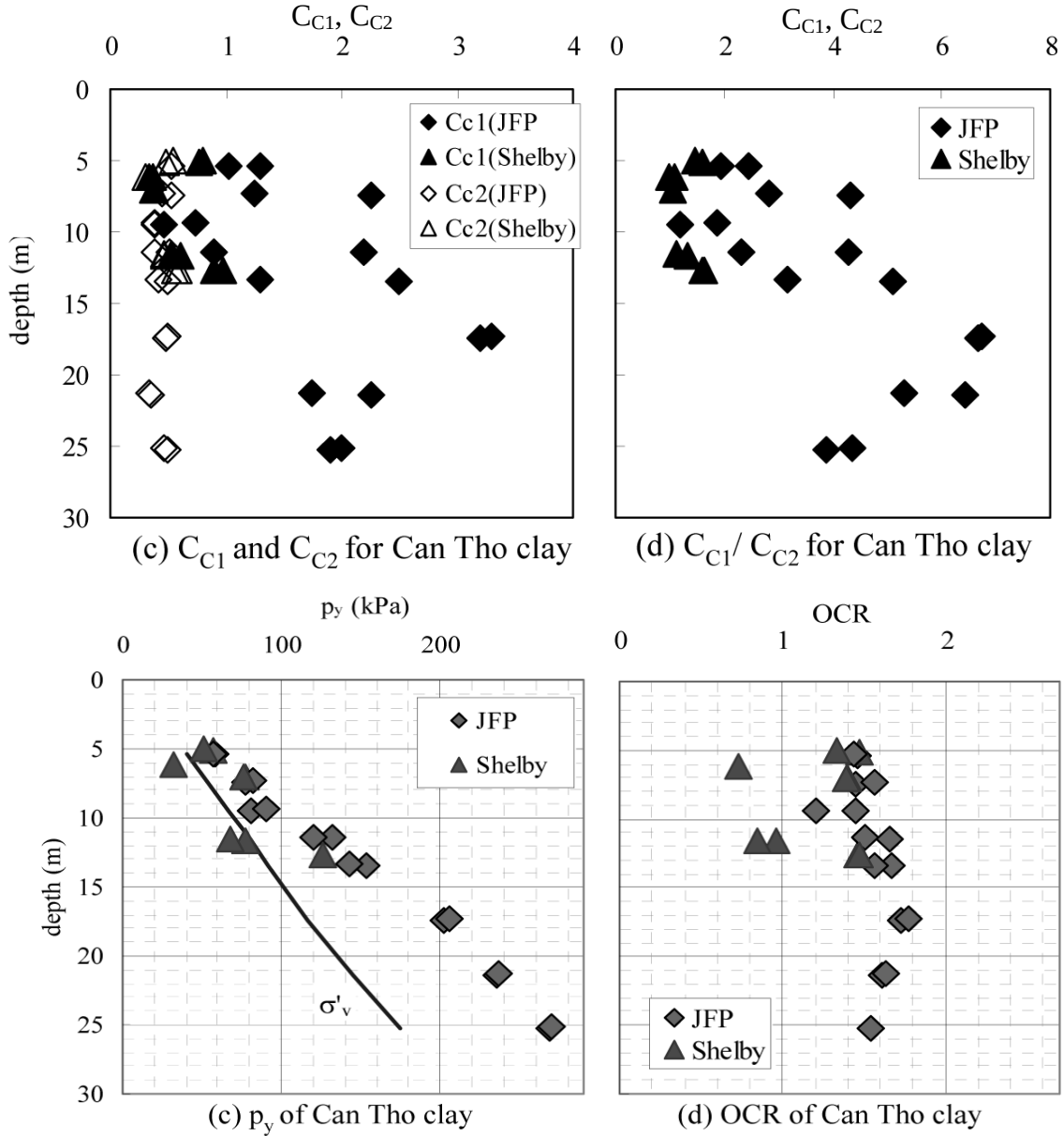


Fig. 1.13.1. Values of C_{C1} , C_{C2} , C_{C1}/C_{C2} , p'_y , and OCR from the CRS with depth for JFP and Shelby samples on the Cantho clay by Takemura et al. (2007).

Takemura et al. (2007) also found the unique relation between $p'_y/p'_{y-JFP \& CRS}$ and $\Delta e/e_0$, where, $\Delta e/e_0$, is an indicator for evaluating sample quality (Lunne et al., 1997) ($p'_{y-JFP \& CRS}$ is yield stress from CRS and sampling with Japanese type thin-walled tube sampler with fixed piston; p'_y is yield stress from the other oedometer tests and sampling; Δe is void ratio decrease due to the recompression to the overburden effective stress, σ'_{vo} ; e_0 is initial void ratio). Fig. 1.13.2 shows the relation between $p'_y/p'_{y-JFP \& CRS}$ and $\Delta e/e_0$ on the Haiphong clay was found out by Takemura et al. (2003).

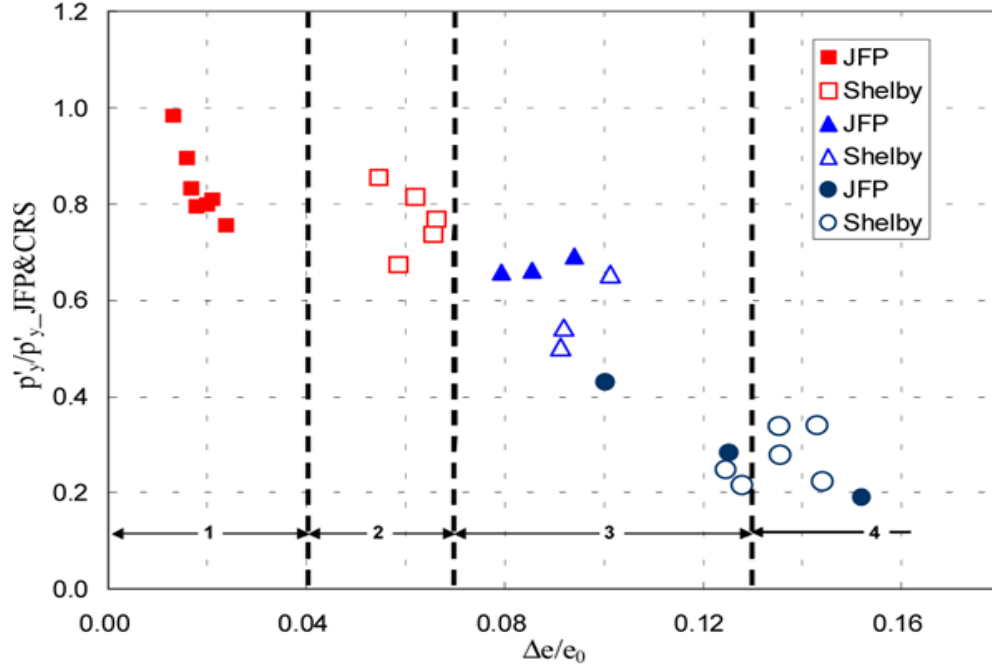


Fig. 1.13.2. Relationship between $\Delta e/e_0$ and $p'_y/p'_{y-JFP \& CRS}$ with the criteria on sample quality of soft clay OCR less than 2 by Lunne et al. (1997) was found out by Takemura et al. (2007).

The distribution of construction-materials of sediments in the MRD based on grain size and Atterberg limit from the ground surface to 10 m depth was studied Dornbusch et al. (1969).

Several studies have been conducted on normally consolidated natural argillaceous sediments deposited during the post-glacial period in the deltas at many places in the world. Burland (1990) was proposed a method of describing the level of structure of the natural clay in the deltas by using the sedimentation compression line (SCL) and the intrinsic compression line (ICL). The micro- and macro-structures of the natural soils cause them to differ from reconstituted soils in a number of important ways (Truong et al., 2011). Mitchell (1976) suggested that the “structure” includes the combination between the “fabric” (arrangement of particles) and the interparticle “bonding”. Burland (1990) reported that the difference between British post-glacial clays present at Shellhaven (Skempton and Henkel, 1953) and Gosport (Skempton, 1970) based on these studying sedimentation compression curves. He also showed that the structures of the late Pleistocene-Holocene sediments in delta depend on both the depositional conditions and post-depositional processes. The ageing process has a very important role for developing the micro-fabric of clay increasing the resistance to the compression and the resistance does not depend on the volume reduction due to creep Burland (1990) indicated that. He also suggested that the ratio of the intrinsic swelling index (C_s^*) to the undisturbed swelling index (C_s) C_s^*/C_s could be a

sensitive indicator of fabric and interparticle bonding in the natural soils. Maslov (1987) suggested that the consolidated cohesion, c_c , and viscid cohesion, Σ_w could be used for evaluating the shearing resistance of the cohesive soils. Wu (1958) also found that the sedimentary materials and post-depositional processes affected the geotechnical properties of sediments. Lunne et al. (1997) proposed simple formula (1.1) for estimating OCR from CPTU results with values of k being from 0.2 to 0.5. However, it should be noted that a small change of values of k will give arelatively large change of OCR. But for the young sediments, OCRs commonly change small. How to get OCRs in truth is difficult.

$$OCR = k \cdot \left(\frac{q_t - \sigma_{vo}}{\sigma_{vo}} \right) \quad (1.1)$$

Paul (2005) reviewed the Engineering Geology of St. Bernard Parish, Louisiana, in Mississippi River and in Bayou La Loutre and reported about appearance of natural levee and delta plain, and soil classification based on the Atterberg limit.

1.2. Motivation of the research

Since the 1950s, the MRD and the other deltas in the world have been studied by many researchers in many respects such as the geotechnical engineering, engineering geology, sedimentology, general geology, geomorphology, and tectonics; whose results give important background, ideas, and data for research.

Although the MRD late Pleistocene-Holocene sediments are one sequence and have accumulated during the post-glacial period. But this sedimentary sequence consists of several sedimentary facies, especially in the center of sunken basin, each sedimentary facies of which was formed in a different sedimentary environment and has typical sedimentary structures and materials. Given the importance of sedimentary environments on the properties of individual facies, each sedimentary facies would perhaps be expected to possess unique geotechnical properties. However, with respect to the MRD, no research has been conducted to confirm this matter. The consolidation governs the strength and strain of soil ground. For construction, the geotechnical characteristics of the soft ground are important. For example, the consolidation settlements of the soft clay layers often are large, may create problems in building. In overall plans, traffic system is the most important infrastructure for the development projects in MRD. Above all, the consolidation parameters are used in calculations for the consolidation settlement;

to contribute to decide to choose the best solution in the soft ground improvement. But, the characteristics of consolidation of the late Pleistocene-Holocene sediments in the MRD are still not clearly understood. Maybe there are different causes with the low sample quality that lead the values of OCR decrease with depth, less than one, and the strange shift. So there are several questions on these issues, such as different consolidation-levels that deep cause may be differences in sedimentary condition and mechanism of consolidation progress for the late Pleistocene-Holocene sediments. How are variations of geotechnical/consolidation properties and soil structures on both a large and small scales? What is clear consolidation characteristic? What are causes of change of OCR profile? How to estimate the OCRs is also a matter for the specific conditions of MRD. Geological history or poor geotechnical investigation practice may be a possible reason.

Therefore, a study of “Influence of sedimentary environment on geotechnical properties and consolidation characteristics of Mekong Delta late Pleistocene-Holocene sediments” was conducted.

1.3. Objectives of the research

The aims of the research are as follows:

1. Influences of sedimentary environments & conditions on geotechnical properties of the sediment facies in the MD.
2. Critical factors influence consolidation properties of the MD late Pleistocene Holocene sediments such as:

- . Levels of microstructure development,
- . Variation of soil on both large & small scales,

And then, to infer:

- . A rational investigation procedure including
 - >> Clear geotechnical profile,
 - >> How to obtain reasonable values of OCR,
- . Finally, precise geological structure model for the Mekong Delta which can contribute safe and economic infrastructure constructions.

CHAPTER 2

SEDIMENTARY GEOLOGY OF MEKONG RIVER DELTA

2.1. General geological structure of MRD

General geological stratum of the MRD is shown in Fig. 2.1. According to the geological and mineral resources map of the MRD with a scale of 1:200,000 (Tran, et al., 1995) and Vietnamese General Directorate of Geology (Nguyen and Tran, 2002), the geological structures of the MRD are in form of sunken basin, the center of the sunken basin is a region between the Mekong River and Bassac River with a rock basement 900 m in depth. And two uplift-wings are the northern region of the Mekong River and the southern region of the Bassac River. The Mekong River and Bassac River are locations of faults (Tran, 1993, and Nguyen, et al., 2000). The rock basement with more than 65 million yr BP exposes in Hatien and Angiang (Fig. 2.2) (Nguyen, et al., 2002). The rock basement is covered by the Neogene sediment to the late Pleistocene basement coastal to fluvial sediments with the age of greater than 43,400 yr BP; and the top sediment layer includes the latest Pleistocene-Holocene incised-valley-fill sediments and deltaic sediments with their age of 15,000-0 yr BP (Ta, et al., 2002b). In the following sections, geological history and sedimentary environments which have formed the latest Pleistocene-Holocene sediments are explained.

2.2. Geological history in the formation of Mekong Delta latest Pleistocene-Holocene sediments

2.2.1. Changes in sea-level and stages of development of Mekong Delta

The last glacial lowest sea level was approximately -120 m in Southeast Asia at around 18,000-20,000 ^{14}C yr BP from the curve, B, by Hanebuth et al. (2000) (Fig. 2.3). In the MRD, the sea-level curve, A, for the last 15 ka, the lowest was around -70 m by Nguyen et al. (2000). And then, the sea level rose rapidly and continuously; the highest sea level was approximately

+4.5 m above a.p.s.l about 6,000– 5,000yr BP (Fig. 2.3). The MRD was entirely in the marine environment excepting some upland in the north and western parts as islands (Fig. 2.4a). Evidence that we can see is the vestiges of wave-erosion on the limestone cliffs in Hatien (Fig. 2.5). Subsequently the sea level went gradually down to around 0.0 m as the present sea level. The coastlines were found in each stage of the marine regression such as about 4,500 and 4,000– 3,000yr BP shown in Figs 2.4b-c (Nguyen et al., 2000).

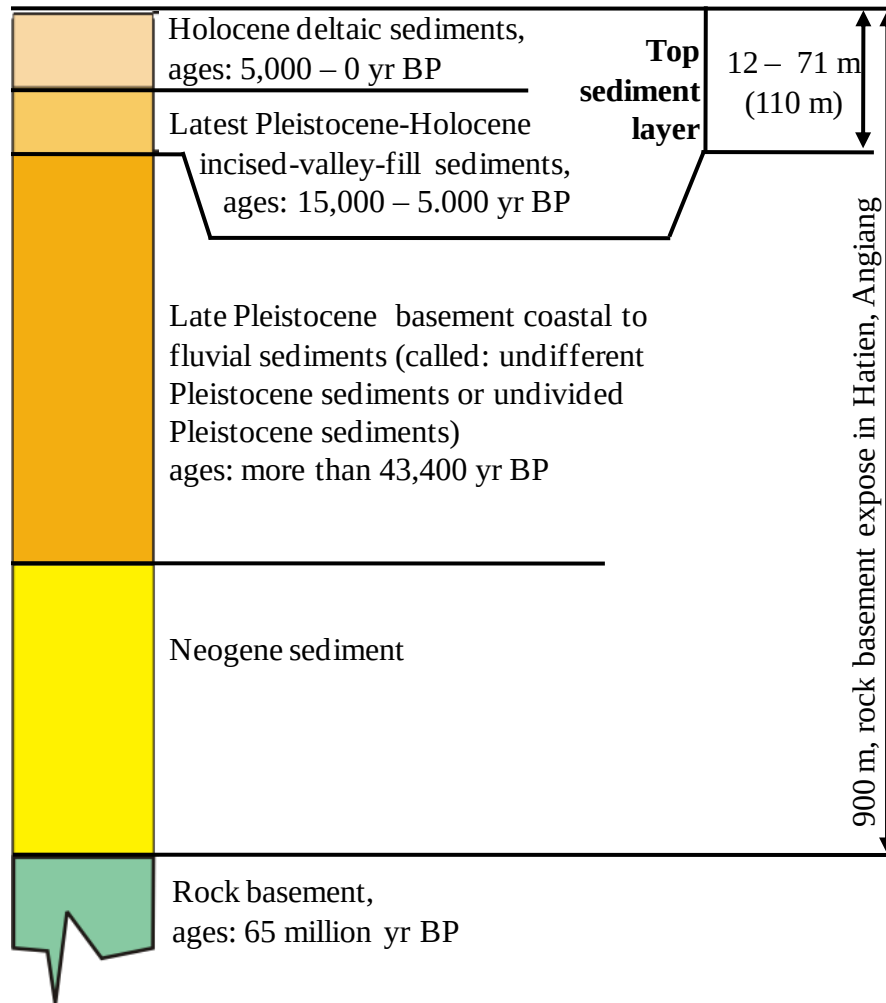


Fig. 2.1. Diagram of general geological stratum of the MRD.

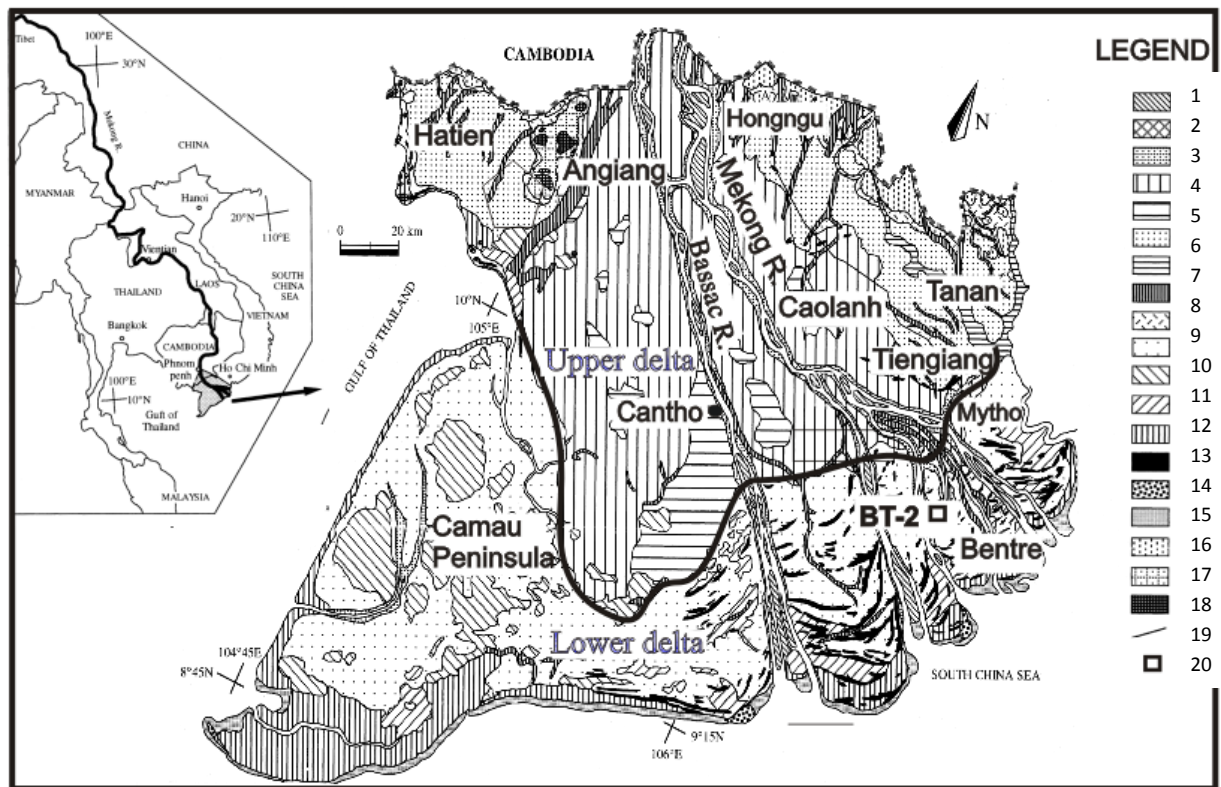


Fig. 2.2. Environmental sedimentary map of the Mekong River Delta (Nguyen et al., 2000) and location of the BT2 core site (Ta et al., 2001, 2002a): 1. Channel bar, 2. Point bar, 3. Bank, 4. Flood basin, 5. Back swamp, 6. Swamp, 7. Flood plain, 8. Abandoned channel, 9. Alluvial apron, 10. Coastal plain, 11. Marsh, 12. Salt marsh, 13. Mangrove marsh, 14. Relict beach ridge or sand dune, 15. Sand spit, 16. Tidal flat, 17. Undivided deposits of late Pleistocene age, 18. Weathered land, 19. Basement rock, 20. Line of profile, 21. Site core.

The Holocene delta evolution and depositional models of the MRD proposed by Ta et al. (2005) represent such as: That the late Pleistocene-Holocene sediment-strata of the MRD region include the late Pleistocene basement coastal to fluvial sediments (or called undifferentiated Pleistocene sediments or undivided Pleistocene sediments), the overlying latest Pleistocene-Holocene incised-valley-fill sediments, and deltaic sediments of the Mekong River Formation. The formation consists of transgressive and regressive facies successions, and involves three stages of development:

(1) The erosional stage about the time of the last glacial maximum (LGM), when the valleys were incised and the interfluvies were subaerially exposed.

- (2) The transgressive incised-valley-filling stage from the LGM to the early Holocene.
- (3) The regressive delta-development stage was from the early Holocene to the present.

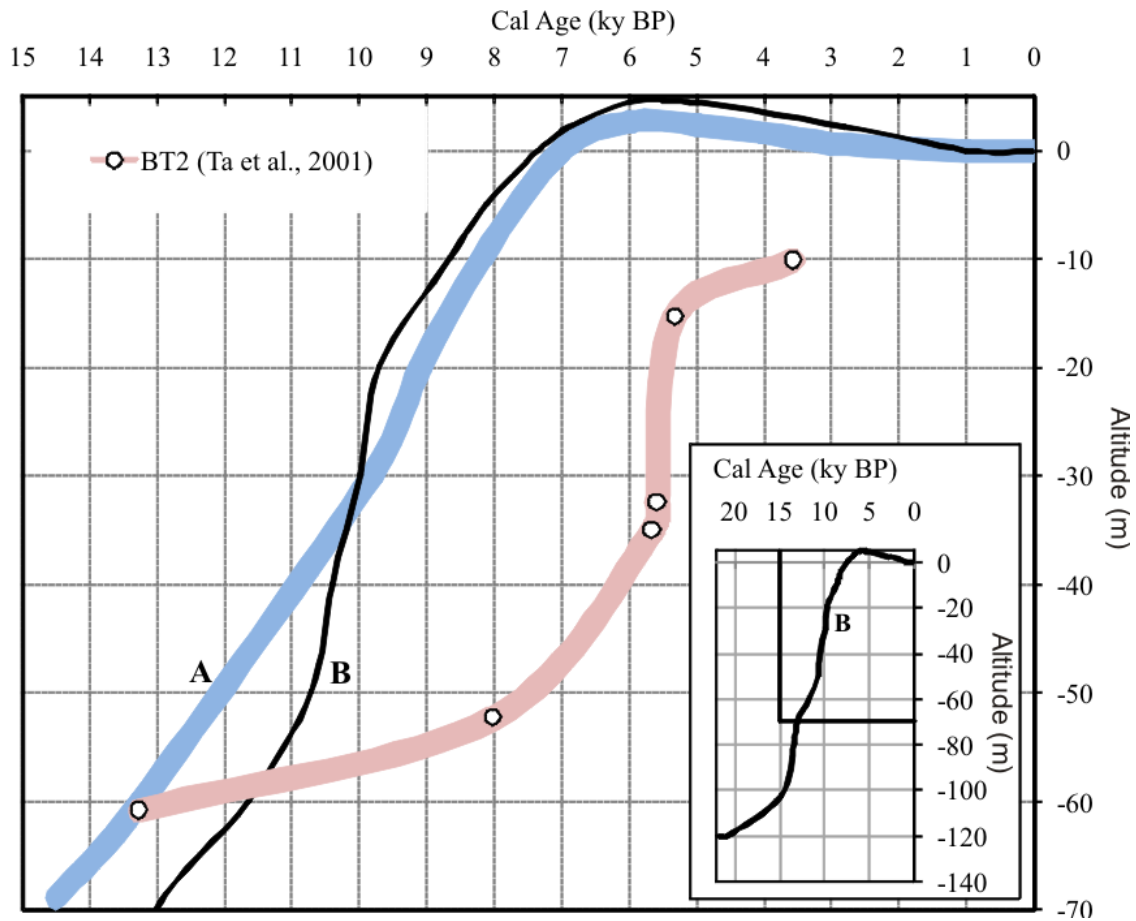


Fig. 2.3. Age-depth curves at the BT2 core site (Ta et al., 2002a) and sea level curves: (A) sea-level curve for the last 15 kyrs of MRD (Nguyen et al., 2000); (B) sea-level curve for the last 20 kyrs of the Sunda Shelf (Hanebuth et al., 2000).

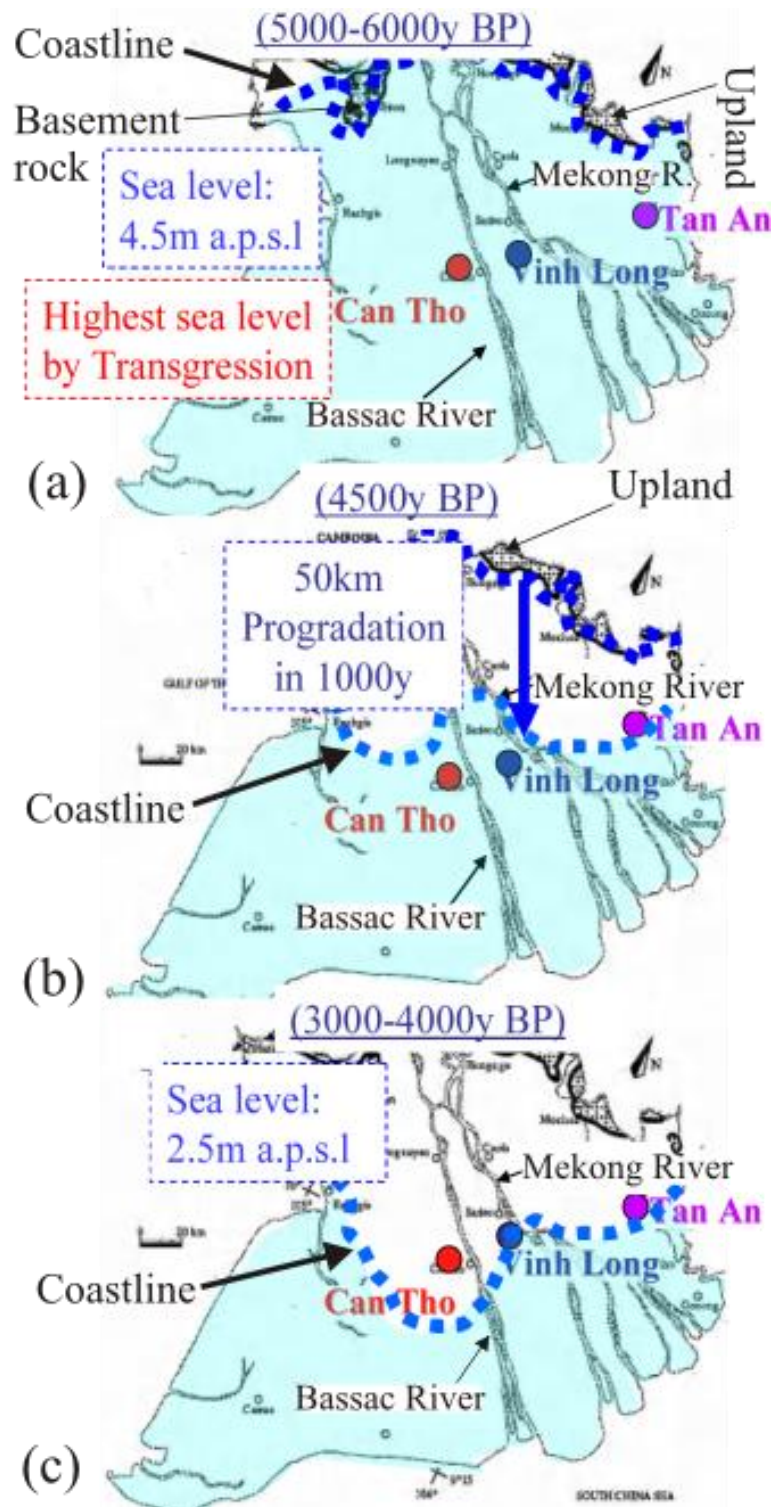


Fig. 2.4. Progradation of Mekong Delta (Nguyen et al., 2000).



Fig. 2.5. Vestiges of wave-erosion on limestone cliffs at $z = +3.3\text{m}$ and $+4.5\text{m}$ in Hatien, MRD.

2.2.2. Late Pleistocene-Holocene sediments

To coincide with those rise and reduction of sea levels, the highly sedimentary discharge and stableness allow the formation of the latest Pleistocene-Holocene sedimentary facies. The altitude of the Mekong Delta continuously increased during the late Pleistocene-Holocene period.

The topography of undifferentiated Pleistocene sediment surface at about the time of the LGM varies very large throughout the MRD. A topography unevenness of the incised valleys and subaerially exposed interfluvies was very large. Therefore, the thicknesses of the top sediment layer complexly vary in the MRD. In general, the thicknesses of the top sediment layer gradually decrease in the two directions of each uplift-wing. According to the results of Ta et al. (2005) in the center of sunken basin between the Mekong River and Bassac River, the thicknesses of the top sediment layers largely varied from 12 to 71 m; and the largest one can obtain 110 m according to Vietnamese General Directorate of Geology (Nguyen and Tran, 2002). In addition, an incised valley zone is in the center of sunken basin identified by Nguyen et al. (2010) in Fig. 2.6. All indicate that the late Pleistocene-Holocene sediments in the center of sunken basin between the Mekong River and Bassac River are very complex.

The late Pleistocene basement coastal to fluvial sediments with the age over 43,400 yr BP are undivided/undifferentiated Pleistocene sediments (Ta et al., 2002a, 2002b). The top sediment layer with the age of 15,000-0 yr BP is the late Pleistocene-Holocene sediments (Ta, et al.,

2002b). The late Pleistocene-Holocene sediments unconformably overlay the undifferentiated Pleistocene sediments. The characteristics of the undifferentiated Pleistocene sediments are very different to those of the top sediment layer such as stiff to hard, slightly oxidized, yellowish gray silty sand and fine-medium sand bearing scattered quartz pebbles 0.5-1 cm in diameter, and laterite. These characteristics are signs that help us to define the boundary between the undifferentiated Pleistocene and late Pleistocene-Holocene sediments during the sampling and in situ tests.

During the transgressive and regressive marine periods, the landforms, sedimentary structures, thickness and material composition of sedimentary facies in the late Pleistocene-Holocene deltaic sediments have undergone complex changes (Ta et al., 2002a, 2002b and Umitsu et al., 2003). And the late Pleistocene-Holocene deltaic sediments include the latest Pleistocene-Holocene incised-valley-fill sediments with the age of 15,000-5,000 yr BP and regressive deltaic sediments with the age of 5,000-0 yr BP (Ta, et al., 2002b).

The late Pleistocene-Holocene sedimentary environments and facies in the MRD were rebuilt by Ta, et al. (2001, 2002a, and 2002b) based on the fossil assemblages, sedimentary structure, grain sizes, and ages of the sediments. And then, the Holocene delta evolution and depositional models of the MRD proposed by Ta, et al. (2005).

Resulting in a typical sufficient late Pleistocene-Holocene stratum including eight sedimentary facies with thickness being 71 m was found at the BT2 core site in Bentre province in the lower delta plain and in the incised-valley zone (Figs. 2.2 and 2.6) (Ta et al., 2001).

But according to the association branch of Engineering Geology-Vietnam (1984), a general stratum of the MRD in the Pleistocene-Holocene period was displayed such as in ascending order: (1) the Pleistocene sediment, (2) lower Holocene sediment, (3) middle Holocene sediment, and (4) upper Holocene sediment which including 4 sublayers like very soft organic clay, very soft peat clay, very soft clay with alternation of silty sand seams, and clay.

The delta-development followed into a direction of the sea level fell down from the west to east shown in Figures 2.4b-c (Nguyen et al., 2000). Namely, the sedimentary facies like prodelta, delta front, sub- to intertidal flat will form from inner forward to sea; or the delta developed according to horizontal direction. A great flat plain of 62,520 km² has been created by the progradation of the delta during high stand and marine regression over the last 4550 yr BP (Nguyen et al., 2000).



Fig. 2.6. Location of incised-valley zone and map by Nguyen et al., 2010.

The soft ground-distribution map of the MRD with a scale of 1:500,000 displays five broad types of soft soil zone based on the characteristics of petrographic composition, natures of engineering geology and hydrogeology, and thickness of the sublayers (Nguyen and Tran, 2002). The origin and distribution of materials in the MRD can be generally reviewed on the environmental sedimentary map with a scale of 1:2,000,000 in Fig. 2.2 (Nguyen, et al., 2000) and sedimentary map with a scale of 1:250,000 (Tran, 1986).

In general, the Holocene sediment covered about 96% of the area of the delta (Tran, 1993). This late Pleistocene-Holocene sediments/top sediment layer is mostly subjected to a stress increase of foundation-construction.

2.3. Delta formation mechanisms and their characteristics in Mekong delta and other deltas

2.3.1. Delta formation mechanisms and their characteristics in Mekong delta

The area of the MRD was listed the large deltas in the world with 93,781 km² shown in Tab. 2.1 and Fig. 2.7 (Coleman and Wright, 1975).

The MRD was classed in term of tide influence (Fig. 2.8) with mean tidal range of 2-3 m and mean wave height around 100 cm (Fig. 2.9). And the basic environments and shape of the tide-dominated delta identified by Hori and Saito (2003) is shown in Fig. 2.10a. The components of the MRD based on morphology and sedimentary environment had a typical shape of the tide-dominated delta; the length of the delta front platform forward the South China Sea was long in Fig. 2.11b.

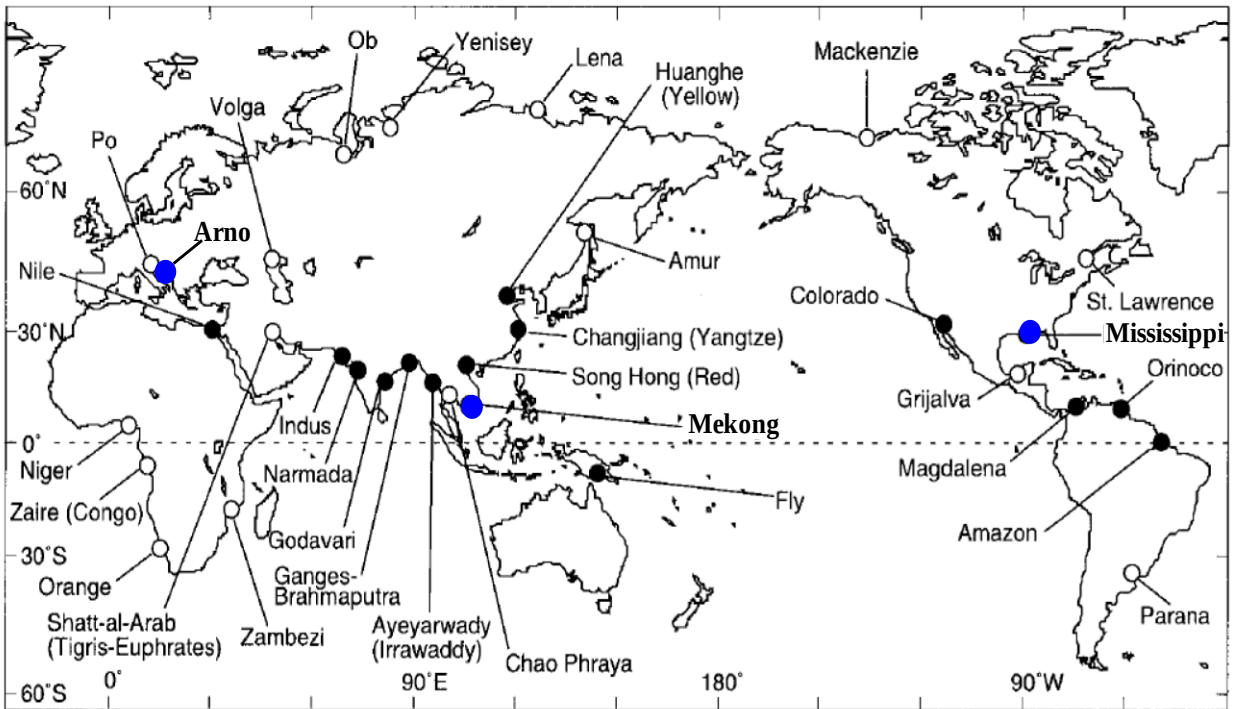


Fig. 2.7. Map showing the location of major deltas (Hori and Saito, 2003). After Hori and Saito (2003). The Arno Delta added into the map. Circles indicate deltas with area in Table 2.1.

Tab. 2.1. Delta areas of selected major river systems, suspended load, water discharge, drainage area. After Hori and Saito (2003). The Arno Delta added into the list.

	Delta area	Suspended load	Water discharge	Drainage area
River	(km ²)	(x10 ⁶ ton/y)	(x10 ⁴ m ³ /s)	(x 10 ⁶ km ²)
Amazon	467,078	1200	20.00	6.15
Ganges-Brahmaputra	105,641	1080	3.09	1.59
Mekong	93,781	160	1.49	0.55
Changjiang (Yangtze)	66,669	480	2.85	1.94
Lena	43,563		1.62	2.43
Huanghe (Yellow)	36,272	1080		
Indus	29,524	250		
Mississippi	28,568	400	1.80	3.34
Volga	27,224			1.35
Orinoco	20,642	150	3.49	
Arno*	450	7.5	0.20	0.0082

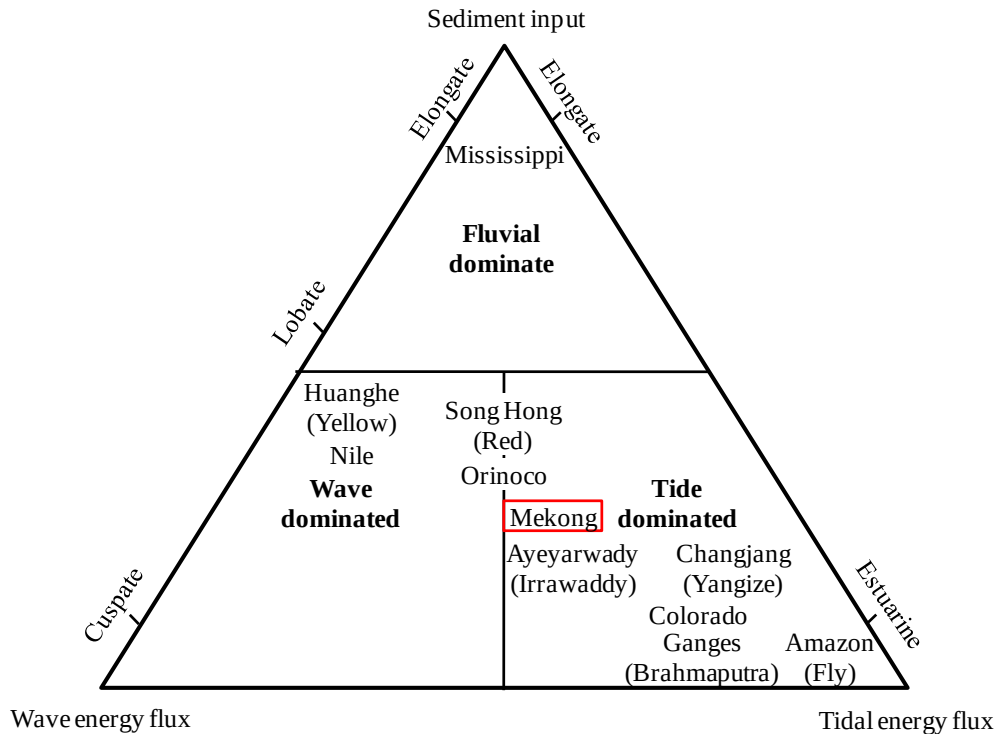


Fig. 2.8. A classification of deltas in terms of fluvial, wave and tide influence (Hori and Saito, 2003).

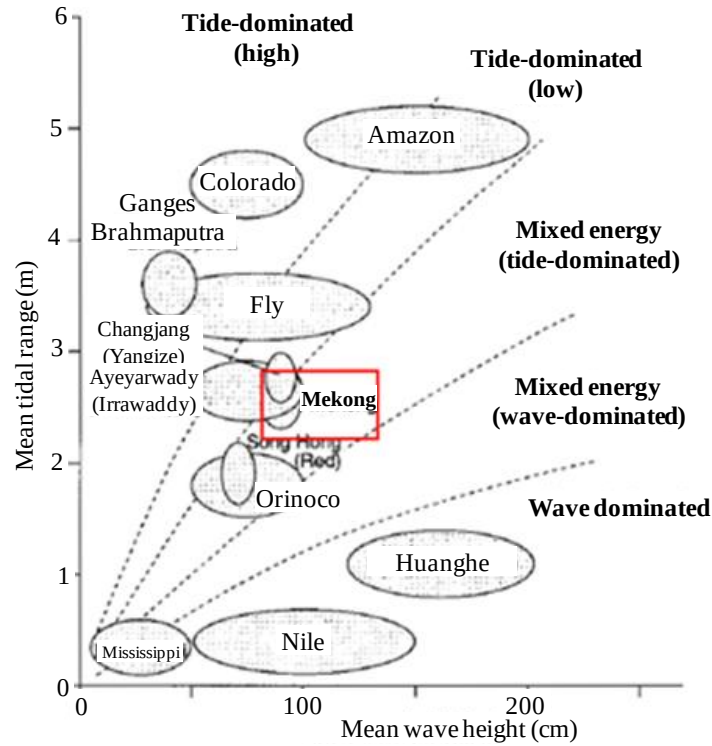


Fig. 2.9. Mean wave height versus mean tidal range for major large-river deltas (Hori and Saito, 2003).

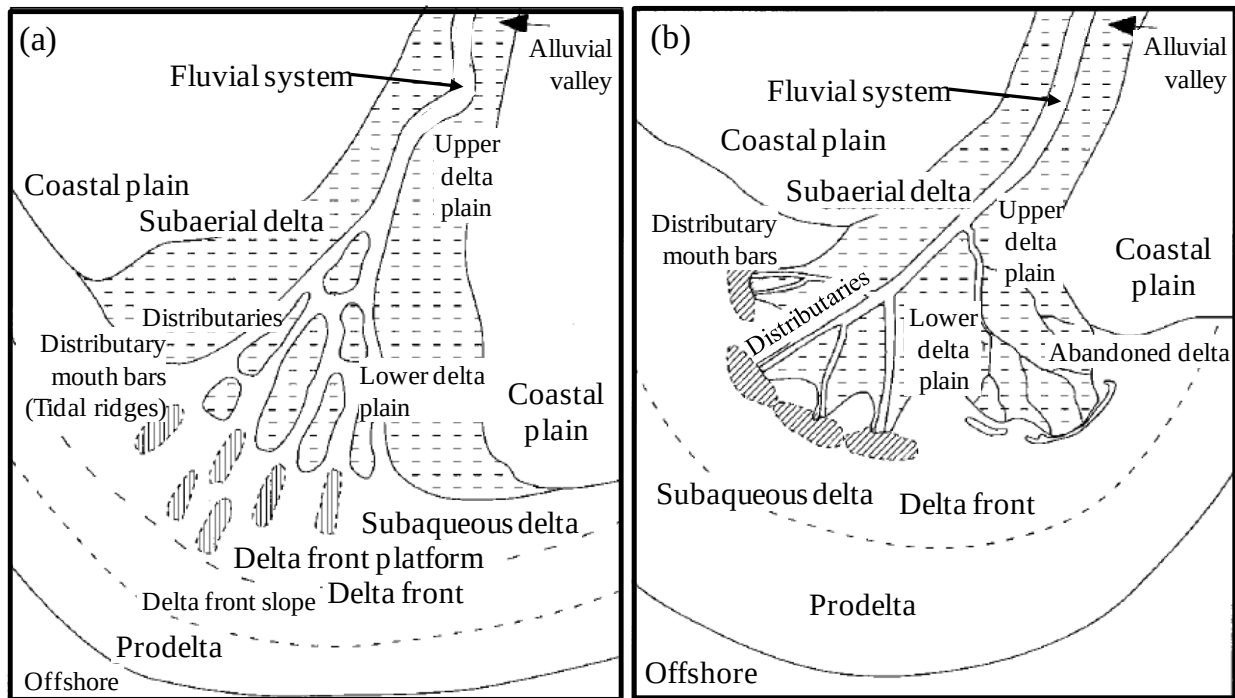


Fig. 2.10. Basic environments of deltas (Hori and Saito, 2003):
(a) Tide-dominated delta, (b) Fluvial-dominated delta.

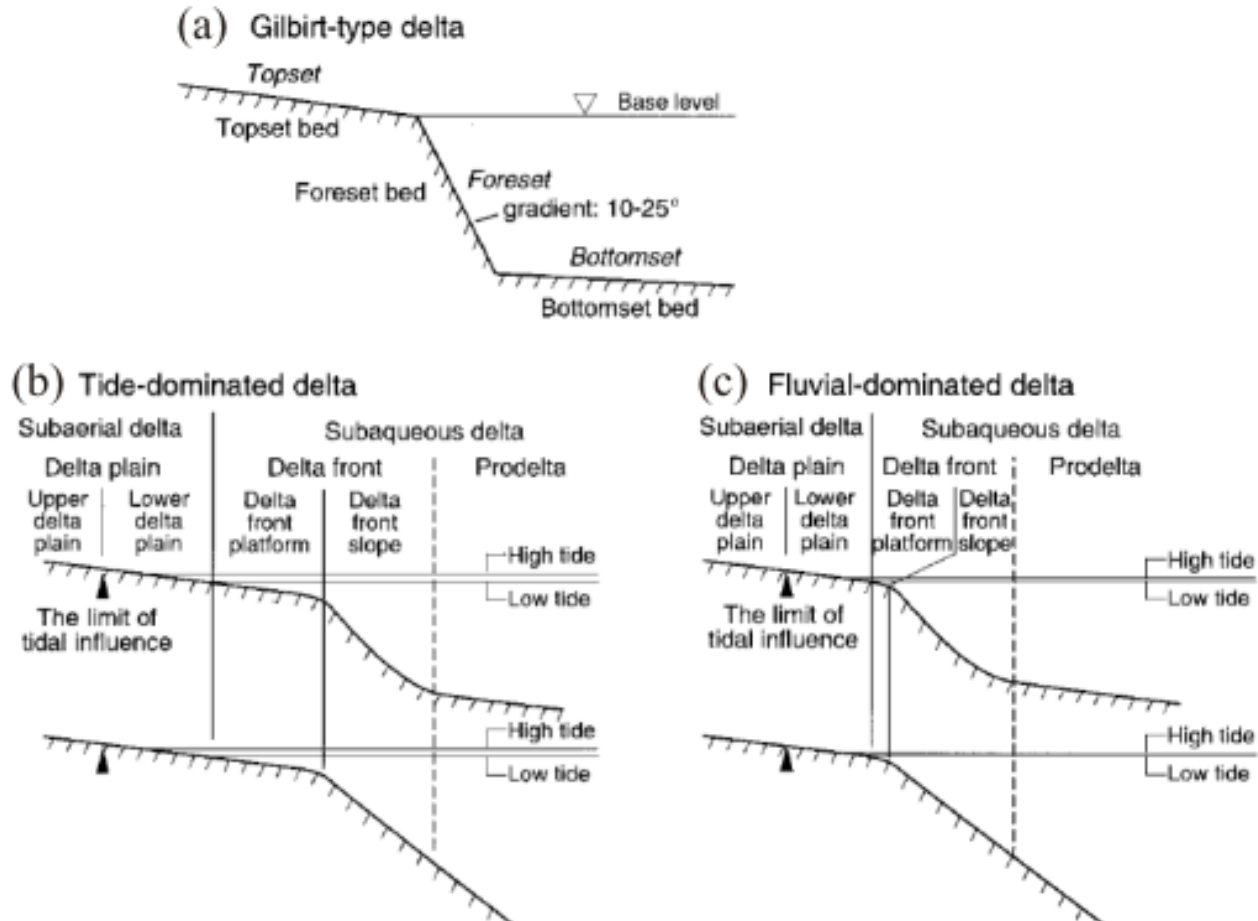


Fig. 2.11. Components of deltas based on morphology and sedimentary environment. (a) Gilbert-type delta, (b) Tide-dominated delta, (c) Fluvial-dominated delta (Hori and Saito, 2003).

The Holocene delta evolution and depositional model of the MRD proposed by Ta, et al. (2005) has two types of delta system including the tide-dominated delta and the tide- and wave-dominated delta (Fig. 2.12), with differences such as:

(1) The tide-dominated delta: During the sea-level high stand to slightly falling sea level, from 6,000 to 3,000 yr BP, the MRD was tide-dominated (Fig. 2.4c). That it is clearly displayed in both sedimentary facies and subaerial delta morphology (Ta, et al., 2005). The source was due to the river mouths of the delta were sheltered from the dominantly southwest ward-trending waves by the headland east of Ho Chi Minh City. Namely, in the front of the delta seaward the South China Sea was the bay during 6,000 to 3,000 yr BP (Ta, et al., 2005).

The characteristics of the tide-dominated delta are a coarsening-upward succession from open to inner bay to prodelta mud to delta front and subtidal flat (delta front platform) muddy sand,

which the fining-upward succession including the muddy subtidal to intertidal-flat facies covered them (Ta, et al., 2005). These characteristics of the tide-dominated delta were found at the zone in the upper delta and close to the boundary between the upper and lower delta. At around 3,000 yr BP the progradational delta obtained the upper delta of the MRD (Fig. 2.2). The coarsening-upward succession of the tide-dominated delta in the MRD by Ta, et al. (2005) is typical of a tide-dominated delta by Willis et al. (1999), Hori et al.(2001), and Hori et al.(2002c). And the fining-upward tidal-flat succession of the tide-dominated delta in the MRD by Ta, et al. (2005) is typical of a tide-dominated delta by Reineck and Singh (1980). Two models of schematic facies-succession for the tide-dominated delta and were suggested by Ta et al. (2002) in Fig. 2.13.

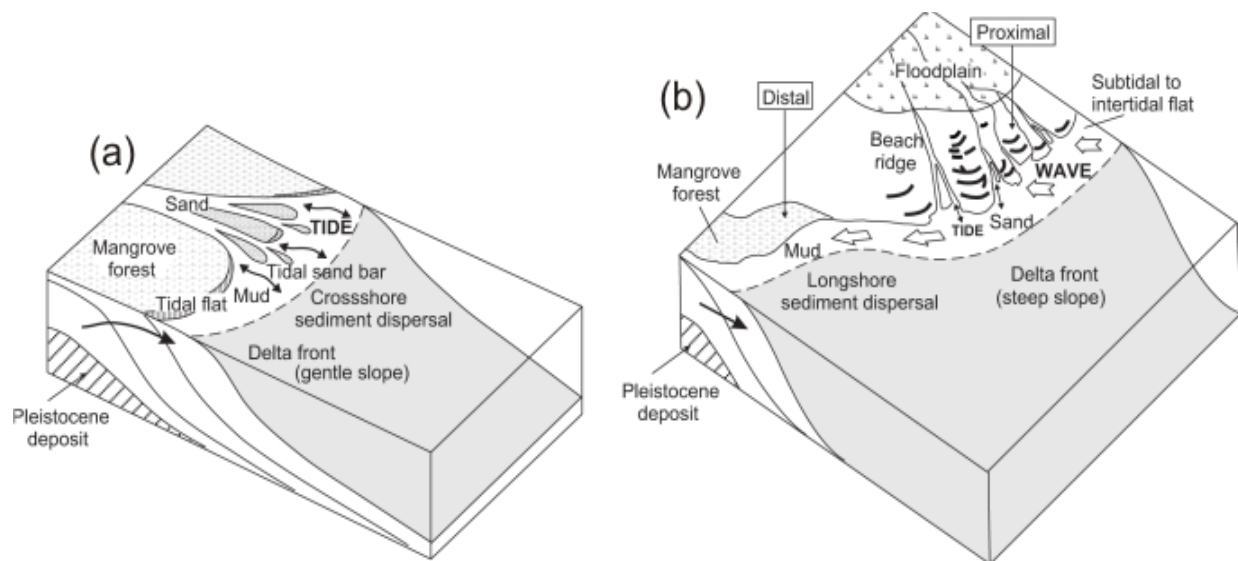


Fig. 2.12. Schematic depositional models of tide-dominated delta (a) and tide- and wave-dominated delta (b) (Ta et al, 2005).

(2) The tide- and wave-dominated delta: After 8,000 yr BP, the Holocene MRD began to form and evolved from a dominantly aggradational to a progradational delta. Actually, the progradational delta overcame further a tide-dominated delta; at after about 3,000 yr BP the progradational delta was a mixed tide- and wave-dominated delta (Ta, et al., 2005). This change occurred because the wave energy increasing when the delta prograded until it projected beyond the sheltered bay-like environment toward the South China Sea; where and at after 3,000 yr BP it directly faced the dominant monsoon waves. Simultaneously, the delta prograded seaward and projected past the headland east of Ho Chi Minh City during the last 3,000 yr BP, the

environment became much wave influenced, and the sediment facies and topography began to resemble those of the present delta (Ta, et al., 2002a and 2002b).

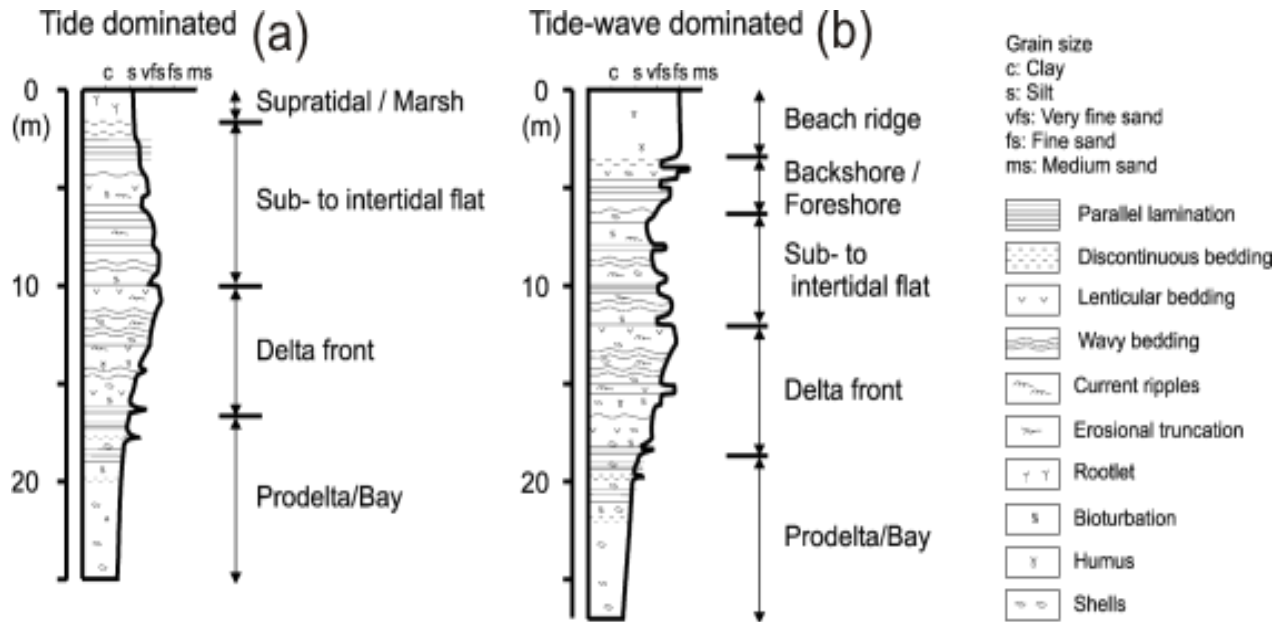


Fig. 2.13. Two models of schematic facies-succession for the tide-dominated delta (a) and tide- and wave-dominated delta (b) (Ta et al., 2002).

The characteristics of the tide- and wave-dominated delta in the lower delta of the MRD are coarser sediments and display a typical coarsening-upward succession from prodelta to delta front and to foreshore facies. The facies successions in the lower delta consists of coarsening-upward from the delta front slope to delta front platform, fining-upward sub- to tidal-flat, and coarsening-upward succession including foreshore-dune or fining-upward intertidal flat or salt marsh (Ta, et al., 2005).

The accumulation rates were relatively high in the tide-dominated delta in the upper delta of the MRD. And the progradation rates of the tide-dominated delta in the upper delta were higher than those of the tide- and wave-dominated delta in the lower delta of the MRD (Ta et al., 2005).

The characteristics of the tide-dominated delta and the tide- and wave-dominated delta from the sea-level highstand to present sea level, 8,000-0.0 yr BP, of the MRD are summarized in Table 2.2.

Tab. 2.2. Characteristics of the tide-dominated delta and the tide- and wave-dominated delta in MRD from the sea-level highstand to present sea level, 8,000-0.0 yr BP (Ta et al., 2005 and Nguyen et al., 2000).

Characteristic	Tide-dominated delta	Tide- and wave-dominated delta
Geomorphology	Inland delta plain	Beach-ridge delta plain
Formation time	Before 3,000 yr BP	After 3,000 yr BP
Progradation rate	Higher than	Lower than
Accumuration rate	Higher than	Lower than
Succession	(3) Fining succession of the muddy flood plain/marsh or flood and nature levee facies in the uppermost part (2) Fining-upward succession of the muddy subtidal to intertide-flat facies (1) Coarsening-upward succession from open to inner bay to prodelta mud to delta front and subtidal flat (delta front platform) muddy sand	(3) Coarsening-upward foreshore-dune succession or fining-upward intertidal flat or salt marsh in the uppermost part (2) Fining-upward succession: sub- to tidal-flat (1) Coarsening-upward succession: from prodelta to delta front
Grain size	Less than	Coarser than

2.3.2. Comparison with other deltas

After the last glacial maximum, the rapid and continuous increase and decrease in sea-level resulted in many deltas in the world have formed in the Late Quaternary e.g. Mississippi, Arno, and Mekong River Deltas (Fig. 2.7). And the late Pleistocene-Holocene sediment sequences have been formed in these deltas. The Arno delta is in the central region of Italy. The Mississippi delta is in the southeast of the America. Naturally, there are differences about the initial conditions and their mechanisms of formation.

In comparison with the Mississippi delta: The Mississippi delta was classed in term of fluvial influence (Fig. 2.8) with so small mean tidal range of 0.1-0.7 m and mean wave height of 0-50 cm (Fig. 2.9). And the basic environments and shape of the fluvial-dominated delta identified by Hori and Saito (2003) is shown in Fig. 2.10b. The components of the Mississippi Delta based on morphology and sedimentary environment also had a typical shape of the fluvial-dominated delta and are different with the MRD; the length of the delta front platform forward sea is shorter than those of the MRD in Fig. 2.11c (Hori and Saito, 2003).

In comparison with the Amazon delta: The Amazon delta was also classed in term of tide influence as the MRD but the MRD was influenced of the wave so greater than the Amazon (Fig. 2.8) (Hori and Saito, 2003). The Amazon delta with so large mean tidal range of 4.8-5.2 m and mean wave height of 110-210 cm (Fig. 2.9), and the basic environments and shape of the tidedominated delta identified by Hori and Saito (2003) is shown in Fig. 2.10a.

In comparison with the Arno delta: The Arno delta was classed in term of wave influence (Margherita, et al., 2007).

In general, the values of the mean wave height and mean tidal range such as: the MRD is medium; the Mississippi Delta is the lowest; and the Amazon Delta is the largest (Fig. 2.9) (Hori and Saito, 2003).

The late Pleistocene-Holocene sediment sequence of the MRD is compared with those of the Mississippi delta (Heinrich, 2005) and Arno delta (Giovanni et al., 2012). The transgressive incised-valley fill sediment succession including estuary and bay facies, and the regressive Holocene delta sediment succession including prodelta, delta front, sub- to intertidal flat/intertidal flat, flood plain/marsh, and natural levee facies were found in all three deltas. Up to this time, the marsh facies in the transgressive incised-valley fill sediment succession have not been found in the Mississippi delta (Heinrich, 2005), and Arnodelta (Giovanni et al., 2012).

The thickness of the MRD late Pleistocene-Holocene sediment sequence is the largest, and more sediment facies than in comparison with those of the Mississippi delta (Heinrich, 2005) and Arno delta (Giovanni et al., 2012). Cause isat source, the elevation of the MRD undifferentiated Pleistocene sediment-basement-surface during the post-Last Glacial Maximum was the deepest and. Namely, at the BT2 core site was at $z = -69$ m (Ta et al., 2002) and at the VLM1 core site was at $z = -46.05$ m (Truong et al., 2011) in the MRD.

But, in the Arno delta, the elevation of the undifferentiated Pleistocene sediment-basement-surface was the shallowest, $z = -40$ m (Giovanni et al., 2012), and $z = -48$ m (Margherita et al., 2007). The thicknesses of the Arno late Pleistocene-Holocene sediment sequence is from 8 to 40 m (Giovanni et al., 2012) and about 51 m of Holocene sediments beneath the present Arno River valley (Margherita et al., 2007). The Arno incised-valley-fill succession including the estuarine and coastal plain sediments with ages between 13,000-8,000 yr BP lie upon this undifferentiated Pleistocene sediment-basement-surface (Giovanni et al., 2012). And then, the Holocene delta sediment succession, namely, the Arno incised-valley fill bay facies overlies by this regressive

coarsening-upward succession (Giovanni et al., 2012). Finally, refining-upward succession includes sub- to tidal-flat and flood plain/marsh in the uppermost part. These sedimentary facies successions of Arno delta (Giovanni et al., 2012) are similar with those of MRD (Truong et al., 2011).

For the Mississippi delta, the lowest elevation of the undifferentiated Pleistocene sediment-basement-surface was at $z = -45$ m, which were covered by the thin layer of shelly marine sands with ages of late Pleistocene (Heinrich, 2005). And then, the Holocene delta sediment succession in the Mississippi delta, specifically, the bay sediment lies upon the shelly marine sand layer (Heinrich, 2005). The thicknesses of deltaic sediments within St. Bernard Parish in the Mississippi delta range from less than 15 m to over 46 m (Heinrich, 2005).

The change in the thickness of the MRD late Pleistocene-Holocene sediment sequence is the largest, from 71 m at the BT2 core site (Ta et al., 2002) to 10.5 m at the BT1 core site (Ta et al., 2005), in comparison with those of the Mississippi (Heinrich, 2005) and Arno (Giovanni et al., 2012) deltas. The incised-valley system in the MRD is so large with 190 km in length, 16.7 km in wide, 71 m in maximum thickness (Nguyen et al., 2010). That in the Arno delta is 64 km in length, 5-7 km in wide, 40 m in thickness (Giovanni et al., 2012). It could say that the MRD sufficiently presented the sedimentary facies of the late Pleistocene-Holocene sediments.

2.4. Summary

General geological stratum of the MRD includes the rock basement with more than 65 million yr BP covered by the Neogene sediment to the late Pleistocene basement coastal to fluvial sediments with the age of greater than 43,400 yr BP, and the late Pleistocene-Holocene sediments with ages of 15,000-0 yr BP. The geological structures of the MRD are in form of sunken basin, the center of the sunken basin is a region between the Mekong River and Bassac River with a rock basement 900 m in depth. And two uplift-wings are the northern region of the Mekong River and the southern region of the Bassac River. The rock basement also exposes in the north and western parts of the MRD.

The MRD late Pleistocene-Holocene sediment-stratum includes the late Pleistocene basement coastal to fluvial sediments (or called undifferentiated Pleistocene sediments or undivided Pleistocene sediments), the overlying transgressive latest Pleistocene-Holocene incised-valley-

fill sediments with ages of 15,000-5,000 yr BP, and regressive deltaic sediments with ages of 5,000-0yr BP of the Mekong River Formation. The formation consists of transgressive and regressive facies successions with three stages of development: (1) the erosional stage about the time of the LGM, when the valleys were incised and the interfluvies were subaerially exposed. (2) The transgressive incised-valley-filling stage from the LGM to the early Holocene. (3) The regressive delta-development stage was from the early Holocene to the present.

The thicknesses of the late Pleistocene-Holocene sediment succession gradually decrease in the two directions of each uplift-wing. The thicknesses of the late Pleistocene-Holocene sediment succession in the sunken basin largely varied from 12 to 71 m; and the maximum thickness is in the incised-valley zone. The typical sufficient late Pleistocene-Holocene sediment facies succession including eight facies was in the lower delta plain and in the incised-valley zone.

The characteristics of the undifferentiated Pleistocene sediments like stiff to hard, slightly oxidized, yellowish gray silty sand and fine-medium sand bearing scattered quartz pebbles 0.5-1 cm in diameter, and laterite, help us to define the boundary with the late Pleistocene-Holocene sediments during the sampling and in situ tests.

The delta-development followed into a direction of the sea level fell down from the west to east. Namely, the sedimentary facies like prodelta, delta front, sub- to intertidal flat were formed from inner forward to sea (the delta developed according to horizontal direction). It means the age of each sedimentary facies will increase according to this direction.

The Holocene sediment covered about 96% of the area of the delta. The late Pleistocene-Holocene succession is mostly subjected to a stress increase of foundation-construction.

The Holocene delta evolution and depositional model of the MD includes: (1) the tide-dominated delta was formed during the sea-level highstand to slightly falling sea level, from 6,000 to 3,000 yr BP. The characteristics of the tide-dominated delta are a coarsening-upward succession from open to inner bay to prodelta mud to delta front and subtidal flat (delta front platform) muddy sand, which the fining-upward succession including the muddy subtidal to intertidal-flat facies covered them. These characteristics of the tide-dominated delta were found at the zone in the upper delta and close to the boundary between the upper and lower delta. At around 3,000 yr BP the progradational delta obtained the upper delta of the MRD. (2) The tide- and wave-dominated delta was formed after 3,000 yr BP. Simultaneously the topography began to resemble those of the present delta. The characteristics of the tide- and wave-dominated delta

in the lower delta of the MRD are coarser sediments and display a typical coarsening-upward succession from prodelta to delta front and foreshore facies. The facies successions in the lower delta consists of coarsening-upward from the delta front slope to delta front platform, fining-upward sub- to tidal-flat, and coarsening-upward succession including foreshore-dune or fining-upward intertidal flat or salt marsh. Two models of the schematic facies-succession were typical for the tide-dominated delta in the upper delta plain and the tide- and wave-dominated delta in the lower delta plain of the MRD. The accumulation rates were relatively high in the tide-dominated delta. And the progradation rates of the tide-dominated delta were higher than those of the tide- and wave-dominated delta in the lower delta of the MRD.

The late Pleistocene-Holocene sediment sequence of the MRD is compared with those of the Mississippi delta and Arno delta. The transgressive incised-valley fill sediment succession including estuary and bay facies, and the regressive Holocene delta sediment succession including prodelta, delta front, sub- to intertidal flat/intertidal flat, flood plain/marsh, and natural levee facies were found in all three deltas. The succession of five uppermost sedimentary facies of MRD is similar with those of Arno delta and Mississippi delta.

The thickness of the MRD late Pleistocene-Holocene sediment sequence is the largest, and more sediment facies than in comparison with those of the Mississippi delta and Arno delta. The change in the thickness of the MRD late Pleistocene-Holocene sediment sequence is the largest in comparison with those of the Mississippi and Arno deltas.

All indicate that the late Pleistocene-Holocene sediments in the center of sunken basin in MRD are very complex. Delta formation mechanisms, and sedimentary environments and conditions created materials, sedimentary structures and soil ground structures. The materials, sedimentary structures, and time, play a role to produce geotechnical properties.

Simultaneously, the parts of work in this study are also referred from here such as methodology, lay-out of investigation sites, investigating influence of sedimentary environment and condition on geotechnical properties and characteristics of consolidation, rebuilding soil structure models and advantages and disadvantages for the infrastructure construction in MRD. The following chapters will particularly present.

CHAPTER 3

RESEARCH STRATEGY -STUDY SITES AND METHODOLOGY

3.1. Methodology

An integrated survey of the geotechnical engineering and sedimentary geology was conducted according to in the direction of the development of the MRD like discussing in 2.2.2, as follows:

(1) The geotechnical engineering investigation included the in-situ and lab tests. The in-situ tests were Cone Penetration Test (CPTU) using a piezo-cone penetrometer with friction sleeve and Standard Penetration Test (SPT). The lab tests were basic geotechnical properties, unconfined compressive tests, and the tests on one-dimension consolidation properties including incremental loading oedometer test (IL) and constant rate of strain consolidation tests (CRS). From these test-results, the characteristics of geotechnical properties of each sublayer were discussed.

(2) The sedimentary geology investigation consisted of sedimentary structures, carbon isotope (^{14}C) ages, clay mineral, fossils, grain size, color, and natures. From these results of investigation, the sedimentary environments and facies, and stratigraphy of the cores were reconstructed. Changes of sedimentary facies and development of the delta in the late Pleistocene-Holocene period were also inferred.

A combination of the investigations (1) and (2) could provide the relationships between the sedimentary facies and geotechnical properties and characteristics, and mechanisms of consolidation process. Typical consolidation properties were collated with sediment formation mechanism, sedimentary history, e.g., inferring microstructure developments and discussing its effects on the consolidation levels, such as overconsolidation ratio.

The soil investigation program about sedimentary geology, geological engineering, information of sites, and plan layout of investigation sites, instruments, and methods for analyzing the in-situ and lab test results, are presented in the following sections.

3.2. Introduction and summary of investigation

The five investigative sites were arranged 20 to 46 km apart on average. Two cores with

continuous samples have totaling 87 m in length. Eight points of CPTU tests have totaling 248.9 m in length and 9 times of pausing for measuring the pore water pressure dissipation. Five points of SPT tests have totaling 192 m in length. All boreholes, CPTU tests, and SPT tests were carried out from the ground-surface to the end of the MD late Pleistocene-Holocene sediments, and a part of the undifferentiated Pleistocene sediments. How to define the boundary between the undifferentiated Pleistocene sediment and the late Pleistocene-Holocene sediments during the sampling and in-situ tests is similar to that presented in 2.2.2. The results of the sedimentary geology of three core sites in Bentre province, MRD of Ta et al. (2001; 2002a; 2005) were also analyzed. A list of the site information, boreholes and in-situ tests in the MRD is shown Tab.3.1.

3.3. Soil investigation program

3.3.1. Investigation sites

From the analyses in the overview of previous researches, background and objectives of the research in chapter 1 and 2, a detail investigation program was established as follows: A plan layout of five investigation sites was arranged from the upper delta plain to lower delta plain (Fig. 3.1). The Caolanh site designated CLM1 is in the Caolanh province; and the Vinhlong site designated VLM1 is in the Vinhlong province at center of the MRD in the upper delta plain (Fig. 3.1). The locations of investigation sites are also shown on the map of the MRD and provinces simplified after Ma et al. (2003) as shown in Fig. 3.2.

The CLM1 and VLM1 sites were carefully investigated both the sedimentary geology and geotechnical engineering. The plan layouts of these two investigation-sites including borehole and sampling, CPTU and SPT tests are shown in Figs. 3.3.1 and 3.3.2.

Simultaneously, three unprejudiced investigation sites about the geotechnical engineering were also conducted close to the BT1, BT2, and BT3 boreholes in the Bentre province (Fig. 3.2), which the late Pleistocene-Holocene sedimentary facies and environments were studied by Ta et al. (2001; 2002a; 2005). The Bentre-1 site being at the BT1 borehole (Ta et al., 2001; 2002a; 2005) is at the border between the upper delta plain and the lower delta plain (Fig. 3.1). The Bentre-2 site being at the BT2 borehole (Ta et al., 2001; 2002a; 2005) is in the lower delta plain (Fig. 3.1). And the Bentre-3 site being at the BT3 borehole (Ta et al., 2001; 2002a; 2005) is in the lower delta plain and current coast (Fig. 3.1). The plan layouts of these three investigation-

sites including borehole, sampling and SPT tests, and CPTU tests are shown in Figs. 3.3.3 to 3.3.5. The goal of these three investigative sites is to collate the sublayers divided by the geotechnical properties of this study with the sedimentary facies identified by Ta et al. (2001; 2002a; 2005). The symbols of the investigative sites are also symbols of the boreholes/core in Fig. 3.1.

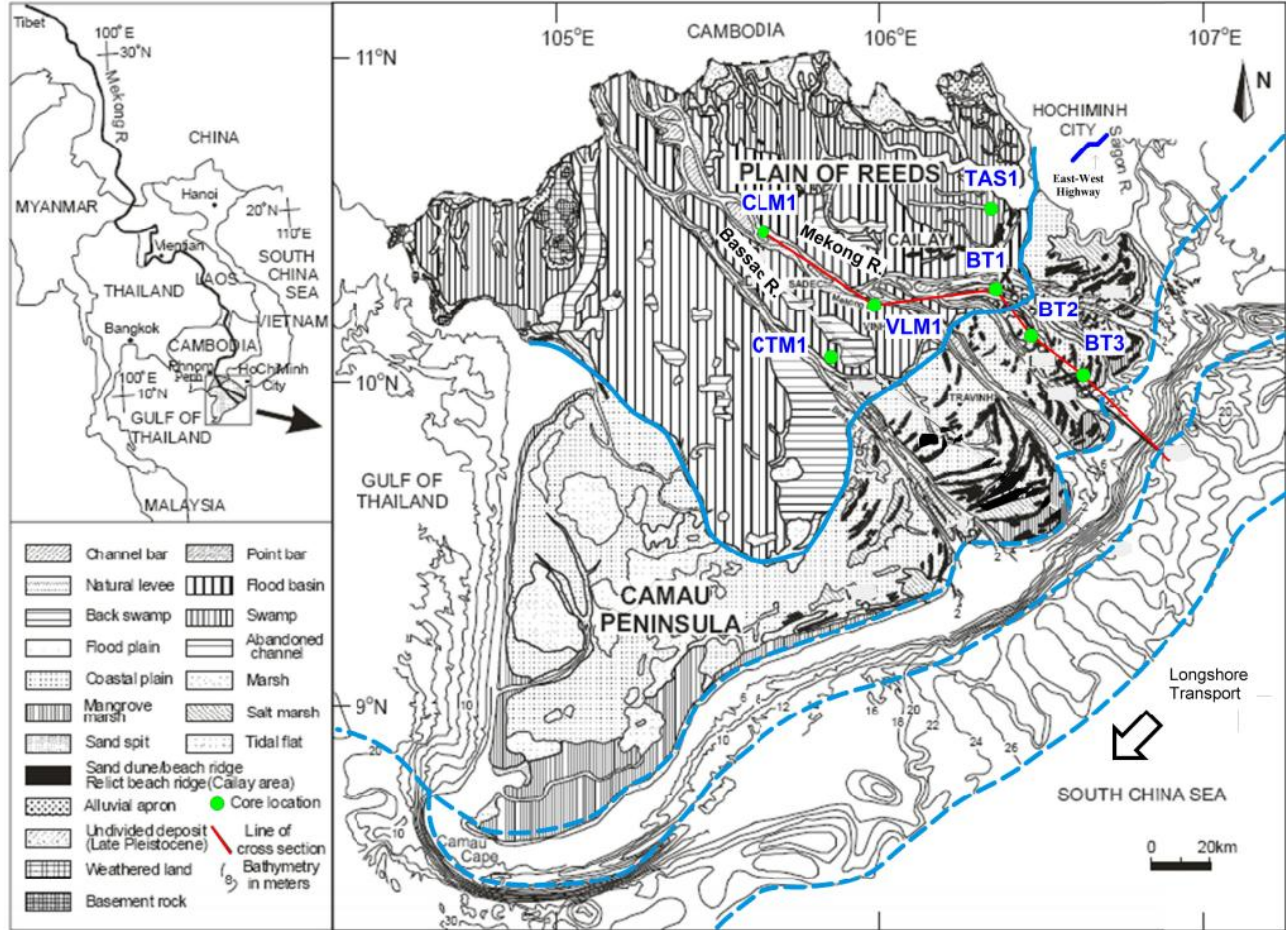


Fig. 3.1. Plan layout of the investigation sites. Investigation sites: Caolanh (CLM1), Vinhlong (VLM1), Bentre-1 (BT1), Bentre-2 (BT2), and Bentre-3 (BT3) in this study, and Cantho (CTM1) and Tanan (TAS1) sites of Takemura et al. (2007). On the sedimentary map of Mekong River Delta (Ta et al. 2005).

Table 3.1.

List of the site information, boreholes, and in-situ tests in this study and reference data

	Site information				In-situ Works								
					In-situ tests					Sampling			
No.	Site	Location			CPTU			SPT		Borehole		In this study	Reference
		Latitude	Longitude	Altitude	Symbol	Depth	Dissip-ation	Symbol	Depth	Symbol	Depth		
		Symbol			(m)		(m)	times		(m)			
1	Caolanh CLM1	10 ⁰ 27' 39.50'' N	105 ⁰ 38' 20.00'' E	+2.9	CPTU1-CL	-35.0	1	SPT-CL	-37	CLM1	-38.1	Have	
2	Vinhlong VLM1	10 ⁰ 14' 02.00'' N	105 ⁰ 59' 08.00'' E	+1.0	CPTU1-VL	-47.8	3	SPT-VL	-60	VLM1	-46.05	Have	
				+1.0	CPTU2-VL	-21.7							
3	Bentre-1 BT1	10 ⁰ 17'01'' N	106 ⁰ 21' 34'' E	+3	CPTU1-BT1	-13.5	2	SPT- BT1	-27	BT1	-10	No	Have (Ta et al., 2002a)
4	Bentre-2 BT2	10 ⁰ 08' 18.06'' N	106 ⁰ 28' 7.20'' E	+2.0	CPTU1-BT2	-30.0		SPT- BT2	-33	BT2	-69	No	Have (Ta et al., 2001)
				+2.0	CPTU2-BT2	-35.0							
				+2.0	CPTU3-BT2	-28.0							
5	Bentre-3 BT3	10 ⁰ 01' 05'' N	106 ⁰ 37' 44'' E	+2.0	CPTU1-BT3	-22	3	SPT- BT3	-28	BT3	-20	No	Have (Ta et al., 2002a)
	*Cantho CTM1	10 ⁰ 4'23.14'' N	105 ⁰ 51' 9.14'' E	+1.4	*CPTU-CT	-28.0				CTM1	-24.6	No	No
	*Tanan TAS1	10 ⁰ 4' 23.14'' N	106 ⁰ 20' 44.12'' E		*CPTU-TA	-17.0				TAS1	-7.5	No	No
*: Data from Takemura et al., 2007.													

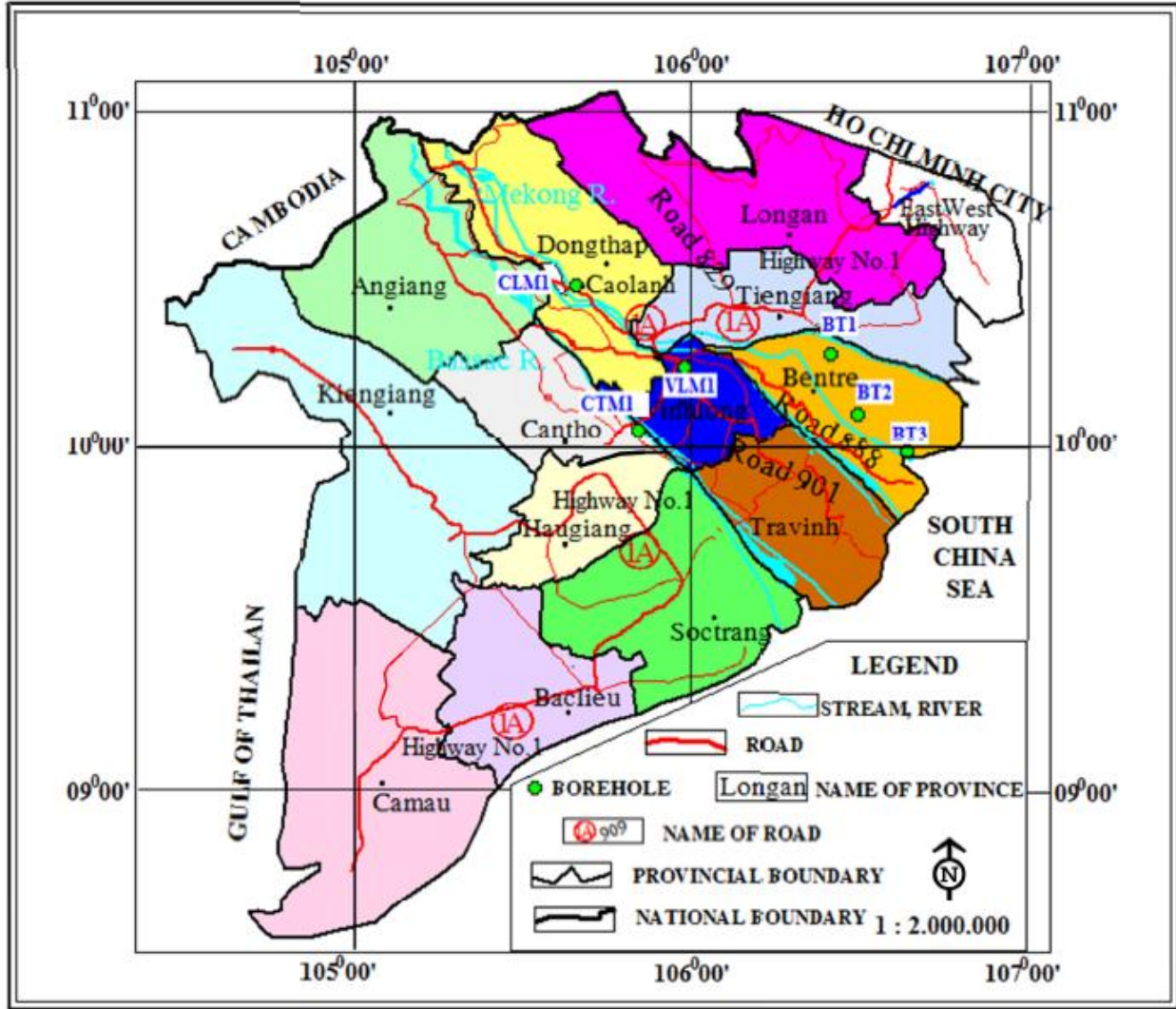


Fig. 3.2. Location of CLM1, VLM1, BT1, BT2, and BT3 investigation sites in this study, and CTM1 and TAS1 sites of Takemura et al. (2007) on administrative map of MRD simplified after Ma et al. (2003).

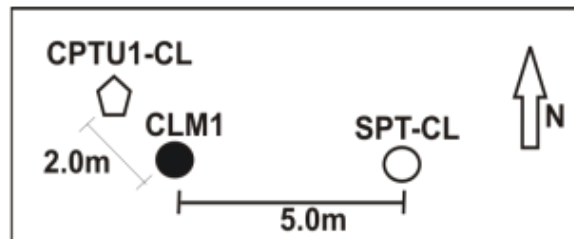


Fig. 3.3.1. Plan layout of CLM1 borehole, CPTU1-CL, and SPT-CL tests at the Caolanh (CLM1) site in Fig. 3.2.

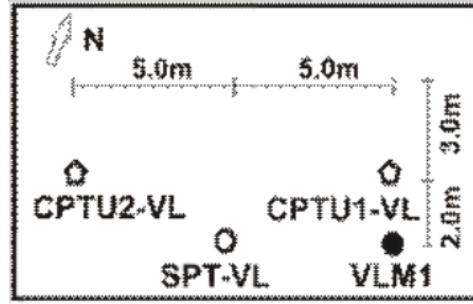


Fig. 3.3.2. Plan layout of VLM1 borehole, CPTU1-VL, CPTU2-VL, and SPT-VL tests at the Vinhlong (VLM1) site in Fig. 3.2.

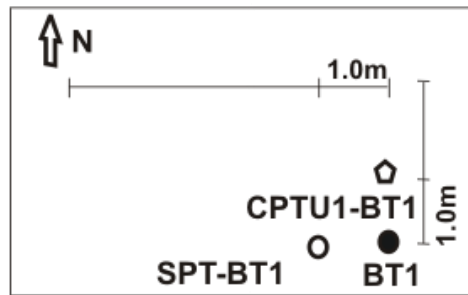


Fig. 3.3.3. Plan layout of CPTU1-BT1 and SPT-BT1 tests near borehole BT1 (Ta et al., 2001) at Bentre-1 (BT1) site in Fig. 3.2.

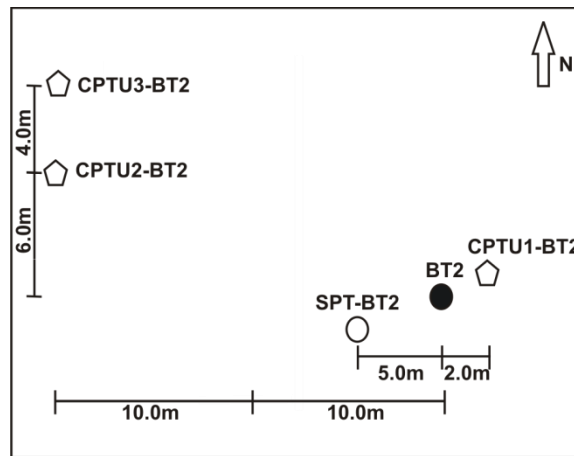


Fig. 3.3.4. Plan layout of CPTU1-BT2, CPTU2-BT2, CPTU3-BT2, and SPT-BT2 tests near borehole BT2 (Ta et al., 2001) at Bentre-2 (BT2) site in Fig. 3.2.

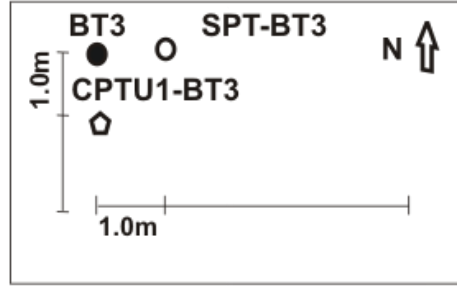


Fig. 3.3.5. Plan layout of CPTU1-BT3 and SPT-BT3 tests near borehole BT3 (Ta et al., 2001) at Bentre-3 (BT3) site in Fig. 3.2.

3.3.2. Boring and sampling, and geological investigations

The soil samples were taken by the hydraulic type thin-walled tube sampler with a fixed piston. Fig. 3.4 shows a stainless steel sampling tube with 710 mm length, 2 mm thickness, 85 mm inside diameter and was pushed into the ground by water pressure. The soil samples were taken from the ground surface to the end of the late Pleistocene-Holocene sediment sequence and part of the Pleistocene undifferentiated sediments; and the soil samples were continuously taken as much as possible. For example, photos of the boring and sampling at Vinhlong site are shown in Fig. 3.5. The soil samples were kept in the stainless steel tube sampler, cleaned and covered by the paraffin, plastic and sticking-plaster (Figs. 3.5d & 3.5e). The soil samplers were enveloped by soft materials and contained in the wooden boxes to protect against the shock during the transportation (Figs. 3.5f and 3.5g).

The VLM1 borehole was located at latitude $10^{\circ} 14' 2''$ N, longitude $105^{\circ} 59' 8''$ E at an altitude of $z = +2$ m above the average present sea level (a.p.s.l) and reached to $z = -46.05$ m. The ground water level was $z = +1.35$ m (a.p.s.l) on September 07th, 2007 at the middle of the rainy season.

The CLM1 borehole was located at latitude $10^{\circ} 27' 39.50''$ N, longitude $105^{\circ} 38' 20.00''$ E, and at an altitude of $z = +2.9$ m (a.p.s.l), from which the boring and sampling were conducted to $z = -38.1$ m. The ground water level was $z = +1.6$ m (a.p.s.l) on September 23rd, 2008 at the middle of the rainy season. The cores were divided into several samples, each 10 cm in height, which were individually inspected and photographed. From the appearance of the soil surface, the detailed soil profiles were determined.

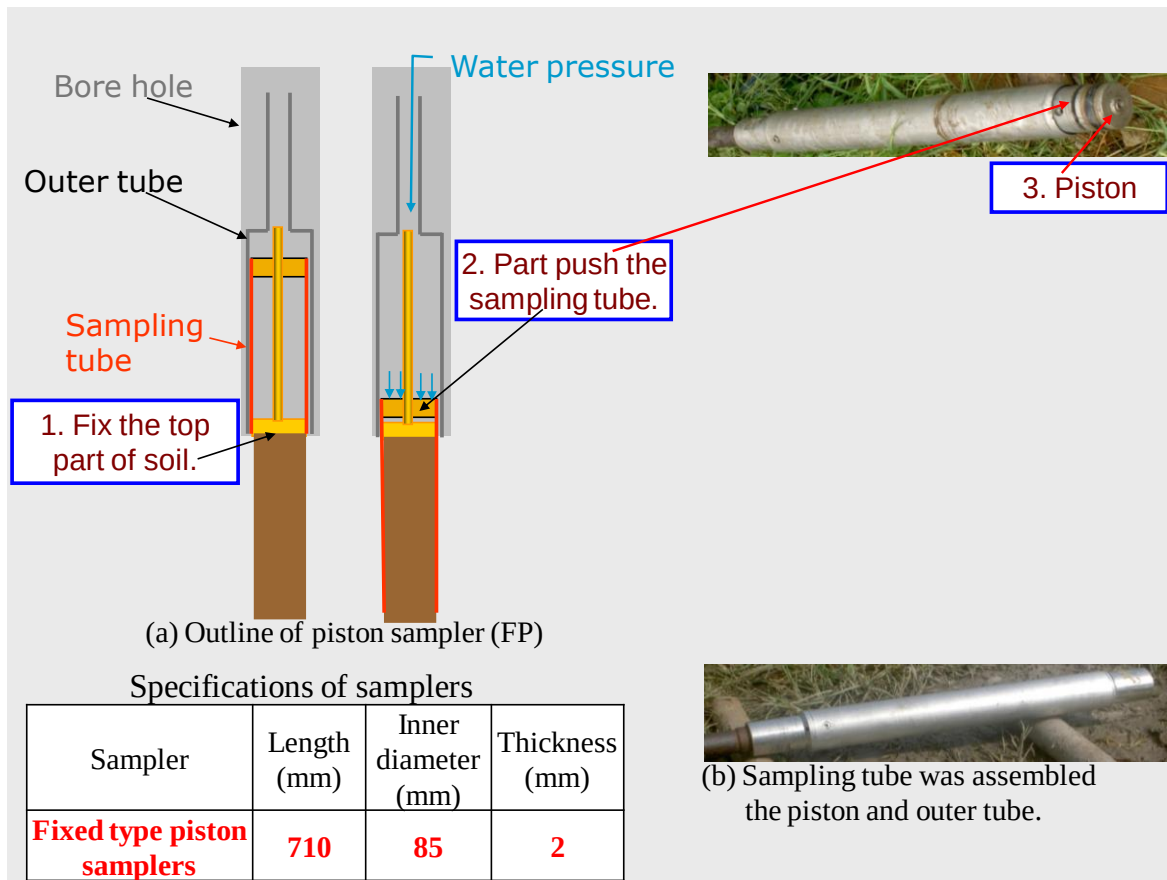


Fig. 3.4. Hydraulic type thin-walled tube sampler and a fixed piston.

3.3.3. In-situ tests

3.3.3.1. Plan layouts of each investigation site and instruments

The specifications of CPTU are cone angle 60° , diameter 35.7 mm, length of cone 25 mm, thickness of porous stone used for pore pressure measurement 5 mm, length of friction sleeve 134 mm (Fig. 3.6), the material of equipment is stainless steel. The cone was continuously pushed by hydrostatic oil-press. As an example, CPTU tests used at the Vinhlong site is shown in Fig. 3.7.

The specification of SPT, standard penetration sampler has inside and outside diameters of 34.93 mm and 50.8 mm, respectively, and the length is 533.4 mm. The hammer weighs for the SPT 63.5 kilogram. The drop height of hammer is 762 mm. Tests were carried out every 2 m (Fig. 3.8).



(a) Tube sampler was assembled the fixed piston and joint, and then checking move of piston.



(b) Tube sampler and fixed piston was assembled rod.



(c) Boring machine was working at Vinhlong site in Vinhlong province MRD.



(d) Soil sample in tube sampler was taken out of the borehole and was cleaned at Vinhlong site.



(e) Soil sample in tube sampler was covered by paraffin, plastic and sticking-plaster.



(f) Samplers arranged and covered by soft material with water, sampler-barrel was carried.



(g) Sampler-barrels were transported to the lab.

Fig. 3.5. For an example: boring and sampling were conducted at Vinhlong site in Vinhlong province, MRD.

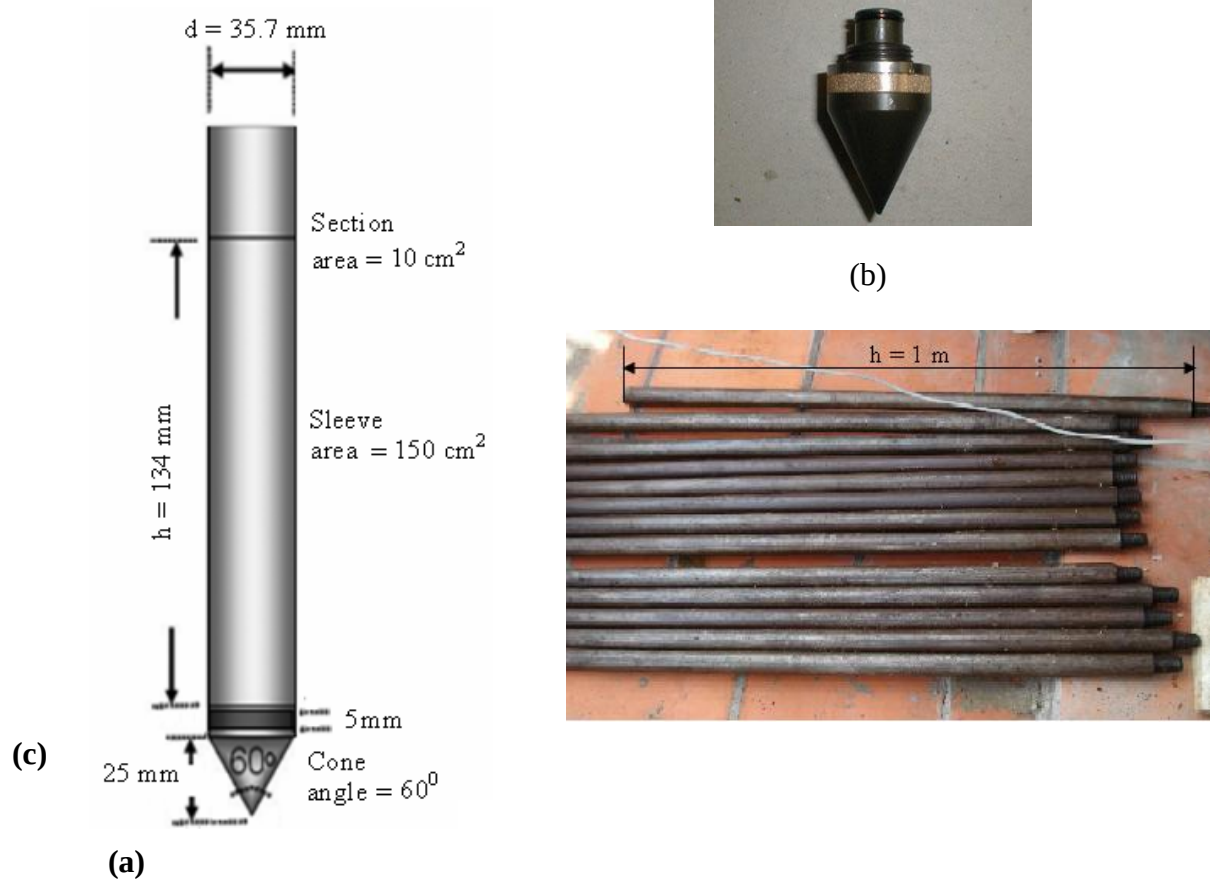


Fig. 3.6. Piezo-cone penetrometer (CPTU), (a) details of CPTU, (b) cone tip, (c) penetrating rods.



Fig. 3.7. CPTU test was conducting at Vinhlong site in Vinhlong province MRD.



Fig. 3.8. Cleaning sand and remainder soil fragment and checking the depth before conducting SPT test at Vinhlong site in Vinhlong province MRD.

At the Caolanh site (Fig. 3.3.1) one CPTU, designated CPTU1-CL, was conducted to a depth of $z = -35$ m, and the pore water pressure dissipation were measured at $z = -8.33$ m in depth. One SPT, designated SPT-CL, was also performed every 2 m to a depth of $z = -37.2$ m. Other

information about the location, altitude, depths of boring and sampling of a borehole, CPTU and SPT tests, is presented in Table 3.1.

At the Vinhlong site, two CPTU tests were conducted. One CPTU, designated CPTU1-VL, was conducted to a depth of $z = -47.8$ m with three pause-points for measuring the pore water pressure dissipation at $z = -7.91$ m, -13.5 m, and -19.49 m, respectively. And the other, designated CPTU2-VL, reached to $z = -21.7$ m. One SPT test, designated SPT-VL, was also carried out every 2 m to a depth of $z = -60$ m. A plan layout of the boreholes and in-situ tests are in Fig. 3.3.2, and other information is in Table 3.1.

At the Bentre-1 site, one CPTU, designated CPTU1-BT1, was conducted from the altitude of $z = +3$ m (a.p.s.l) to a depth of $z = -13.5$ m with two pause-times for measuring the pore water pressure dissipation at $z = -2.88$ m, and $z = -7.31$ m, respectively. One SPT (SPT-BT1) was also carried out to the depth of $z = -27$ m. The ground water level was $z = +2.5$ m (a.p.s.l) on April 23rd, 2013 at the end of the dry season. A plan layout of the investigation is shown in Fig. 3.3.3, and other information is in Tab. 3.1.

At the Bentre-2 site the altitude of $z = +2$ m above the a.p.s.l three CPTU tests were conducted from the ground surface of with symbols being CPTU1-BT2, CPTU2-BT2, and CPTU3-BT2, respectively (Fig. 3.3.4). The CPTU1-BT2 was reached to $z = -28.2$ m; the CPTU2-BT2 was reached to $z = -32.94$ m; the CPTU3-BT2 was reached to $z = -26.72$ m. One SPT (SPT-BT2) was also conducted to $z = -33$ m. The ground water level was $z = +1.75$ m (a.p.s.l) on November 05th, 2010 at the end of the rainy season. And other information is shown in Table 3.1.

As shown in Fig. 3.3.5 at the Bentre-3 site at an altitude of $z = +2$ m one CPTU, designated CPTU1-BT3, was conducted to $z = -22$ m with three pause-times for measuring the pore water pressure dissipation at $z = -6.48$ m, $z = -12.1$ m, and $z = -15$ m, respectively. One SPT (SPT-BT3), was also conducted every 2 m to the depth of $z = -28$ m. The ground water level was $z = 0.0$ m (a.p.s.l) on April 24th, 2013 at the end of the dry season. And other information is shown in Tab. 3.1.

3.3.3.2. Methods for analyzing in-situ test results

3.3.3.2.1. Piezo-cone penetrometer tests, CPTU

a. Measured quantities

Measured quantities obtained by the CPTU tests, including sleeve friction, f_s , cone resistance,

q_t , and pore water pressure measured behind the cone tip, u_2 . All of these values show an increasing trend with depth. The sudden increase in q_t and f_s with a corresponding drop in u_2 indicates the appearance of a sand seam or of intermediate soils with high permeability (i.e., cohesionless soil). As the cone penetrates into a cohesionless soil, the pore water pressure immediately dissipates and reduces to the hydrostatic water pressure. The pore water pressure drops further, becoming lower than the hydrostatic water pressure, u_0 , when the cone encounters pure sand soil which is due to dilating of soil. These observations help us to identify the different types of cohesionless soils quickly and easily. The alternation of cohesionless and cohesive soil layers, results in a saw-tooth shape in the overall plot of q_t , f_s & u_2 as a function of depth. The change in the amplitude of the saw-tooth depends on the arrangement of the soil seams and the mixed levels of sand, silt and clay soil. If their thickness is large, the fluctuation in the amplitude will also become large, and the soil layers are inhomogeneous.

b. Soil-behavior-type classification

A typical soil profile can be identified by soil-behavior-type classification using the following normalized values (Robertson, 1990 and 1999) and the chart of Q_t of F_R for determining soil behaviors types proposed by Robertson (1990) (Fig. 3.9):

$$\text{Normalized cone resistance: } Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \quad (3.1)$$

$$\text{Normalized friction ratio: } F_R = \frac{f_s}{q_t - \sigma_{vo}} \times 100\% \quad (3.2)$$

$$\text{Normalized pressure ratio: } B_q = \frac{u - u_o}{q_t - \sigma_{vo}} \quad (3.3)$$

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

In cohesive soil layers with homogeneous material properties, Q_t , F_R and B_q are all rather constant with depth and the normalized values Q_t , F_R , B_q from CPTU change very little with depth.

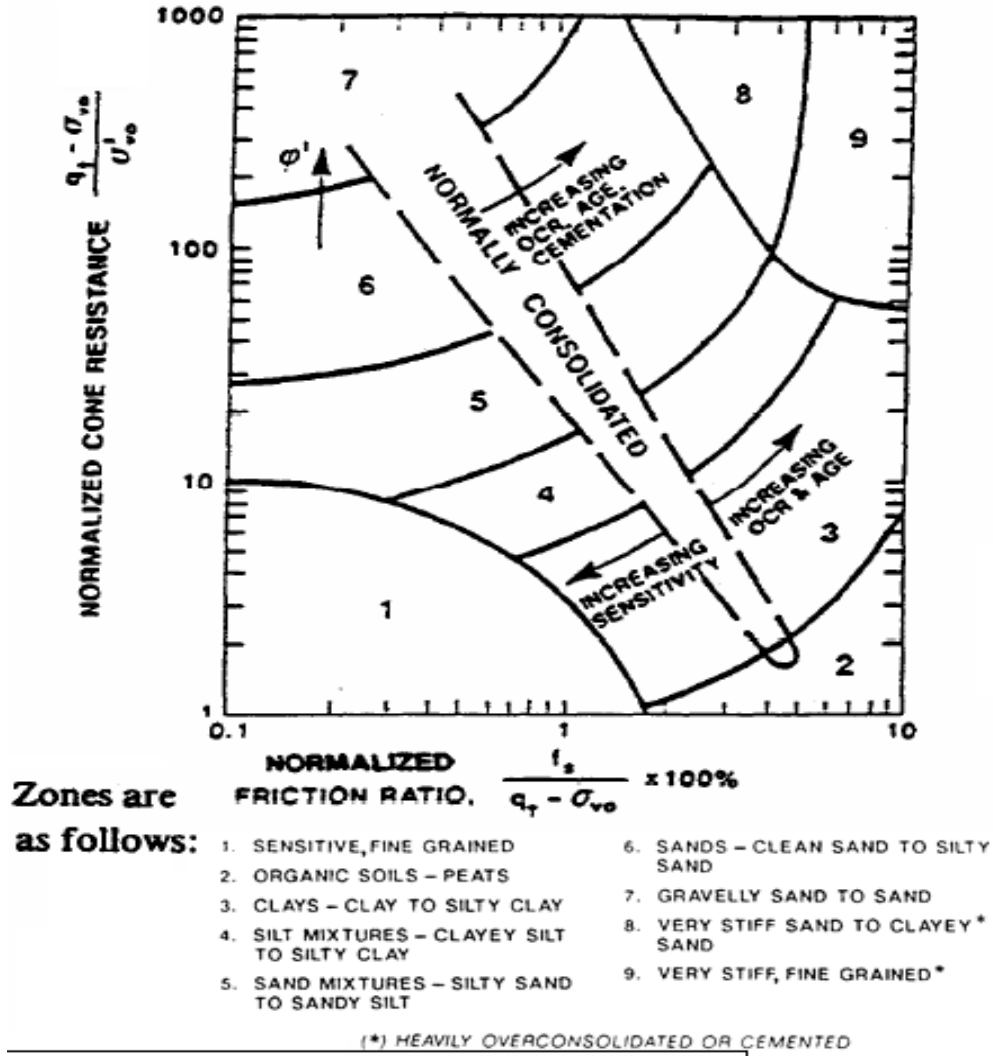


Fig. 3.9. Chart of Q_t of F_R for determining soil behaviors types proposed by Robertson (1990).

c. Overconsolidation ratio, OCR, calculated by the CPTU results

The values of OCR can be calculated from the CPTU results by the simple formula (3.4) with k constant from 0.2 to 0.5 (Lunne et al., 1997),

$$\text{Yield stress ratio: } OCR = k \cdot \left(\frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \right) \quad (3.4)$$

d. Undrained shear strength calculated by the CPTU results

The undrained shear strength, S_u , of the cohesive fine-grained soils at all the investigation sites will be estimated from the piezocone penetrometer tests according to equation (3.5). The cone factor $N_{kt} = 10$ for the normally to lightly overconsolidation clays, and 14 for the

overconsolidation clays and alternation of clay seams and sandy seams and at the greater depths. The undrained shear strength profiles estimated from the CPTU at all the investigation sites will be presented in the following chapter 4.

$$S_u = \frac{q_t - \sigma_{vo}}{N_{kt}} \quad (3.5)$$

e. Coefficients of consolidation calculated by the CPTU results

From the results of CPTU test, coefficients of consolidation in horizontal direction, c_h , obtained from the chart of c_h against time, t_{50} , (Lunne et al., 1997). The t_{50} is requisite time for dissipating 50% of pore water pressure during the CPTU test. The formula (3.6) on a degree of dissipation (U) infers a formula (3.7) for calculating a pore pressure ($u_{t=50}$) corresponding to the degree of dissipation by 50 percent. And then, the values of $u_{t=50}$ will be combined with the curve of the dissipated pore pressure against time to get a values of t_{50} (Lunne et al., 1997). According to Jamiolkowski et al. (1985), the possible field values of k_h/k_v are gotten for soft clays as a nature of clay (k_h : coefficient of permeability in horizontal direction and k_v : coefficient of permeability in vertical direction). The coefficient of consolidation in the vertical direction, c_v , is then calculated by the formula (3.8) (Lunne et al., 1997).

$$U = \frac{u_t - u_0}{u_i - u_0} \cdot 100\% \quad (3.6)$$

where

u_t is pore pressure at time t

u_0 is equilibrium pore pressure in-situ

u_i is pore pressure at start of dissipation test.

$$u_{t=50} = u_i - (u_i - u_0) \frac{50}{100} \quad (3.7)$$

$$c_v = c_h \cdot (k_v/k_h) \quad (3.8)$$

3.3.3.2.2. Standard penetration test, SPT

The N value from the SPT is the blow count for the standard penetration going into the ground with 30 cm depth and finished when N value reaches 50. Numbers of falling hammer, N, are crude without adjustments with symbol in full points of the graphs in the results.

3.3.4. Laboratory geotechnical tests

3.3.4.1. Basic geotechnical properties

Various basic geotechnical properties, including natural water content w_n , were measured every 10 cm. The plastic limit w_p , liquid limit w_L , unit weight γ , specific gravity G_s (Head, 1985a) were measured, and unconfined compression (UC) tests were conducted to identify unconfined compressive strength on undisturbed soils, q_u , and remolded soil, q_{ur} at several depths.

From the plasticity chart, all cohesive soils were classified. The liquidity index, LI, was estimated from w_n , w_p , and w_L , and the relative consistencies of cohesive soils in the natural state were defined by LI. On the other hand, vertical effective stress, σ'_{v0} , was estimated from γ_{sat} .

The plasticity chart, all cohesive soils of the sedimentary facies in the sites, was classified.

3.3.4.2. One-dimensional consolidation tests

As well as one-dimensional consolidation tests, i.e., Incremental loading (IL) tests (Head, 1985b). Constant Rate of Strain (CRS) tests (JGS, 2000) were conducted on typical soil samples at Tokyo Institute of Technology (TIT) and at the Engineering Geology Lab at Ho Chi Minh City University of Science, Vietnam (HCMCUS). The vertical yield stresses σ'_{y-IL} and σ'_{y-CRS} were estimated from the IL and CRS results. The intrinsic compression curve can be obtained from samples reconstituted at a water content of between $1.2w_L$ and $1.5w_L$ (Burland, 1990).

Void indices, I_{v0} , for in-situ void ratio e_0 were estimated by using equation (3.9) (Burland, 1990).

$$\text{Void indices: } I_{v0} = \frac{e_0 - e_{100}^*}{e_{100}^* - e_{1000}^*} \quad (3.9)$$

Where e_{100}^* and e_{1000}^* are the void ratios of the intrinsic compression curve at $\sigma'_v = 100$ kPa and 1000 kPa, respectively. The compression curves (e - $\log \sigma'_v$ relation) obtained from the IL and CRS tests on undisturbed argillaceous soil, and reconstituted specimens at certain depths are depicted. The intrinsic swelling index, C_s^* , is calculated as the slope of the intrinsic swelling line (ISL); the undisturbed swelling index, C_s , is calculated as the slope of the undisturbed swelling line (USL). And a range of vertical effective stress is less than the vertical effective

overburdened pressure (much less than consolidation pressure) for both C_s^* and C_s . They are swell pressures. A swell sensitivity ratio is calculated by the formula (3.10), and is used to discuss the level of bonding.

$$\text{Swell sensitivity, a ratio: } \frac{C_s^*}{C_s} \quad (3.10)$$

Coefficients of consolidation in vertical direction, c_v , with t_{50} corresponding to 50% primary consolidation ($U = 50\%$) is calculated from the IL tests, c_v was calculated by equation (3.11) (Head, 1985b) as follows:

$$c_v = \frac{0.026}{t_{50}} \cdot H_{av}^2 \left(\frac{m^2}{year} \right) \quad (3.11)$$

Where: H_{av} is mean specimen height during the load increment, measured in mm, and t_{50} is the time for 50% dissipation of pore water pressure, measured in minutes in the IL test. The values of t_{50} are evaluated from the curve of the deformation versus square-root-time ($d-\sqrt{t}$) from the IL results. The values of c_v by t_{50} from the IL tests will compare with those from the CPTU tests like presentation in 3.3.3. 2.

Coefficients of consolidation in vertical direction, c_v , with t_{90} corresponding to 90% primary consolidation ($U = 90\%$) is also calculated from the IL tests, c_v was calculated by equation (3.12) (Head, 1985b) as follows:

$$c_v = \frac{0.112}{t_{90}} \cdot H_{av}^2 \left(\frac{m^2}{year} \right) \quad (3.12)$$

Where: t_{90} is the time for 90% dissipation of pore water pressure, measured in minutes in the IL test. The values of t_{90} are evaluated from the curve of the deformation versus square-root-time ($d-\sqrt{t}$) from the IL results.

From the in-situ and lab test results, geotechnical properties of the sites were determined.

3.3.5. Carbon isotope age, clay minerals, and chemical analyses

Carbon isotope (^{14}C) dating of the organic material in some soil samples was performed by the Beta Analytic Radiocarbon Dating Lab, Japan. Ten soil samples of Caolanh and Vinhlong cores were analyzed for the ^{14}C dating.

Clay mineral analyses based on the X-ray diffraction methods were conducted using the D8 ADANCE at the Analysis Lab Center, Vietnam Petroleum Institute. Ten soil samples of Vinhlong

core and fourteen soil samples of Caolanh core were analyzed for the clay mineral.

Based on the typical cohesive soil samples of each sedimentary facies at the Caolanh and Vinhlong cores, the exchangeable irons were extracted using 0.1N H₂SO₄; and Al, Ca, and Mg were extracted using 1N KCl. These extracted solutions were used for determining the exchangeable ions, and the total carbon (Page et al., 1982) at HCMCUS. The total contents of ions including Fe, Al, Na, K, Ca, Mg, and Si were determined by UV-Vis and ICP at the Department of Sciences and Technology of HCMC Center of Analytical Services. The total content contained both unexchangeable ions and exchangeable, i.e., all the types of ions of one element which existed in the soil.

3.3.6. Image analyses

Petrography-images in thin sections (PTS) were taken on the cohesive soil samples being carefully sheared perpendicularly (symbol, $\perp$) and parallel (symbol, $=$) to the sedimentary layers. The cohesive soil samples were selected, and then they were dyed for placing securely and observing easily space pores about their density and size. After dyeing, the dyed soil samples were cut and created thin sections. The space pores are in the blue color, the light and bold levels and distribution of the blue color on the thin sections under the polar nicol (PN) will indicate density and size of the space pores. The fabric and bonding by cements of facies' cohesive soil samples will be considered under the polar nicol (PN), crossed nicol (XN) of the microscope for interpreting development-levels of microstructure (Hibbard, 1995). Six soil samples of Vinhlong core and one soil sample of Caolanh core were selected for petrography-images in thin section.

The Scanning electron micrographs (SEM) were also taken perpendicularly to the sedimentary layers by Bruker Nano EVO/MA10 machine. They were carried out at the Analysis Lab Center, Vietnam Petroleum Institute (VPI). Four soil samples of Vinhlong core and two soil samples of Caolanh core were selected for the SEM.

3.4. Summary

This chapter presented about the methodology which was employed for the works of the study. The integrated surveys of the geotechnical engineering and the sedimentary geology on the MD late Pleistocene-Holocene sediments and a part of the undifferentiated Pleistocene sediments were

conducted. The plan layout of investigation sites according to in the direction of the development of the MRD, from the upper delta plain to lower delta plain, was established through the discussing in chapter 1 and 2, and also indicated on the MRD map.

Total of the investigative works conducted at the five sites from 20 to 46 km apart on average in this study were represented. The CLM1 and VLM1 cores with continuous samples have a total 87 m in length, and study both geotechnical engineering and sedimentary geology.

This chapter also presents how to carry out the geotechnical tests including the in-situ tests like CPTU, SPT, and boring and sampling from the ground surface to the end of the late Pleistocene-Holocene sediments and the top part of the undifferentiated Pleistocene sediments. Ten points of CPTU tests with total 310 m length were conducted with 9 times of pausing for measuring the pore water pressure dissipation. At six points SPT tests were done with total 235 m length.

Based upon the characteristics of the undifferentiated Pleistocene sediments like the stiff to hard, slightly oxidized, yellowish gray silty sand and fine-medium sand bearing scattered quartz pebbles 0.5-1 cm in diameter, and laterite, defined was the boundary with the late Pleistocene-Holocene sediments during the sampling and in-situ tests.

Three unprejudiced investigation sites about the geotechnical engineering were also established close to the BT1, BT2, and BT3 boreholes in the Bentre province, which were reported about the late Pleistocene-Holocene sedimentary facies and environments by Ta et al. (2001; 2002a; 2005).

How to symbol for the investigation sites, and boreholes/core, CPTU and SPT tests at each site were clearly described. The borehole, CPTU and SPT tests at each site were laid and presented in the plan layout of the investigation site. The specifications of CPTU and SPT instruments were represented. A list of the site information, boreholes and in-situ tests of this study and reference data in the MRD was shown.

Specifications of the hydraulic type thin-walled tube sampler with a fixed piston used to obtain soil samples, how to maintain the soil samples, methods for analyzing the in-situ test results including CPTU and SPT tests, were also presented in this chapter.

Lab basic geotechnical tests like natural water content, were measured every 10 cm. The plastic limit, liquid limit, unit weight, specific gravity were introduced, and unconfined compression tests were conducted to measure unconfined compressive strength of undisturbed soils, and remolded soils at several depths. The incremental loading tests (Head, 1985b), constant

rate of strain tests (JGS, 2000), were also conducted on typical soil samples at TIT and at the Engineering Geology Lab at HCMCUS. All cohesive soils were classified from the plasticity chart. How to calculate the other parameters of geotechnical properties from the parameters of the lab test results were presented.

Ten soil samples of Caolanh and Vinhlong cores were analyzed for the ^{14}C dating by the Beta Analytic Radiocarbon Dating Lab, Japan. Ten cohesive soil samples of Vinhlong core and fourteen cohesive soil samples of Caolanh core were analyzed for the clay mineral based on X-ray diffraction methods using the D8 ADANCE at the Analysis Lab Center, Vietnam Petroleum Institute. To determine the contents of the exchangeable ions such as Fe, Al, Na, K, Ca, Mg, and Si and the total carbon content was determined (Page et al., 1982) at HCMCUS. These total contents of ions were analysed by UV-Vis and ICP at the Department of Sciences and Technology of HCMC Center of Analytical Services.

Space pores of the cohesive soil was visualized by the dyeing on the petrography-images in thin sections according to perpendicularly (symbol, $\perp$) and parallel (symbol, $=$) to the sedimentary layers. The space pores are in the blue color, the light and bold levels and distribution of the blue color on the thin sections under the polar nicol (PN) will indicate density and size of the space pores. The fabric and bonding by cements of facies' cohesive soil samples will be considered under the polar nicol (PN), crossed nicol (XN) of the microscope for interpreting development-levels of microstructure. Six soil samples of Vinhlong core and one soil sample of Caolanh core were selected for petrography-images in thin section. The SEM of four soil samples of Vinhlong core and two soil samples of Caolanh core were also taken perpendicularly to the sedimentary layers by Bruker Nano EVO/MA10 machine at the VPI.

The results of the geotechnical and sedimentary geology tests, sublayers, sedimentary environments and facies, and stratigraphy of the cores, will present in the next chapter.

CHAPTER 4

INVESTIGATION RESULTS ON SEDIMENTARY GEOLOGY AND GEOTECHNICAL PROPERTIES

4.1. Introduction

This chapter presents about results of the sedimentary geology and the geotechnical engineering. The results of sedimentary geology like grain size; state, sedimentary structure, clay minerals, fossils, color, and carbon isotope (^{14}C) ages of the sediments of each core will be presented. From these results, characteristics of the lithostratigraphic units of each core will be identified. And then, sedimentary environment and facies will be inferred based on the characteristics of the unit. Finally, stratigraphy at the VLM1 and CLM1 core site will be rebuilt. Moreover, stratigraphy and sedimentary environments of reference cores including BT1, BT2, and BT3 (Ta et al., 2001, 2002a, and 2002b) are also presented in this chapter. One sedimentary cross-section including CLM1, VLM1, BT1, BT2, and BT3 cores will be rebuilt to base on the sedimentary results of the CLM1 and VLM1 cores of this study combined with three reference cores BT1, BT2, and BT3 cores (Ta et al., 2001, 2002a, and 2002b). Sedimentary facies changes and late Pleistocene-Holocene development of the delta going through stages will be discussed on this sedimentary cross-section. Changes in sedimentary structures and materials on transgressive incised-valley-filling sediments and regressive Holocene delta sediments will be presented. Delta formation mechanisms influenced on sedimentary facies succession and grain size, and their characteristics also discussed.

The in situ and lab geotechnical results including base properties, consolidation, CPTU, SPT of CLM1, VLM1, BT1, BT2, and BT3 sites were presented. The geotechnical profile will be divided into sublayers based on combination of the in situ and lab geotechnical results. Characteristics and changes of geotechnical properties between sites and according to depth will also be displayed. The abilities of present of the CPTU and SPT results are about the variations of the strength and soil-behavior-types on the MD late Pleistocene-Holocene sediments.

All will be presented in the following sections of this chapter.

4.2. Sedimentary geology results

The stratigraphy and sedimentary environments of the VLM1 and CLM1 cores were rebuilt based upon the combination of the characteristics of grain size, state, sedimentary structure, clay minerals, fossils, color, and carbon isotope (^{14}C) ages of the sediments.

4.2.1. Lithostratigraphy and inferred depositional facies of Vinhlong core

Based on sedimentary properties of the Vinhlong (VLM1) core, the sediments can be identified eight lithostratigraphic units. The eight sedimentary facies are inferred based on the characteristics of the units (Fig. 4.1). The sedimentary characteristics of these units, corresponding sedimentary facies are presented in ascending order in Fig. 4.1.

(1) Unit 1 (z = -46.05 to -41.5 m: below the a.p.s.l)/estuarine channel facies

The sedimentary materials include silty clay to clayey silt with darkish and greenish-gray in color (Fig. 4.1b) and discontinuous fine sand laminae of 2 mm thickness (Fig. 4.2A). It also contains scattered laterite (5-10 mm in diameter) and angular quartz (maximum 15 mm in length) pebbles (Fig. 4.2A). Sedimentary structures are common parallel and lenticular beddings. The smectite mineral content of this layer is the highest, while the chlorite and illite contents are the lowest in comparison to other facies (Tab.4.1). These characteristics indicate that the sediments were deposited under dynamic hydrological conditions, which might be caused by the presence of an estuarine channel.

(2) Unit 2 (z = -41.5 to -27.8 m)/salt marsh facies

Unit 2 consists of two parts. The lower part (-41.5 to -37 m) is characterized by inter-bedded, brownish gray silty clay and clayey to sandy silt. Faint bedding exists in the brownish-gray silt (Figs. 4.1b & 4.2B). The upper part of Unit 2 (-37 to -27.8 m) contains discontinuous parallel laminae, wavy, flaser (Fig. 4.2D), parallel and lenticular bedding, humus material, bioturbation, calcareous concretions, and mollusca (Fig. 4.2C). Mica flakes are scattered throughout the unit. The clay mineral contents of the specimens in unit 2 are almost equal and the illite mineral content is the highest in comparison with all the units (Tab. 4.1). The results indicate high homogeneity. These relatively homogeneous conditions with high content of fine material imply that these sediments were deposited under relatively low hydrological conditions so that concretions of soft calcareous material produced calcareous pebbles in the sandy and clayey silts.

Mollusca fossils indicate a marine-brackish water habitat. The sediment accumulated in a muddy tidal flat/salt marsh environment, and at -41.5 m is dated at $9,910 \pm 50$ ^{14}C yr BP and at -30.75 m is dated at $9,090 \pm 40$ ^{14}C yr BP (Tab. 4.2). These are all features of a salt marsh facies.

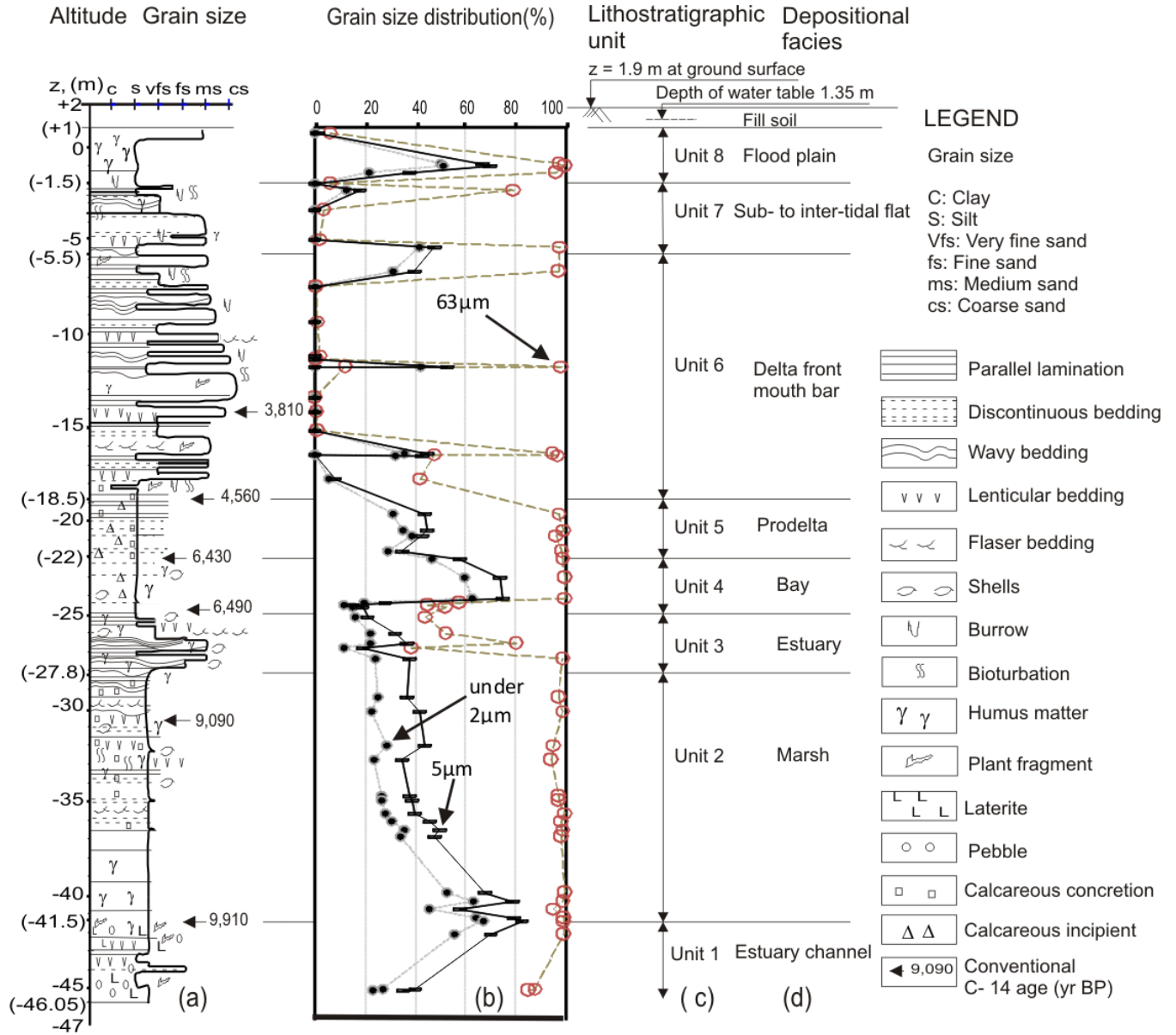


Fig. 4.1. Geological column of VLM1 core and its correlation with lithostratigraphic units.

Table 4.1. Results of clay mineral content analysis of argillaceous sediments of the facies from Vinhlong core.

Altitude (m)	Unit	Sedimentary Facies	Illite (%)	Kaolinite (%)	Chlorite (%)	Smectite (%)	Mixture of Illite and Smectite (%)
-2.15	7	Sub- to inter-tidal flat	54.6	17.4	14.4	11.7	1.8
-5.18	7		57.0	17.1	13.4	10.7	1.8
-18.1	6	Delta front	56.7	21.8	18.6	1.4	1.4
-20.04	5	Pro-delta	58.8	15.9	12.3	11.6	1.3
-24.88	4	Open-bay	54.2	17.7	15.2	11.4	1.6
-27.2	3	Estuarine marine	62.6	16.6	13.4	6.0	1.4
-32.8	2	Marsh	63.8	15.6	13.6	5.3	1.7
-36.4	2		61.1	15.0	15.3	6.9	1.8
-37.58	2		60.7	15.1	14.5	8.4	1.4
-45.85	1	Estuarine channel	44.7	16.6	10.7	26.4	1.7

Table 4.2. List of ^{14}C ages from the VLM1 core.

Altitude (m)	Materials	Delta ^{13}C (permil)	Conventional ^{14}C age (yr BP)	Estimated depositional rate (mm/year)
-14	Organic	-25.5	3810 ± 40	6
-18.5	Organic	-26	4560 ± 40	1.84
-21.95	Organic	-25.4	6430 ± 40	48.8
-24.88	Organic	-26.1	6490 ± 40	2.3
-30.75	Organic	-27	9090 ± 40	13
-41.5	Organic	-25.6	9910 ± 50	

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

(3) Unit 3 (z = -27.8 to -25 m)/estuarine marine facies

Unit 3 can be divided into two parts. The part from -27.8 to -26.4 m, has of intercalated darkish gray silty sand to medium sand and clayey silt to silty clay (Fig. 4.2E), coarsening in upward succession.

The upper part (-26.4 to -25 m), consists of greenish-gray silty sand and greenish-gray clayey silt (Figs. 4.1b & 4.2F). In general, parallel laminae, wavy bedding (Fig. 4.2E), lenticular bedding, and flaser bedding (Fig. 4.2F) characterize the unit. Shell fragments and humus material are scattered throughout unit 3. This unit has plentiful structures and materials. These characteristics and the marine bivalve fossils such as mollusca indicate that the sand and sandy silt were deposited in an estuarine environment. We can say that a transgressive lag sediment or estuarine channel deposit affected by strong tidal currents.

(4) Unit 4 (z = -25 to -22.0 m)/open bay mud facies

This unit consists of darkish-gray clayey silt with sets of interbedded gray clay (25-55 mm thickness) and dark clay (2-5 mm thickness), and greenish-gray mud (Figs. 4.1b & 4.2G) with discontinuous, very thin sandy bedding. Some sets of faintly parallel laminae are also seen, which can be produced by seasonal fluctuations in suspended sediment load or variations of the amount and kinds of supplied organic materials, or, alternatively, by tidal influences. Although the grain size distribution shows a fining-upward succession, the unit is relatively homogeneous with the highest mud content among all the facies (Fig. 4.1b). Humus matter, mica flakes, shell fragments, calcareous incipience are scattered throughout the unit. It ended at $6,490 \pm 40$ ^{14}C yr BP at -24.88 m (Tab. 4.2). From above observations, this unit is inferred as open bay facies.

(5) Unit 5 (z = -22.0 to -18.5 m)/pro-delta mud facies

Unit 5 can be divided into two parts. The sediments of the lower part (-22 to -20 m) are silty clay and very fine sand with gray color. The sediments are commonly interbedded greenish-gray clayey silt (25-30 mm thickness), silty clay (2-5 mm thickness) (Fig. 4.1b), and discontinuous parallel laminated mud (Fig. 4.2H). They are dated at $6,430 \pm 40$ ^{14}C yr BP at -21.95 m and ended at $4,560 \pm 40$ ^{14}C yr BP at -18.5 m (Tab. 4.2). The sediments of the upper part (-20 to -18.5 m) are many parallel laminated very fine sand seams (Fig. 4.2I). In general, mica flakes, calcareous nodules (Fig. 4.2I) and calcareous incipient are scattered throughout the unit. There are significant variations in the lithology and sedimentary structures of the layer, which could be by the effects of higher sediment supply and/or more hydrodynamics than previous time when sedimentary environment transiting from prodelta to delta front. However, the unit is homogeneous in comparison with the overlying unit (Unit 6).

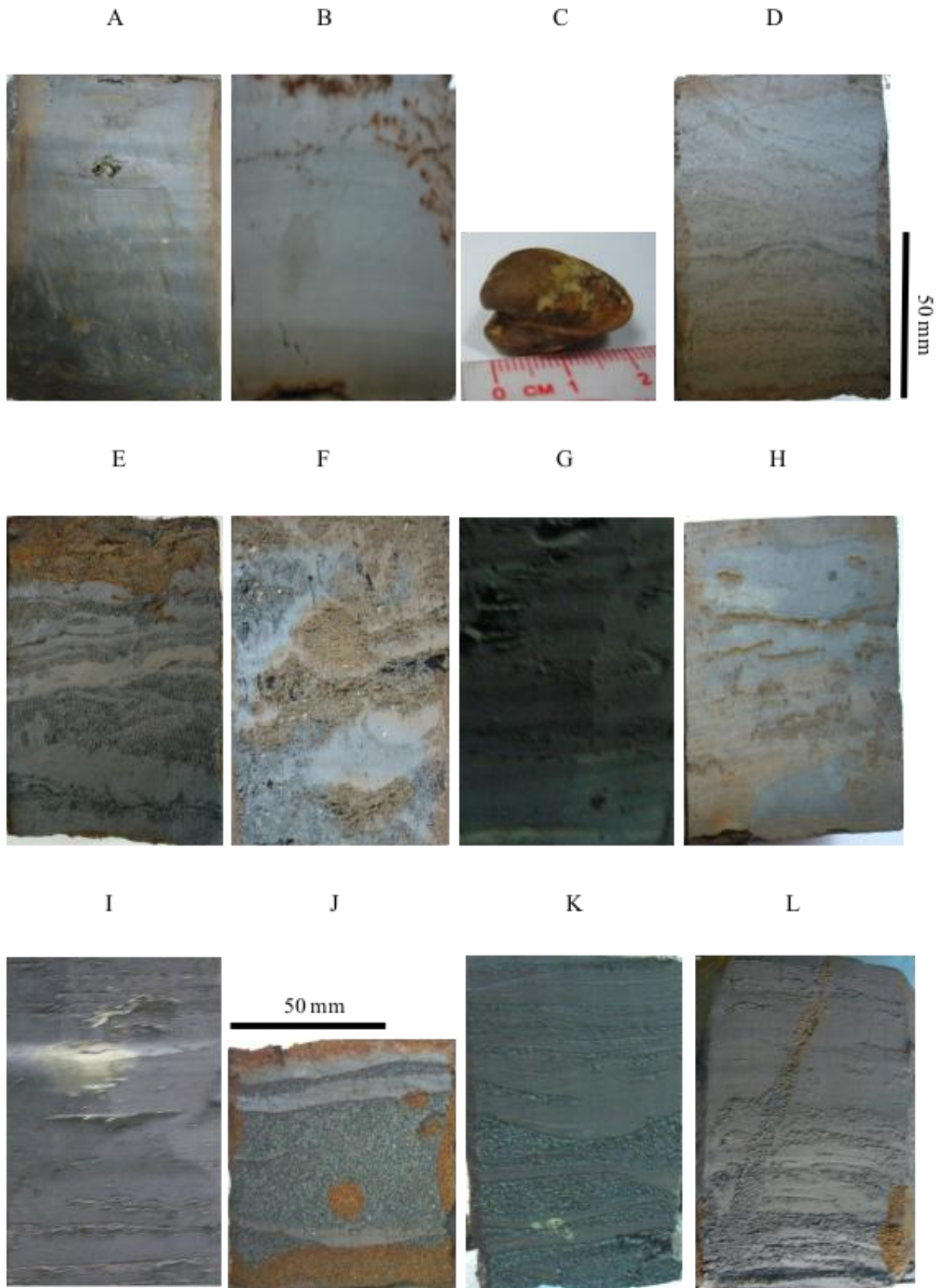


Fig. 4.2. -Selected photographs of sedimentary structures from the VLM1 core: **A)** (at depth -

44.5 m) discontinuous fine sand laminae of 2mm thick, angular quartz pebbles; clay mass, **B**) (-40.95 m) inter-bedded, brownish gray silty clay and clayey to sandy silt, faint bedding, **C**) (-32.6 m) mollusca, **D**) (-30.1 m) discontinuous parallel laminae, wavy and flaser, **E**) (-27.35 m) parallel laminae, wavy bedding, **F**) (-25.0 m) lenticular and flaser bedding, **G**) (-22.15 m) clayey silt and silty clay mud with discontinuous, very thin sandy bedding and calcareous incipient, **H**) (-21.21 m) discontinuous sand laminae, **I**) (-19.54 m) many parallel laminated very fine sand seams and calcareous nodules, **J**) (-13.75 m) fine to coarse sand layers with parallel clayey laminae, **K**) (-7.70 m) parallel, discontinuous, lenticular and wavy bedding, **L**) (-2.6 m) intercalated sand laminae and mud (tidal rhythmites), humus matter and burrow.

(6) Unit 6 (z = -18.5 to -5.5 m)/delta front-mouth bar facies

Unit 6 contains intercalated greenish-gray clay and silt, greenish-gray sandy silt, and from coarse to fine sand. This facies is highly inhomogeneous, with several sandy layers of various thicknesses. Some of sand seams are large thick and parallel clayey laminae (Figs. 4.1b & 4.2J). In general, medium to coarse sands are common soil types of the facies (Figs. 4.1a-b). The sedimentary structures like flaser, lenticular and wavy bedding can be seen in Fig. 4.2K, burrow, bioturbation, plant fragments and mica flakes are also scattered throughout the sediment. The smectite mineral content is the lowest of the argillaceous sediments, and the kaolinite and chlorite mineral contents are the largest among all the facies (Tab.4.1). These characteristics show strong hydrodynamic conditions mainly resulting from tidal currents and flooding causing high depositional rates. It is inferred that the sedimentary process forming this facies 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 (Tab.3.2).

(7) Unit 7 (z = -5.5 to -1.5 m)/sub- to inter-tidal flat facies

Unit 7 consists of greenish- and darkish-gray clayey silt, sandy silt and very fine to medium sand, showing parallel laminae, discontinuous parallel laminae, and lenticular and wavy bedding. The sediments in part (-2.4 to -3 m) consist of intercalated sand and mud which resemble tidal rhythmites (Figs. 4.1b & 4.2L). Humus matter, bioturbation and burrows (Fig. 4.2L) are present. These features characterize sub- to inter-tidal flat facies.

(8) Unit 8 (z = -1.5 to +1 m)/flood plain facies

This unit contains greenish-darkish gray clayey silt mud and silty clay mud (Fig. 4.1b) with small yellowish-greenish spots from -1.5 to +0.5 m and medium to fine sandy mud with greenish- and darkish-gray in color, rich in organic materials, from +0.5 to +1.0 m (Fig. 4.1a).

These sediments show that this facies was formed by flooding.

4.2.2. Lithostratigraphy and inferred depositional facies of Caolanh core

The sediments of the CLM1 core can be divided into seven lithostratigraphic units. Then, seven depositional facies are inferred based on the characteristics of the units. The characteristics of these units, corresponding depositional facies of Caolanh core are presented below in ascending order in Fig. 4.3.

(1) Unit 1 (z = -36.6 to -32.1 m)/Tidal flat/Marsh facies

The sediments include firm to stiff darkish and gray silty clay to sandy silt. Its characteristic is brown seams of very fine sand silt with 8 mm in maximum thickness and gray mud seams alternated rhythmically (Fig. 4.4A). The parallel, lenticular beddings and discontinuous very fine sand silt laminae are common (Fig. 4.4A). Organic materials are also found. These characteristics indicate that the sediments were deposited under lightly dynamic hydrological conditions, which can be caused by the presence of a fluvial operation. It is dated at $11,350 \pm 60$ ^{14}C yr BP at -34.6 m (Tab. 4.3).

(2) Unit 2 (z = -32.1 to -26.1 m)/sub- to intertidal flat facies

This unit consists of gray to darkish gray clayey silt and silty clay and the structure is parallel, lenticular, discontinuous sand to sandy silt layers. Peaty seams, organic material, and bioturbation are common (Fig. 4.4B). The deposits are characterized by intercalated silty sand and mud which resemble tidal rhythmites. Sand content in the sandy silt seams of unit 2 obtained 40% (Fig. 4.3b). The smectite contents of upper depth in this unit are generally higher than those of the other facies (Tab. 4.4). From these observations, unit 2 is inferred as sub- to intertidal flat facies.

(3) Unit 3 (z = -26.1 to -21.9 m)/prodelta/bay facies

The sediments include brownish, darkish gray clay, silt, and silty sand. Figs. 4.3a-b show that coarsening-upward succession is a characteristic of this unit. The sedimentary structures are lenticular, flaser, discontinuous parallel laminae and mica flakes and bioturbation are scattered throughout unit 3 (Figs. 4.4C & 4.4D). In the upper part (-24.6 to -21.9 m), the amount and thickness of parallel sand laminae are more and larger than those of the low part.

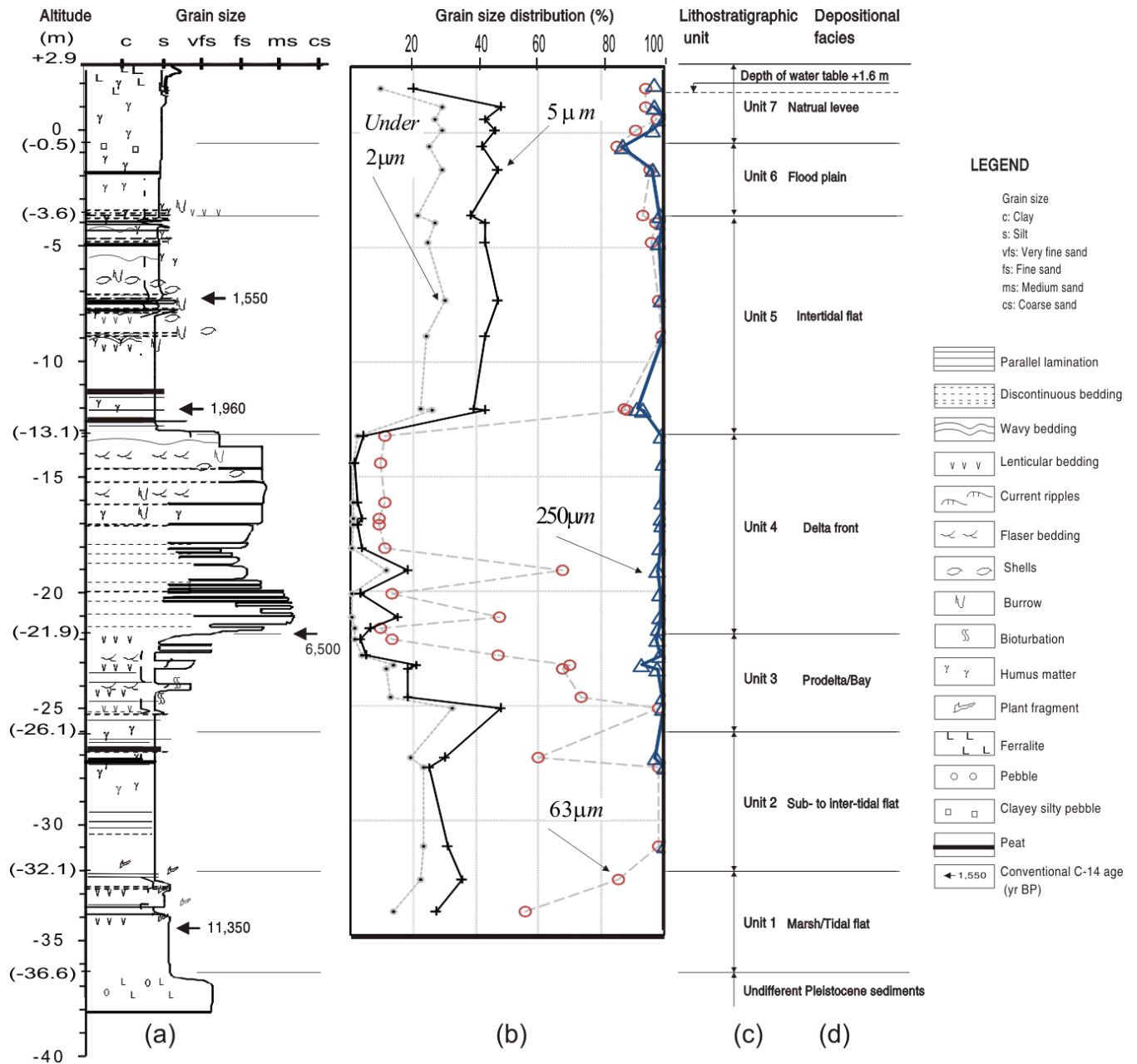


Fig. 4.3. Geological column of the CLM1 core and its correlation with lithostratigraphic units.

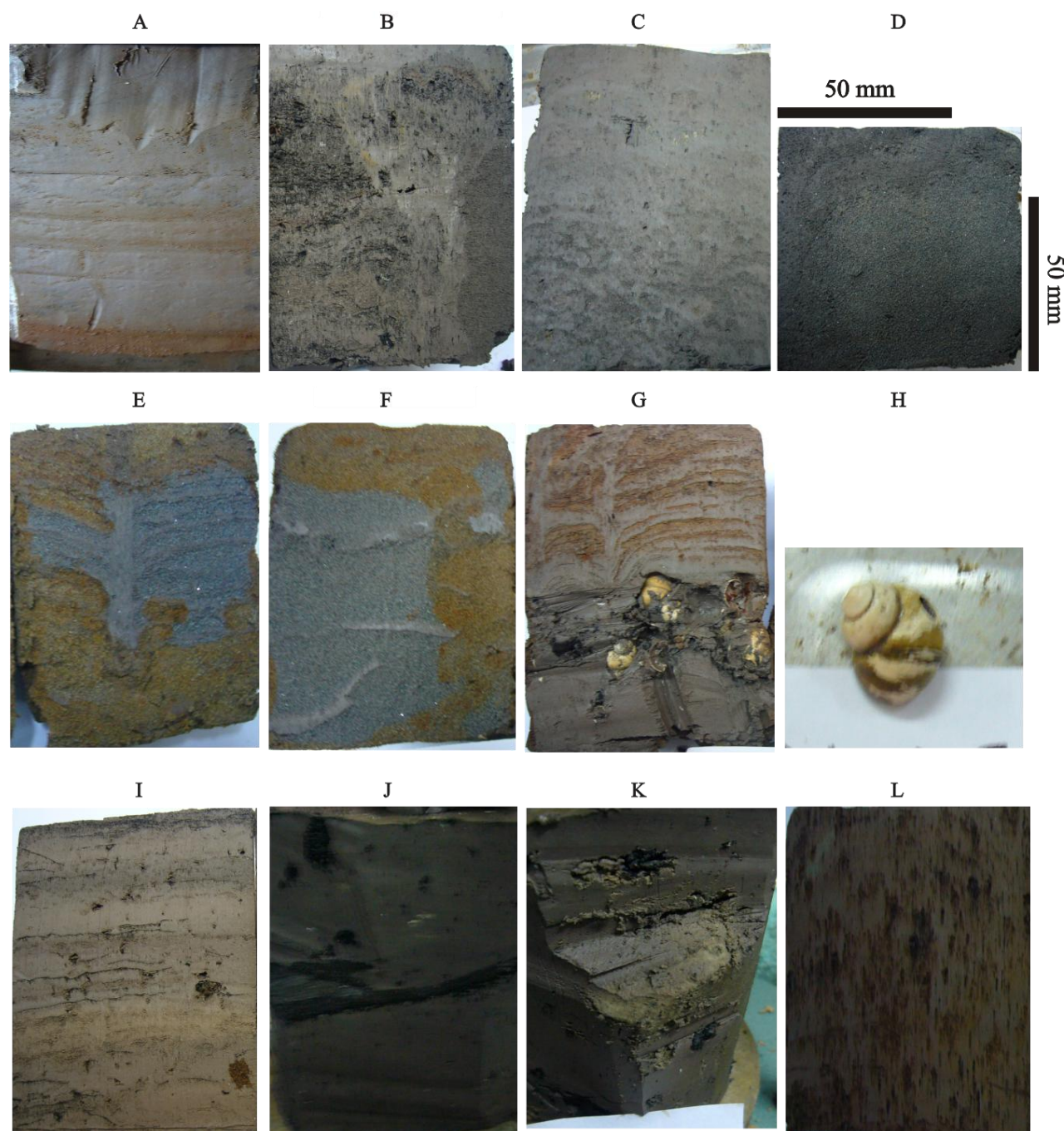


Fig. 4.4. -Selected photographs of sedimentary structures from the CLM1 core: **A)** (at depth - 34.9 m) brown seams of very fine sand silt with 8 mm in maximum thickness and gray mud seams alternated rhythmically, **B)** (-28.25 m) Peaty seams, organic material, and bioturbation, **C)** (-26.1 m) lenticular, discontinuous sand to sandy silt layers and bioturbation, **D)** (-23.8 m) lenticular laminae, mica flakes, **E)** (-16.23 m) flaser, continuous, parallel laminae, mica flakes, humus matter, and burrow, **F)** (-15.43 m), flaser, wavy, discontinuous parallel laminae, **G)** (-8.2 m) discontinuous parallel laminae, lenticular bedding, shell, burrow, organic materials, **H)** (-8.15 m) shells, **I)** (-5.7 m) discontinuous parallel laminae, lenticular bedding, organic materials, **J)** (-

2.8 m) organic materials, peaty seam, **K**) (-1.92 m) whitish gray clayey silty pebbles, 50mm diameter, and dry, organic materials, **L**) (-0.27 m) mix of silt, clay, and very fine sand, reddish, brownish, and yellowish gray, ferrallite.

Table 4.3. List of ^{14}C ages from the CLM1 core.

Altitude (m)	Materials	Delta ^{13}C (permil)	Conventional ^{14}C age (yr BP)
-7.3	Organic	-26.3	1530 $\pm$ 40
-12.02	Organic	-25.5	1960 $\pm$ 40
-21.9	Organic		6500 $\pm$ 300
-34.6	Organic	-24.8	11350 $\pm$ 60

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

Table 4.4. Results of clay mineral content analysis of argillaceous sediments of the facies from Caolanh core.

Altitude (m)	Unit	Sedimentary	Illite (%)	Kaolinite (%)	Chlorite (%)	Smectite (%)	Mixture of Illite and Smectite (%)
1.09	7	Natural levee	72.1	12.1	8.1	3.9	3.9
0.5	7		70.5	13.7	10.8	1.4	3.7
-1.7	6	Flood plain	66.5	13.7	12.5	0	7.3
-4.01	5	Intertidal flat	61.2	19.9	14	3.6	1.4
-8.95	5		66.3	15.7	14.7	0	3.2
-12.12	5		63	15.1	13.1	5	3.8
-12.22	5		57.1	15.9	13.1	4.1	9.8
-13.33	4	Delta front	65.5	16.9	10.4	4.3	2.9
-23.3	3	bay/ Prodelta	57.1	14	12	13	3.8
-23.5	3		62.9	16.5	14.4	3.7	2.6
-24.7	3		64.6	14.5	15.3	0	5.6
-25.2	3		69	9.6	12.7	0	8.7
-27.35	2	Sub- to inter-tidal flat	58.5	18.3	12.6	6.2	4.4
-27.75	2		64.9	13.6	12.8	3	5.7

There are variations in the lithology and sediment-structures of unit 3, which could be caused by the effects of higher sediment supply and/or more active hydrodynamics than previous time

when depositional environment transited from the prodelta/bay to the delta front. Smectite content changes largely from 0 to 13% (Tab. 3.4). This unit is considered relatively homogeneous in comparison with overlying unit 4.

(4) Unit 4 ($z = -21.9$ to -13.1 m)/delta front facies

In this unit, materials are commonly greenish gray fine sand with an intercalation of brownish-gray to gray clay and silt laminae in 1-5 mm thickness, in coarsening-upward succession. The clay and silt laminae are parallel, flaser, wavy and continuous or discontinuous in the core (Figs. 4.4E & 4.4F). Sand content increases upward from the lower part (-21.9 to -17.8 m) to upper part (-17.8 to -13.1 m) with about 90% (Fig. 3.3b). The shells, mica flakes, humus matter, and burrow are also scattered throughout the sediment (Fig. 4.4E). These sedimentary structures indicate strong hydrodynamic conditions mainly created by tidal currents and flooding resulting in high depositional rates. Chlorite content is smaller than the other units but unit 7 (Tab. 4.4). These features are typical characteristics of delta front facies.

(5) Unit 5 ($z = -13.1$ to -3.6 m)/intertidal flat facies

This unit contains darkish brown-gray mud with thin layers of very fine sand in a fining-upward succession, and amount of the thin sand layers and the grain size decreases from the lower part to the upper part in this unit (Figs. 4.4G & 4.4I). The sedimentary structures are parallel laminae, discontinuous parallel laminae, lenticular bedding (Figs. 4.4G & 4.4I). The shell, burrow, organic materials are plentiful (Figs. 4.4G & 4.4H). They are dated at $1,960 \pm 40$ ^{14}C yr BP at $z = -12.02$ m and $1,550 \pm 40$ ^{14}C yr BP at -7.3 m (Tab. 4.3). Kaolinite and chlorite contents of unit 5 are higher than these of overlying units 6 and 7 (Tab. 4.4). It is characterized by relatively homogeneous condition. These sediments show that this facies was formed by intertidal environment.

(6) Unit 6 ($z = -3.6$ to -0.5 m)/flood plain facies

This facies contains clayey silt to silty clay with darkish gray, brownish gray in color and no specific structure can be found in the unit. The soil contains rich organic materials with peaty seam; it contains the whitish gray clayey silty pebbles, 50 mm diameter, and dried state (Figs. 4.4J & 4.4K). Chlorite contents of unit 6 are clearly greater than those of unit 7 but smaller than unit 5. Smectite contents of unit 6 are smaller than those of unit 7 but contents of mixture of illite and smectite are greater than those of unit 7 and of upper part of unit 5 (Tab. 4.4). These characteristics show that this facies was formed by flooding.

(7) Unit 7 ($z = -0.5$ to $+2.9$ m)/natural levee facies

The sediment is generally a mixture of silt, clay, and very fine sand with reddish, brownish, and yellowish gray colors, which are typical feature of a ferrallite (Fig. 4.4L). One of important properties of this unit is high stiffness. The natural levee facies is in conformity with the characteristics of top sediments of the CLM1 core. Illite content is the highest but contents of kaolinite and chlorite are lower in comparison with the units under laid (Tab. 4.4).

4.3. Stratigraphy and sedimentary environments of reference cores

The lithostratigraphy and depositional facies of the BT1, BT2, and BT3 cores are collected from the published results of Ta et al. (2001, 2002a, and 2002b). They are represented below in summary in under items.

4.3.1. Lithostratigraphy and depositional facies of BT1 core

The sediments of the BT1 core were divided into three lithostratigraphic units to correspond with three depositional facies. They include the delta front, sub-to intertidal flat, and flood plain/marsh facies. The thickness of the late Pleistocene-Holocene sediments at BT1 core site seems to be the smallest in comparison with the other investigation core sites, 10.5 m in thickness. The characteristics of these units, corresponding depositional facies are represented below in ascending order in Fig. 4.5.

(1) Unit 1 ($z = -8.5$ to -4.0 m)/delta front facies

The delta front facies contains intercalated clayey silt, sandy silt, and very fine to fine sand, which is inhomogeneous, with several sandy layers. Some of the sandy layers are relatively thick with parallel clayey laminae (Fig. 4.5). In general, very fine to fine sands are common soil types of unit 1 (Fig. 4.5). Parallel lamination and lenticular beddings are also scattered throughout the sediment. These various sedimentary structures and grain sizes may indicate that the delta front facies was created in strong hydrodynamic conditions. This delta front facies directly covers the undifferentiated Pleistocene sediment at the BT1 core site at -8.5 m in depth.

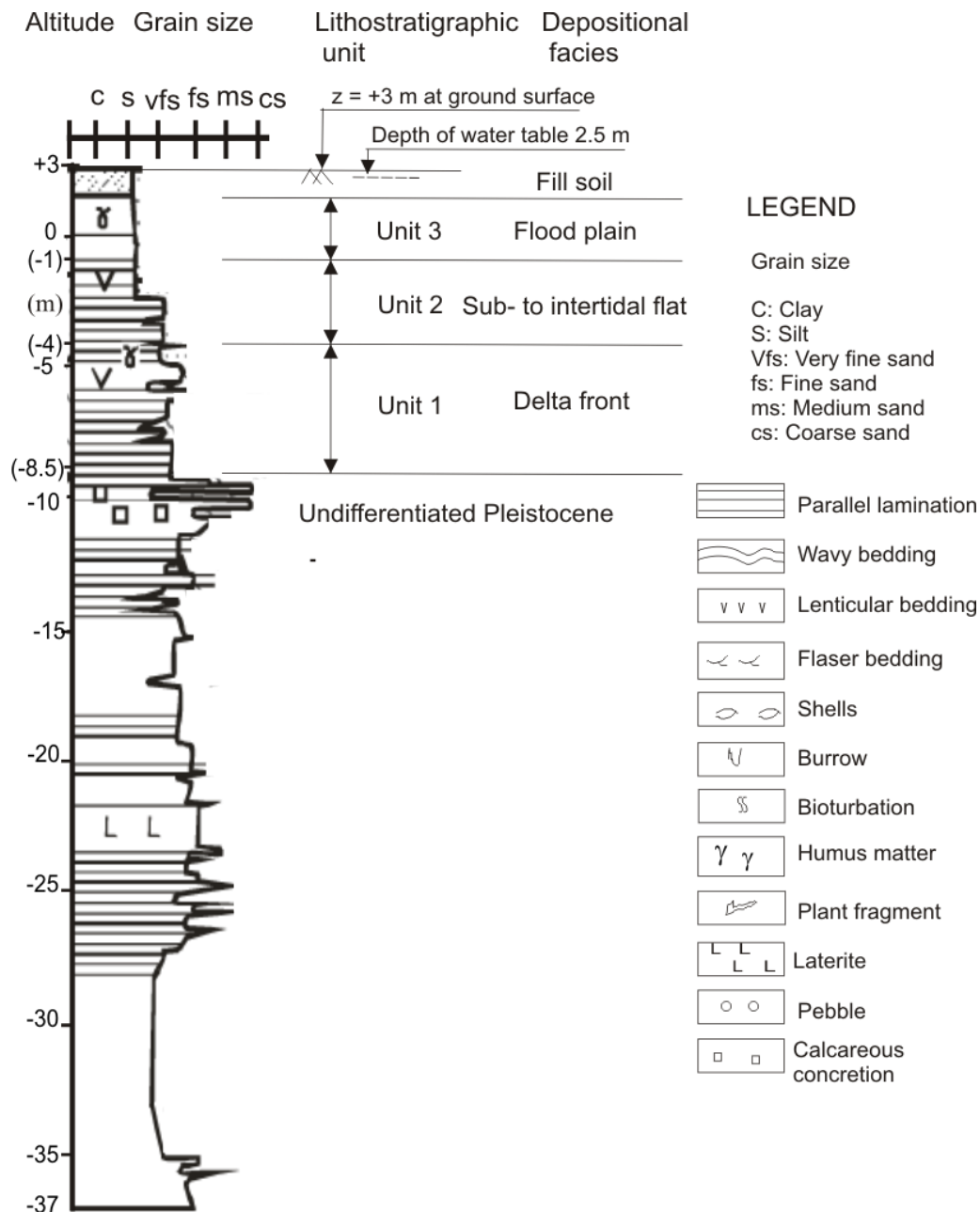


Fig. 4.5. Geological column of the BT1 core and its correlation with lithostratigraphic units (Ta et al. 2002a, and 2002b).

(2) Unit 2 ($z = -4.0$ to -1.0 m)/sub- to inter-tidal flat facies

The lower part of this facies contains very fine sand and the upper part contains clay and silt. The facies at the BT1 core displays a fining-upward succession with parallel lamination and lenticular bedding (Fig. 4.5). The sedimentary structures are not plentiful. The grain sizes are not coarse. And this facies is covered by a subaerial delta plain facies (flood plain/marsh facies).

These features of this facies are tide-influenced, and it is interpreted as a sub-tidal to intertidal flat facies.

(3) Unit 3 ($z = -1.0$ to $+2.0$ m)/flood plain facies

The sediment is dark silt and sandy silt with rich organic matter, rootles, and mica flakes. The sedimentary structures are characterized by discontinuous parallel lamination and lenticular bedding (Fig. 4.5). The facies represents an intertidal to supra-tidal flat/salt marshy deposit.

4.3.2. Lithostratigraphy and depositional facies of BT2 core

The late Pleistocene-Holocene sediments of the BT2 core were divided into eight lithostratigraphic units to correspond with eight depositional facies. The characteristics of these units, corresponding depositional facies are represented below in ascending order in Fig. 4.6.

(1) Unit 1 ($z = -69.00$ to -62.30 m: below the a.p.s.l)/estuarine channel facies

In general, this facies is inhomogeneous sediments about sedimentary structures and materials; and it was created in estuary channel/tidal river environment with oxidizing and hydrodynamic conditions. The lowest part of the core characterized by slightly oxidized yellowish grey silty sand and fine to medium sand bearing scattered quartz pebbles (10-15 mm in diameter) in the lower part (Fig. 4.6). The sedimentary structures are common lenticular bedding and parallel in the upper part of this facies. The sediments in the lower part were deposited under oxidizing and hydrodynamic conditions. The condition could be stronger than those of the upper part commonly displaying parallel laminae and lenticular bedding that were influenced by tides.

(2) Unit 2 ($z = -62.30$ to -55.0 m)/marsh facies

In general, this facies has no more sedimentary structures and almost fine materials; the sediments were deposited under relatively quiet hydrodynamic conditions. The sediments accumulated in a muddy tidal flat/salt marsh environment. The facies characterized by fining upward succession, interbedded, stiff brownish grey silty clay together with faint laminae in the lower part and is replaced by discontinuous parallel laminae in the upper part of the facies. It is dated at $11,340 \pm 115^{14}\text{C}$ yr BP at -60.87 m (Fig. 4.6).

(3) Unit 3 ($z = -55.0$ to -35.95 m)/estuarine marine facies

The sedimentary materials include intercalated yellowish grey coarse sand and greenish grey silty sand, with round to angular quartz pebbles (5-15 mm in diameter) in the lowest part of the facies (Fig. 4.6). Brownish grey sandy silt and silty clay are in the upper part of the lowest part.

An intercalated dark grey silt, silty sand and fine sand in a coarsening upward succession is in upper part of the facies. The facies characterized by parallel laminae, wavy bedding and current ripples. Small shell fragments and humus material are scattered throughout the facies. These materials were deposited in an estuarine marine environment in relation to the rise of sea level in a drowned valley formed during the last glacial episode. The facies was strongly influenced by tides. They are dated at $7,590 \pm 60$ ^{14}C yr BP at $z = -52.38$ m and $4,970 \pm 40$ ^{14}C yr BP at -35.16 m (Fig. 4.6).

(4) Unit 4 ($z = -35.95$ to -20.00 m)/open bay mud facies

In Fig. 4.6, generally, the sediments are clayey silt and sandy silt, highly homogeneous. The lower part (-35.95 to -33.50 m), sedimentary structures consist of common wavy bedding, intercalated dark grey clayey silt and sandy silt, parallel laminae, and bioturbation. The upper part (-35.50 to -20.00 m), sediment is homogenous greenish grey mud. Grain sizes are a fining-upward succession. The mud content is over 95%. The sediments accumulated in a muddy tidal flat/salt marsh environment and deposited creating open bay mud facies, under relatively quiet hydrodynamic conditions. They are dated at $5,320 \pm 80$ ^{14}C yr BP at $z = -35.10$ m and $5,210 \pm 90$ ^{14}C yr BP at -32.54 m (Fig. 4.6).

(5) Unit 5 ($z = -20.00$ to -17.00 m)/pro-delta mud facies

The sediments are common dark grey silty clay and very fine sand with coarsening upward. The sedimentary structure the lower part is in normally interbedded greenish grey silt and silty clay parallel laminae, this structure was clearly seen in the X- radiographs. The massive mud also decreases in the lower part of the pro-delta mud facies in comparison with the open bay mud facies. These considerable lithologic variation and sedimentary structures indicate that the site could be affected by a high sediment supply and/or by active hydrodynamics in comparison to the underlying bay mud (Fig. 4.6). Simultaneously, the upper part of this facies contains discontinuous and very fine sand parallel laminae indicate that the site could begin to change highly active hydrodynamics.

(6) Unit 6 ($z = -17.00$ to -8.00 m)/delta front facies

Generally, the facies characterizes an intercalated greenish grey silt, dark grey sandy silt and fine sand in a coarsening upward succession. The sedimentary structures are commonly current ripples, lenticular and wavy bedding and contorted structures. The plentiful matters and sedimentary structures may indicate strong hydrodynamic conditions by mainly tidal currents

and high depositional rates. The small shell and wood fragments, and mica flakes are scattered throughout the sediment. The measured ^{14}C age at -15.40 m is $4,590 \pm 90$ ^{14}C yr BP and at -10.20 m is $3,660 \pm 80$ ^{14}C yr BP (Fig. 4.6).

(7) Unit 7 (z = -8.00 to -2.00 m)/sub- to inter-tidal flat facies

The facies characterizes by laminated dark grey sandy silt and fine sand. The sedimentary structures are wavy bedding, parallel laminae, and contorted structures, current ripples in the lower part. The lenticular bedding and discontinuous parallel laminae are common in the upper part. And the deposits from -6.0 to -6.7 m are interbedded sand and mud which look like tidal rhythmites (Fig. 4.6).

(8) Unit 8 (z = -2.0 to +2.0 m)/sand dune facies

This facies contains darkish gray sandy mud and well-sorted greenish gray fine sand in the lower part with discontinuous parallel laminae and lenticular bedding. The lower part of this facies was created in sub-to inter-tidal/salt marshy environment. And the well-sorted yellowish brown and grey fine sand in the upper part was constituted a beach ridge (Fig. 4.6).

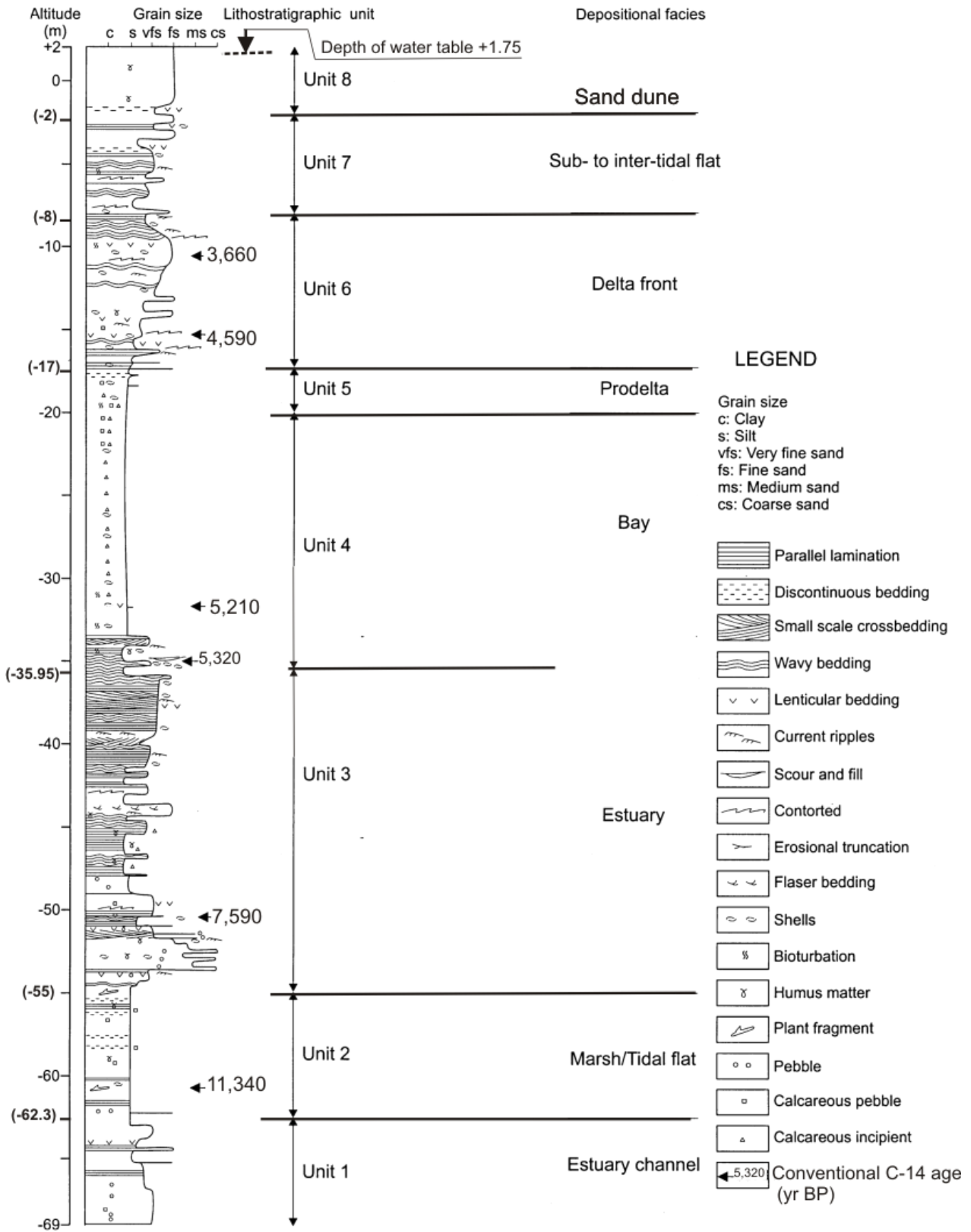


Fig. 4.6. Geological column of the BT2 core and its correlation with lithostratigraphic units (Ta et al. 2001).

4.3.3. Lithostratigraphy and depositional facies of BT3 core

The late Pleistocene-Holocene sediments of the BT3 core were divided into four lithostratigraphic units to correspond with four depositional facies. The characteristics of these units, corresponding depositional facies are represented below in ascending order in Fig. 4.7.

(1) Unit 1 ($z = -18.0$ to -15.0 m)/pro-delta mud facies

This facies characterizes a coarsening upward succession. Specially, at the lower part of the facies contains fine to coarse sand layers with large thicknesses (Fig. 4.7). The greenish gray silt layers interbedded with silty clay layers. The discontinuous and parallel lamination contains very fine sand layers in the upper part. This facies was strongly influenced by marine processes. Calcareous concretions are common. This facies is dated at $4,170 \pm 90$ ^{14}C yr BP at -18.00 m. This pro-delta facies directly covers the undifferentiated Pleistocene sediment at the BT3 core site at -20.0 m in depth.

(2) Unit 2 ($z = -15.00$ to -8.00 m)/delta front facies

The facies characterizes coarsening upward succession, intercalated greenish grey sandy silt and fine sand. The sedimentary structures are common cross-lamination, lenticular bedding, and wavy bedding (Fig. 4.7). The facies was influenced by fluvial discharge, i.e. it was created strong hydrodynamic conditions.

(3) Unit 3 ($z = -8.00$ to -2.00 m)/sub- to inter-tidal flat facies

The size grains are from sandy silt to medium sand. The sediments show a fining upward succession. The sedimentary structures are plentiful including wavy bedding, flaser bedding, cross lamination, discontinuous bedding, and parallel lamination. The facies was influenced by tides and part of waves as presented in 2.2; it was generally created strong hydrodynamic conditions. They are dated at $1,990 \pm 80$ ^{14}C yr BP at $z = -7.52$ m, $1,730 \pm 60$ ^{14}C yr BP at $z = -4.97$ m, and $1,300 \pm 90$ ^{14}C yr BP at -2.94 m (Fig. 4.7).

(4) Unit 4 ($z = -2.0$ to $+1.0$ m)/sand dune facies

This facies in the BT3 site contains well-sorted fine yellowish brown and gray sand, some rootlets and scattered shell fragments. The sedimentary structures are discontinuous parallel laminae and lenticular bedding (Fig. 4.7). The sediment facies at the BT3 site is sand dune/foreshore sand forming beach ridges.

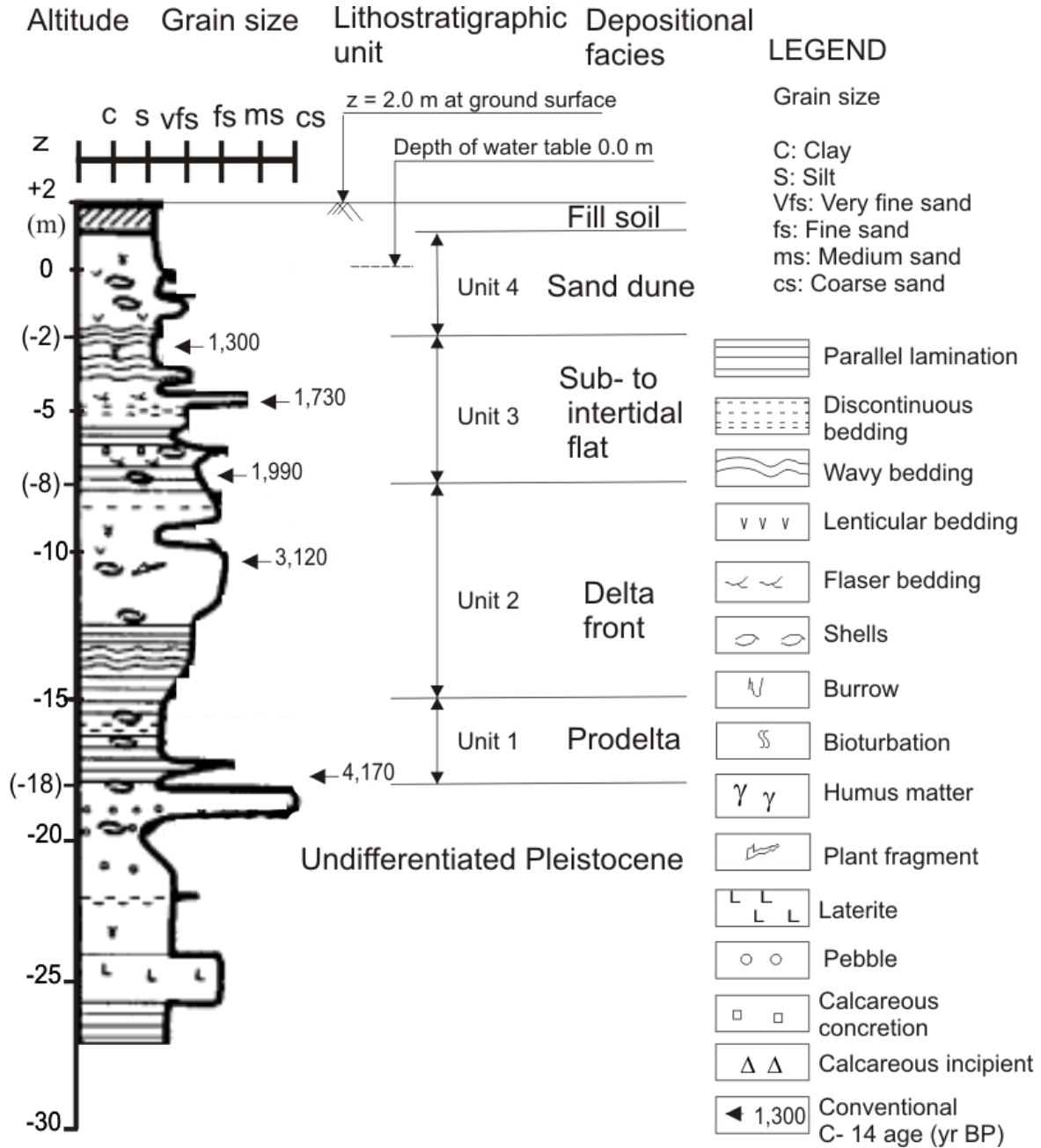


Fig. 4.7. Geological column of the BT3 core and its correlation with lithostratigraphic units (Ta et al. 2002a and 2002b).

4.4. Sedimentary facies changes and late Pleistocene-Holocene development of the delta

One sedimentary cross-section is rebuilt to base on the results of CLM1 and VLM1 cores of this study combined with three reference cores (BT1, BT2, and BT3 cores) (Ta et al., 2001, 2002a, and 2002b) as the above presentation. The sedimentary cross-section is from the upper

delta plain to the lower delta plain and perpendicular to the present coastline. This sedimentary cross-section is in Caolanh, Vinhlong, and Bentre provinces around the Mekong River and Bassac River in the MRD and illustrated in Fig. 4.8.

4.4.1. Transgressive marine stage

At the end of the last glacial maximum, the topography of the undifferentiated Pleistocene sediment-ground (basement) was not an entirely flat terrain likely to form incised-valley with different altitudes (Fig. 4.8). Namely, altitudes of basement: at CLM1 core site is -36.6 m, at VLM1 core site is -46.05 m, at BT1 core site is -8.5 m, at BT2 core site is -69 m, and at BT3 core site is -20 m. The maximum appearance-altitude of basement is at $z = -8.5$ m at the BT1 core site; the minimum appearance-altitude of basement is at $z = -69$ m at the BT2 core site; and a difference between theirs is 60.5 m (Fig. 4.8). This value indicates that the difference of basement-topography was so large. The results of VLM1 core site are compared with data of the BT2 core site in the incised valley zone (Ta et al., 2001; 2002a) and the VL1 core site in the inter fluvial zone (Ta et al., 2002b). The VLM1 and BT2 core sites began with estuarine channel sediment but the VL1 core site began with an open bay sediment at basement-altitude $z = -34.5$ m (Ta et al., 2002b). Hence, it is likely that the VLM1 core site was located in an incised valley zone; and it was in the incised-valley zone (Nguyen et al., 2010).

According to a mechanism of incision proposed by Woodroffe (1993) and Hanebuth et al. (2000) following the last glacial stage, sea level rose rapidly. From about 15,000 to 5,000 years BP, the sea-level increased continuously in the MD region by Nguyen et al. (2000). The earliest stage of water level rise at the VLM1 core site was at -46.05 m (Fig.4.1). An estuarine channel environment was formed at the VLM1 core site and began to receive sediment. The estuarine channel facies was formed and altitude obtained -41.5 m at the VLM1 core site (Fig.4.1). The earliest stage of water level rise at the CLM1 core site was at -36.6 m (Fig. 4.3). The CLM1 core site is outside but closed to the incised valley zone (Nguyen et al., 2010). According to Nguyen et al. (2010), the basement in MRD can be divided into two areas: the first area with basement-altitudes being shallower than -35 m and the second area with basement-altitudes being deeper than -45 m. The basement depth of CLM1 core site was -36.6 m, implying that the CLM1 core site could be identified in the edge of the incised valley zone. Conversely, this result could further confirm the accuracy of the incised valley zone suggested by Nguyen et al. (2010) in Fig.

2.6.

In the estuarine channel facies of the VLM1 core, the laterite pebbles are splintered and perfectly round in shape (Figs. 4.1 and 4.2A). These characteristics are reliable indicators of their origin. These laterite pebbles were formed in the last glacial stage and existing in the undifferentiated Pleistocene sediments, which were affected by high hydrodynamic activity. They then moved into the above estuarine channel sediments. These facts demonstrate the estuary channel facies unconformably overlayed the undifferentiated Pleistocene sediment. The fact that the shapes of the plant fragments are unchanged in the top part of the estuarine channel facies confirms that the water level rose rapidly with plentiful sediment-supply in this specific type of environment.

The river mouth shifted gradually landwards. The rapid transgression of the channel led to speedy horizontal translation of the shoreline that reached several tens of meters per year in Southeast Asia (Woodroffe, 1993). Because of different topographical conditions, the appearance-altitudes of the sedimentary facies at the core-sites in the MD are different (Fig. 4.8 and Tab. 4.5). The shoreline in the MRD site probably created a huge marsh environment, which is confirmed by the VLM1 core site. It can be inferred that the sea level was over -30.75 m at about $9,090 \pm 40$ yr BP and the lowest part of the marsh facies in the VLM1 ($z = -41.5$ m) yielded an age of $9,910 \pm 50$ yr BP. From these data, it can be estimated that a salt marsh environment existed at the VLM1 core site between 9,910-8,800 yr BP, the salt marsh facies was formed with a sedimentation rate of 13 mm/year (Tab. 4.2). For the CLM1 core site, the marsh/tidal flat environment was formed and began to receive the sediment at -36.6 m. It can be inferred that the sea level was over -34.6 m at about $11,350 \pm 60$ yr BP. The marsh/tidal flat facies was formed whose altitude is estimated of -32.1 m at the CLM1 core site (Fig. 4.8).

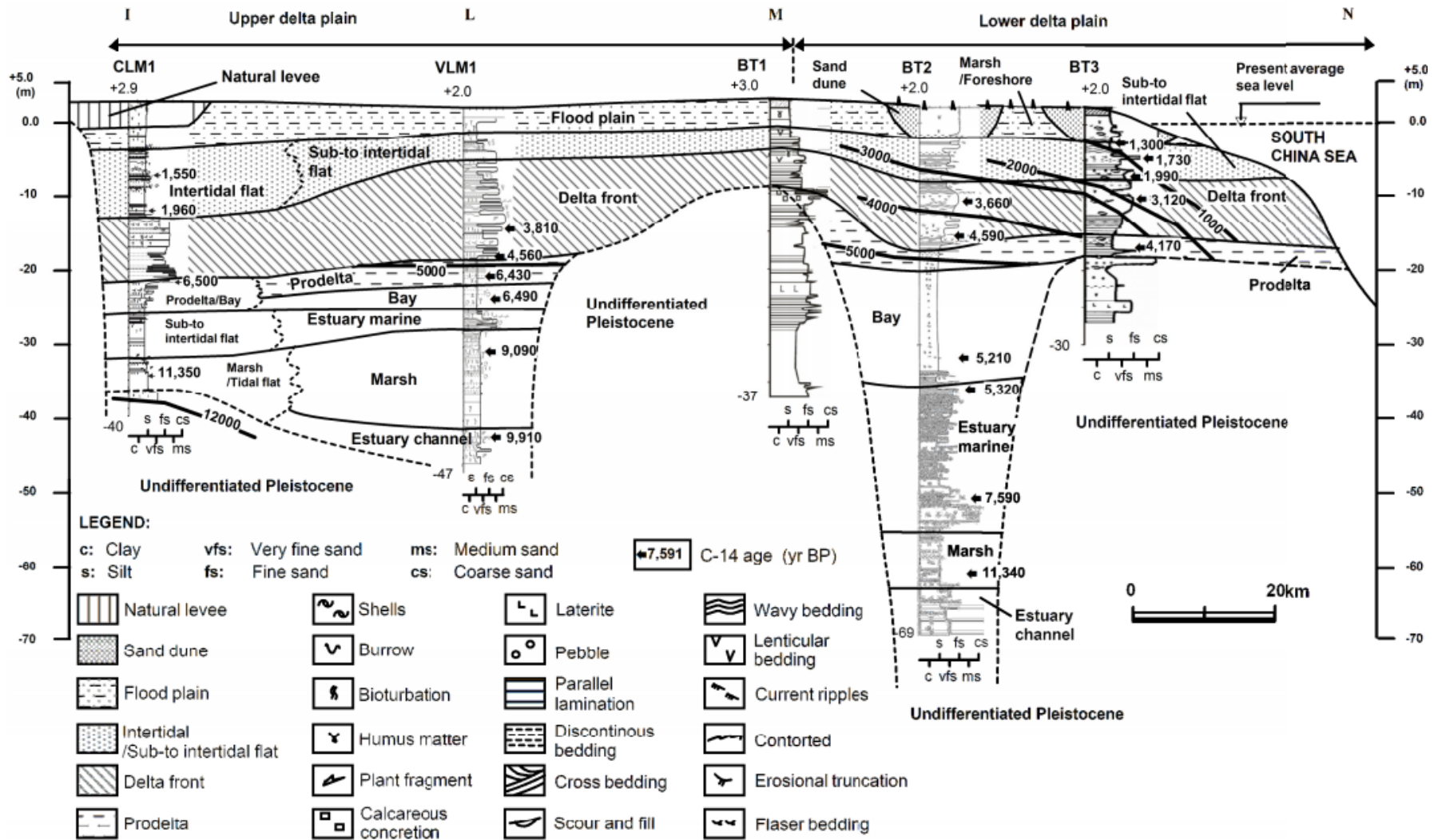


Fig. 4.8 Sedimentary cross-section is rebuilt to base on the sedimentary results of the CLM1 and VLM1 cores combined with three reference cores (Ta et al., 2001, 2002a, and 2002b).

Table 4.5.

Comparison of thickness, altitude of appearance of sedimentary facies, ^{14}C age, and altitude difference between maximum and minimum appearances of the VLM1 and CLM1 cores with BT1, BT2, BT3, VL1, and DT1 cores (Ta et al., 2002a, 2002b, 2001, and Nguyen et al., 2010).

	Mekong River Delta late Pleistocene-Holocene sediments									POST-GLACIAL SEDIMENT
	Transgressive incised-valley fill sediments				Regressive Holocene delta sediments					STAGE
Core	Estuary channel	Marsh/ tidal flat	Estuary /Sub- to intertidal flat	Bay	Pro- delta	Delta front	Sub- to intertidal flat /intertidal flat	Marsh/ flood plain/ Fore- shore	Natural levee	Facies
VLM1	-41.5	-27.8	-25	-22	-18.5	-5.5	-1.5	+1		Altitude of appearance (m)
	>4.5	13.7	2.8	3	3.5	13	4	2.5		Thickness of facies (m)
	9,910 (-41.5)	9,090 (-30.8)	6,490 (-24.9)	6,430 (-22)	4,560 (-18.5)	3,810 (-14)	-	-		^{14}C age (year BP) (at altitude (m))
CLM1	-36.6*	-32.1	-26.1	-21.9	-13.1	-3.6	-0.5	+2.9		Altitude of appearance (m)
	Base- ment	4.5	6	4.2	8.8	9.5	3.1	3.4		Thickness of facies (m)
	11,350 (-34.6)	-	-	-	-	1,550 --1,960 (-7.3)--(-12.02)	-	-		^{14}C age (year BP) (at altitude (m))
BT1	-8.5*	-8.5*	-8.5*	-8.5*	-8.5*	-4.0	-1.0	+2		Altitude of appearance (m)
	Basement					4.5	3	3		Thickness of facies (m)
										^{14}C age (year BP) (at altitude (m))
BT2	-62.3	-54.5	-35.95	-20	-17	-8	-2	+2		Altitude of appearance (m)
	6.7	7.8	18.55	15.95	3	9	6	4		Thickness of facies (m)
		13,258 (-60.9)	8,021 (-52.38)	5,578 (-32.5)	-	5,309 (-15.4)	-	-		^{14}C age (year BP) (at altitude (m))
BT3	-18.0*	-18.0*	-18.0*	-18.0*	-13.7	-8.0	-2	+1		Altitude of appearance (m)
	Basement				4.3	5.7	6	3		Thickness of facies (m)
					4,237 (-18)	1,177 (-10.09)	1,535 — 868 (-7.52)--(-2.94)			^{14}C age (year BP) (at altitude (m))
VL1	-35.0*	-35.0*	-35.0*	-24.5	-14.5	-4.5	0.0	+2		Altitude of appearance (m)
	Basement			11	10	10	4.5	2		Thickness of facies (m)
				6,111 (-33.7)	4,826 (-18.6)	3,622 (-9.96)		3,425 (+0.45)		^{14}C age (year BP) (at altitude (m))
DT1		-34.0	-24.2	-20.8	-6.9	0.0	+2			Altitude of appearance (m)
		15.5	9.8	3.4	13.9	6.9	2			Thickness of facies (m)
		11,285 (-45.87)	8,880 (-27.72)	8,439 (-23.92)	6,818 (-20.37)					^{14}C age (year BP) (at altitude (m))
	53.8	46	27.45	16	13.4	9.1	3.6	2.5		Altitude difference between maximum and minimum appearances (m)

*: undifferentiated Pleistocene sediments (basements) exist directly below the late Pleistocene-Holocene sediments.

Subsequently, sea level continued to increase, and the transgression advanced landward, resulting in the simultaneous formation of an estuarine marine environment. The estuarine marine facies was created with a sedimentation rate of 1.2 mm/year at the VLM1. For the CLM1 core site, the sub- to intertidal flat sedimentary environment was formed and the sub- to intertidal flat facies was created from $z = -32.1$ to -26.1 m (Fig. 4.8). The rate of transgression for the VLM1 core site was so rapid that it was converted into an open bay environment. The open bay facies with fining upwards succession was created with a rate of 48 mm/year at the VLM1 core site (Tab.4.2). This rate is the rapidest among all the sedimentary facies, which indicates that a maximum transgression, dated at 6,430 yr BP, occurred at the time of this open bay facies at the VLM1 core site. These data coincide with the maximum Holocene transgression at around 6,000 yr BP in the MRD (Nguyen et al., 2000). From the ^{14}C ages of $11,340 \pm 115$ yr BP at -60.87 m in the BT2 core site (Ta et al., 2001) and 6,430 yr BP at -21.95 m in the VLM1 core site, it might be said that a marine transgression succession might have occurred during the 11,500-6,400 yr BP. The VLM1 and CLM1 core sites were filled by the estuarine channel, marsh, estuarine marine, sub- to intertidal flat and open bay mud facies, which can be confirmed from the evidence about altitude-differences at the bay mud facies. At the time, the altitude-difference at the bay mud facies at the other core sites becomes smaller than those of the previous stages; it is 16 m (Tab. 4.5 and Fig. 4.8).

4.4.2. Regressive marine stage

Subsequently, a marine regression caused by the combined effects of sea level fall and high sediment supply occurred. At the VLM1 core site (Fig. 4.8), the regression began and a coarsening-upward succession in the pro-delta facies was gradually formed with very fine sand to fine laminae with a depositional rate of 1.84 mm/yr (Tab. 4.2). And about 4,170 yr BP at -18 m in the BT3 core site in the lower delta plain, the pro-delta environment began to occur and the pro-delta sediment simultaneously deposited on the undifferentiated Pleistocene sediments (Ta et al., 2002b) (Tab. 4.5 and Fig. 4.8). The marine regression continuously occurred. And the delta front environment appeared. It can seem the earliest at the CLM1 core site and the latest at the BT3 core site in the investigative profile (Fig. 4.8). From the ^{14}C ages of $4,560 \pm 40$ yr BP at -18.5 m in the VLM1 core site and $1,300 \pm 90$ yr BP at -2.94 m in the BT3 core site (Ta et al., 2002b), it might be said that a delta front succession might have occurred during the 5,000-1,200

yr BP in the investigative profile (Fig. 4.8). The coarsening-upward succession can be seen most clearly in the delta front with the fine to coarse sand in the CLM1 and VLM1 cores. In the VLM1 core, the coarse sand layers are so abundant that their thicknesses increase from 1-2 mm (at -14.8 m) to 1.3 m (at -12 m) (Fig. 4.1). The lower part of the delta front facies of the VLM1 core was formed with a rate of 6 mm/yr (Tab.4.2). The delta front facies in the VLM1 core with ages of around 3,810 yr BP at -14 m, and in the VL1 core with ages of around 3,630 yr BP at -10.0 m (Ta et al., 2002b), are consistent with the unconfirmed coastlines in the idealized model of coastal evolution during 4,500-3,000 yr BP of Nguyen et al. (2000). These data coincide with the evidence of coastal evolution in the marine regression during the 4,000-3,000 yr BP relative to the positions of the VLM1 and VL1 cores (Figs. 2.4c and 3.1). Therefore, the results of the regression stage in the VLM1 core support the model by Nguyen et al. (2000). The regression stage is estimated as 6,400-1,200 ^{14}C yr BP in the investigative profile (Fig. 4.8).

After 2,400 yr BP, the marine regression was completed and a sandy silt facies was formed in a sub- to inter-tidal flat sedimentary environment at the VLM1 core site. At the CLM1 core site, the intertidal environment occurred, and the intertidal facies with a fining-upward succession was formed with rate of 11.5 mm/yr, during 1,960-1,550 ^{14}C yr BP, at the altitude from -13.1 m to -3.6 m, (Fig. 4.3). The last phase is the development of the flood plain/marsh environments in both the CLM1 and VLM1 core sites. After the marine regression was completed, the topography of the MRD was not entirely a flat terrain likely to form marshes. The VLM1 core site was located flood basins and the flood plain/marsh facies was created from here shown in Fig. 3.1. For the CLM1 core site in the flood season, the water level rose high and overflows the banks of rivers (levees). The sediments simultaneously deposited on the area around banks. The formation-cycle per year would continuously occur and produce a natural levee facies. The natural levee facies was formed at the top of the CLM1 core with so small age, less than 1,550 yrs BP; the altitude obtained +2.9 m (Fig. 4.3). The altitude differences at the other core sites decrease with time as shown in Table 3.5. At the present, marsh/flood plain or marsh/foreshore facies, the altitude-differences at the other core sites becomes very smaller than those of the previous stages; it is only about 2.5 m (Tab.4.5 and Fig. 4.8).

The late Pleistocene-Holocene developments at the VLM1 and CLM1 core sites are inherently a continuous natural process. The appearances and changes in the late Pleistocene-Holocene sedimentary facies are according to positions of the core site in the MRD as shown in

Fig. 4.8. The late Pleistocene-Holocene sediment facies were created with different depositional speeds for example at the VLM1 core sites (Tab. 4.2). They also follow normal sedimentary laws; i.e., in the marine transgression, the trend is fining upwards; and in the marine regression, a trend is coarsening upwards. The sedimentary environments that created each sedimentary facies are different, but sometimes reciprocally affected to some extent, especially at the beginning and the ending of each sedimentary environment. As a result, the sedimentary facies formed often display somewhat differences at bottom and top parts of the facies but they still carry the sedimentary facies' main characteristics, like the marsh and pro-delta facies. If sedimentary environment changed rapidly, sedimentary facies formed will be entirely different from the previous one, like estuarine marine and the delta front facies (Fig. 4.8).

4.5. Changes in sedimentary structures and materials of MRD late Pleistocene-Holocene sediments

The late Pleistocene-Holocene sediments at the investigated sites unconformably overlay the undifferentiated Pleistocene sediments as follows: The VLM1 core was formed in the incised valley zone and started at -49.6 m depth. The CLM1 core was formed in the edge of the incised valley zone and started at -37.5 m depth. The BT2 core was formed in the incised valley zone and started at -69.0 m depth. The VLM1 core site located in the lower area of the upper delta plain (Fig. 3.1) and the top layer was the marsh/flood plain facies with silt, clay, and sand. The CLM1 core site located in the upper area of the upper delta plain (Fig. 3.1) and the top layer was the natural levee facies with stiff silt, clay. The BT1 core site located in the border between the upper delta plain and lower delta plain (Fig. 3.1) and the top layer was the flood plain/marsh facies. The BT2 core site located in the center area of the lower delta plain (Fig. 3.1) and the top layer was the beach ridge facies with sand. The BT3 core site located in the lower delta plain and current coast (Fig. 3.1), and the top layer was the beach ridge facies with sand.

4.5.1. Transgressive incised-valley-filling sediments

The estuary channel and estuary marine facies creating in the high dynamic hydrological conditions and strongly influenced by tides have plentiful sedimentary structures including discontinuous laminae, parallel laminae, parallel and lenticular beddings, wavy bedding, and

flaser bedding. And their grain sizes are clay, silt, and common fine to coarse sands (e.g., VLM1 and BT2 in Fig. 4.8). The coarsening in upward succession is in the estuary marine facies. Specially, the estuary channel facies contains scattered laterite (5-10 mm in diameter) and angular quartz (maximum 15 mm in length) pebbles, and slightly oxidized.

The marsh, tidal flat, sub- to intertidal flat, bay facies (called transgressive sediments) creating in the relatively quiet hydrological conditions have simply sedimentary structures including faint, parallel, and discontinuous beddings. And their grain sizes are common clay, silt, and discontinuous and very thin fine sand bedding (e.g., CLM1, VLM1 and BT2 in Fig. 4.8). Specially, the bay facies are mud content over 95%, quiet hydrological conditions and by slight tidal influences. The grain size distribution shows a fining-upward succession.

There is a small difference between the geological columns of CLM1 with VLM1 and BT2 core sites (Figs. 4.8) such as: The marsh facies of CLM1 core had more intercalations of thin sand-layers than VLM1 and BT2 cores (Fig. 4.8). And the sub- to intertidal flat facies replaced the estuary marine facies in CLM1 core (Fig. 4.8). Causes of the differences may be due to CLM1 core site was closer to the source of material supply of the Mekong River system than VLM1 and BT2 core sites (Fig. 3.1); and the CLM1 core site was in the edge of the incised valley zone and more influenced by tidal but the VLM1 and BT2 core sites in the incised valley zone at the time period as the above discussion in 4.3. These can be characteristics of early Holocene sedimentary facies in the inner region of the upper delta plain.

4.5.2. Regressive Holocene delta sediments

The prodelta, intertidal flat and flood/marsh facies creating in the relatively quiet hydrological conditions have simply sedimentary structures including massive mud, discontinuous parallel laminated mud, and many parallel laminated very fine sand seams. And their grain sizes are common clay, silt, and fine sands in the thin seams.

The delta front, sub- to intertidal flat facies creating in strong hydrodynamic conditions have plentiful sedimentary structures including commonly current ripples, lenticular and wavy bedding and contorted structures. Their plentiful matters are common fine to coarse sand, and silt clay.

The regressive Holocene delta facies successions in the CLM1 and VLM1 cores in the upper delta are also typical tide dominated delta proposed by Ta, et al., 2005 as presented in 2.2. The

coarsening-upward succession from bay to prodelta to delta front and to lower part of the sub- to intertidal flat facies (called subtidal) can realize in the CLM1 and VLM1 cores (Fig. 4.8). The coarsening-upward succession from the open to inner bay can also realize in the bay facies of the VLM1 and BT2 core sites to the prodelta/bay facies of the CLM1 core site. The progradation and accumulation rates in tide dominated delta possibly occurred relatively rapidly at the CLM1 core site. The CLM1 core site closer to the source of material supply of the Mekong River system may also be cause of high accumulation rates. Therefore, the prodelta/bay facies of the CLM1 core have many sand seams and we cannot differ between the prodelta facies and bay facies of the CLM1 core as those of the VLM1 and BT2 cores (Fig. 4.8). The delta front facies of CLM1 core is almost sand in comparison with one of VLM1 core (Figs. 4.8). The fining-upward sub- to intertidal flat facies overlain directly the delta front facies of CLM1 and VLM1 cores is typical of the tide-dominated delta (Ta, et al., 2005). The grain sizes of the sub- to intertidal flat and inter-tide flat facies of the CLM1, VLM1, and BT1 cores in the tide dominated delta are less than those of the BT2 and BT3 cores in the tide and wave dominated delta (Fig. 4.8) (Ta, et al., 2005). Finally, the fining succession of the muddy flood/marsh and nature levee facies in the upper most part of the CLM1, VLM1, and BT1 cores in the upper delta is also typical of the tide-dominated delta (Ta, et al., 2005). The grain sizes of the muddy flood/marsh and nature levee facies of the CLM1, VLM1, and BT1 cores in the tide dominated delta are also less than those of the BT2 and BT3 cores in the tide and wave dominated delta (Fig. 4.8).

In general, there are changes in sedimentary materials (about the grain size and composition of clays minerals) from the upper to the lower delta plain. It can be by different influences of tide and wave and being closer to the source of material supply of the Mekong River system.

The contents of clay mineral types of the all sedimentary facies of the CLM1 and VLM1 cores were generally in descending order from the illite, kaolinite, chlorite, smectite. The illite contents are the largest, over 44%, in comparison with the other mineral contents in the all sedimentary facies. One possible cause could be due to the material-source from the Mekong River system. Zhifei et al. (2004) reported that the high contents of illite, kaolinite, and chlorite, and low content smectite in the metamorphic and granitic parent rocks and the surface soils; which occurred because of physical erosion and chemical weathering in the Tibetan Plateau, Vientiane, and MRD along the Mekong River system to the Southwest slope of the East Sea in the interglacial, glacial, and post-glacial stages of the Pleistocene-Holocene periods. The

distributions of these clay minerals in the MRD late Pleistocene-Holocene sediments in this study are similar to those in the report of Zhifei et al. (2004). The contents of illite and of mixture of illite and smectite of CLM1 core are larger than those of VLM1 core, but the smectite contents generally increased in VLM1 core. The illite content in the natural levee facies is largest in comparison with the illite contents in the other facies, and they are more than 70% (Tabs 4.1 and 4.4). Cause may be due to the specific gravity ($G_s=2.8$) of the illite is greater than these of the others; for this reason, the illite settled on the area around the banks, and also did not go far. So, the illite content in the natural levee facies was high, and there are the differences of mineral contents between the CLM1 and VLM1 cores. And these could also be characteristics of the MRD late Pleistocene-Holocene sediments.

The appearances and changes of the sedimentary facies of the CLM1 and VLM1 cores in this study are generally similar to those of the reports of Ta et al. (2001; 2002a; 2005), and Nguyen et al. (2005) in the MRD. The sedimentary facies and their appeared depths of the CLM1 and VLM1 cores and those of the collected cores including BT1, BT2, BT3, DT1, VL1, TC1, TV1, VC1, CD1, GC1, and CM1 of Ta et al. (2001; 2002a; 2005), and Nguyen et al. (2005) in the MRD are shown in Fig. 4.9, and counted in Tab. 4.6.

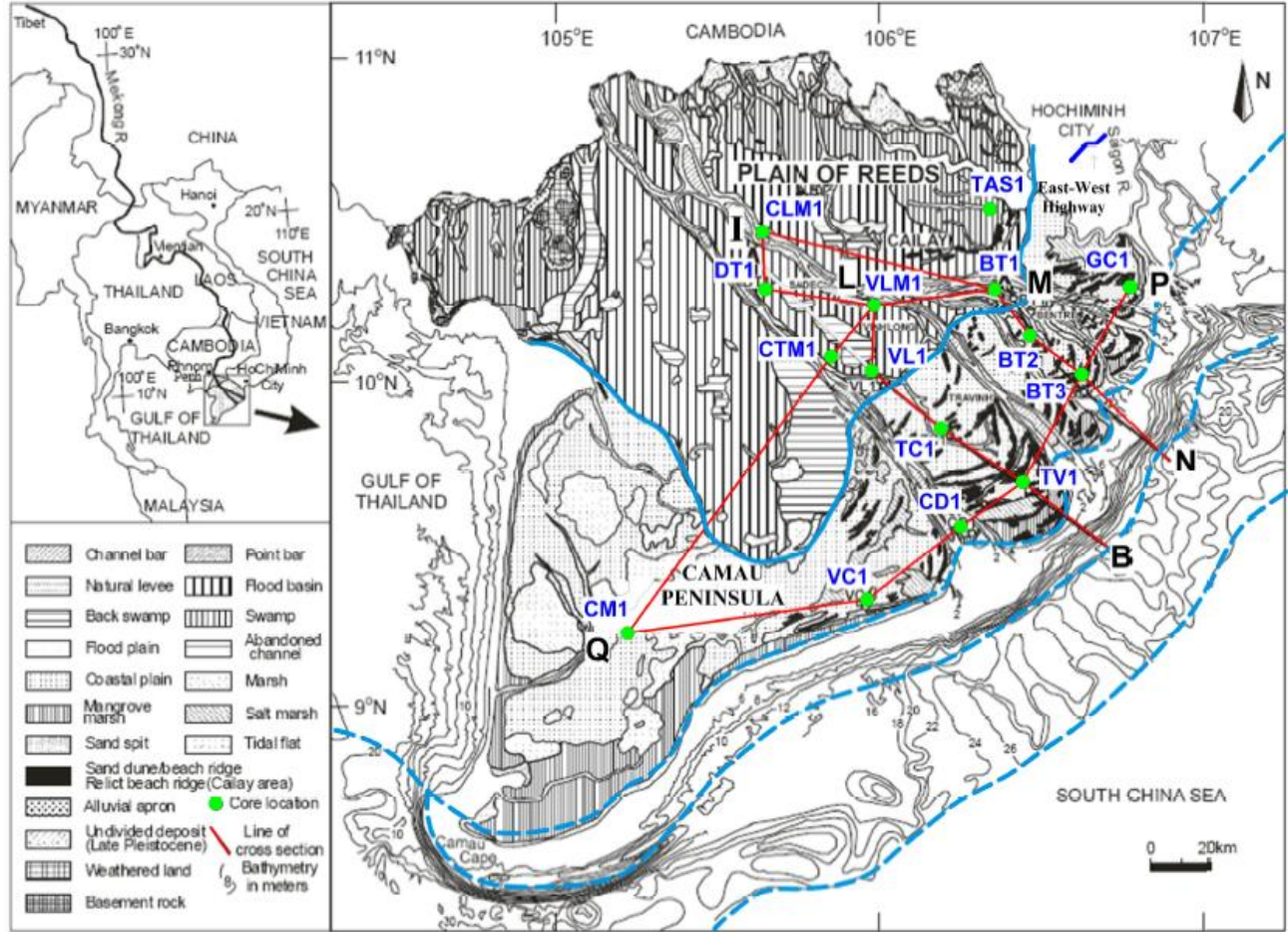


Fig. 4.9. Investigative core sites: CLM1, VLM1 in this study. Core sites: BT1, BT2, BT3, DT1, VL1, TC1, TV1, VC1, CD1, GC1, and CM1 (Ta et al., 2005 and Nguyen et al., 2004). TAS1 and CTM1 core sites (Takemura et al., 2007). Plan layout of core sites of a soil structure model with cross sections ILB, IMN, QBP, and LQ. Sedimentary map of Mekong River Delta (Ta et al., 2005).

Table 4.6. Information of sediment facies of core sites in this study and collected core sites (Ta et al., 2001; 2002a; 2005; and Nguyen et al., 2005).

Site information				Sedimentary facies										Undiffer- entiated Pleistocene sediment	
Bore- hole (core)	Location			Natural levee	Flood plain	Sand dune/ Marsh	Sub- to inter- tidal flat	Delta front	Pro- delta	Bay	Estuary marine	Marsh	Estuary channel		
Symbol	Latitude (N)	Longi- tude (E)	Alti- tude (m)	Appear from... to... (m)										Appear at... (m)	
CLM1	10°27’39.5”	105° 38’ 20”	2.9	2.9 to 0.5	-0.5 to -3.6		-3.6 to -13.1	-13.1 to -21.9	-21.9	to	-26.1	-26.1 to-32.1	-32.1 to -36.6		-36.60
VLM1	10° 14’ 2”	105° 59’ 8”	1		1 to -1.5		-1.5to -5.5	-5.5 to -18.5	-18.5 to -22	-22 to -25	-25 to -27.8	-27.8 to -41.5	-41.5 to -46		-46.05
CTM1	10°4’23.14”	105° 51’ 9.2”	1.4		1.4 to -1.6		-1.6 to -7.7	-7.7 to -15.2	-15.2 to -19.6	-19.6 to 5.7					-25.70
CM1	9° 12’52.3”	105° 13’28.9”	1			1 to 0	0 to -2.5	-2.5 to -12	-12 to -20.5						-20.50
BT1	10 ⁰ 17’ 01”	106 ⁰ 21’ 34”	3		3 to -1.5		-1.5 to -4.5	-4.5 to -9							-9.00
BT2	10 ⁰ 08’ 18”	106 ⁰ 28’ 07”	2			2 to -2	-2 to -8	-8 to -17	-17 to -20	-20 to -35.9	-35.9 to -54.5	-54.5 t -62.3	-62.3 to -69		-69.00
BT3	10 ⁰ 01’ 05”	106 ⁰ 37’ 44”	2			2 to -2	-2 to -8	-8 to -15	-15 to -20						-20.00
DT1	10 ⁰ 17’02”	105 ⁰ 38’ 51”	2		2 to 0		0 to -6	-6 to -15	-15 to -19.4	-19.4 to -22	-22 to -26	-26 to -49.5			-49.50
VL1	10 ⁰ 01’46”	105 ⁰ 58’ 42”	2		2 to 0		0 to -5	-5 to -14.5	-14.5 to-23.5	-23.5 to -35					-35.00
TC1	9° 41’04”	106 ⁰ 26’ 48”	2			2 to -1.2	-1.2 to -5	-5 to -12.5	-12.5 to -19.5						-19.50
TV1	9° 51’04”	106 ⁰ 11’ 37”	0.8			0.8 to 0	0 to -6.5	-6.5 to -15	-15 to -20						-20.00
VC1	9° 19’13”	105° 57’ 54”	2			2 to -1	-1 to -4	-4 to -11	-11 to -16.5						-16.50
CD1	9° 32’51”	106 ⁰ 15’ 16”	2			2 to -1	-1 to -8	-8 to -14.5	-14.5 to -19.4						-19.40
GC1	10 ⁰ 17’27”	106 ⁰ 46’ 37”	1			1 to -1	-1 to -5	-5 to -10	-10 to -14.5						-14.50

4.6. In-situ geotechnical test results

4.6.1. Vinhlong site

Measured quantities of the cone penetration tests (CPTU1-VL and CPTU2-VL) named sleeve friction, f_s , cone resistance, q_t , and pore water pressure measured behind the cone tip, u_2 , and together with the standard penetration tests (SPT-VL) are shown in Figs. 4.10 and 4.11. A typical soil profile can be identified by soil-behavior-type classification using the above normalized values from Equation 3.1 to 3.3 and charts (Fig. 3.9) (Robertson 1990 and 1991). The depth variations in the normalized values obtained from the CPTU1-VL and CPTU2-VL are shown in Fig. 4.12. The soil-behavior types estimated from the relationship between Q_t and F_R in classifications charts (Fig. 3.9) (Robertson, 1990 and 1991) are shown in Figs. 4.10b and 4.11a. The soil-behavior types estimated from the relationship between Q_t and B_q were almost the same as those estimated from the Q_t - F_R relationship. The values of t_{50} , c_h , and c_v calculated from the results of pore water pressure-dissipation test at -7.91 m, -13.5 m, and -19.49 m during CPTU1-VL at the Vinhlong site are shown in Figs. 4.16.1-3.

To consider the results of the CPTU1-VL, CPTU2-VL, and SPT-VL at the Vinhlong site in Figs. 4.10, 4.11, 4.12, and 4.13. At -47.8 m, the N value and q_t value increase greatly (Fig. 4.10a and c). Although the penetration machine used for the investigation could not penetrate through this layer since its capacity limit was already reached. And then, from -49.6 to -60 m, N values suddenly increase to over 50 (Fig. 4.10a). Hence, at around $z = -47.8$ m is a boundary between two consecutive sediment-sequences with very clearly different strengths. The sediment-sequence with the low strengths located above $z = -47.8$ m to the ground surface; and the sediment-sequence with the so high strength located below $z = -47.8$ m (Fig. 4.10).

The soil profile from -47.8 m to the ground surface at the Vinhlong site is divided into 8 sublayers based on the results of the CPTU1-VL, CPTU2-VL, and SPT-VL; and presented in ascending order such as:

To base the CPTU and SPT results, the sublayer located above $z = -47.8$ m is identified from -47.8 to -41.5 m. This sublayer is called to be the sublayer 1. The sublayer 1 is characterized by the normalized values of Q_t , F_R and B_q varying largely (Fig. 4.12). Soil-behavior-type from the normalized values includes various types such as clays-clay to silty clay, silt mixture-clayey silt to silty clay, and sand mixtures-silty sand to sandy silt (Figs. 4.10b and 4.13a). Simultaneously,

N value on the sublayer 1 also increases from 3 to 25 at around $z = -47.8$ m (Fig. 4.10a).

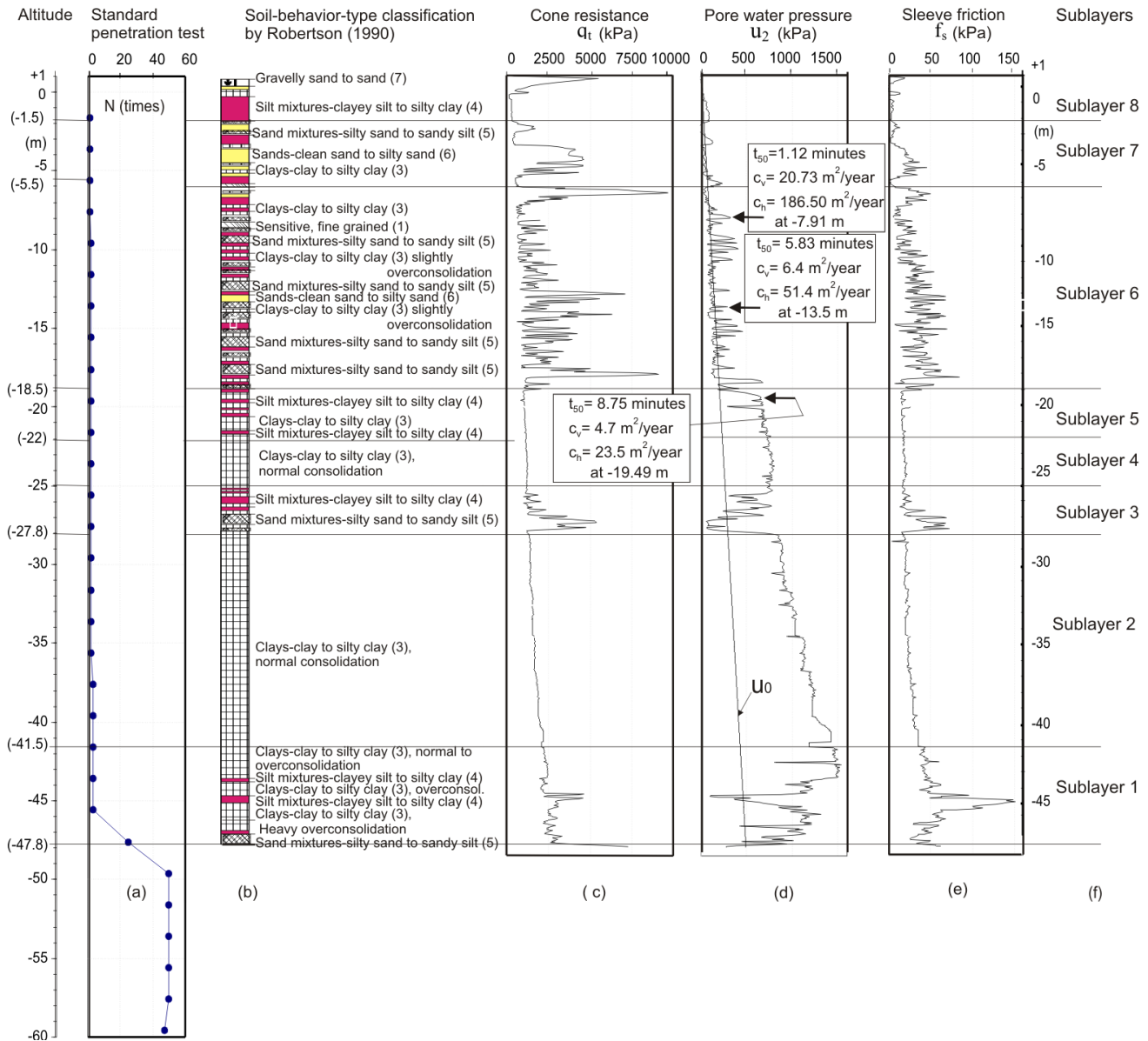


Fig. 4.10. Results of the *in situ* tests at the Vinhlong site: From SPT-VL: (a) N value. From CPTU1-VL: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , in addition, requisite time, t_{50} , for dissipating 50% of pore water pressure, and values of c_v and c_h calculated from t_{50} at the each depth, (f) sublayers divided based on the results of CPTU1-VL and SPT-VL.

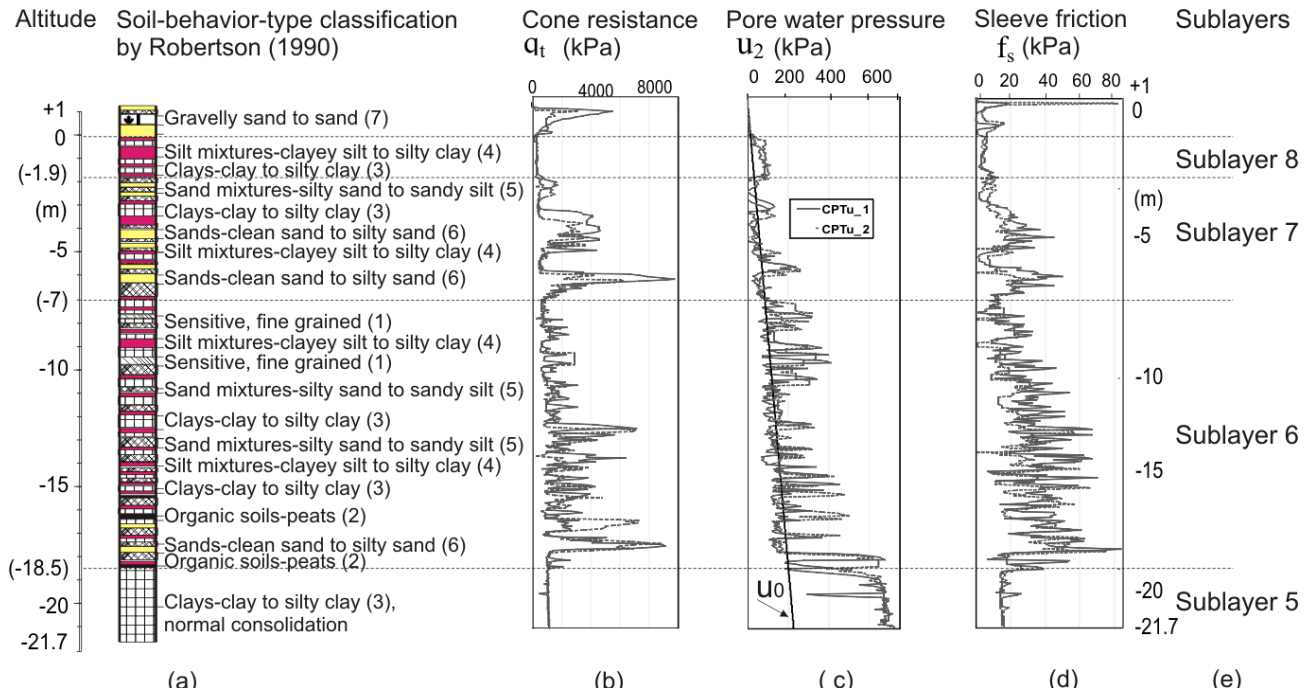


Fig. 4.11. Results of the CPTU2-VL at the Vinhlong site: (a) soil-behavior-type classification by Q_t and F_R , (b)–(d) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , of CPTU2-VL compared with those of CPTU1-VL.

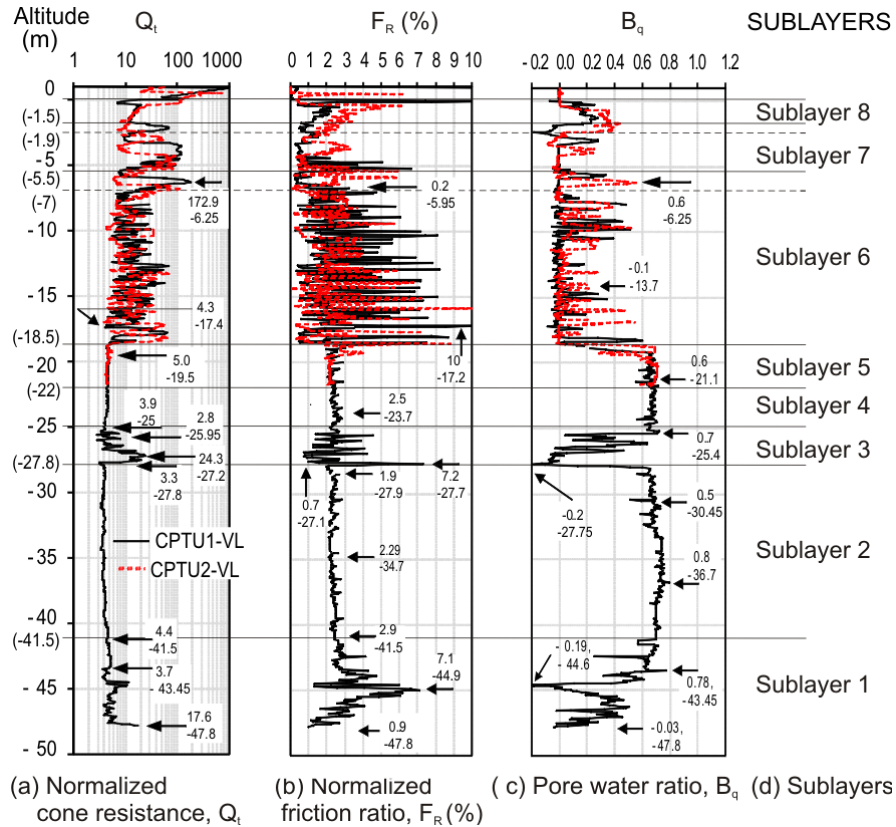


Fig. 4.12. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU1-VL and CPTU2-VL at the Vinhlong site.

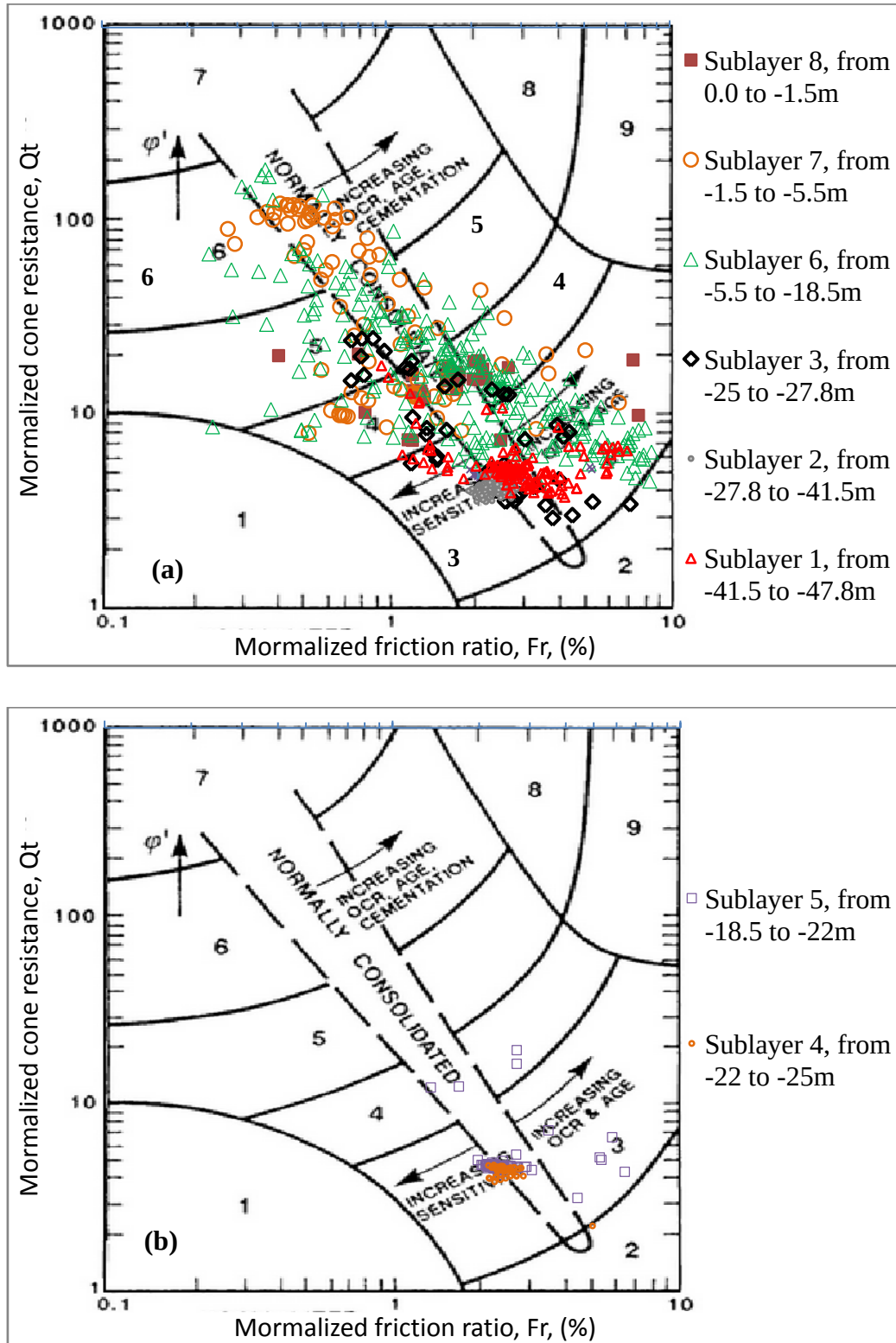


Fig. 4.13. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained by CPTU1-VL at Vinhlong site: (a) Sublayers 1, 2, 3, 6, 7, and 8; (b) Sublayers 4 and 5.

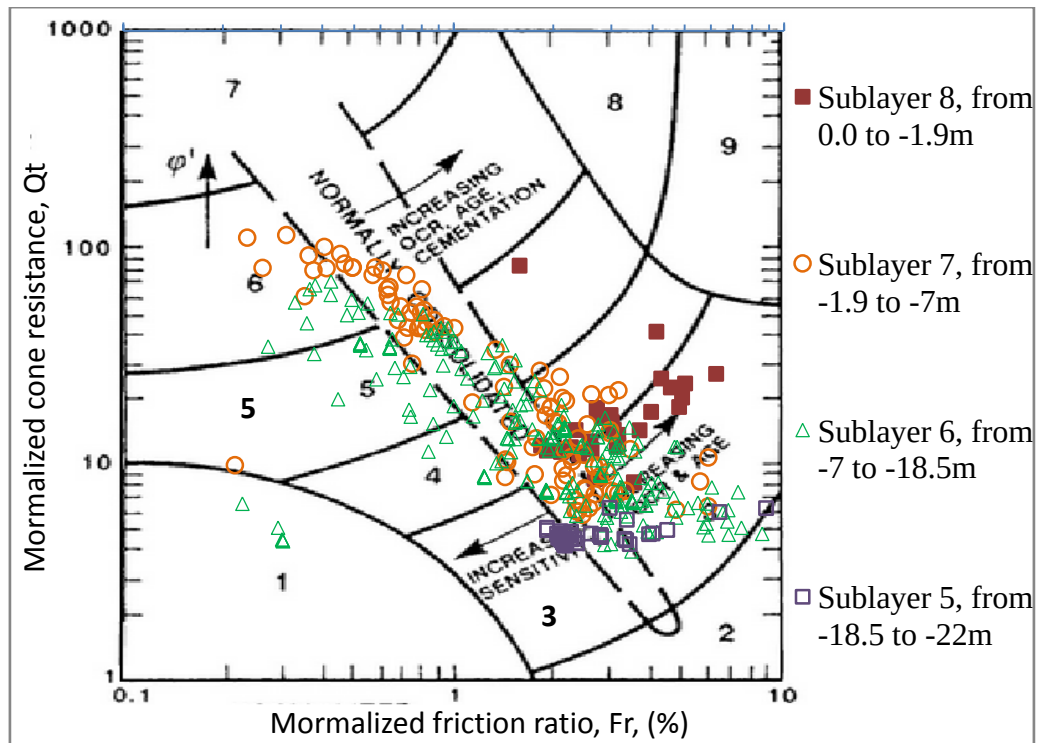


Fig. 4.14. Soil-behavior-types of each sublayer by classifications chart Q_t - F_r (Robertson, 1990), obtained from CPTU2-VL at the Vinhlong site: Sublayers 5 to 8.

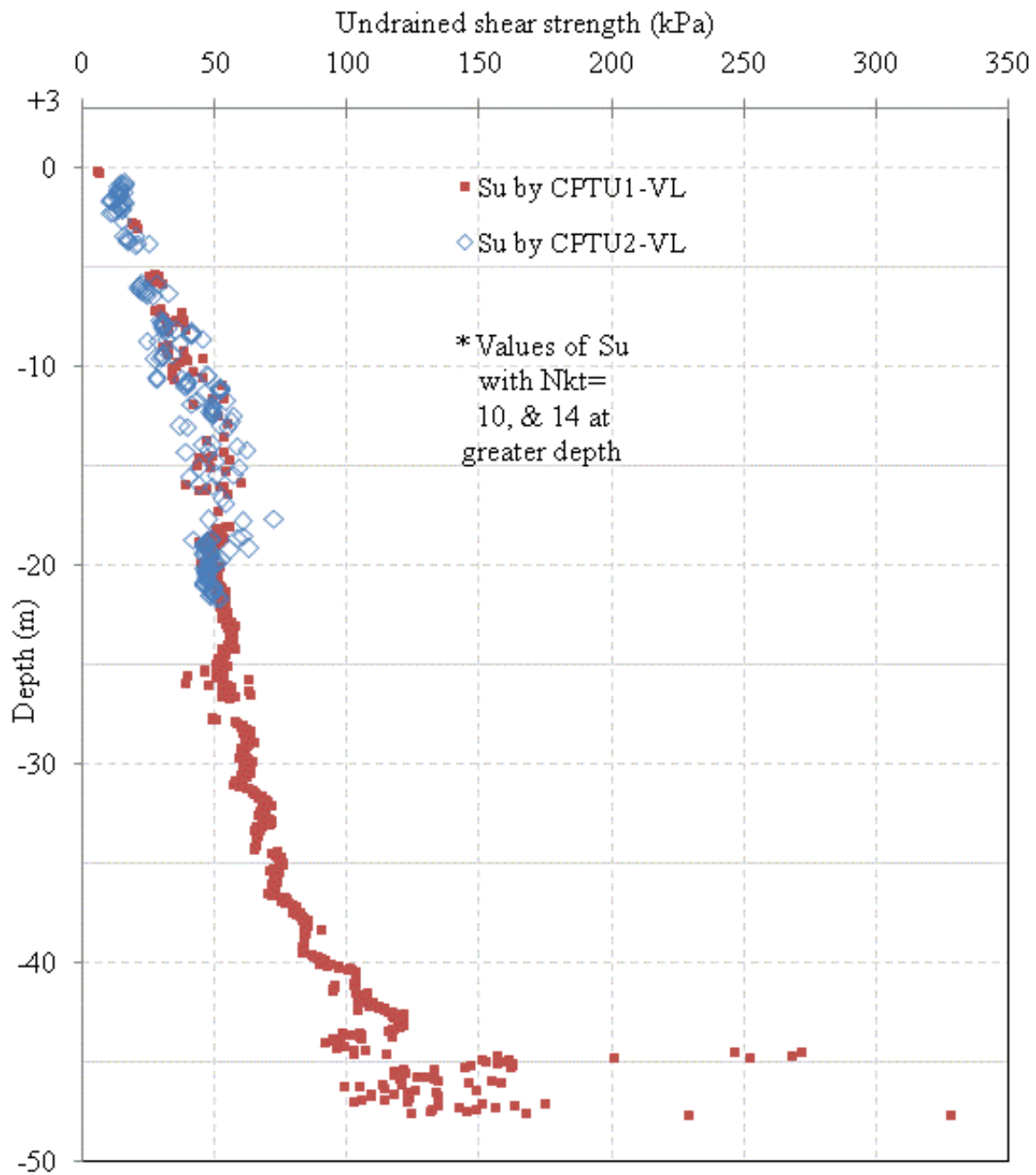


Fig. 4.15. Undrained shear strengths vs. depth obtained from CPTU1-VL and CPTU2-VL at the Vinhlong site.

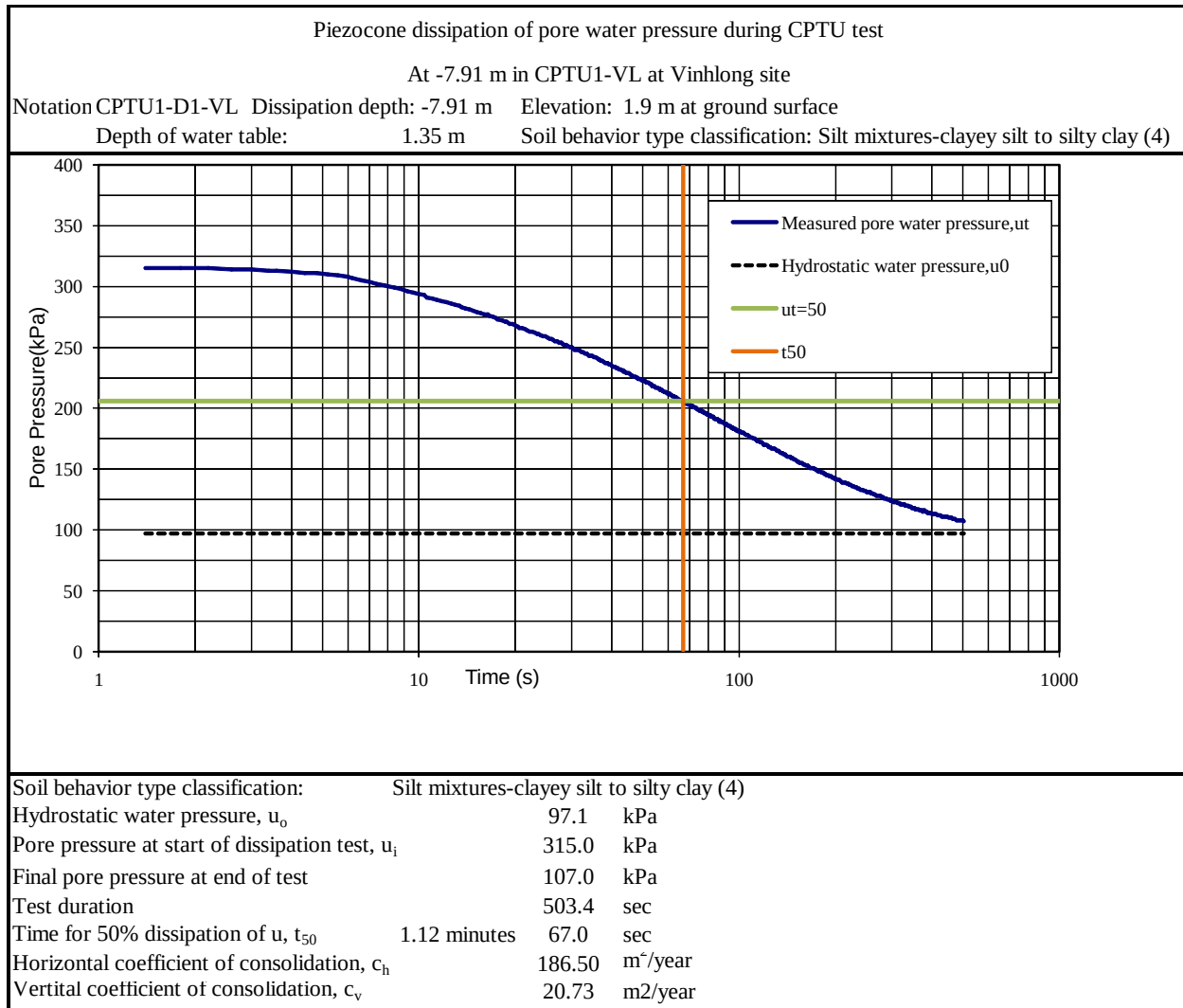


Fig. 4.16.1. Results of pore water pressure-dissipation test at -7.91 m during CPTU1-VL at the Vinhlong site.

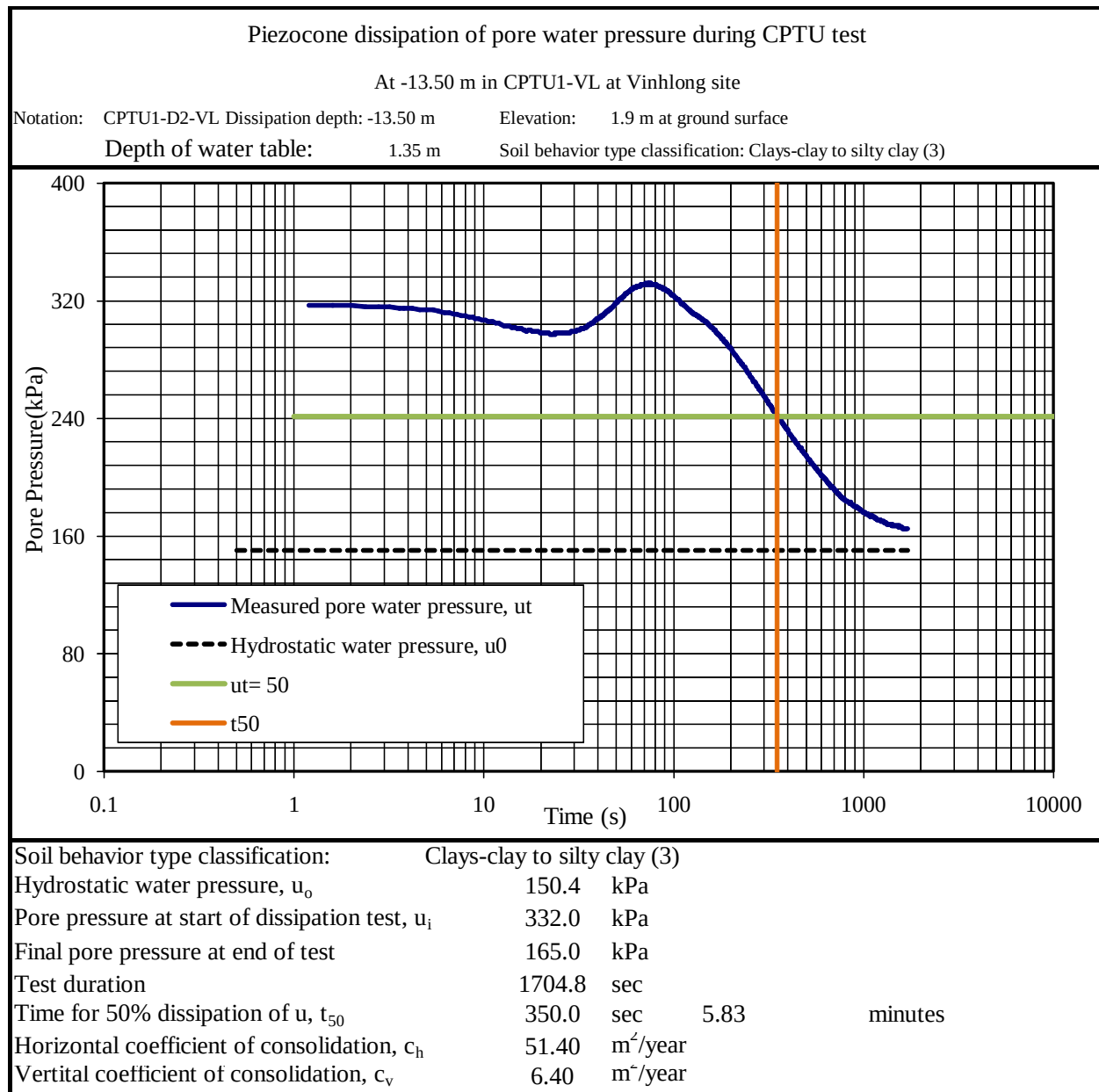


Fig. 4.16.2. Results of pore water pressure-dissipation test at -13.5 m during CPTU1-VL at the Vinhlong site.

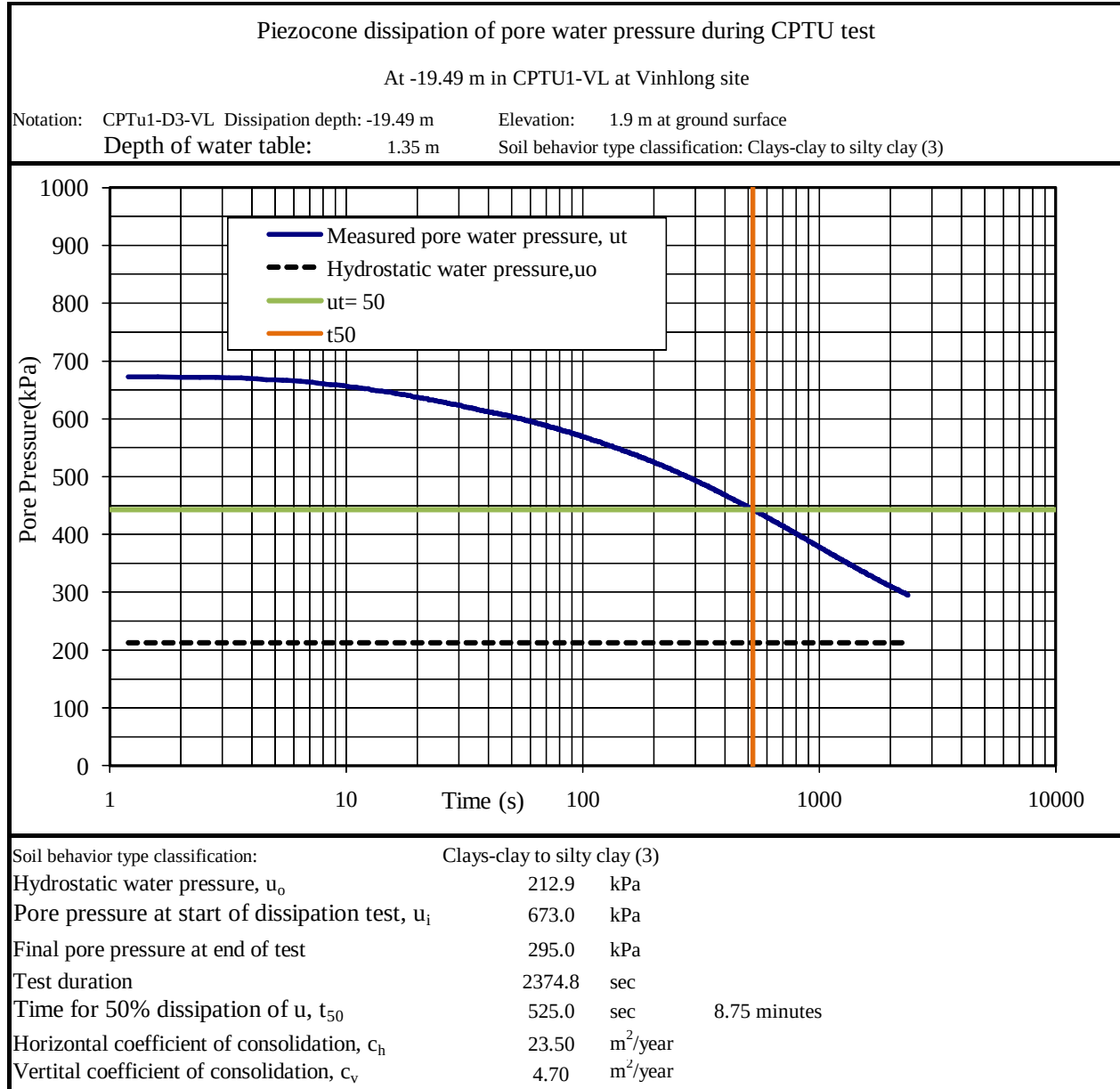


Fig. 4.16.3. Results of pore water pressure-dissipation test at -19.49 m during CPTU1-VL at the Vinhlong site.

We consider the sublayer 2 (from -41.5 to -27.8 m). On the results of CPTU1-VL, values of Q_b , F_R and B_q are all rather constant with depth (Fig. 4.12). Soil-behavior-type of the sublayer 2 is only clays-clay to silty clay (Figs. 4.10b and 4.13a). The increase of q_b , u_2 , and f_s are linear with depth (Figs. 4.10c-e). The CPTU1-VL results on the sub-layer 2 are so clearly different with those of the sublayer 1 and sublayer 3. But, the SPT-VL results on the sublayer 2 are not clearly different with the sublayer 1 and sublayer 3. Namely, the SPT-VL results on the sublayer 2 (Fig. 4.10a): Form -27.8 to -37 m, the N-values are very small and do not increase, regularly equal 2 at

each location of the SPT-VL test. Or the N values increase with a little quantity in the range of -37 to -41.5 m and then regularly equal 3 (Fig. 4.10a). The sublayer 2 is characterized by highly homogeneous.

The sublayer 3 (from -27.8 to -25.0 m), on the CPTU1-VL results, the normalized values vary considerably (Fig. 4.12) and the identified soil behavior-types are normally consolidated to slightly overconsolidated clay to silty clay, slightly sensitive silt mixtures of clayey silt to silty clay, and slightly sensitive sand mixtures of silty sand to sandy silt (Figs. 4.10b and 4.13a). But, the SPT results on the sublayer 3 are not different with those of the sub-layer 4 and of the upper part (from -27.8 to -37 m) of the sublayer 2 (Fig. 4.10a). The sublayer 3 is characterized by inhomogeneous.

The sublayer 4 (from -25.0 to -22.0 m), in the CPTU1-VL results, values of Q_t , F_R and B_q are all constant with depth (Fig. 4.12). Soil-behavior-type of the sublayer 4 is only clays-clay to silty clay (Figs. 4.10b and 4.13a). But, the SPT-VL results do not have difference between the sublayer 4 with the sublayer 3 and the sublayer 5; they regularly equal 2 at each location of the SPT (Fig. 4.10a). The sublayer 4 is characterized by highly homogeneous.

The sublayer 5 (from -22.0 to -18.5 m), on the results of CPTU1-VL and CPTU2-VL, values of Q_t , F_R and B_q are all rather constant with depth (Fig. 4.12). Soil-behavior-type of the sublayer 5 is almost clays-clay to silty clay and rarely silt mixtures-clayey silt to silty clay (Figs. 4.10b, 4.11a, 4.13b and 4.14). The sublayer 5 and the sublayer 4 are rather similar but the homogeneous-level of the sublayer 5 is less than that of the sublayer 4; the graphs of F_R and B_q on the sublayer 5 vary more than those on the sublayer 4 (Figs. 4.10d-e, and 4.12b-c). But, the SPT-VL results of the sublayer 5 do not have difference with those of sublayers 4 and the sublayer 6. It can tell that it is difficult to discriminate between the sublayer 5 and the sublayer 4.

The sublayer 6, the results of CPTU1-VL and CPTU2-VL, the variation of the normalized values are the most significant with very high frequency variations with depth as shown in Fig. 4.12. The inhomogeneous characteristics of this sublayer 6 were confirmed by both CPTU1-VL and CPTU2-VL results at the VLM1 core site (Figs. 4.10 to 4.14). As a result, a variety of soil behavior-types is obtained with very thin thickness, including sensitive fine-grained, normally consolidated to slightly overconsolidated clay, slightly sensitive to sensitive, and normally consolidated to slightly overconsolidated silt mixtures, slightly sensitive to sensitive sand mixtures, and slightly sensitive sands. From the comparison of the results of CPTU1-VL and CPTU2-VL shown in Figs. 4.10 to 4.14, some differences can be confirmed in the two tests,

implying that soil variations may exist horizontally even in the distance of 10m (Fig. 3.3.2). However, values of N from the SPT on the sublayer 6 and the sublayer 5 also don't change; they regularly equal 2 at each location of the SPT (Fig. 4.10a). The boundaries between the sublayer 6 and the sublayer 7 at the different locations of the CPTU tests still have differences. Namely, the boundary between the sublayer 6 and the sublayer 7: at the CPTU1-VL is -5.5 m; and at the CPTU2-VL is -7 m (Figs. 4.10, 4.11, and 4.12).

The sublayer 7, in the all results of two CPTUs at the Vinhlong site such as: The alternation of cohesionless soil seams and cohesive soil seams results in a saw-tooth shape in the overall plot of q_b , f_s and u_2 as a function of depth (Figs. 4.10c-e, and 4.11c-e). The variations of values of Q_b , F_R and B_q are all rather regular with depth (Fig. 4.12) and that the soil-behavior-types are such as: The cohesionless soil is the sands-clean sand to silty sand and sand mixtures-silty sand to sandy silt; the cohesive soil is the silt mixtures-clayey silt to silty clay and clays-clay to silty clay (Figs. 4.10b, 4.11a, 4.13a and 4.14). The N values from the SPT-VL on the sublayer 7 are 1 at each location of the SPT; the N values on the sublayer 7 are also less than those on the sublayer 6 (Fig. 4.10a). The boundaries of the sublayer 7 at the different locations of the CPTUs are such as: at the CPTU1-VL are from -5.5 m to -1.5 m; but at the CPTU2-VL are -7.0 m to -1.9 m (Figs. 4.10, 4.11, and 4.12).

The sublayer 8, in the results of the CPTU1-VL and CPTU2-VL, values of Q_b , F_R and B_q are all rather constant with depth (Fig. 4.12). Soil-behavior-type of the sublayer 8 is a mostly clayey-silt to silty clay (Fig. 4.10b and 4.11a). In general, the sublayer 8 is homogeneous. However, the boundaries of the sublayer 8 at the different locations of the CPTUs are such as: at the CPTU1-VL are from -1.5 m to +1.0 m; but at the CPTU2-VL are -1.9 m to +1.0 m (Figs. 4.10, 4.11, and 4.12).

From the comparison of the results of CPTU1-VL and CPTU2-VL shown in Figs. 4.10, 4.11, and 4.12, some differences can be confirmed in the results of the two tests, implying that soil variations may exist horizontally even in the distance of 10 m (Fig. 3.3.2).

The SPT results at the Vinhlong site (Fig. 4.10a), from -1 to -37 m, however, the N -values are very small and do not increase, or increase with a little quantity in the range of -37 to -45 m with depth at the VLM1 core site. Simultaneously, N values on homogeneous and inhomogeneous soil layers are not clearly different in the SPT-VL test.

4.6.2. Caolanh site

Measured quantities of the cone penetration tests (CPTU1-CL) named sleeve friction, f_s , cone resistance, q_t , and pore water pressure measured behind the cone tip, u_2 , are as shown in Fig. 4.17 together with the standard penetration tests (SPT-CL). A typical soil profile can be identified by soil-behavior-type classification using the above normalized values from Equation 2.1 to 2.3 (Robertson 1990 and 1991). The depth variations in the normalized values obtained from the CPTU1-CL are shown in Fig. 4.18. The soil-behavior types were estimated from the relationship between Q_t and F_R (Robertson, 1990 and 1991) are shown in Figs. 4.17b and 4.19. The values of t_{50} , c_h , and c_v calculated from the results of pore water pressure-dissipation test at -8.33 m during CPTU1-CL at the Caolanh site are shown in Figs. 4.21.

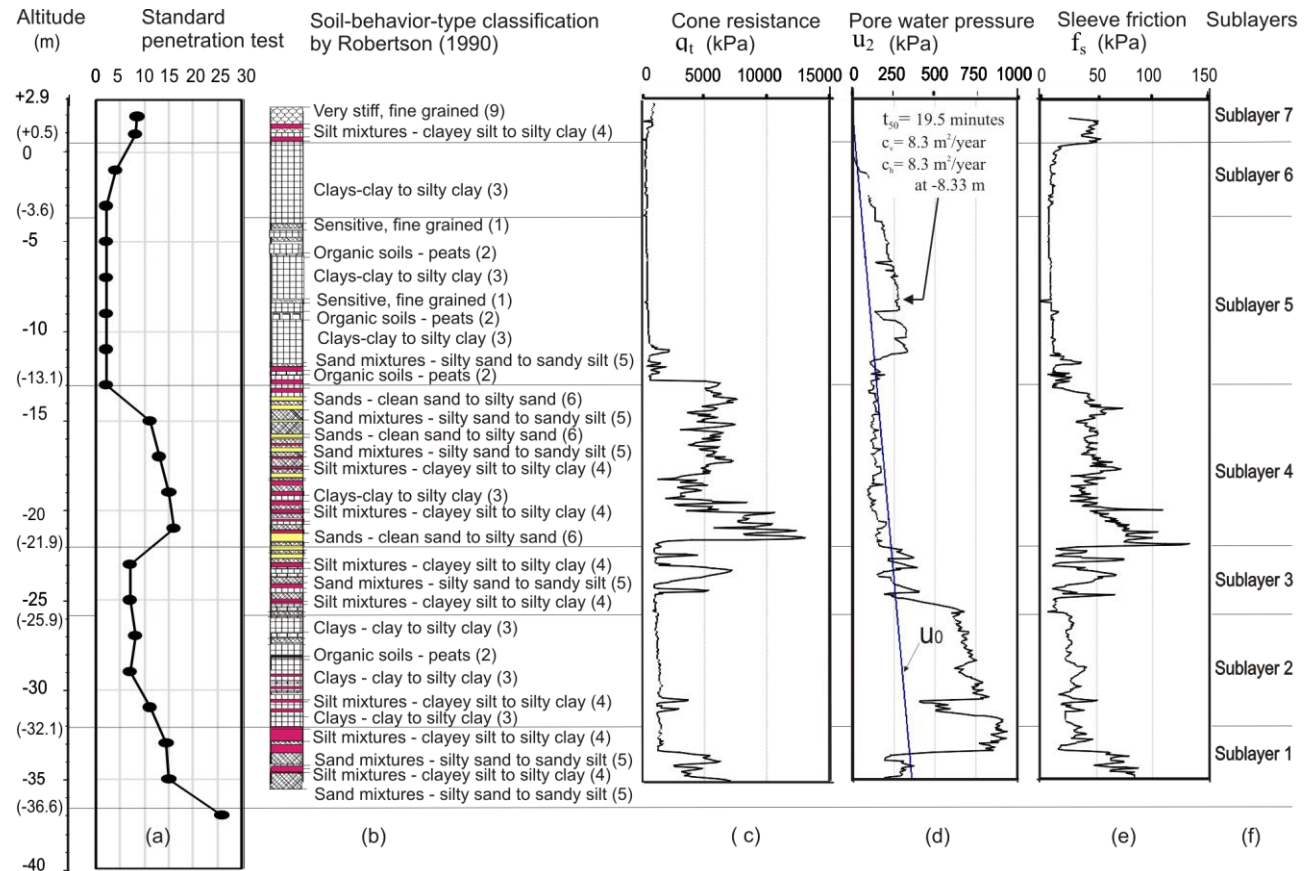


Fig. 4.17. Results of the *in situ* tests at the Caolanh site: From SPT-CL: (a) N value. From CPTU1-CL: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , in addition, requisite time, t_{50} , for dissipating 50% of pore water pressure, and values of c_v and c_h calculated from t_{50} at the each depth, (f) sublayers divided based on the results of CPTU1-CL and SPT-CL.

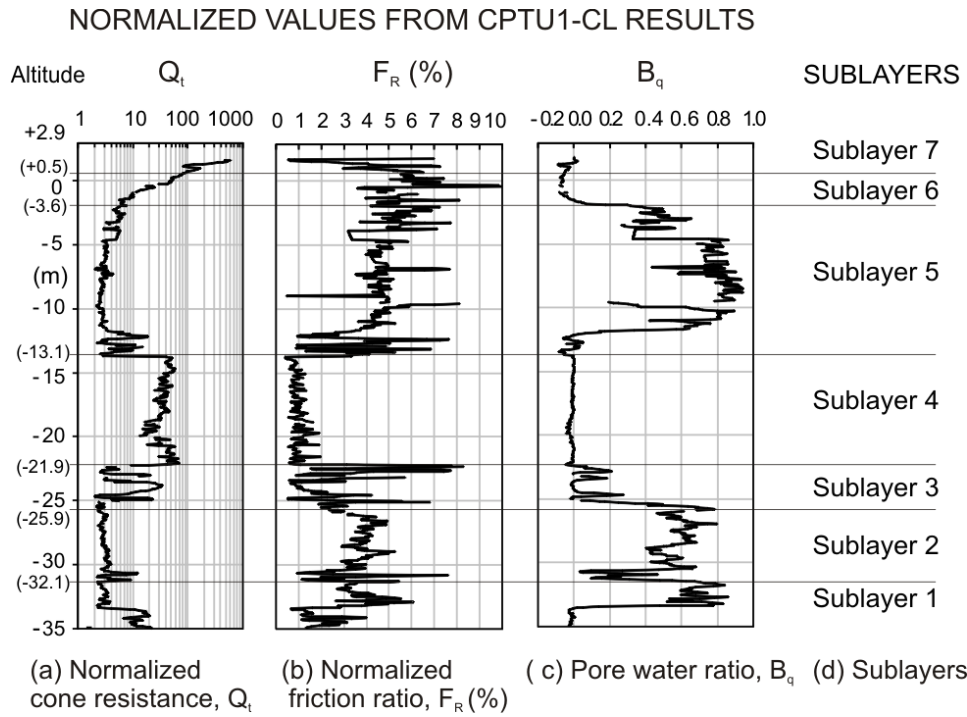


Fig. 4.18. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU1-CL at the Caolanh site.

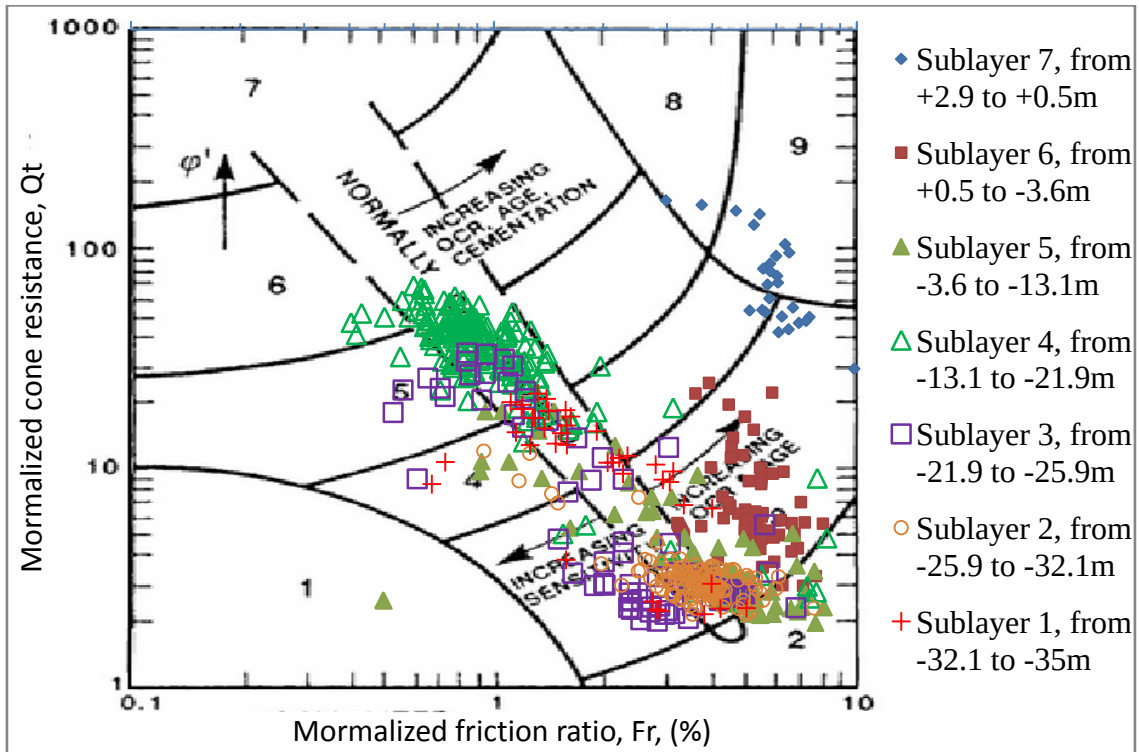


Fig. 4.19. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU1-CL at the Caolanh site: Sublayers 1 to 7.

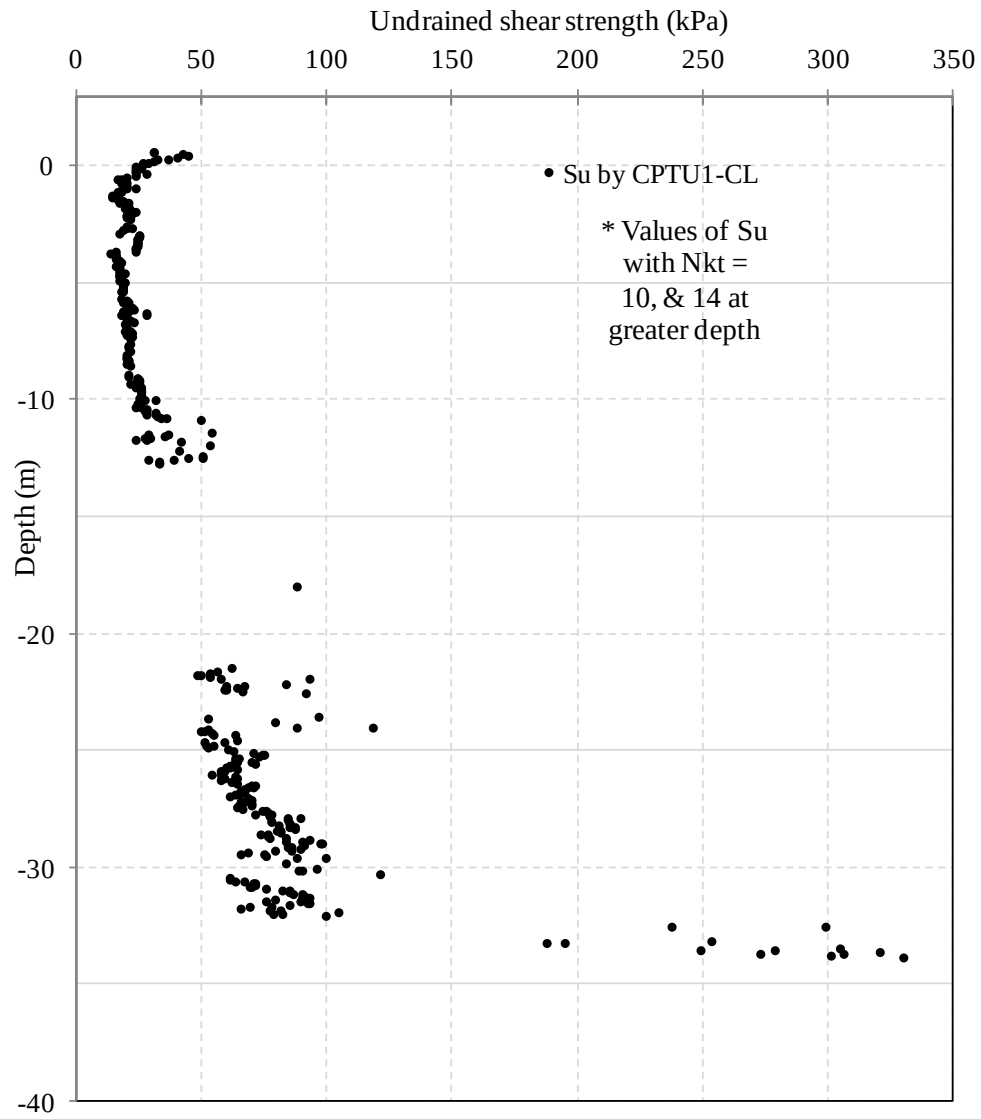


Fig. 4.20. Undrained shear strengths vs. depth obtained from CPTU1-CL at the Caolanh site.

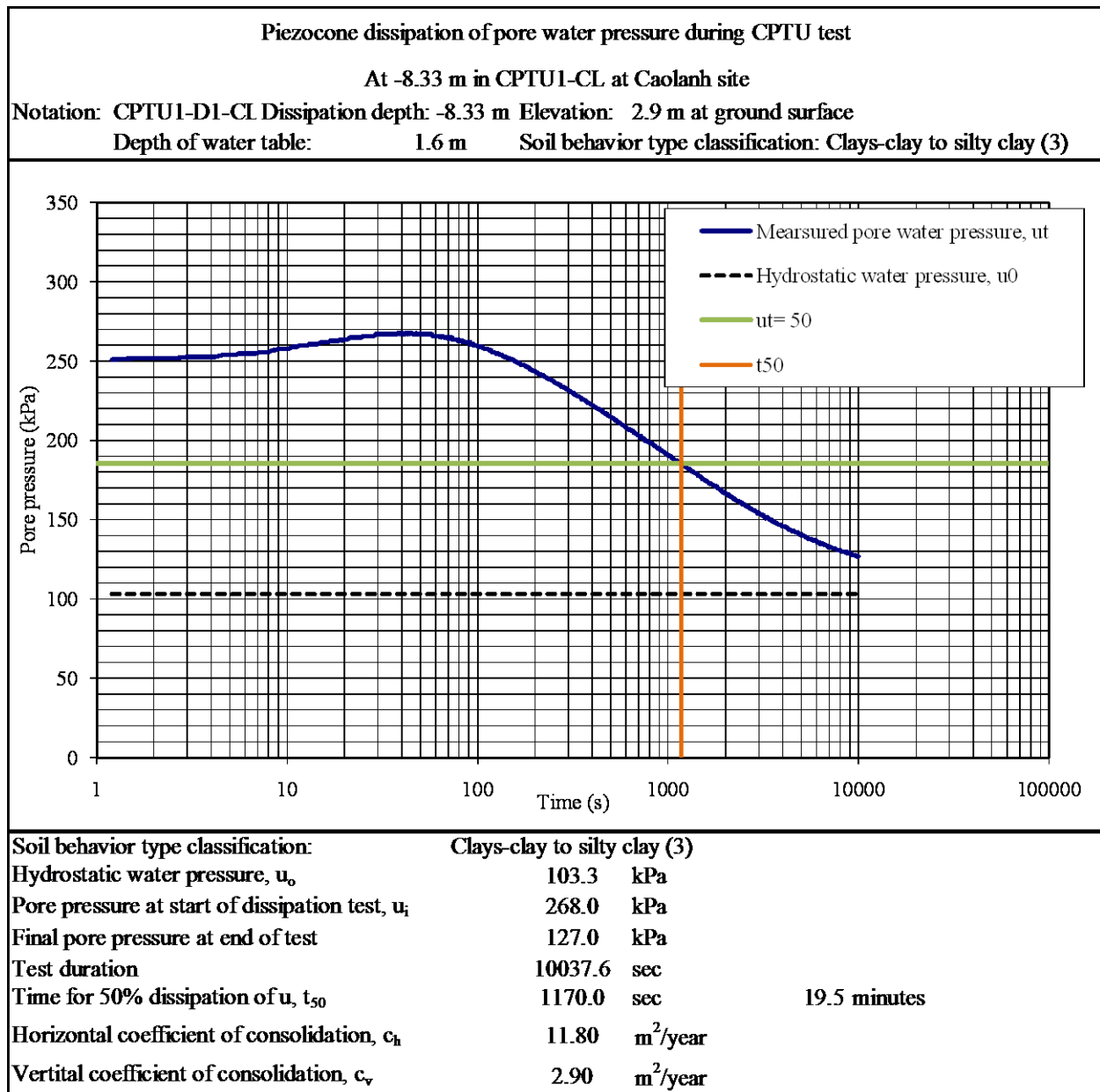


Fig. 4.21. Results of pore water pressure-dissipation test at -8.33 m during CPTU1-CL at the Caolanh site.

At the Caolanh site, at altitude, $z = -36.6$ m, values N from SPT increase highly; the penetration machine used for the investigation could not penetrate through this layer since its capacity limit was already reached. At this altitude ($z = -36.6$ m) can seem to be a boundary between two different consecutive sediment-sequences. The sediment-sequence located below $z = -36.6$ m has high strength, N value by the SPT-CL is 26 at $z = -37$ m (Fig. 4.17a). The second sediment-sequence from -36.6 m to the ground surface has low strength (Figs. 4.17a, c, and e). The soil profile at the Caolanh site is divided into 7 sublayers based on the results of the CPTU

and SPT (Figs. 4.17 and 4.18) such as:

The sublayer 1 is identified from -36.6 to -32.1 m. The normalized values of Q_t , F_R and B_q change with depth (Fig. 4.18). Soil-behavior-type from the CPTU1-CL results on the sublayer 1 is commonly clays-clay to silty clay and silt mixtures-clayey silt to silty clay (Figs. 4.17b and 4.19). Moreover, layers of sand mixture-silty sand to sandy silt insert in the layer of clays and silt mixtures in the sublayer 1 (Figs. 4.17b and 4.19). The layers of sand mixture-silty sand to sandy silt have a little high values of N , around 15 (Fig. 4.17a).

We consider the CPTU1-CL results on a range of -32.1 to -25.9 m at the Caolanh site. Q_t , F_R and B_q are rather constant with depth (Fig. 4.18); and the soil-behavior-type is mostly clays-clay to silty clay with thin layers of sand mixture-silty sand to sandy silt and organic soils-peats (Fig. 4.17b). Values of N from the SPT are commonly from 7 to 8. Value of N on the sand mixtures obtains 11 (Fig. 4.17a). This range is called the sublayer 2.

The sublayer 3, from -25.9 to -21.9 m at the CLM1 core site, Q_t , F_R and B_q change slightly with depth (Fig. 4.18); and the soil-behavior-type is mostly clays-clay to silty clay, silt mixture-clayey silt to silty clay, and thin layers of sand mixture-silty sand to sandy silt and organic soils-peats (Figs. 4.17b and 4.19). Values of N are mostly 6 (Fig. 4.17a).

The sublayer 4, from -21.9 to -13.1 m at the CLM1 core site, the CPTU1-CL results, which are shown in Figs. 4.17b-e, the behavior types tend to be cohesionless soils (Figs. 4.17b and 4.19). Q_t , F_R and B_q varied (Fig. 4.16). The q_t and f_s values show saw-tooth graphs with large variations and the largest magnitudes among all sublayers. Simultaneously, values of N increase relatively regularly from 11 to 16 (Fig. 4.17a).

The sublayer 5, from -13.1 to -3.6 m at the CLM1 core site, Q_t , F_R and B_q have saw-tooth graphs with small amplitudes (Fig. 4.18). The main soil-behavior-type classification is clays-clay to silty clay with intercalating sensitive fine grained, sand mixtures-silty sand to sandy silt, and organic soils-peats (Figs. 4.17b and 4.19). The q_t , u_2 , and f_s values are all linear with depth and the very small magnitudes (Fig. 4.17c-e). Values of N are also constant with depth, 2; the N values cannot indicate the small increase in this case (Fig. 4.17a).

The sublayer 6, from -3.6 to +0.5 m at the CLM1 core site, q_t , u_2 and f_s have saw-tooth graphs with so small amplitudes. Values of f_s decrease but values of u_2 increase with depth (Figs. 4.17d and e). Soil-behavior-type classification is only clays-clay to silty clay (Figs. 4.17b and 4.19). Values of N decrease with depth, from 4 to 2 (Fig. 4.17a). The sublayer 6 is more homogeneous than the sub-layer 5. The strengths on the sublayer 6 are so less than those of the sub-layer 7

(Figs. 4.17a, c, and e).

The sublayer 7, from +0.5 to +2.9 m at the Caolanh site, in the CPTU results of the sublayer 7, q_t and f_s have saw-tooth graphs with small amplitudes (Figs. 4.17c and e). Values of q_t and f_s are so more than those of the sublayer 6 and the sublayer 5, while values of u_2 on the sublayer 7 are less than (Figs. 4.17c and e). Soil-behavior-type classification is silt mixtures-clayey silt to silty clay, very stiff fine grained, and clays-clay to silty clay (Figs. 4.17b and 4.19). Values of N from SPT are large, from 8 to 9 (Fig. 4.17a). Generally, the strengths from the CPTU1-CL and SPT-CL on the sublayer 7 are so greater than those on the sublayer 6 and 5 (Figs. 4.17a, c, & e).

4.6.3. Bentre-1 site

Measured quantities of the cone penetration tests, CPTU1-BT1, named cone resistance, q_t , sleeve friction, f_s , and pore water pressure measured behind the cone tip, u_2 , are shown in Fig. 4.22 together with results of SPT-BT1 test. The depth variations in the normalized values (by Equation 2.1 to 2.3 (Robertson 1990 and 1991)) obtained from the CPTU1-BT1 are shown in Fig. 4.23. The soil-behavior types estimated from the Q_t - F_R relationship and the Q_t - B_q relationship (Robertson, 1990 and 1991) and the typical soil profile are shown in Figs. 4.22b and 4.24. The values of t_{50} , c_h , and c_v calculated from the results of pore water pressure-dissipation test at -2.88 m and -7.31 m during CPTU1-BT1 at the Bentre-1 site are shown in Figs. 4.26.1-2.

At the Bentre-1 site, at altitude, $z = -8.7$ m, in the CPTU1-BT1 results, values of q_t and f_s begin to increase highly. Values of N from SPT increase suddenly and continuously from 18 to 48 in a range of -8.7 to -28 m (Fig. 4.22a). Hence, at this altitude, $z = -8.7$ m, can seem to be a boundary between two different consecutive sediment-sequences. The sediment-sequence located below $z = -8.7$ m has high strength (Fig. 4.22a). The second sediment-sequence from -8.7 m to the ground surface has low strength (Figs. 4.22a, c, and e). The soil profile in the range of -8.7 m to the ground surface at the Bentre-1 site is divided into 3 sublayers based on the CPTU and SPT results such as:

The sublayer 1, from -8.7 to -6.5 m, in the CPTU1-BT1 results, Q_t and F_R show saw-tooth graphs with large variations; q_t and f_s are the largest among all the sublayers except the sublayer below $z = -8.7$ m (Figs. 4.22c and e). Soil-behavior-types classification is varied (Figs. 4.22b and 4.24). In general, soil-behavior-type is commonly cohesionless soils (Figs. 4.22b and 4.24). Values of N from SPT results are from 1 to 3 (Fig. 4.22a).

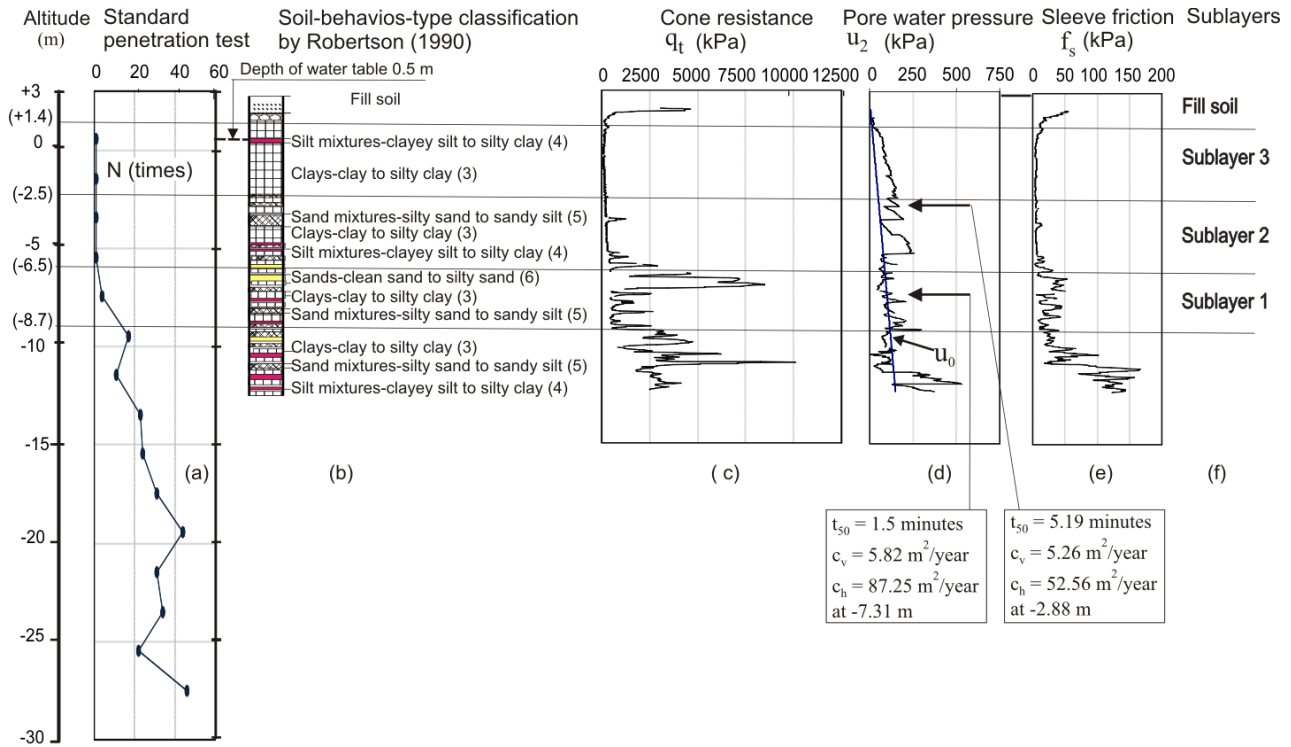


Fig. 4.22. Results of the *in situ* tests at the Bentre-1 site: From SPT-BT1: (a) N value. From CPTU1-BT1: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , in addition, values of t_{50} is requisite time for dissipating 50% of pore water pressure, values of c_v and c_h were calculated at the each depth, (f) sublayers divided based on the results of CPTU1-BT1 and SPT-BT1.

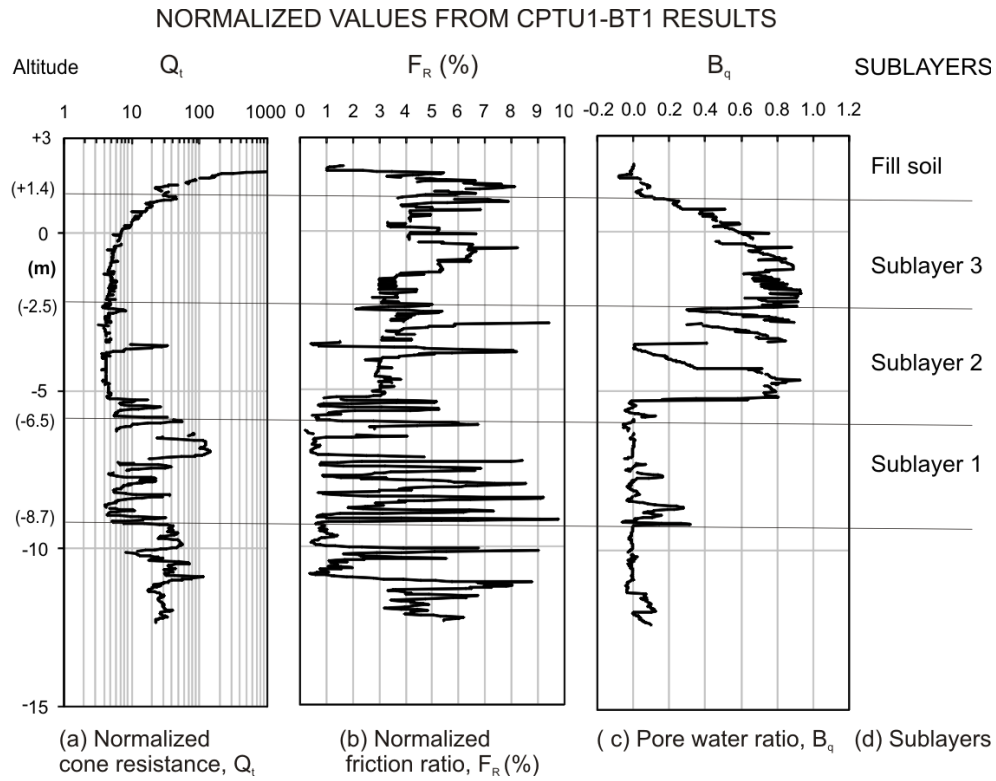


Fig. 4.23. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU1-BT1 at the Bentre-1 site.

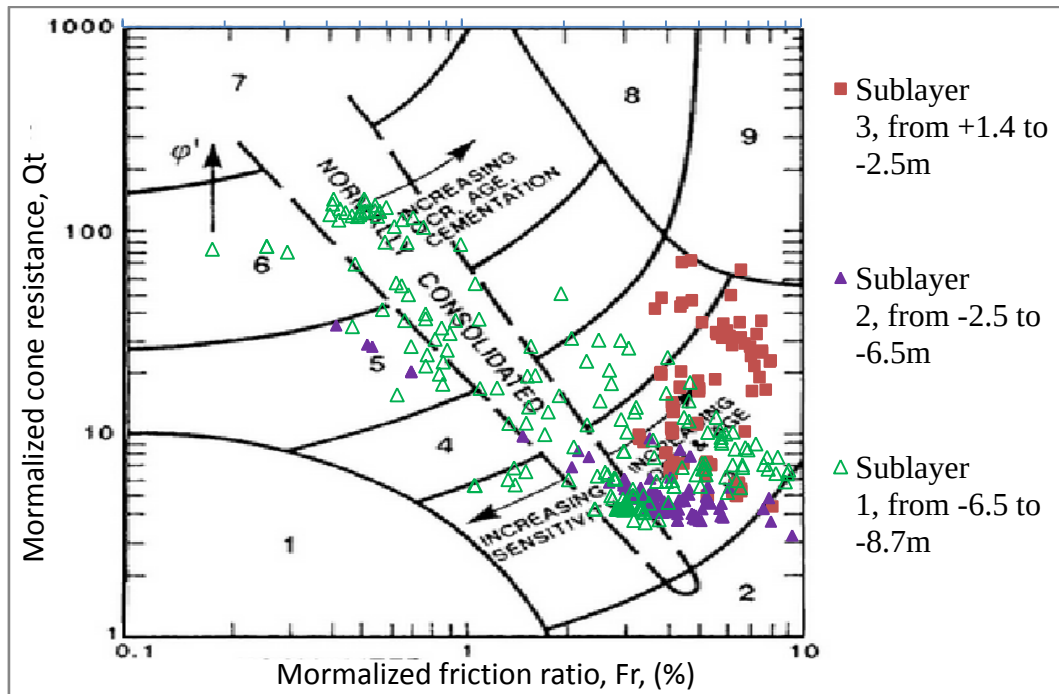


Fig. 4.24. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU1-BT1 at the Bentre-1 site: Sublayers 1 to 3.

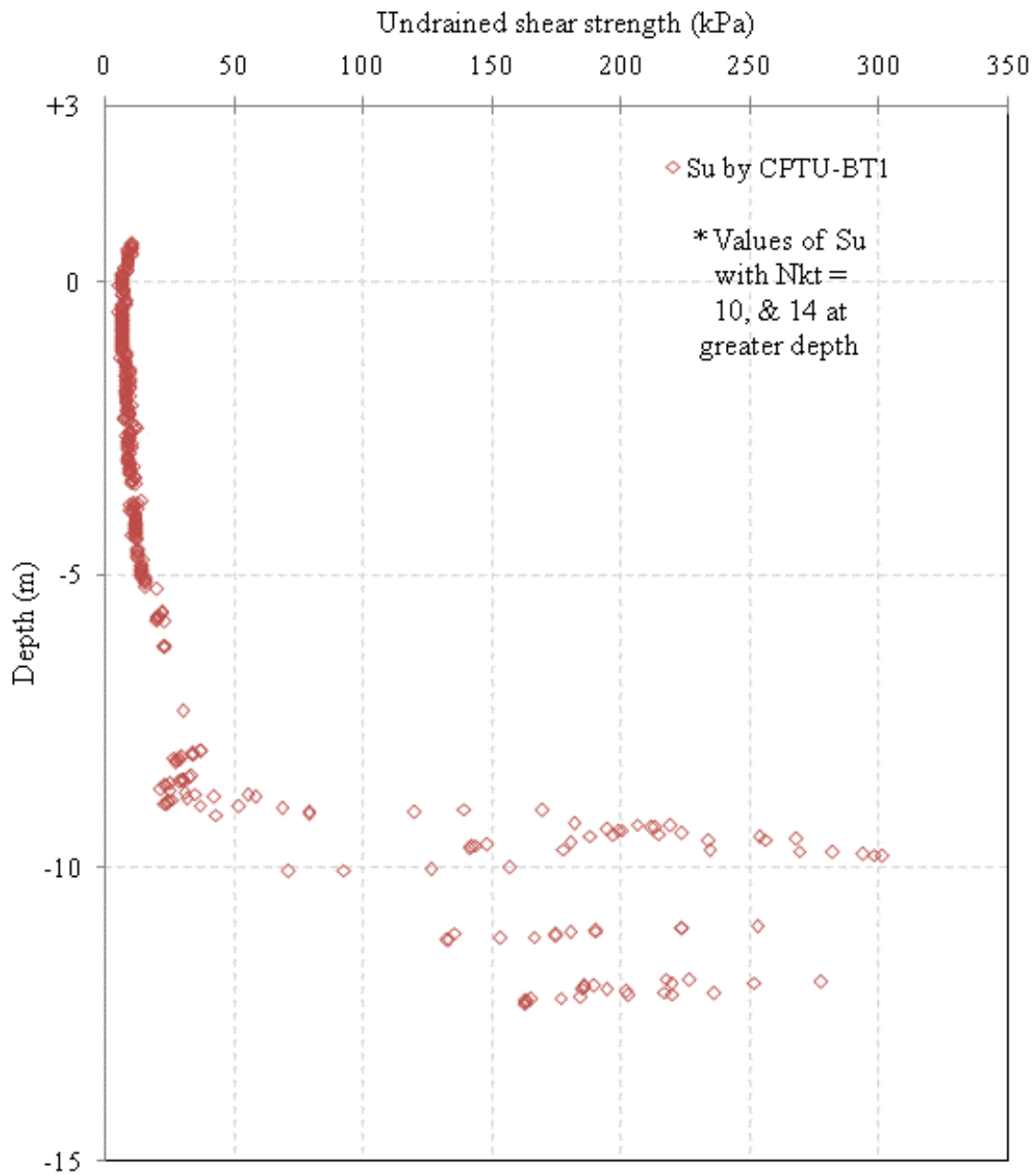


Fig. 4.25. Undrained shear strengths vs. depth obtained from CPTU1-BT1 at the Bentre-1 site.

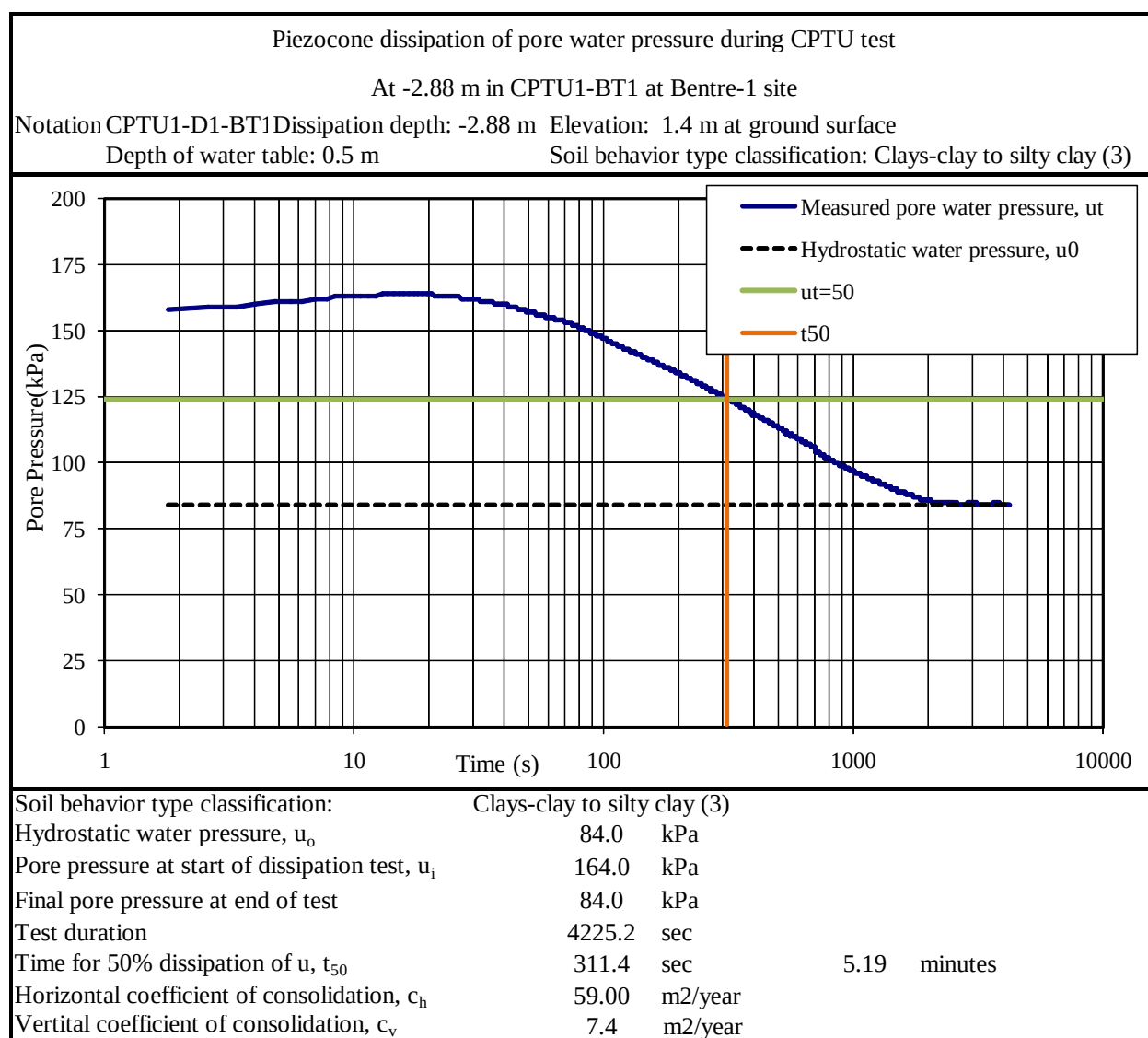


Fig. 4.26.1. Results of pore water pressure-dissipation test at -2.88 m during CPTU1-BT1 at the Bentre-1 site.

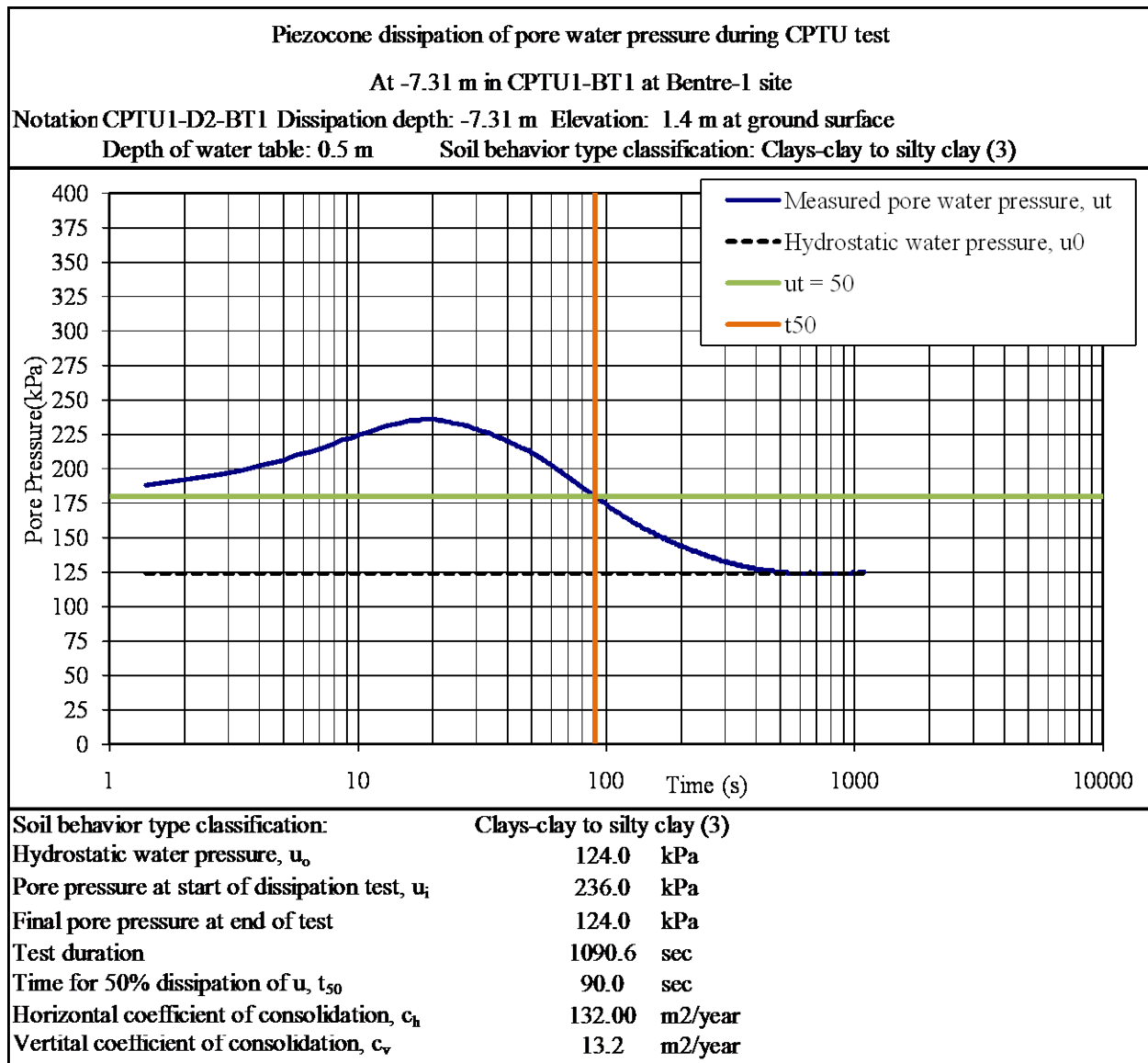


Fig. 4.26.2. Results of pore water pressure-dissipation test at -7.31 m during CPTU1-BT1 at the Bentre-1 site.

The sublayer 2, from -6.5 to -2.5 m, in the CPTU results, Q_b , F_R , and B_q have changes (Fig. 4.23). In general, soil-behavior-type is commonly clays-clay to silty clay; the sand mixtures-silty sand to sandy silt and sands-clean sand to silty sand insert the clays (Figs. 4.22b and 4.24). The q_b , u_2 , and f_s values increase with depth with the very small magnitudes. But the q_b , u_2 , and f_s values sometime have some large changes by appearance of sand mixtures-silty sand to sandy silt and sands-clean sand to silty sand (Figs. 4.22c and e). Values of N from SPT results are very small, 1 (Fig. 4.22a).

The sublayer 3, from -2.5 to +1.4 m, in the CPTU results: The q_b , u_2 , and f_s values slightly

increase with depth (Figs. 4.22c-e). Q_t , F_R , and B_q show saw-tooth graphs with so small variations (Fig. 4.23); soil-behavior-type is mostly clays-clay to silty clay (Figs. 4.22b and 4.24). Values of N from the SPT results are only 1, so small (Fig. 4.22). Simultaneously, values of N from the SPT results on the sublayer 2 and sublayer 3 don't change. In general, the sublayer 3 is more homogeneous than the sublayer 2; and the grain-size of the sublayer 3 trends to be finer than those of the sublayer 2 (Fig. 4.22b). The upper part of the sublayer 3 was subjected by load of the fill soil. Hence, the strengths of the upper part of the sublayer 3 increase highly (Figs. 4.22c and e).

4.6.4. Bentre-2 site

Results of the CPTU1-BT2, CPTU2-BT2, CPTU3-BT2, and SPT-BT2 are presented in Figs. 4.27.1-3, 4.28.1-2, 4.29.1-2, and 4.30.1-2, respectively. The depth variations in the normalized values and soil-behavior-types obtained from the CPTU1-BT2, CPTU2-BT2, CPTU3-BT2 are shown in Figs. 4.28.1-2, 4.29.1-2, and 4.30.1-2, respectively. The penetration machine used for the investigation could not penetrate the end of the late Pleistocene-Holocene sediments since its capacity limit was already reached. The maximum investigation depth at the BT2 site is -36 m (Table 3.1).

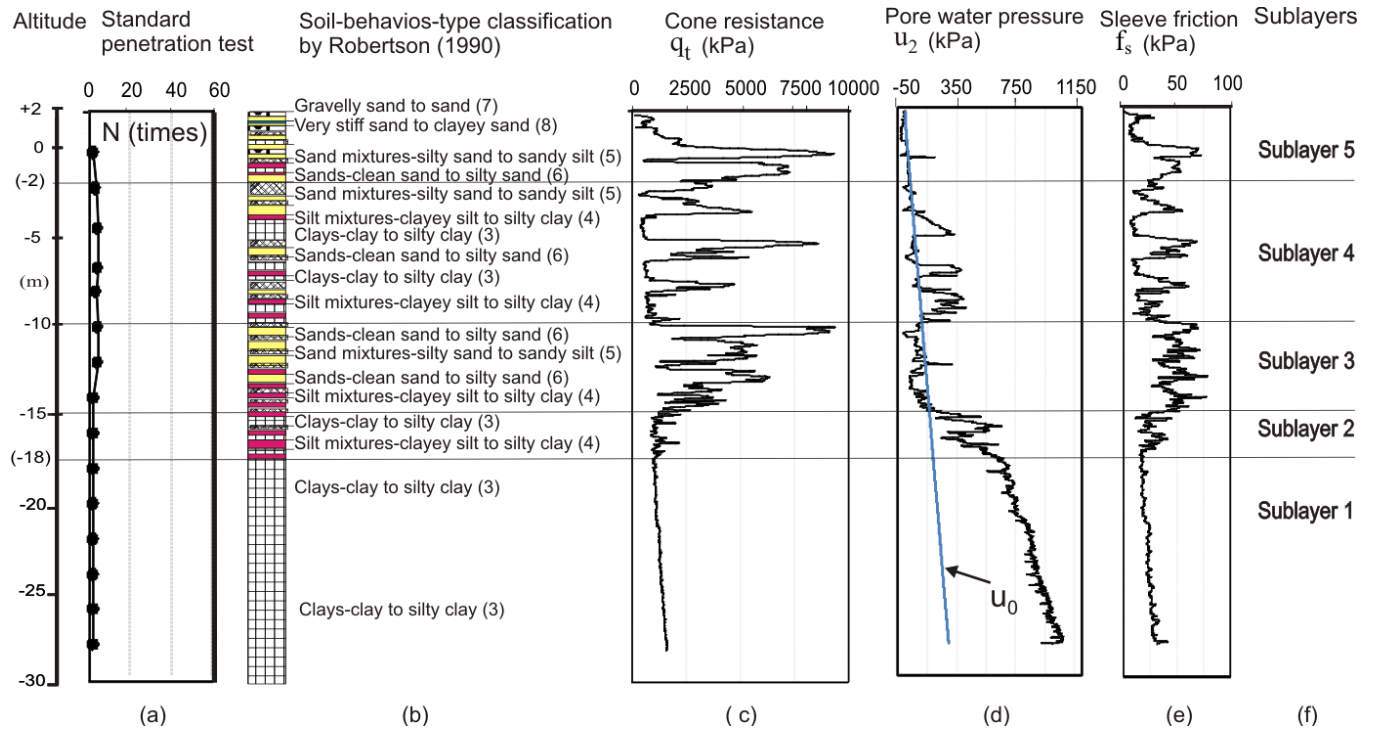


Fig. 4.27.1. Results of the *in situ* tests at the Bentre-2 site: From SPT-BT2: (a) N value. From CPTU1-BT2: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , (f) sublayers divided based on the results of CPTU1-BT2 and SPT-BT2.

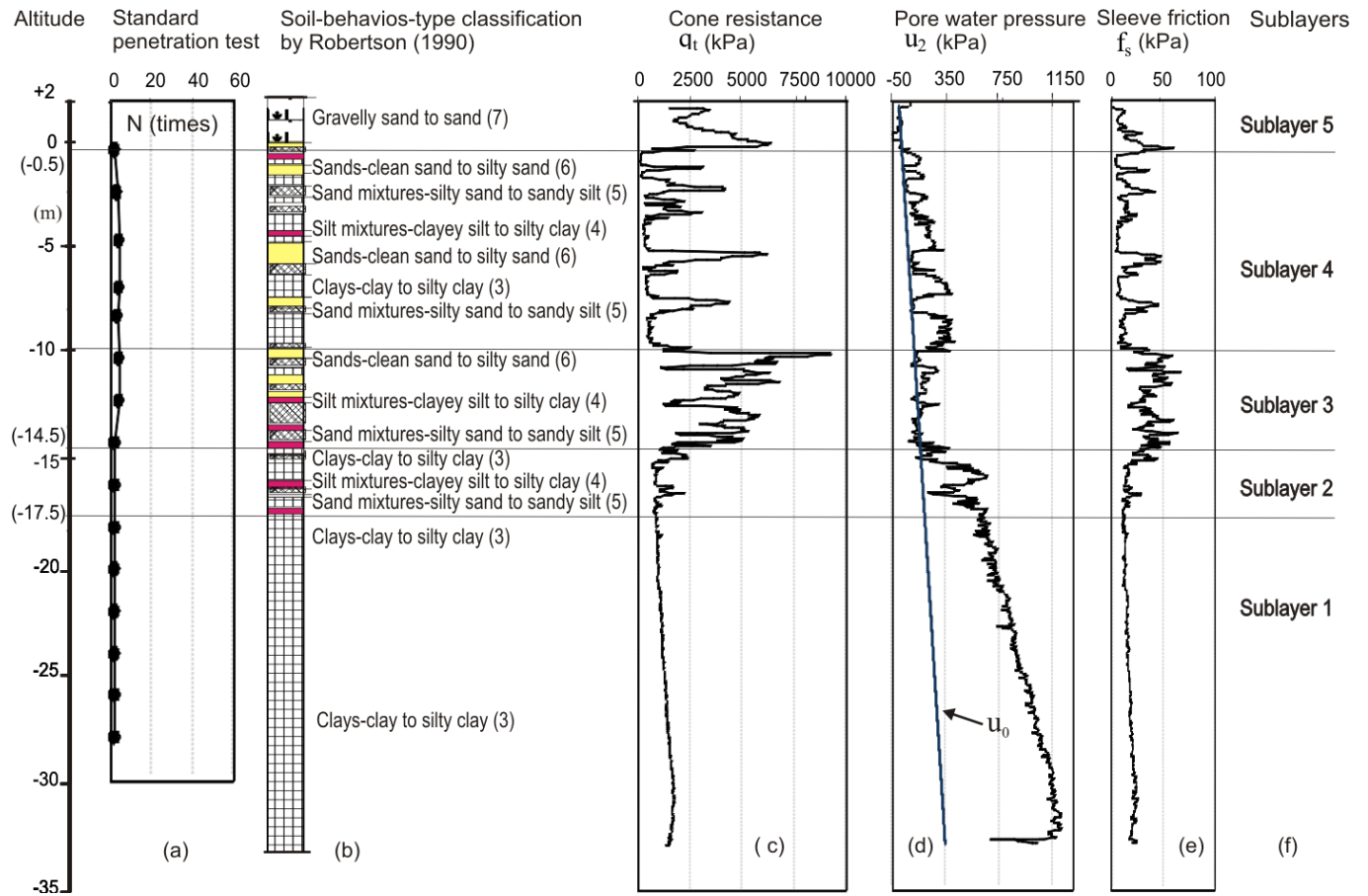


Fig. 4.27.2. Results of the *in situ* tests at the Bentre-2 site: From SPT-BT2 test: (a) N value. From CPTU2-BT2 test: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , (f) sublayers divided based on the results of CPTU2-BT2 and SPT-BT2.

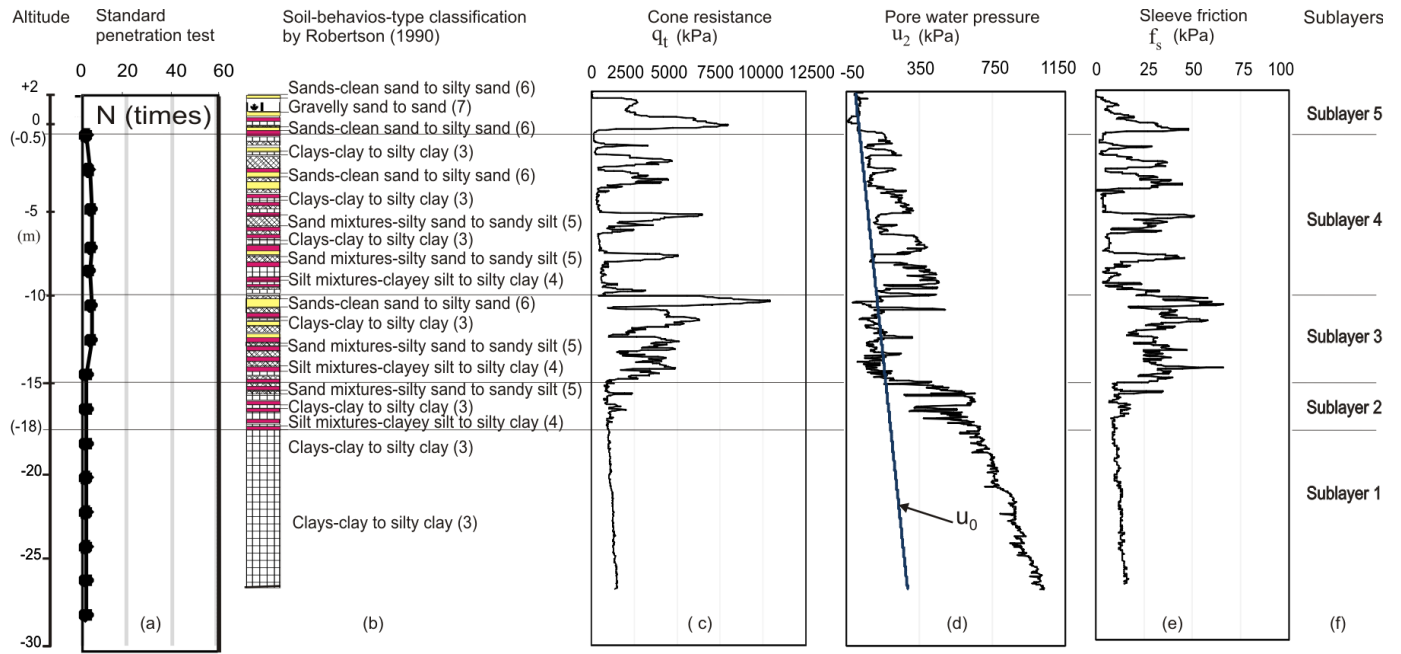


Fig. 4.27.3. Results of the *in situ* tests at the Bentre-2 site: From SPT-BT2: (a) N value. From CPTU3-BT2: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , (f) sublayers divided based on the results of CPTU3-BT2 and SPT-BT2.

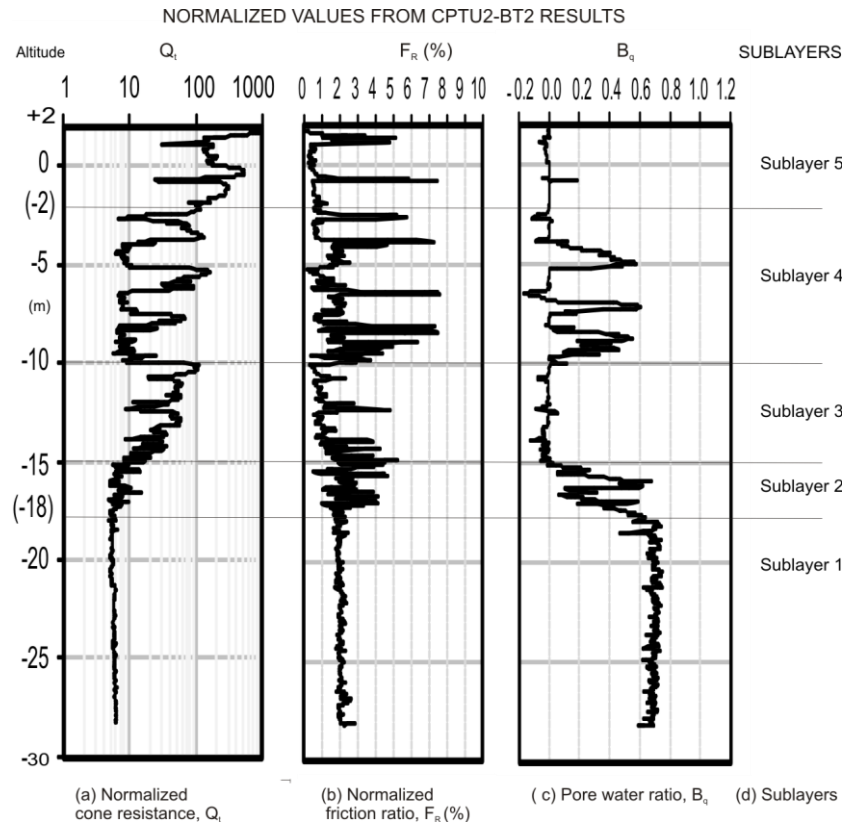


Fig. 4.28.1. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU1-BT2 at the Bentre-2 site.

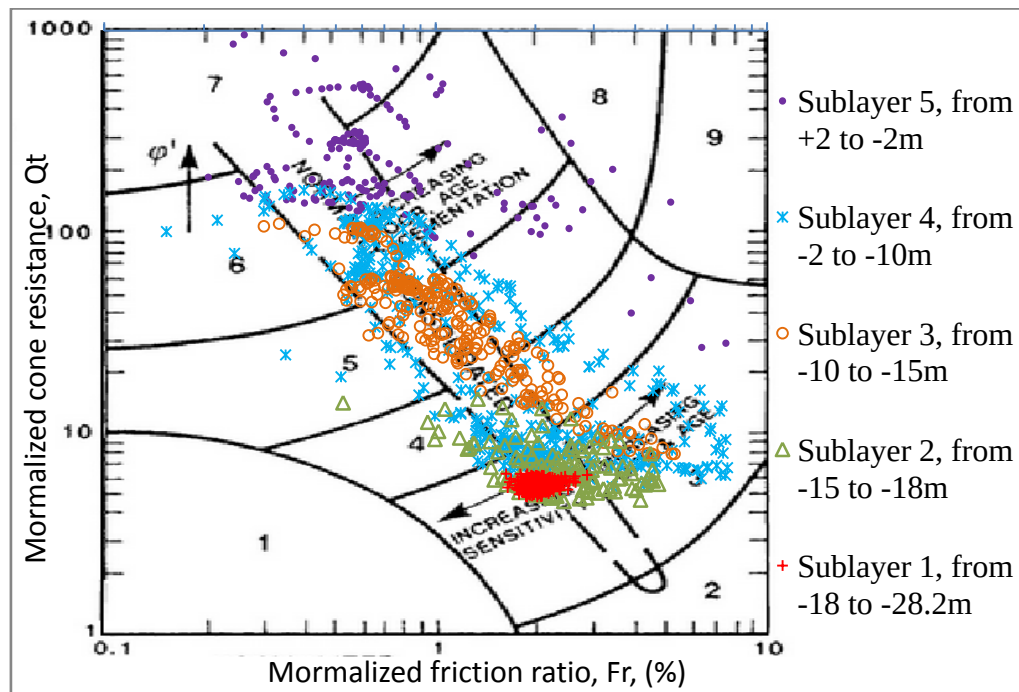


Fig. 4.28.2. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU1-BT2 at the Bentre-2 site: Sublayers 1 to 5.

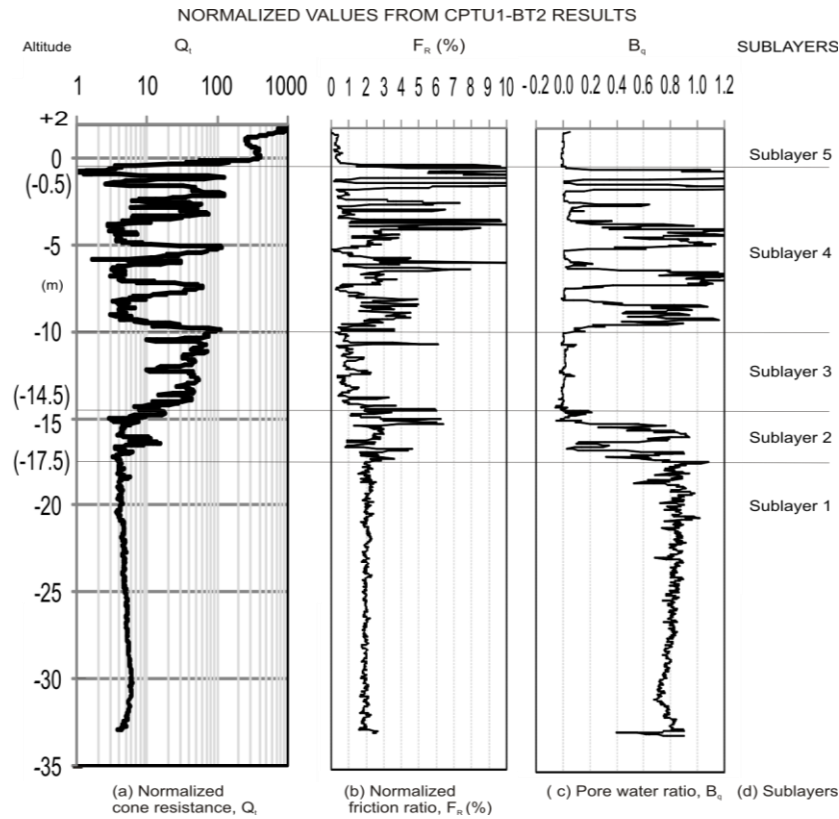


Fig. 4.29.1. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU2-BT2 at the Bentre-2 site.

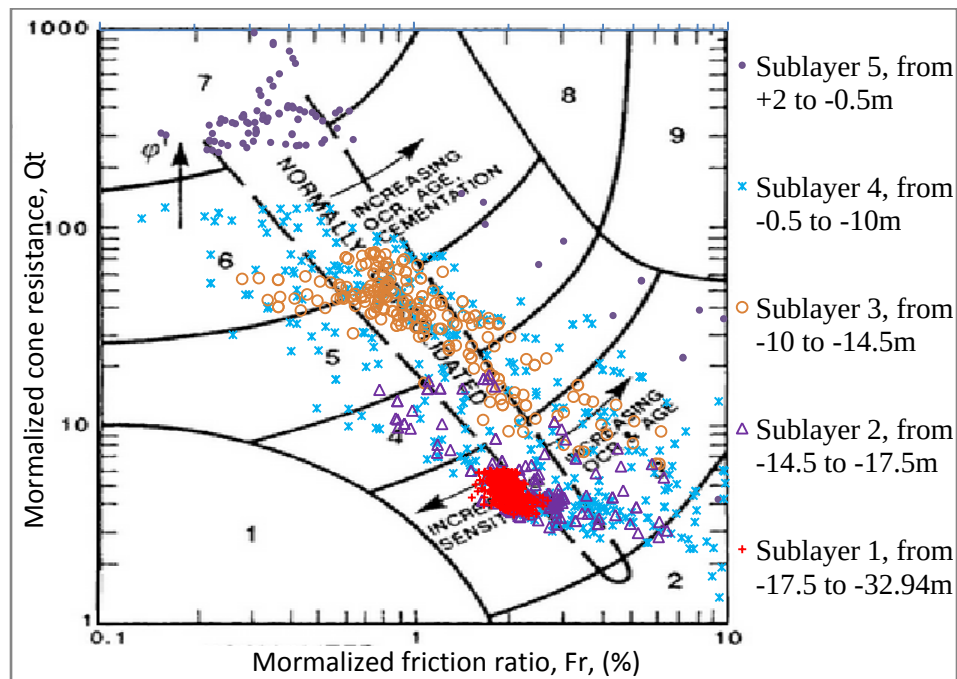


Fig. 4.29.2. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU2-BT2 at the Bentre-2 site: Sublayers 1 to 5.

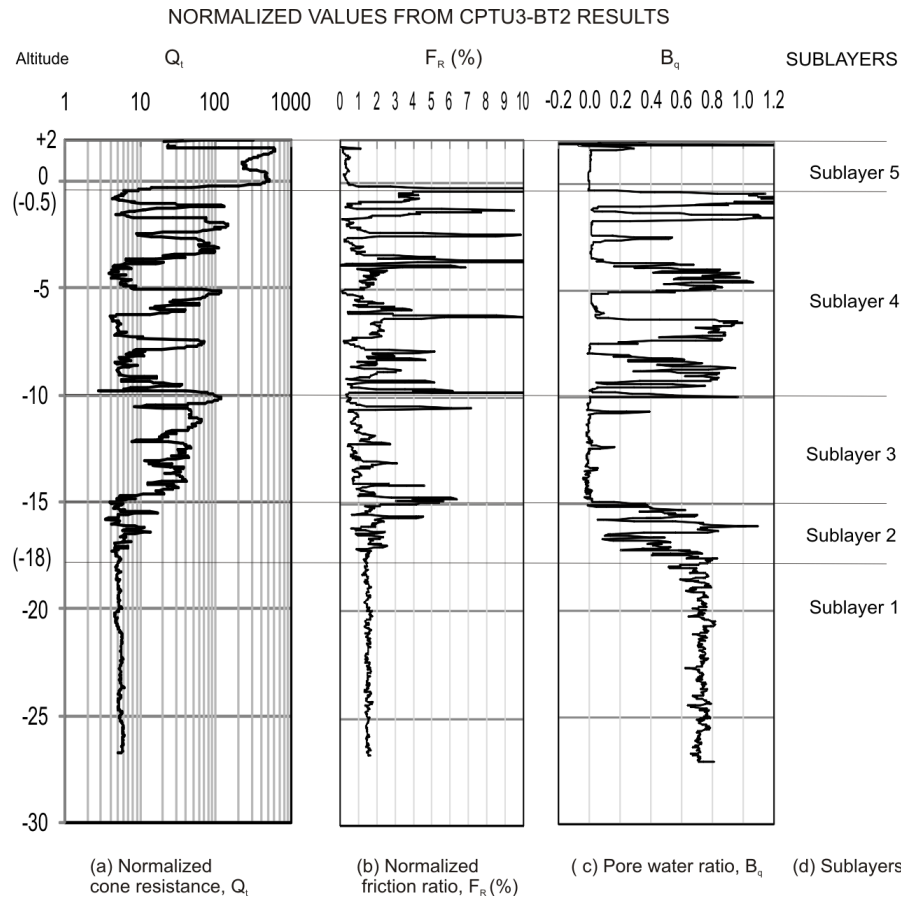


Fig. 4.30.1. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU3-BT2 at the Bentre-2 site.

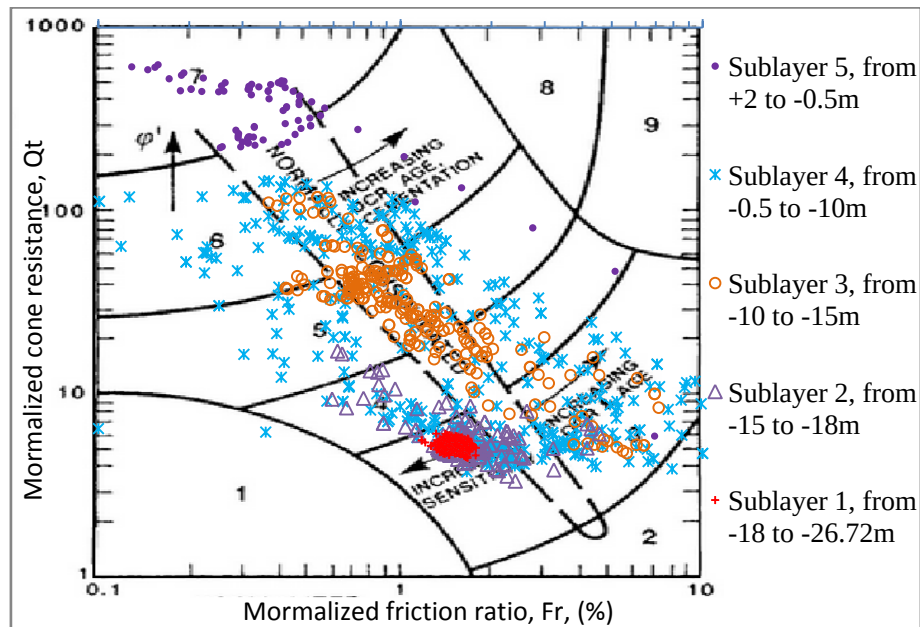


Fig. 4.30.2. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU3-BT2 at the Bentre-2 site: Sublayers 1 to 5.

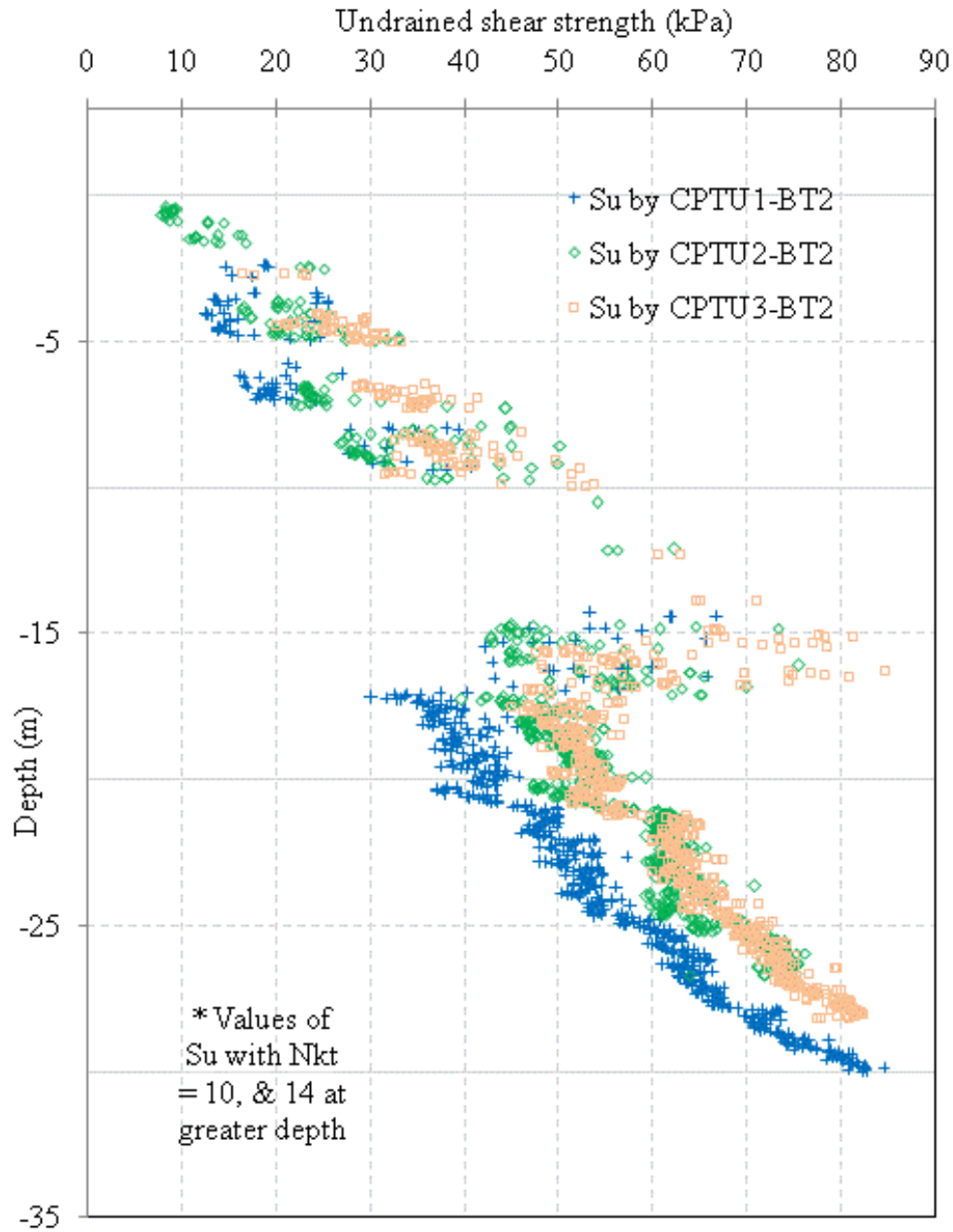


Fig. 4.31. Undrained shear strengths vs. depth obtained from CPTU1-BT2, CPTU2-BT2, and CPTU3-BT2 at the Bentre-2 site.

The soil profile (from -36 to +2 m) at the Bentre-2 site (BT2) is divided into 5 sub-layers based on the results of the CPTUs and SPT such as:

In the results of the CPTU1-BT2, CPTU2-BT2, and CPTU3-BT2, the sublayer 1, the increase of q_t , u_2 , and f_s are linear with depth (Figs. 4.27.1c-e, 4.27.2c-e, and 4.27.3c-e). Values of Q_b , F_R and B_q are all rather constant with depth (Figs. 4.28.1, 4.29.1, and 4.30.1) and that the soil-behavior-type is only clays-clay to silty clay (Figs. 4.27.1b, 4.27.2b, 4.27.3b, 4.28.2, 4.29.2, and

4.30.2). The all results indicate that the sublayer 1 at the BT2 site is high homogeneous. However, the boundaries between the sublayer 1 and sublayer 2 at the different locations of the CPTUs still have differences. Namely, the boundary of the sublayer 1 at the CPTU1-BT2 is -17.5 m; at the CPTU2-BT2 and CPTU3-BT2 are -18 m; (Figs. 4.27.1-3).

The sublayer 2, in results of three CPTUs at the Bentre-2 site: The increase of q_t , u_2 , and f_s trends to be linear with depth (Figs. 4.27.1c-e, 4.27.2c-e, and 4.27.3c-e). Soil-behavior-types classification is general clays-clay to silty clay and silt mixtures-clayey silt to silty clay, and an interference of sand mixtures-silty sand to sandy silt (Figs. 4.27.1b, 4.27.2b, 4.27.3b, 4.28.2, 4.29.2, and 4.30.2). The interference of the sand mixtures-silty sand to sandy silt increases from bottom to top of this sublayer 2. Values of Q_t , F_R , and B_q indicate the increase of the interference of the sand mixtures-silty sand to sandy silt from bottom to top of the sublayer 2 (Figs. 4.28.1, 4.29.1, and 4.30.1). The interference of the sand mixtures-silty sand to sandy silt made the q_t and f_s trend to increase from bottom to top of the sublayer 2 (Figs. 4.27.1b-e, 4.27.2b-e, and 4.21.3b-e). Values of N from the SPT results on the sublayer 1 and sublayer 2 are constant with depth, equal 2 and so small (Fig. 4.27.1a). The values of N from the SPT cannot indicate the interference of the sand mixtures-silty sand to sandy silt in this case. In general, soil-behavior-types of the sublayer 2 are cohesive soil but the homogeneous of the sublayer 2 is less than that of the sublayer 1 (Figs. 4.27.1b, 4.27.2b, and 4.27.3b). The boundaries of the sublayer 2 at the different locations of the CPTUs also have small differences. Namely, the boundaries of the sublayer 2 at the CPTU2-BT2 are from -17.5 m to -14.5 m; at the CPTU1-BT2 and CPTU3-BT2 are -18.0 m to -15.0 m(Figs. 4.27.1-3).

The sublayer 3, in the all results of three CPTUs at the Bentre-2 site such as: Values of q_t and f_s are so high and the largest in comparison with the other sublayers. The values of q_t and f_s trend to decrease with depth from top to bottom of the sublayer 3 (Figs. 4.27.1c-e, 4.27.2c-e, and 4.27.3c-e). In general, soil-behavior-types trend to be cohesionless. Soil-behavior-types classification is common sands-clean sand to silty sand, sand mixtures-silty sand to sandy silt, and an interference of silt mixtures-clayey silt to silty clay and clays-clay to silty clay (Figs. 4.27.1b, 4.27.2b, and 4.27.3b). The interference of the silt mixtures-clayey silt to silty clay and clays-clay to silty clay decreases from bottom to top of this sublayer 3. Values of Q_t , F_R , and B_q indicate the variation of this interference (Figs. 4.28.1, 4.29.1, and 4.30.1). In addition, the values of N from the SPT also trend to decrease from the top to bottom of the sublayer 3 in this case. Namely, values of N in the upper part of the sublayer 3 are 4, and values of N in the lower part of

the sublayer 3 are 2 (Fig. 4.27.1a). This decrease of values of N is also according to the increase of the interference of silt mixtures-clayey silt to silty clay and clays-clay to silty clay (Figs. 4.27.1a-b, 4.27.2a-b, and 4.27.3a-b). From the comparison of the results of CPTU1-BT2, CPTU2-BT2, and CPTU3-BT3 shown in Figs. 4.27.1-3, 4.28.1-2, 4.29.1-2, and 4.30.1-2, some differences can be confirmed in the three tests, implying that soil variations may exist horizontally even in the distance of 4 m (Fig. 3.3.4). The boundaries of the sublayer 3 at the different locations of the CPTUs also have small differences. Namely, the boundary of the sublayer 3 at the CPTU2-BT2 is from -14.5 m to -10.0 m; at the CPTU1-BT2 and CPTU3-BT2 are -15.0 m to -10.0 m (Figs. 4.27.1-3).

The sublayer 4, in the all results of three CPTUs at the Bentre-2 site such as: The alternation of cohesionless layers and cohesive soil layers results in a rather regular saw-tooth shape in the overall plot of q_t , f_s and u_2 as a function of depth in the sublayer 4 (Figs. 4.27.1b-e, 4.27.2b-e, and 4.27.3b-e). The variations of values of Q_t , F_R and B_q are all rather regular with depth (Figs. 4.28.1, 4.29.1, and 4.30.1) and that the soil-behavior-types are such as: The cohesionless soil is the sands-clean sand to silty sand and sand mixtures-silty sand to sandy silt; the cohesive soil is the silt mixtures-clayey silt to silty clay and clays-clay to silty clay (Figs. 4.27.1b, 4.27.2b, 4.27.3b, 4.28.2, 4.29.2, and 4.30.2). The increase and decrease of values of N from the SPT also vary according to the alternation of cohesionless and cohesive soil layers in the sublayer 4; this matter can see at the location of the CPTU3-BT2. Namely, the N values on the sand mixtures-silty sand to sandy silt at around $z = -4.63$ m and sands-clean sand to silty sand at around $z = -6.82$ m is regularly 4; and the N value on the clays-clay to silty clay is 3 at around $z = -8.2$ m (Figs. 4.27.3a-b). However, these values of N cannot indicate the small changes as the CPTU results (Fig. 4.27.3). The boundaries of the sublayer 4 at the different locations of the CPTUs are such as: At the CPTU2-BT2 and CPTU3-BT2 are from -10.0 m to -0.5 m; and at the CPTU1-BT2 is -10.0 m to -2.0 m (Figs. 4.27.1-3).

The sublayer 5, in the results of three CPTUs: The values of q_t and f_s on the sublayer 5 are so high (Figs. 4.27.1c & e, 4.27.2c & e, and 4.27.3c & e). Q_t , F_R and B_q are all rather constant with depth (Figs. 4.28.1, 4.29.1, and 4.30.1) and that the soil-behavior-type is sands-clean sand to silty sand and gravelly sand to sand (Figs. 4.27.1b, 4.27.2b, 4.27.3b, 4.28.2, 4.29.2, and 4.30.2). The boundaries of the sublayer 5 at the different locations of the CPTUs are such as: At the CPTU2-BT2 and CPTU3-BT2 are from -0.5 m to +2.0 m; and at the CPTU1-BT2 is -2.0 m to +2.0 m (Figs. 4.27.1-3).

4.6.5. Bentre-3 site

Measured quantities of the cone penetration tests, CPTU1-BT3, named cone resistance, q_t , sleeve friction, f_s , and pore water pressure measured behind the cone tip, u_2 , are shown in Fig. 4.32 together with the results of SPT-BT3. A typical soil profile can be estimated by soil-behavior-type classification using the above normalized values (Equation 3.1 to 3.3) (Robertson 1990 and 1991). The depth variations in the normalized values obtained from the CPTU1-BT3 are shown in Fig. 4.33.1. The soil-behavior types estimated from the relationship between Q_t and F_R (Robertson, 1990 and 1991) are shown in Fig. 4.32b. The values of t_{50} , c_h , and c_v calculated from the results of pore water pressure-dissipation test at -6.48 m, -12.1 m, and -15.0 m during CPTU1-BT3 at the Bentre-3 site are shown in Figs. 4.35.1-3.

To consider the results of the in-situ tests at the Bentre-3 site we can see that: In the lower part below the altitude, $z = -18.0$ m, N values from SPT-BT3 suddenly increase and obtain 38 at $z = -19.45$ m, and values of q_t and f_s from the CPTU1-BT3 results also suddenly increase (Figs. 4.32a, c, and e). And then, N values increase from 38 to 47 from -18.0 to -28.0 m (Fig. 4.32a). Hence, the investigation soil profile at the Bentre-3 site can divide into two broad parts: The first broad part is below the altitude, $z = -18.0$ m, with high strength; the other part is above the altitude, $z = -18.0$ m, with low strength.

The soil profile, from -18.0 to +2.0 m, at the Bentre-3 site, is divided into 4 sublayers based on the results of the CPTU1-BT3 and SPT-BT3 such as:

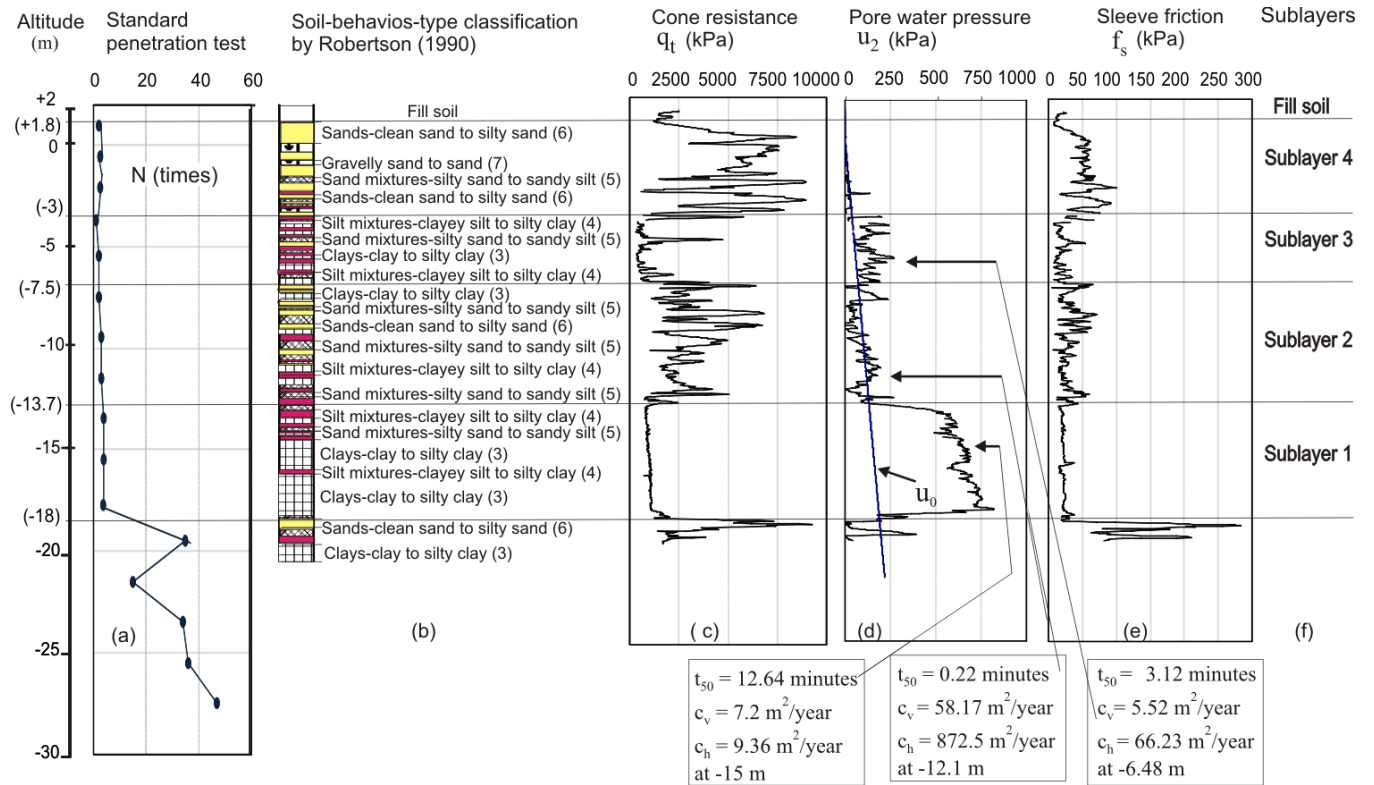


Fig. 4.32. Results of the *in situ* tests at the Bentre-3 site: From SPT-BT3: (a) N value. From CPTU1-BT3: (b) soil-behavior-type classification by Q_t and F_R , (c) – (e) cone resistance, q_t , pore water pressure, u_2 , and sleeve friction, f_s , in addition, values of t_{50} is requisite time for dissipating 50% of pore water pressure, values of c_v and c_h were calculated at the each depth in (d), (f) sublayers divided based on the results of CPTU1-BT3 and SPT-BT3.

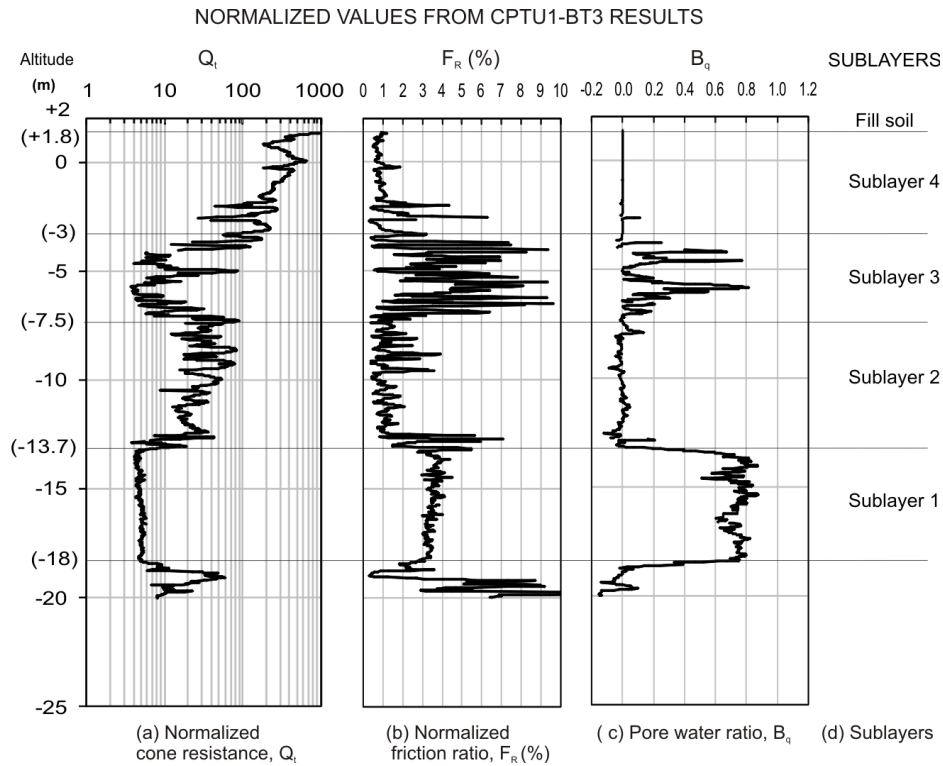


Fig. 4.33.1. Normalized cone resistance, sleeve friction and pore water pressure obtained from CPTU1-BT3 at the Bentre-3 site.

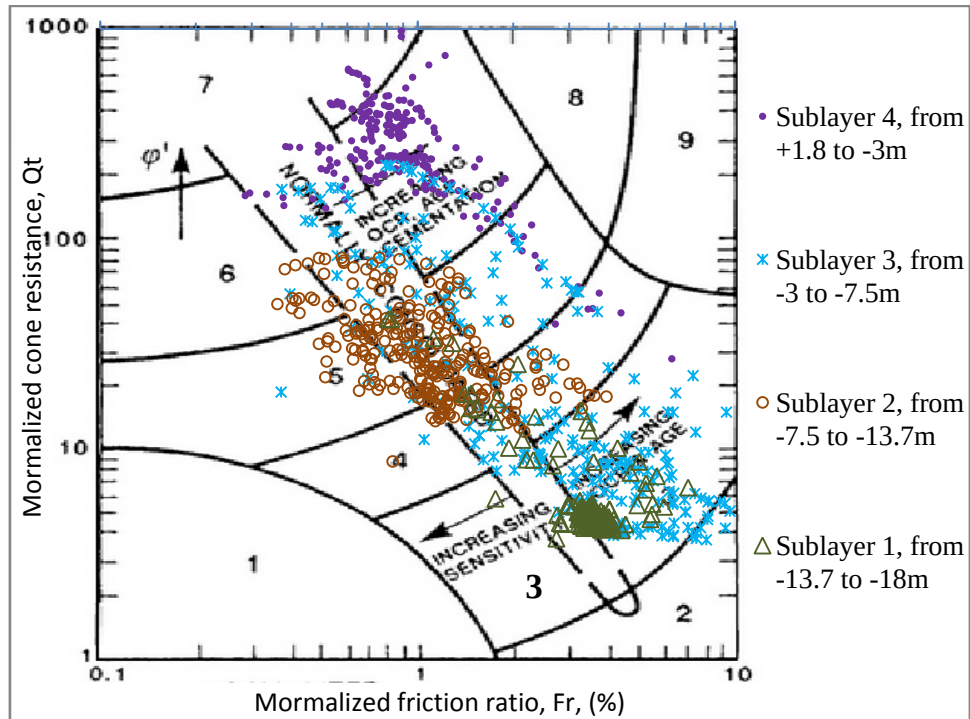


Fig. 4.33.2. Soil-behavior-types of each sublayer by classifications chart Q_t - F_R (Robertson, 1990), obtained from CPTU1-BT3 at the Bentre-3 site: Sublayers 1 to 4.

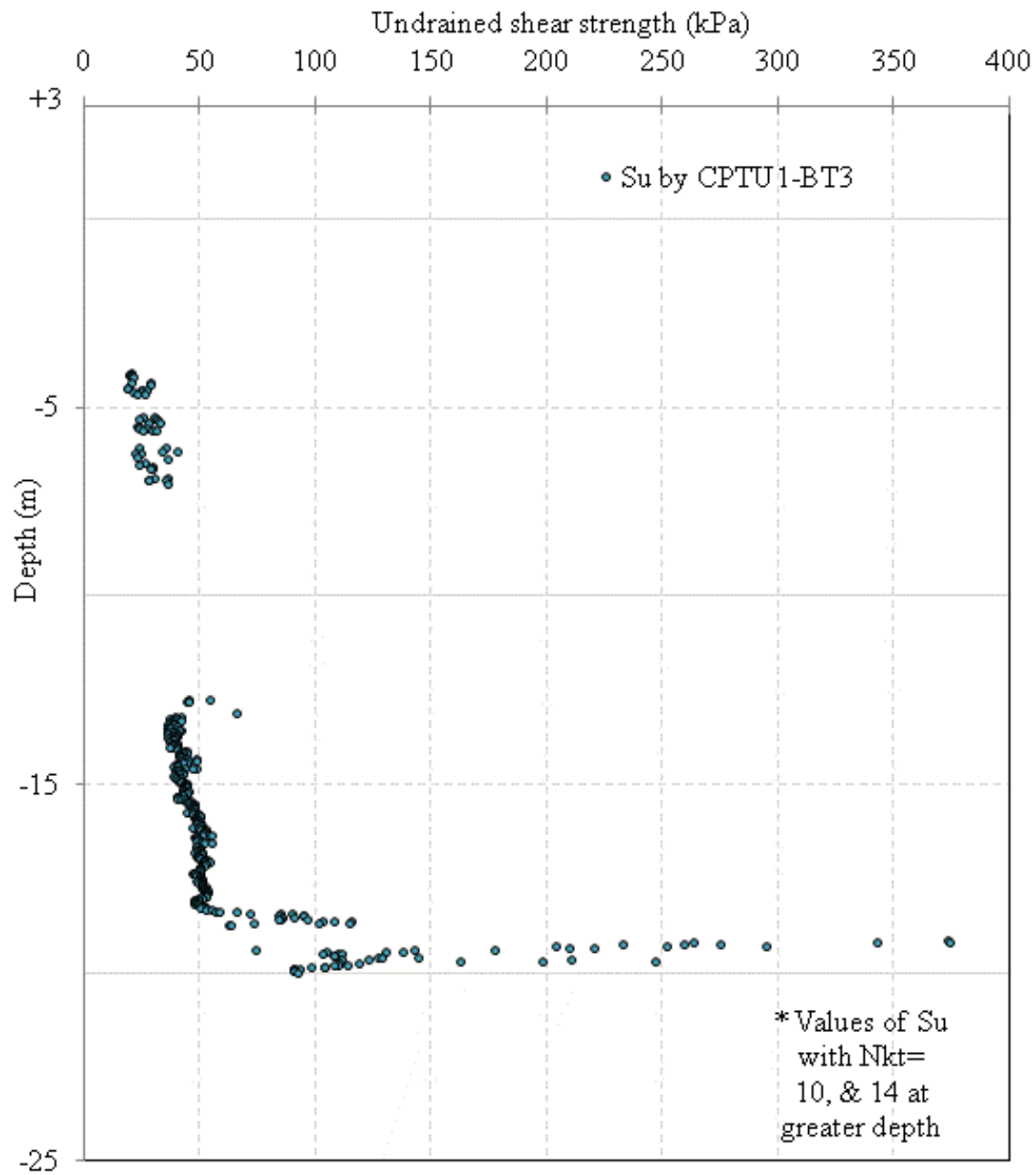


Fig. 4.34. Undrained shear strengths vs. depth obtained from CPTU1-BT3 at the Bentre-3 site.

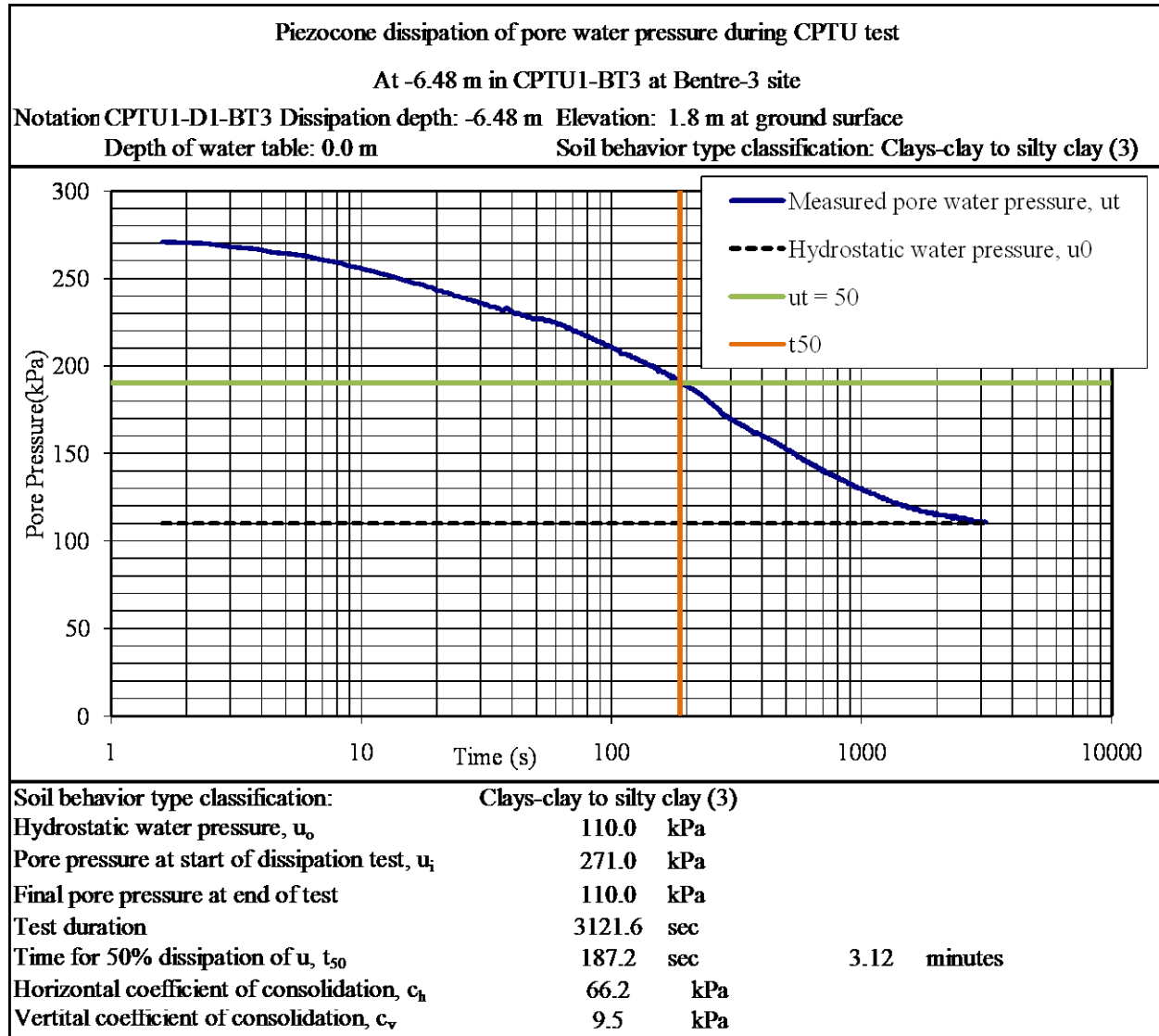


Fig. 4.35.1. Results of pore water pressure-dissipation test at -6.48 m during CPTU1-BT3 at the Bentre-3 site.

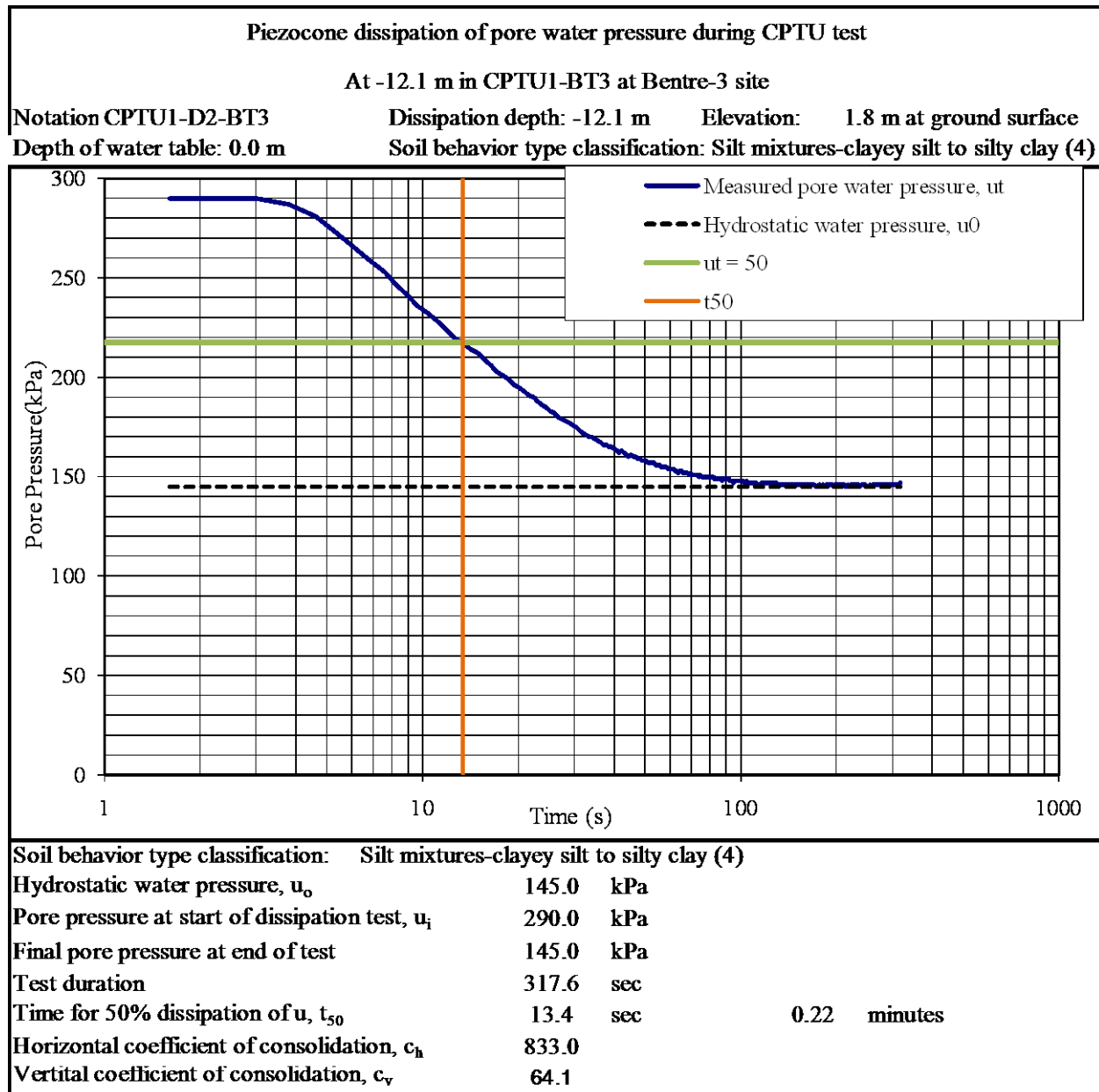


Fig. 4.35.2. Results of pore water pressure-dissipation test at -12.1 m during CPTU1-BT3 at the Bentre-3 site.

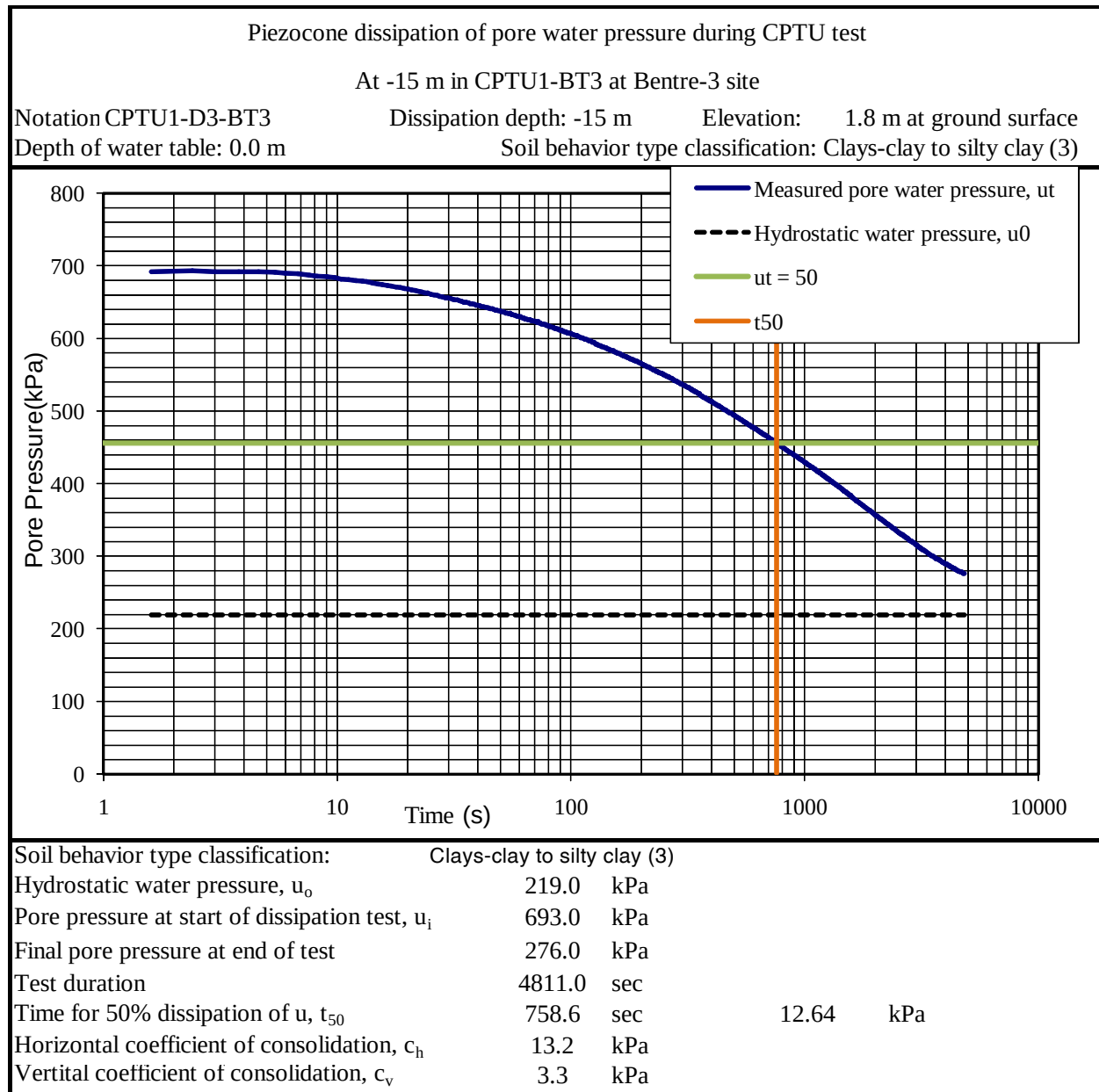


Fig. 4.35.3. Results of pore water pressure-dissipation test at -15 m during CPTU1-BT3 at the Bentre-3 site.

The sublayer 1, from -18.0 to -13.7 m, in the CPTU1-BT3 results: Q_b , F_R and B_q are all rather constant with depth (Fig. 4.33.1) and that the soil-behavior-type is common clays-clay to silty clay (Figs. 4.32b and 4.33.2). It is sometimes an insertion of the silt mixtures-clayey silt to silty clay into the sublayer 1 (Figs. 4.32b and 4.33.2). And in the upper part of the sublayer 1 at the Bentre-3 site, there is an appearance of the type of sand mixtures-silty sand to sandy silt (Fig. 4.32b). The increases of values of q_b , u_2 , and f_s generally trend to be linear with depth (Figs.

4.32c-e). However, around the altitude, $z = -17.5$, values of q_t and f_s decrease slightly; conversely, values of u_2 increase higher (Figs. 4.32c-e). But, the values of N by the SPT-BT3 on the sublayer 1 are regularly 4 (Figs. 4.32c-e).

The sublayer 2, from -13.7 to -7.5 m, in the CPTU1-BT3 results: The values of q_t and f_s trend to decrease with depth from top to bottom of the sublayer 2 (Figs. 4.32c & e). Q_t , F_R and B_q exhibit saw-tooth graphs with large variations (Fig. 4.33.1). In general, soil-behavior-type mainly tends to be cohesionless soils (Figs. 4.32b and 4.33.2). The soil-behavior-type of the cohesive soils insert into the cohesionless soils (Fig. 4.32b). The insertion of the cohesive soils decreases from the bottom to top of the sublayer 2 at the Bentre-3 (Fig. 4.32b). The soil-behavior-types classification of the cohesionless soils is the sands-clean sand to silty sand and sand mixtures-silty sand to sandy silt (Figs. 4.32b and 4.33.2). The soil-behavior-types classification of the cohesive soils is the silt mixtures-clayey silt to silty clay and clays-clay to silty clay (Figs. 4.32b and 4.33.2). Values of N from the SPT results on the sublayer 2 are small, from 2 to 3 (Figs. 4.32a-b).

The sublayer 3, from -7.5 to -3.0 m, in the CPTU1-BT3 results: The alternation of cohesionless layers and cohesive soil layers results in a rather regular saw-tooth shape in the overall plot of q_t , f_s and u_2 as a function of depth (Figs. 4.32b-e). The variations of values of Q_t , F_R and B_q are all rather regular with depth (Fig. 4.33.1) and that the soil-behavior-types are such as: The cohesionless soil is the sands-clean sand to silty sand and sand mixtures-silty sand to sandy silt. And the cohesive soil is the silt mixtures-clayey silt to silty clay and clays-clay to silty clay (Figs. 4.32b and 4.33.2). In general, in the sublayer 3 at the Bentre-3 site, the soil-behavior-type mainly tends to be the cohesive soils more than the cohesionless soils (Figs. 4.32b-e). Values of N from the SPT-BT3 results are so small, from 1 to 2 (Fig. 4.32a).

The sublayer 4, from -3.0 to +1.8 m, in CPTU results, Q_t , F_R and B_q are all rather constant with depth (Fig. 4.33.1) and that the soil-behavior-type is general cohesionless soils (Fig. 4.32b). Namely, soil-behavior-types classification is sands-clean sand to silty sand and gravelly sand to sand. The values of q_t and f_s on the sublayer 4 are so high (Figs. 4.32c & e). Q_t , F_R and B_q are all rather constant with depth (Fig. 4.33.1) and that the soil-behavior-type is general cohesionless soils (Figs. 4.32b and 4.33.2). Namely, soil-behavior-types are sands-clean sand to silty sand and gravelly sand to sand (Figs. 4.32b and 4.33.2). Values of N from the SPT-BT3 results are regularly 2 at each location of the SPT on the sublayer 4 at the Bentre-3 site (Fig. 4.32a).

4.7. Lab geotechnical results

4.7.1. Vinhlong core

Basic geotechnical properties, such as grain size distribution, natural water content, w_n , plastic limit, w_p , liquid limit, w_L , unit weight, γ_{sat} , specific gravity, G_s , are plotted against elevation in Figs. 4.36c-e. Liquidity index, IL, compression strength for undisturbed sample, q_u , sensitivity, S_t , evaluated from the unconfined compression strength q_u to remold sample q_{ru} , consolidation yield stresses σ'_{y-IL} and σ'_{y-CRS} are shown in Figs. 4.36f-i. And average coefficients of consolidation (C_{v-IL} or C_{v-CRS}) from in-situ vertical stress/vertical effective overburden stress σ'_{v0} to yield stress from IL oedometer test σ'_{y-IL} or CRS test σ'_{y-CRS} are also shown in Figs. 4.36j. The measured plasticity index, PI, and w_L of the clayey soils for the deeper sublayers in range of -47.8 to -22 m and the shallower sublayers in range of -22 to +1 m are separately plotted in the plasticity chart (Figs. 4.37a-b). All soils are classified inorganic soils with different plasticity.

During sampling, at the deep depth, due to the large resistance of soil the penetration of sampler become difficult in station maximums by penetration pump. Therefore hammering was used for penetrating the sampler. Where, a soil sample gotten was stiff yellowish, laterite pebbles. The sampling process stopped at the depth $z = -47.8$ m.

The soil profile of the VLM1 core (from -47.8 to +1 m) was divided into eight sub layers (Figs. 4.36 and 4.37) based on the lab geotechnical results such as:

The sublayer 1, from -47.8 to -41.5 m, state is from firm to stiff (Fig.4.36b); material is clay, silt, sand, and pebbles (Fig. 4.36c). Cohesive soils are characterized by liquidity indexes, LI, are the lowest in comparison with upper sublayer, from 0 to 1 (Fig. 4.36f); most clays are very high plasticity CV (Figs. 4.36b and 4.37a). Saturated unit weight, γ_{sat} , are so high (Figs. 4.36d). Unconfined compression strengths, q_u , are from 45 to 185 kPa, q_u values are so high in a range of -47.8 to -44 m and so low in a range of -44 to -41.5 m in sublayer 1 (Figs. 4.36g). Conversely, sensitivities, S_t , are very low, from 1.2 to 5.5 (Figs. 4.36h); and average coefficients of consolidation, C_{v-IL} , or C_{v-CRS} are also very low, from 2 to 4 $m^2/year$ and rarely 25 $m^2/year$ (Fig. 4.36j); and they can be the lowest in comparison with upper sublayers in the VLM1 core.

The sublayer 2, from -41.5 to -27.8 m, state is from soft to firm (Fig. 4.36b); material is nearly all silty clay and clayey silt (Fig. 4.36c). Liquidity indexes, LI, are from 1.0 to 1.5 (Fig. 4.36f).

The sublayer 2 is characterized by common medium plasticity clay, CI (Figs. 4.36b and 4.37a). Values of q_u are from 85 to 160 kPa (Fig. 4.36g). Sensitivities, S_t , are from 8 to 40 (Fig. 4.36h). Values of C_{v-IL} , and C_{v-CRS} are high, from 20 to 76 m²/year corresponding to w_n values are high, around and larger than the w_L values (Figs. 4.36e and j).

The sublayer 3, from -27.8 to -25.0 m, state is from soft to firm (Fig. 4.36b); sublayer 3 is characterized such as: materials are common medium sand, silty sand, and a little silty clay and clayey silt (Fig. 4.36c). And sublayer 3 is characterized by clays being nearly low plasticity, CL (Figs. 4.36b and 4.37a). Liquidity indexes, LI, are from 1.0 to 1.5 (Fig. 4.36f). Values of q_u , are from 45 to 95 kPa (Fig. 4.36g). Sensitivities, S_t , are about 25 (Fig. 4.36h).

The sublayer 4, from -25.0 to -22.0 m, state is from very soft to soft (Fig. 4.36b). Material is only silty clay (Fig. 4.36c); liquidity indexes, LI, are from 0.5 to 1.4 (Fig. 4.36f). The sublayer 4 is characterized by clays being only very high plasticity CV (Figs. 4.36b and 4.37a). Values of q_u , are from 45 to 65 kPa (Fig. 4.36g). Sensitivities, S_t , are from 11 to 14 (Fig. 4.36h). Values of C_{v-IL} are low, from 3 to 9 m²/year.

The sublayer 5, from -22.0 to -18.5 m, state is from very soft to firm (Fig. 4.36b); material is common clayey silt (Fig. 4.36c); liquidity indexes, LI, are from 0.6 to 1.7 (Fig. 4.36f). Values of q_u are from 53 to 84 kPa (Fig. 4.36g). Sensitivities, S_t , are from 9 to 18 (Fig. 4.36h). The sublayer 5 is characterized by most clays being medium plasticity, CI, and rare medium plasticity silt, MI (Figs. 4.36b and 4.37a).

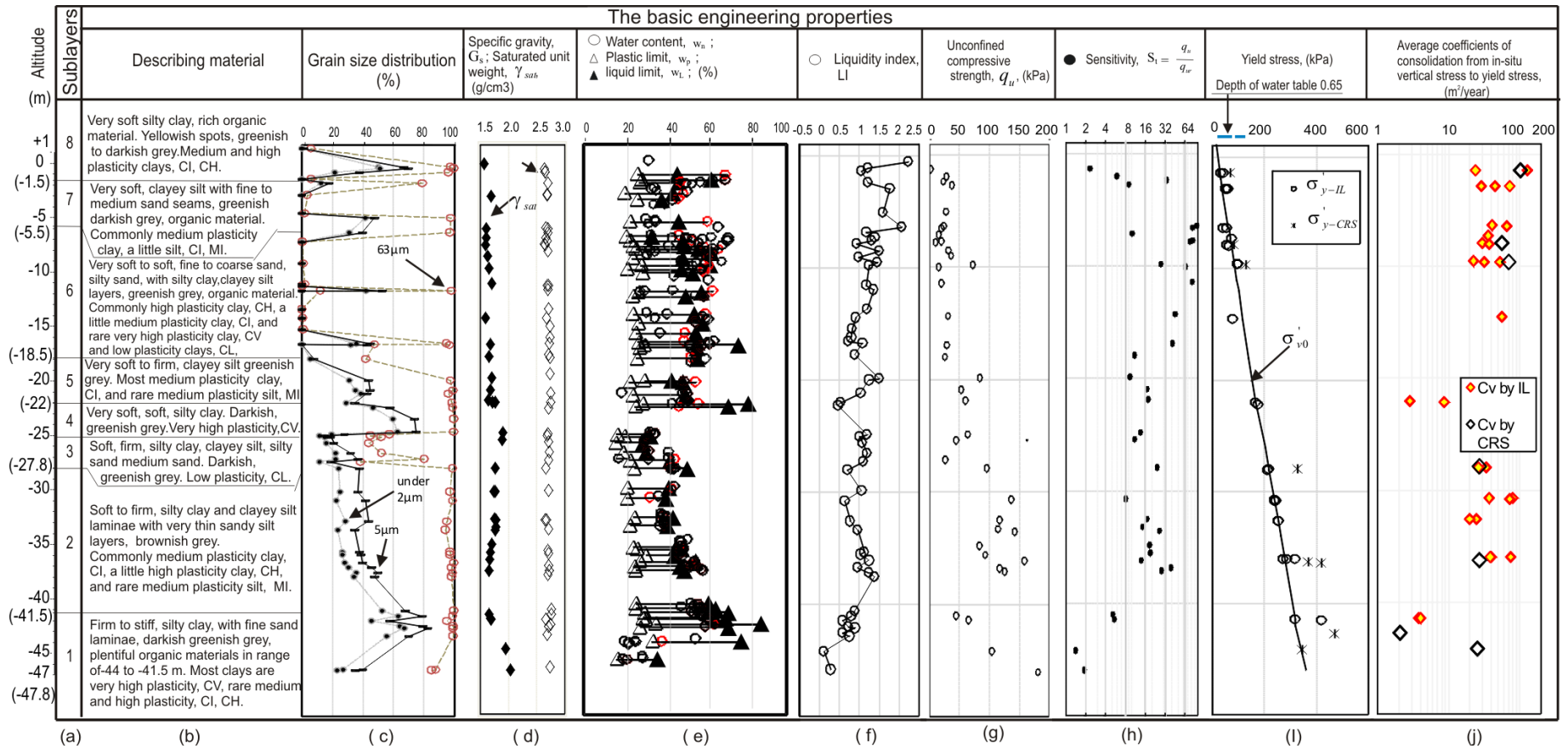


Fig. 4.36. Summary of lab test results of the VLM1 core: **(a)** Sublayers divided by the lab geotechnical test results, **(b)** Description of the material, **(c)** Grain size distribution, **(d)** Saturated unit weight γ_{sat} and specific gravity G_s , **(e)** Natural water content w_n , plastic limit w_p , liquid limit w_L , **(f)** Liquidity index LI, **(g)** Compression strength for undisturbed sample q_u , **(h)** Sensitivity, ratio of compression strength for undisturbed sample q_u to remold sample q_{ru} , **(i)** Yield stress from IL oedometer test σ'_{y-IL} and CRS test σ'_{y-CRS} , with vertical effective overburden stress σ'_{v0} , **(j)** Average coefficients of consolidation from in-situ vertical stress/vertical effective overburden stress σ'_{v0} to yield stress from IL oedometer test σ'_{y-IL} or CRS test σ'_{y-CRS} .

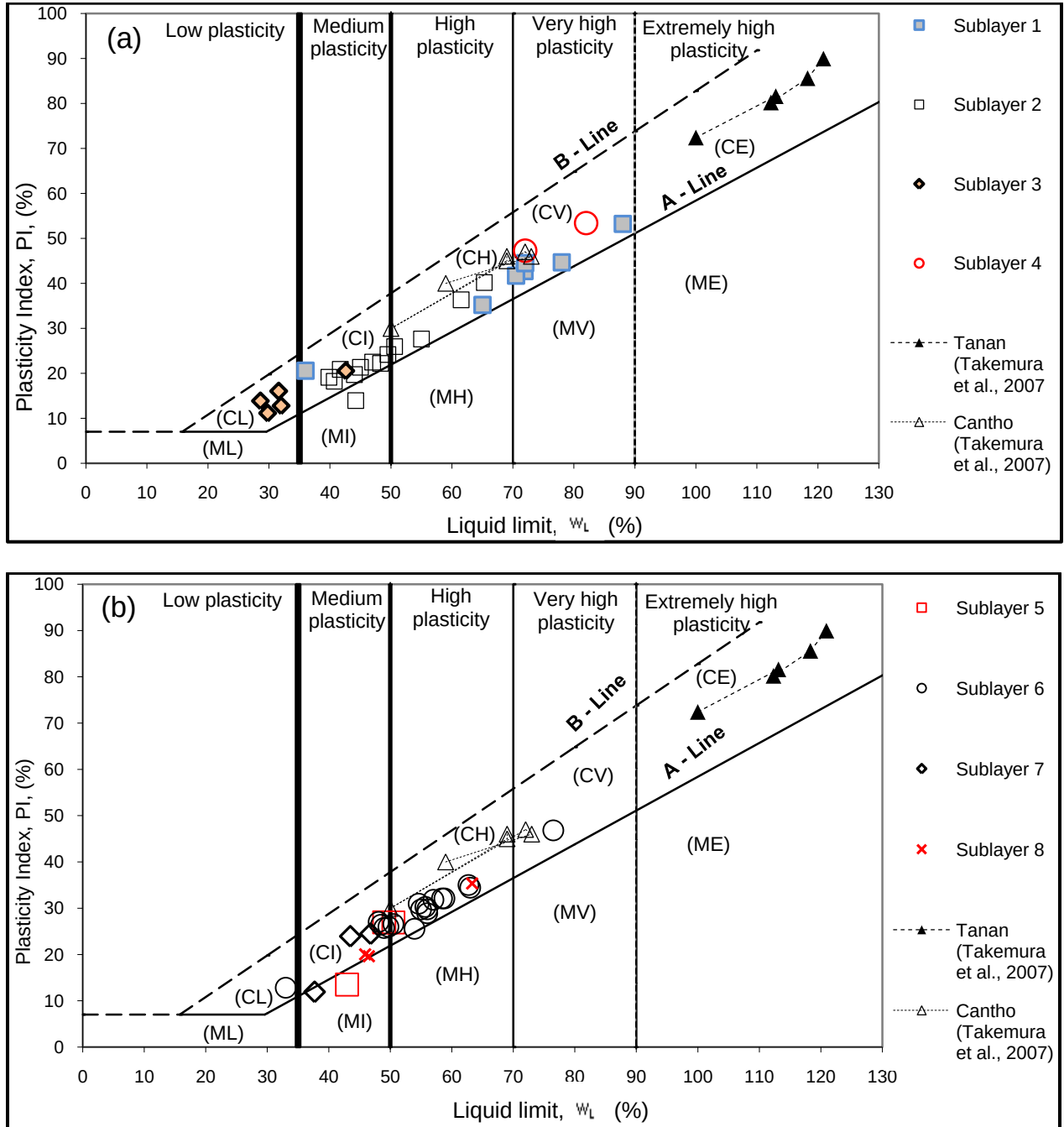


Fig.4.37. Plasticity chart of cohesive soils of the VLM1 core and Tanan and Cantho cores (Takemura et al., 2007): (a) deeper deposits from Sublayer 1 to sublayer 4 and (b) shallower deposits from sublayer 5 to sublayer 8.

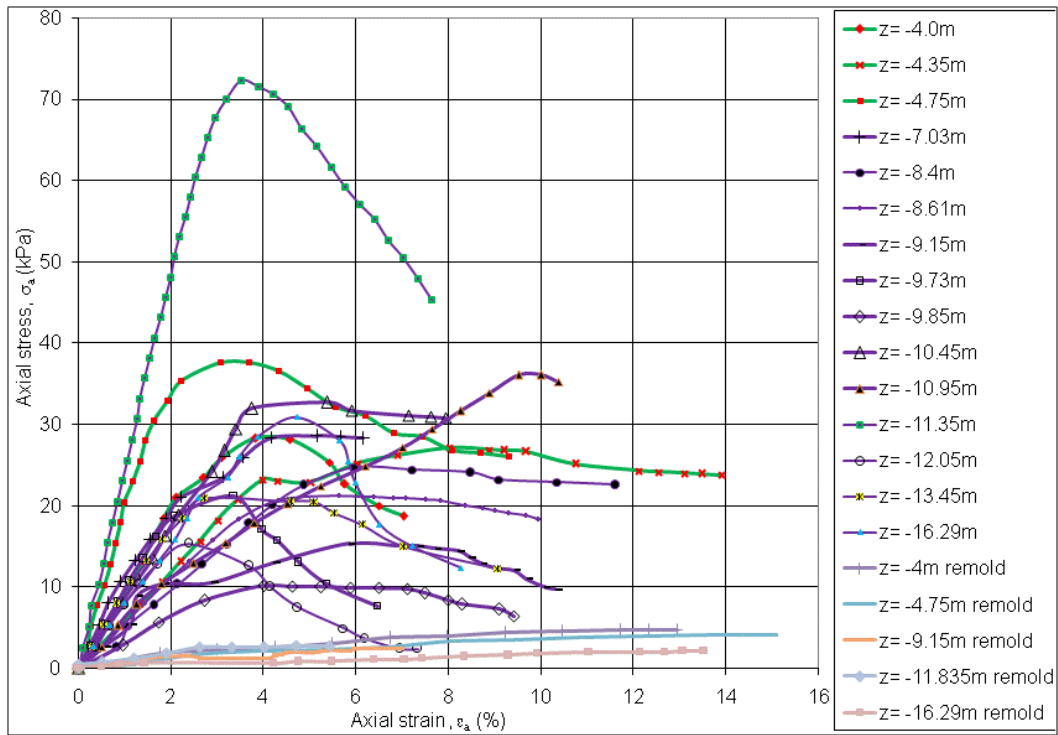


Fig. 4.38.1. Axial stress and strain curves of UC tests from -4 m to -16.5 m of VLM1 core.

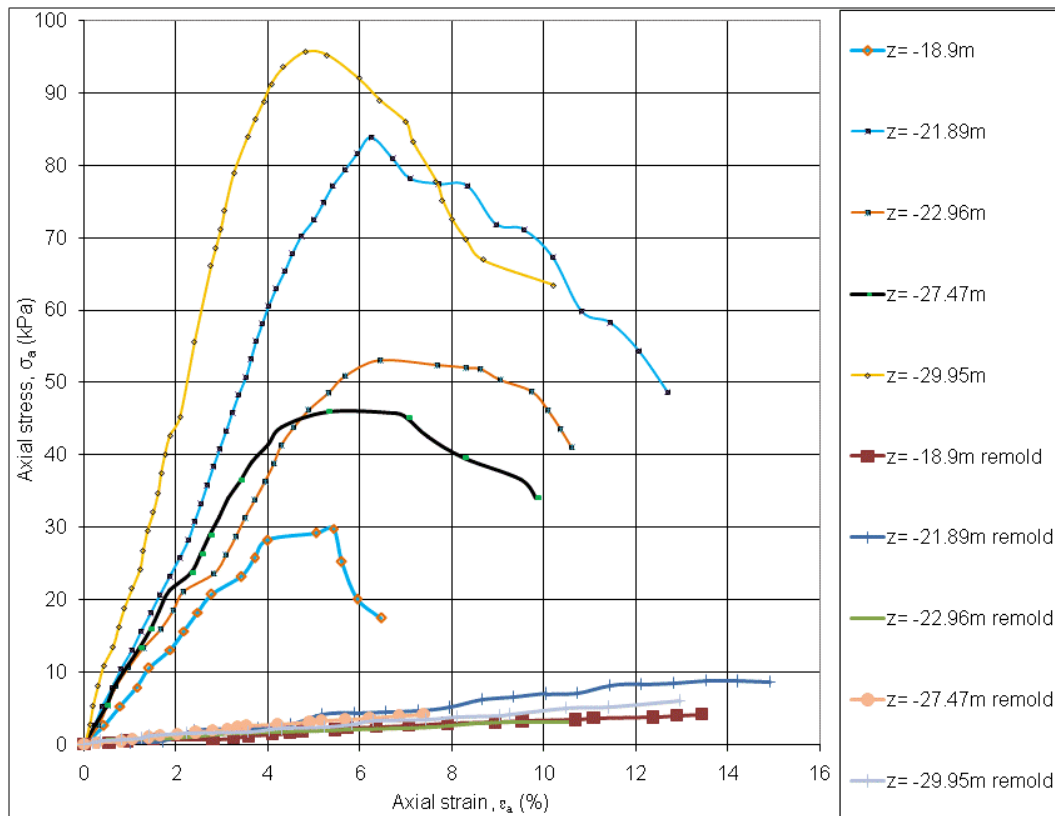


Fig. 4.38.2. Axial stress and strain curves of UC tests from -18.9 m to -29.95 m of VLM1 core.

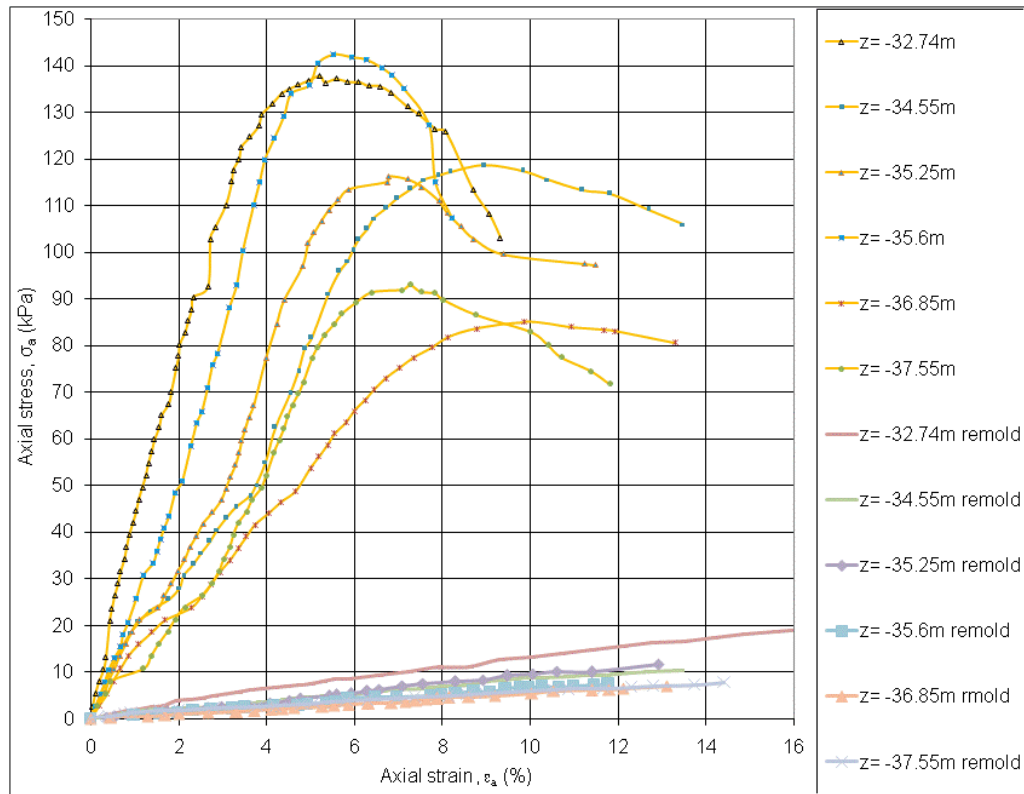


Fig. 4.38.3. Axial stress and strain curves of UC tests from -32.74 m to -37.55 m of VLM1 core.

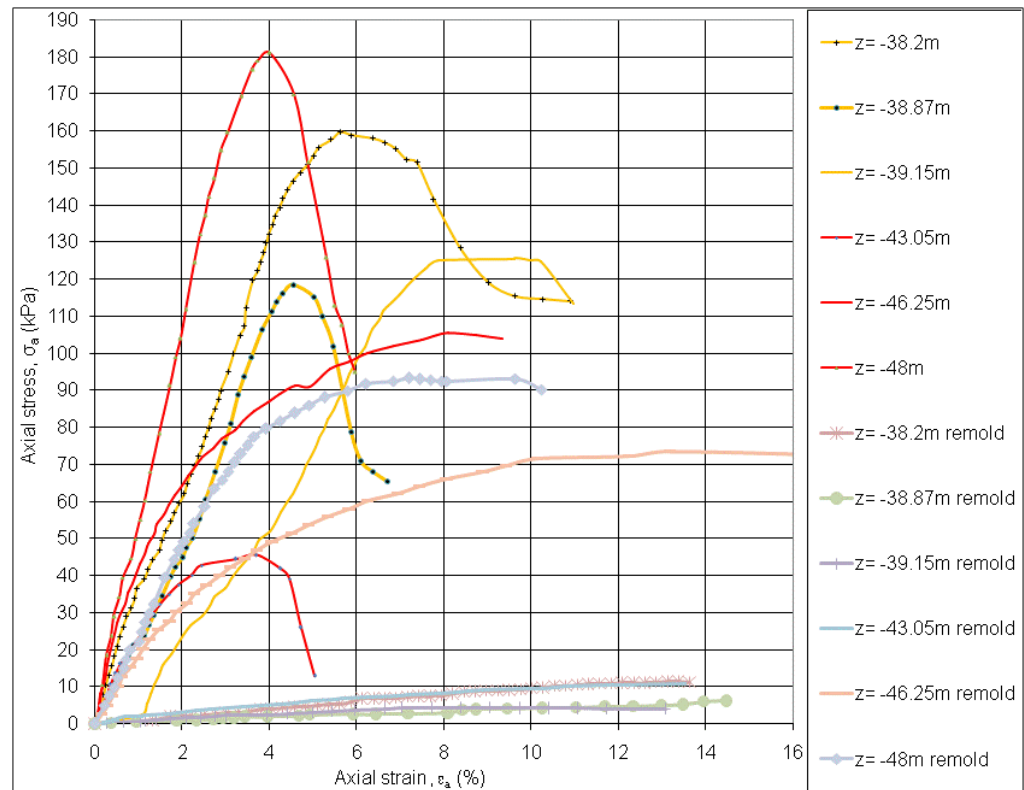


Fig. 4.38.4. Axial stress and strain curves of UC tests from -38.2 m to -48 m of VLM1 core.

The sublayer 6, from -18.5 to -5.5 m, state is from very soft to soft (Fig. 4.36b); material is common fine to coarse sand, silty sand, silty clay, clayey silt (Fig. 4.36c); liquidity indexes, LI, are from 1.0 to 1.7 (Fig. 4.36f). Values of q_u of the cohesive soil specimens and cohesive soil specimens with an alternation of thin sandy seams are normally less than 50kPa and rarely obtain 72 kPa (Fig. 4.36g). Sensitivities, S_t , are large and vary significantly, from 10 to over 64 (Fig. 4.36h). A difference characteristic of the sublayer 6 is by various clays. Clay is common high plasticity, CH; it is a little medium plastic clay, CI, and rare very high plastic silt, CV, and low plastic clay, CL (Figs. 4.36b and 4.37b). Values of C_{v-IL} and C_{v-CRS} are so large, from 22.6 to 72 m²/year (Fig. 4.36j).

The sublayer 7, from -5.5 to -1.5 m, state is very soft (Fig. 4.36b); material is common clayey silt, and fine to medium sand (Fig. 4.36c). Cohesive soils are commonly medium plastic clay, CI, and a little medium plastic silt, MI (Figs. 4.36b and 4.37b). Liquidity indexes, LI, are from 1.7 to 2.2; these LI values are greater than those of the sub-layer 6 and sub-layer 8 (Fig. 4.36f). Values of q_u of the cohesive soil specimens and cohesive soil specimens with an alternation of thin sandy seams are so low, from 23 to 37.6 kPa (Fig. 4.36g). Sensitivities, S_t , are so high and can obtain 114 (Fig. 4.36h). Values of C_{v-IL} are also so large, from 29.2 to 57 m²/year (Fig. 4.36j).

The sublayer 8, from -1.5 to +1.0 m, state is very soft (Fig. 4.36b); material is only silty clay (Fig. 4.36c). The clays are medium plastic, CI, and high plastic, CH (Figs. 4.36b and 4.37b). Liquidity indexes, LI, are from 1.3 to 1.4; and LI of soil specimen contained much organic material obtains 2.3, simultaneously saturated unit weight, γ_{sat} , is also low (Figs. 4.36d and f). Values of q_u are so low, from 3 to 38 kPa (Fig. 4.36g). Sensitivities, S_t , are from 2.3 to 34.3 (Fig. 4.36h). Values of C_{v-IL} and C_{v-CRS} are also so large, from 25 to 130 m²/year (Fig. 4.36j).

Measured liquidity indices are all greater than one for the soils at shallow sublayers (from -18.5 to +1.0 m) and high sensitivity, especially in the sublayer 6 from -18.5 to -5.5 m (Figs. 4.36f&g). Most values of σ'_{y-IL} and σ'_{y-CRS} lie on or above the line σ'_{ov} (Fig. 4.36i), indicating that the argillaceous soils are typically normally consolidated or somewhat overconsolidated on the VLM1 core.

4.7.2. Caolanh core

The quality of the Caolanh and Vinhlone cohesive soil specimens were evaluated by the

criteria of sample quality for cohesive soils of Andresen and Kolstad (1979) and shown in Fig. 4.39. The qualities of them tend to decrease according to depth; especially, the specimens at depths are so lower -25m (Fig. 4.39). The causes can be the sampler inserted by the water pump used and the hammering used for penetrating the sampler. The soil samples below $z = -31$ m were gotten by standard penetration-tube of the SPT tests, so the geotechnical properties cannot be conducted on undisturbed samples at these depths. The all basic geotechnical properties: describing materials, grain size distribution, saturated unit weight, γ_{sat} , specific gravity, G_s , natural water content, w_n , plastic limit, w_p , liquid limit, w_L , liquidity index, LI, compression strength for undisturbed sample, q_u , sensitivities, q_u/q_{ur} , from UC tests are shown in 4.40b-h. The vertical yield stresses σ'_{y-IL} and σ'_{y-CRS} from the IL and CRS results are shown in Figs. 4.40i. And average coefficients of consolidation (C_{v-IL} or C_{v-CRS}) from in-situ vertical stress/vertical effective overburden stress σ'_{v0} to yield stress from IL oedometer test σ'_{y-IL} or CRS test σ'_{y-CRS} are also shown in Figs. 4.40j. All sublayers are divided based on the lab geotechnical results of the Caolanh core and summarized in Fig. 4.40.

During sampling, when, overcame a depth $z = -36.5$ m, a soil sample gotten was stiff yellowish, laterite pebbles. The sampling process stopped.

The soil profile of the CLM1 core (from -36.6 to +2.9 m) is divided into 7 sublayers based on the lab geotechnical results (Fig. 4.40) such as:

The sublayer 1, from -36.6 to -32.1 m, state is from firm to stiff, liquidity indexes, LI, are from 0.28 to 0.04 (Figs. 4.40b and f); material is silt, clay, and very fine sand (Figs. 4.40b-c). The cohesive soils are low plastic clay, CL, (Figs. 4.40b and 4.41).

The sublayer 2, from -32.1 to -26.1 m, state is from soft to firm (Fig. 4.40b); material is clay, silt, sand, and peaty seams and organic materials (Figs. 4.40b-c). The cohesive soils are low plastic clay, CL, and low and medium plastic silts, ML and MI (Figs. 4.40b and 4.41). LI values are from 0.6 to 1.27 (Figs. 4.40b and f). Value of q_u is 40 kPa and sensitivity, S_t , is greater than 7 (Figs. 4.40g-h). Value of C_{v-IL} is 10 m²/year (Fig. 4.40j).

The sublayer 3, from -26.1 to -21.9 m, state is from soft to firm (Fig. 4.40b); material is clay, silt, and silty sand (Figs. 4.40b-c). The cohesive soils are low and medium plastic clay, CL and CI, and medium plastic silt, MI (Figs. 4.40b and 4.41). Values of q_u are 28 to 57 kPa, and sensitivity, S_t , is less than 3.5 to 4.5 (Figs. 4.40g-h). The vertical yield stresses σ'_{y-IL} are greater

than vertical effective overburden stresses σ'_{v0} (Fig. 4.40i). Values of C_{v-IL} are large from 19 to 106.5 m²/year (Fig. 4.40j).

The sublayer 4, from -21.9 to -13.1 m, material is only sand and silty sand (Fig. 4.40b).

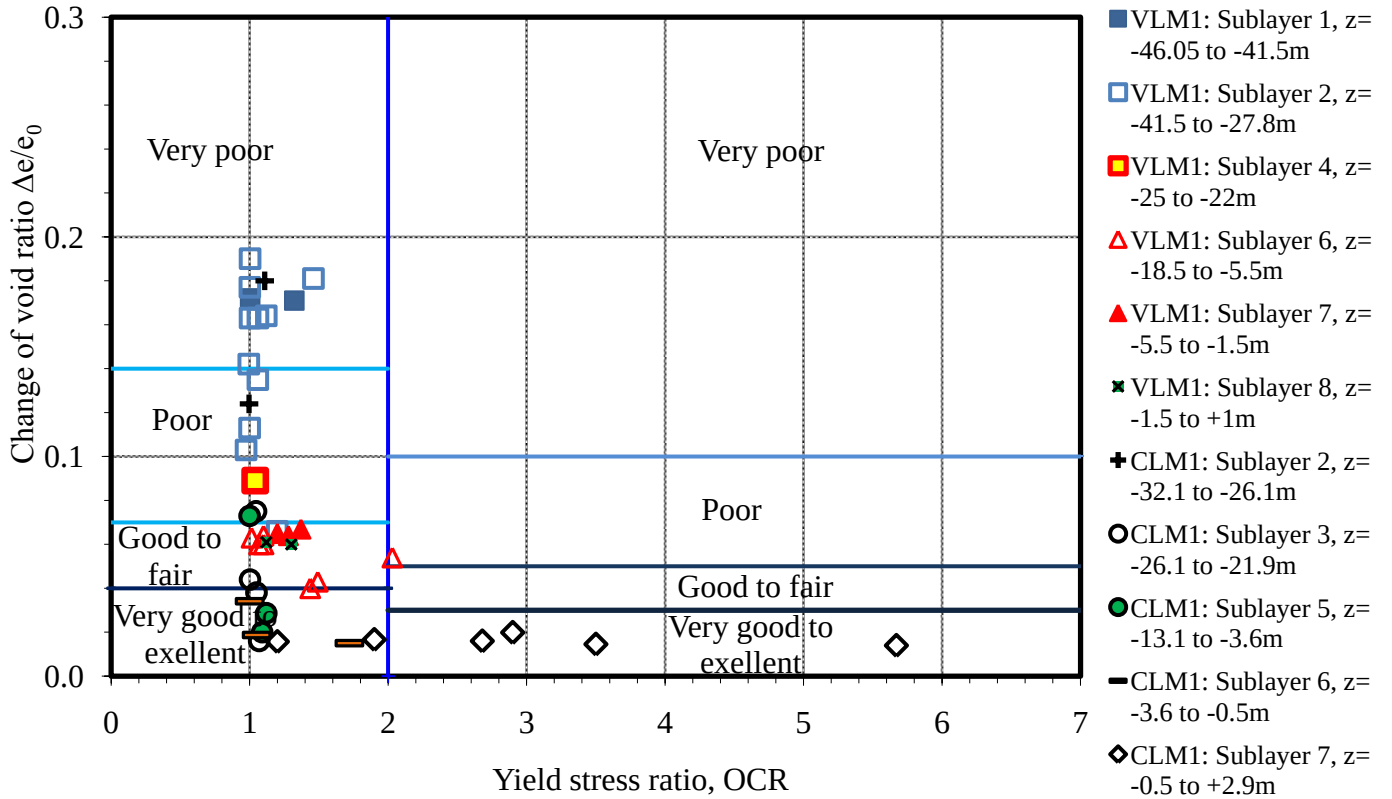


Fig. 4.39. Changes of void ratio due to recompression to the effective overburden stress from oedometer tests on Vinhlong and Caolanh cohesive specimens.

The sublayer 5, from -13.1 to -3.6 m, state is from soft to firm (Fig. 4.40b); material is silty clay, clayey silt with thin very fine sand seams (Figs. 4.40b-c). The cohesive soils are medium plastic clay, CI and high plastic silt, MI (Figs. 4.40b and 4.41). Values of q_u are around 40 kPa and sensitivities, S_t , are from 16 to 20 (Figs. 4.40g-h). Liquidity indexes, LI , are from 0.8 to 1.7 (Fig. 4.40f). The vertical yield stresses σ'_{y-IL} are slightly greater than vertical effective overburden stresses σ'_{v0} (Fig. 4.40i). Values of C_{v-IL} and C_{v-CRS} are large from 10.5 to 57 m²/year (Fig. 4.40j).

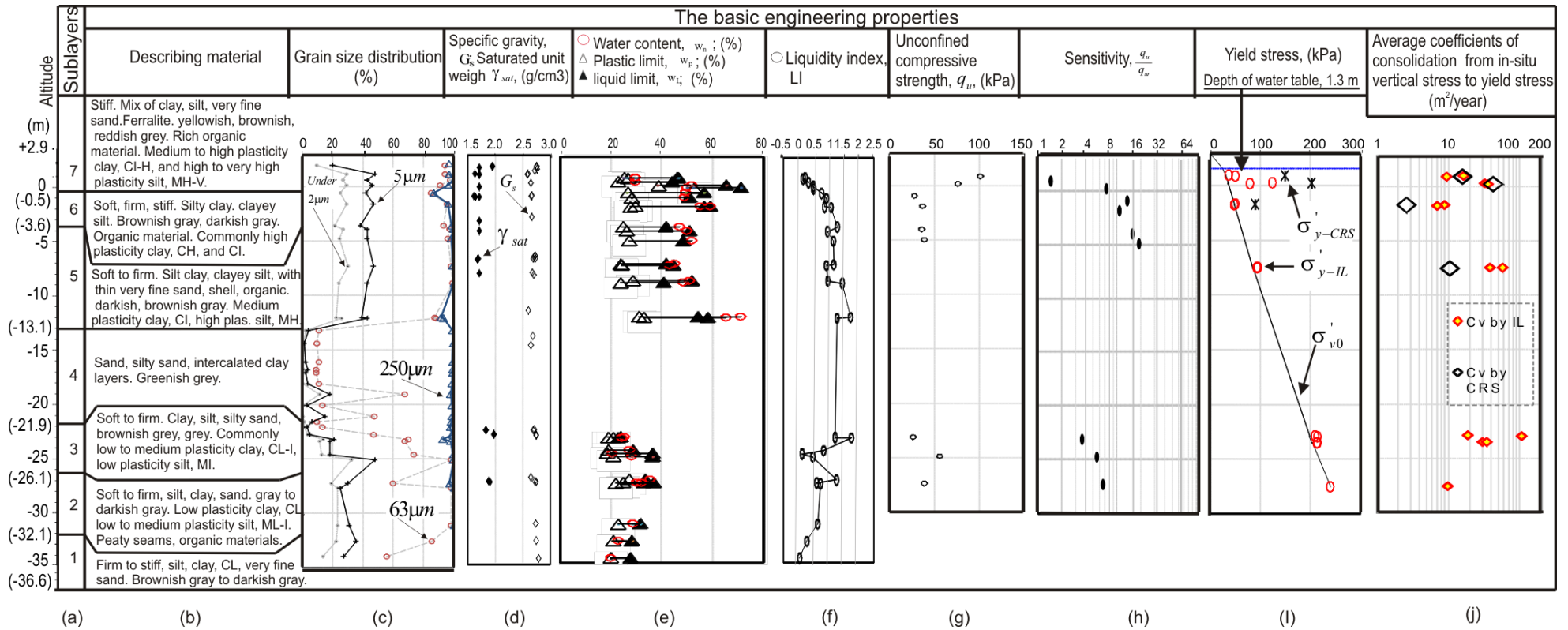


Fig. 4.40. Summary of lab test results of Caolanh site: **(a)** Geological column of the CLM1 core, **(b)** Description of the materials, **(c)** Grain size distribution, **(d)** Saturated unit weight γ_{sat} and specific gravity G_s , **(e)** Natural water content w_n , plastic limit w_p , liquid limit w_L , **(f)** Liquidity index LI, **(g)** Compression strength for undisturbed sample q_u , **(h)** Sensitivity, ratio of compression strength for undisturbed sample q_u to remold sample q_{ru} , **(i)** Yield stress from IL oedometer test σ'_{y-IL} and CRS test σ'_{y-CRS} , with vertical effective overburden stress σ'_{v0} , **(j)** Average coefficients of consolidation (C_v) from in-situ vertical stress/vertical effective overburden stress σ'_{v0} to yield stress from IL oedometer test σ'_{y-IL} or CRS test σ'_{y-CRS} .

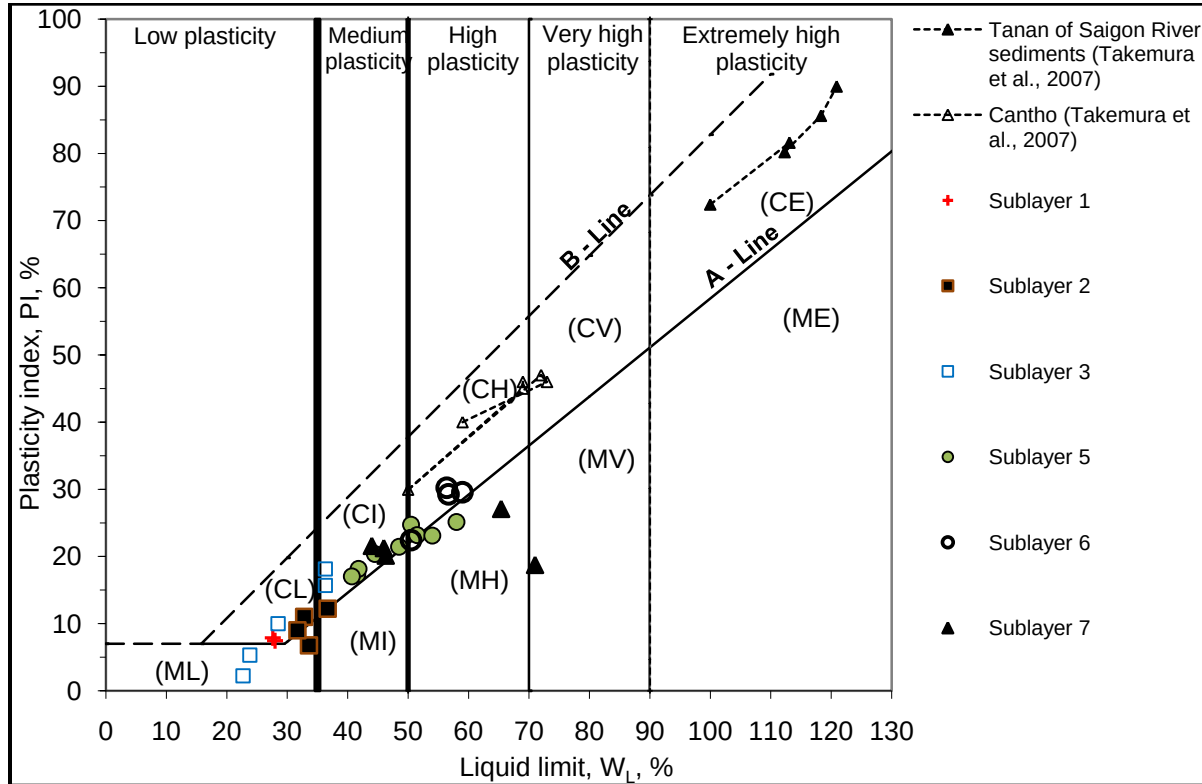


Fig. 4.41. Plasticity chart of deposits in the CLM1 core at Caolanh site;
Tanan and Cantho cores (Takemura et al., 2007).

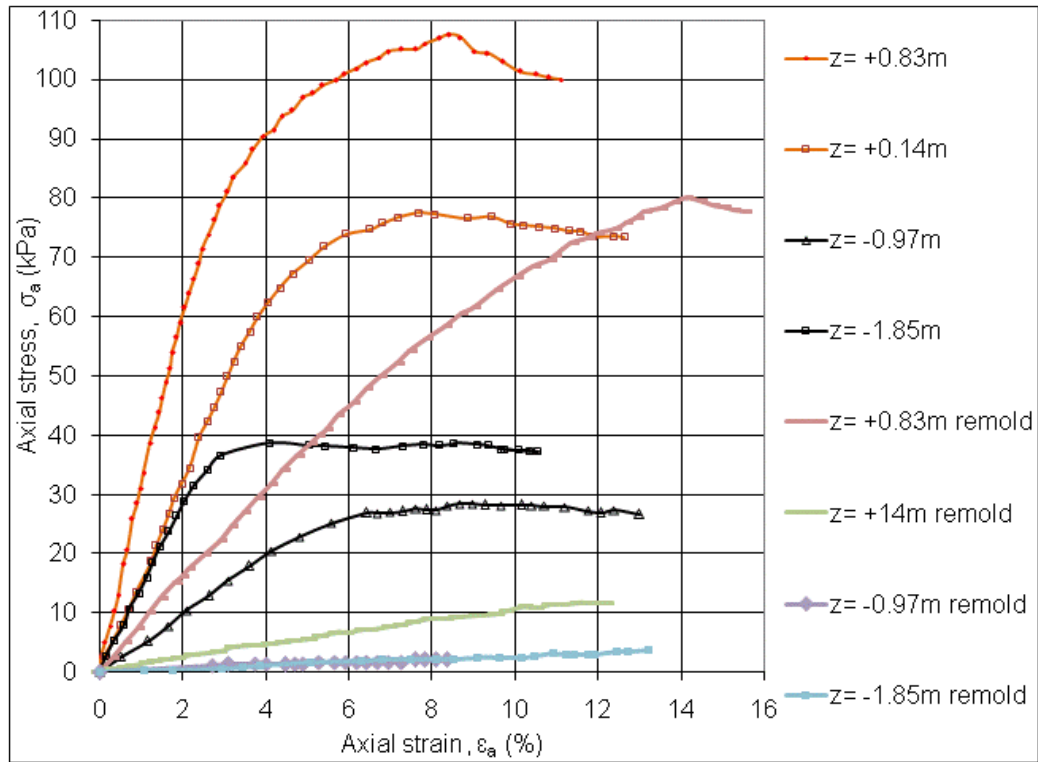


Fig. 4.42.1. Axial stress and strain curves of UC tests from +0.83 m to -1.85 m of CLM1 cores.

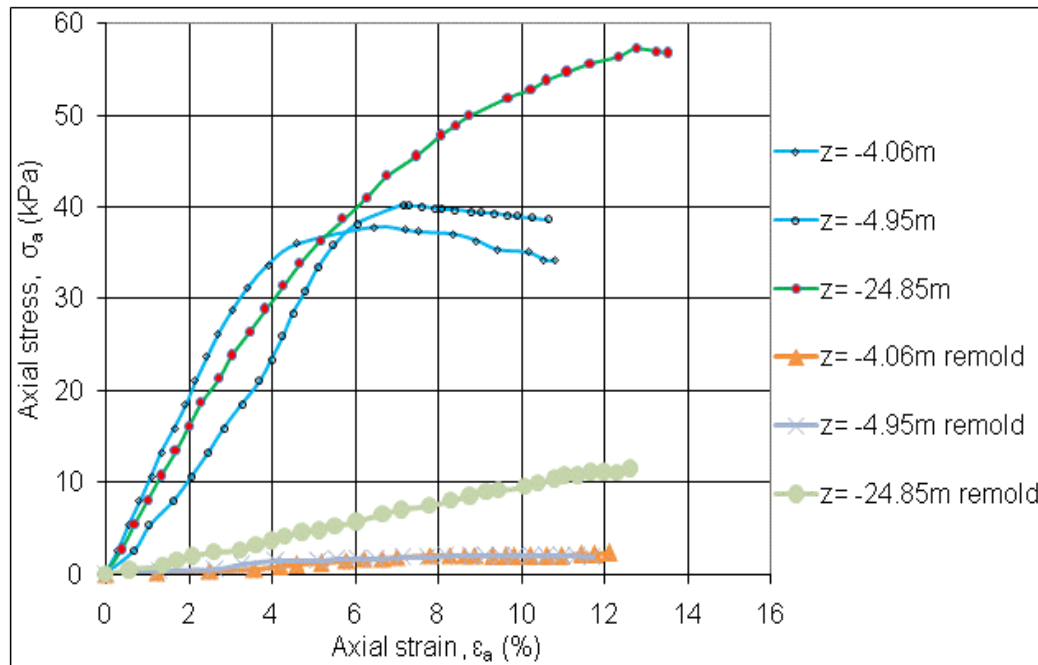


Fig. 4.42.2. Axial stress and strain curves of UC tests from -4.06 m to -24.85 m of CLM1 cores.

The sublayer 6, from -3.6 to -0.5 m, state is from soft to firm, liquidity indexes, LI, are from 0.5 to 1.0 (Figs. 4.40b and f). Material is silty clay, clayey silt (Figs. 4.40b-c). The cohesive soils are high (CH) and medium plastic clay CI (Figs. 4.40b and 4.41). Values of q_u are from 28 to 40 kPa and sensitivities, S_t , are from 10 to 15; these values of the sub-layer 6 are less than those of the sub-layer 5 (Figs.4.40g-h). The vertical yield stresses σ'_{y-IL} and σ'_{y-CRS} are greater than vertical effective overburden stresses σ'_{v0} (Fig. 4.40i). Values of C_{v-IL} and C_{v-CRS} are from 2.6 to 8.8 m²/year (Fig. 4.40j).

The sublayer 7, from -0.5 to +2.9 m, state is stiff; material is mix of clay, silt, sand, and ferralite (Figs. 4.40b-c). Liquidity indexes, LI, are large and decrease with depth, namely from 0 to 0.77 (Figs. 4.40b and f). The cohesive soils are medium (CI) and high plastic clay (CH), and medium (MH) and very high plastic silts (MV) (Figs. 4.40b and 4.41). Specially, saturated unit weight, γ_{sat} , specific gravity, G_s , compression strength, q_u , and σ'_{y-IL} and σ'_{y-CRS} values, are, so high and the greatest in comparison with those of the below sublayers (Figs. 4.40d, g, and i). While sensitivity, S_t , is from 1.4 to 7.0, these values are so low (Fig. 4.40h). Values of C_{v-IL} and C_{v-CRS} are from 9.6 to 36 m²/year and tend to decrease with depth (Fig. 4.40j).

4.8. Characteristics of geotechnical properties of MRD

The geotechnical investigation by the in-situ and lab tests at the all sites provides the following results on the applicability of geotechnical investigation for the characterization of the MRD late Pleistocene-Holocene sediments.

The homogeneous and inhomogeneous characteristics were so clearly identified by the CPTU results. Some small differences about the strength and soil-behavior-types can also be confirmed by the CPTU results such as: At the Vinhlong site in the distance of 10 m (Fig.3.3.2) can be confirmed in the CPTU1-VL and CPTU2-VL results like the above presentation in the 4.6.1 item (Figs.4.10 to 4.12). And at the Bentre-2 site in the distances of 4 to 20 m (Fig. 3.3.4) are also realized in the CPTU1-BT2, CPTU2-BT2, and CPTU3-BT2 results like the above presentation in the 4.6.4 item (Figs. 4.27.1 to 4.27.3, 4.28.1, 4.29.1, and 4.30.1). Simultaneously, these results affirm that soil variations exist horizontally even in the so small distance (4 m) in the sediments with low strength in the MRD.

While, N values by the SPT cannot clearly present the soil variations cases such as: The N

values on homogeneous and inhomogeneous soil layers are not different like at the Vinhlong site (Fig. 4.10a) and at the Bentre-3 site (Fig. 4.32a) like the above presentation in the 4.6 item. And the N values on the cohesive soil layer don't increase with depth like on the sublayer 5 at the Caolanh site (Fig. 4.17a), on the sublayer 2 and sublayer 3 at the Bentre-1 site (Fig. 4.22a), on the sublayer 1 and sublayer 2 at the Bentre-2 site (Fig. 4.27.1a), and on the sublayer 1 at the Bentre-3 site (Fig. 4.32a), like the above presentations in the 4.6 item. Hence, the N values cannot represent the small variation of the penetration resistance precisely, accurately, and continuously observed by the CPTU on the sediments with low strength in the MRD.

The CPTU results can indicate small differences between the homogeneous layers or the inhomogeneous layers; that these small differences also confirm by the lab geotechnical results such as: At the VLM1 site, based on the CPTU1-VL results, the range of -25.0 to -18.5 m divided into the sublayer 4 (from -25.0 to -22.0 m) and the sublayer 5 (from -22.0 to -18.5 m) (Figs. 4.10 and 4.12). The results of the Atterberg limits also show that the soil-types in the sublayer 4 are only very high plastic clay, CV and the soil-types in the sublayer 5 are most medium plastic clay, CI, and rarely medium plastic silt, MI (Figs. 4.36b and 4.37a-b). These results demonstrate that there is a clear difference between the sublayer 4 and sublayer 5 at the VLM1 site. The other case, for the inhomogeneous layers at the VLM1 site, based on the CPTU1-VL and CPTU2-VL results, the range of -18.5 to -1.5 m could divide into the sublayer 6 (from -18.5 to -5.5 m) and the sublayer 7 (-5.5 to -1.5 m) (Figs. 4.10 to 4.12). The results of the Atterberg limits and natural water contents show also that the values of liquidity index, LI, on the sublayer 6 are from 1.0 to 1.7; and the LI values on the sublayer 7 are from 1.7 to 2.2 (Figs. 4.36e and f).

The results indicated that the sublayer identified by the in-situ geotechnical results is relatively identical to the sublayer identified by the lab geotechnical results on the core at the same site. Hence, based on the CPTU results, we can divide into the sublayers, and we can combine the CPTU results with the lab geotechnical results for dividing exactly sublayers.

The maximum values of N by the SPT on the late Pleistocene-Holocene sediments of four sites including Vinhlong, Bentre-1, Bentre-2, and Bentre-3 sites are general less than 5. And the N values on the cohesive soils and cohesionless soils don't have clear difference. The maximum values of N by the SPT on the late Pleistocene-Holocene sediments at the Caolanh site can obtain 16 on the cohesionless soil, and 9 on the cohesive soil. The N values on the late Pleistocene-Holocene sediments at the Caolanh site are general more than those at the Vinhlong, Bentre-1,

Bentre-2, and Bentre-3 sites.

Values of q_u are from 3 to 185 kPa (Figs. 4.36g and 4.40g); and sensitivities, S_t , are from 1.2 to 114 (Figs. 4.36h and 4.40h) on the cohesive soils of the Vinhlong and Caolanh sites.

In general, values of σ'_{y-IL} and σ'_{y-CRS} lie on or above the line σ'_{ov} (Figs. 4.36i and 4.40i), indicating that the argillaceous soils of the Vinhlong and Caolanh sites are typically normally consolidated to overconsolidated except specimens with so low quality. Values of σ'_{y-CRS} from CRS test are greater than σ'_{y-IL} from IL oedometer test (Figs. 4.36i and 4.40i). Values of C_{v-IL} and C_{v-CRS} are from 2 to 130 m²/year (Figs. 4.36j and 4.40j).

4.9. Summary of chapter 4

4.9.1. Sedimentary geology

The sediment cross-section rebuilt (I-L-M-N), at the end of the LGM, the altitude-difference of surface of the undifferentiated Pleistocene sediment-basement is so large, $z = -69$ m at the incised-valley and $z = -8.5$ m at the interfluvies. The earliest water level rise at BT2 site, $z = -69$ m, began to form the estuarine channel environment. The river mouth shifted gradually landwards; and at VLM1 site began to form the estuarine channel environment at $z = -46.05$ m. Subsequently, the sea level and the altitudes continued to increase; the salt marsh environment occurred at BT2 and VLM1 sites; and the marsh/tidal flat environment appeared at CLM1 site. Following, the estuary marine environment was formed at VLM1 and BT2 sites and the sub- to intertidal environment was formed at CLM1 site. During 6,500-5,000 yr BP, at all sites were in the bay environment. After the bay facies formed, the altitude-difference of topography remained 16 m. The marine transgression succession might have occurred during 12,000-5,000 yr BP. The CLM1, VLM1, and BT2 sites were almost fully filled by the estuarine channel, salt marsh, estuarine marine, sub- to intertidal flat, and bay facies.

The estuary channel and estuary marine facies created in the high dynamic hydrological conditions and strongly influenced by tides have plentiful sediment structures and their grain sizes are clay, silt, and common fine to coarse sands. The marsh, tidal flat, sub- to intertidal flat, bay facies created in the relatively quiet hydrological conditions have faint sediment structures, and common clay and silt, discontinuous and very thin fine sand beds. The bay facies are mud content over 95%, in quiet hydrological conditions and by slight tidal influences.

Subsequently, the marine regression was by the combined effects of sea level fall and high sediment supply. The earliest regression began at CLM1 site and the prodelta/bay environment finished before 6,500 yr BP. The sea level shifted gradually seawards and the prodelta environment occurred at VLM1 to BT1 to BT2 and to BT3 sites, 6,430-4,000 yr BP. The delta front environment occurred the earliest at CLM1 site and the latest at BT3 site. Afterward, the intertidal flat environment occurred at CLM1 site. The sub- to inter-tidal flat environment formed at VLM1 to BT1 to BT2 and to and completed BT3 sites. The regression stage was during 6,500-1,300 yr BP. The last phase: the flood plain/marsh environments occurred at CLM1, VLM1, and BT1 sites; the foreshore/salt marsh environments were at BT2 and BT3 sites. The altitude-difference between all investigation sites was only 2.5 m.

The regressive Holocene delta facies successions: The coarsening-upward succession from bay to prodelta to delta front and to subtidal flat facies in CLM1 and VLM1 cores in the upper delta plain are typical tide-dominated delta. The bay facies in VLM1 and BT2 cores to the prodelta/bay facies in CLM1 core is typical coarsening-upward succession from the open to inner bay. The coarsening-upward successions from prodelta to delta front and to foreshore facies in BT2 and BT3 cores in the lower delta plain also display typical tide- and wave-dominated delta. The fining-upward sub- to intertidal flat facies overlain the delta front facies at all cores. The uppermost part: the fining muddy flood/marsh and nature levee facies are in the upper delta plain, and the foreshore-dune and salt marsh facies are in the lower delta plain. The sand contents in the sub- to intertidal flat, intertidal flat, flood/marsh, and nature levee facies in the cores in the tide-dominated delta are less than those in the sub- to intertidal flat, foreshore-dune, and salt marsh facies in BT2 and BT3 cores in the tide-and-wave-dominated delta.

The prodelta, intertidal flat, and flood/marsh facies created in the relatively quiet hydrological conditions have faint sediment structures and common clay, silt, and thin fine sand seams. The coarsening-upward succession in the prodelta facies was gradually formed with very fine sand to fine laminae. The coarsening-upward succession was the most clearly in the delta front facies with the fine to coarse sand. The delta front and sub- to intertidal flat facies created in the strong hydrodynamic conditions have plentiful sediment structures with alternate clay and sand seams.

The changes in the late Pleistocene-Holocene sediment facies were according to topographical conditions of the undifferentiated Pleistocene sediments, delta formation mechanisms, and source of material supply. The marine transgression the trend is fining upwards; and the marine regression the trend is coarsening upwards. Each facies was created in the distinct sediment

environment, sometimes reciprocally affected to some extent, especially at the beginning and the ending of each environment. As a result, the facies often display somewhat differences at bottom and top parts but they still carry the facies' main characteristics, like the marsh and prodelta facies. If sediment environment rapidly changed, sediment facies formed will be entirely different with the previous one, like estuarine marine and delta front facies.

The contents of clay mineral types of the all sediment facies were in descending order from the illite, kaolinite, chlorite, smectite. The illite contents are the largest, over 44%, in the natural levee facies over 70%. It could be due to the material-source from the Mekong River system.

4.9.2. Geotechnical properties

The soil profile at each investigation site includes two sediment-sequences. The deep sediment-sequences have N values greater than 38 and rarely 12. And the shallow sediment-sequences have N values from 1 to 3 and rarely 16.

The shallow sediment-sequence at each investigation site was divided into various sublayers based on the CPTUs and lab geotechnical results. The sublayers can divide into two groups. The first group including sublayers which have q_t , u_2 , f_s , vary largely in saw-tooth shape. They have various soil behavior types. The second group including sublayers which have q_t , u_2 , f_s , increase linearly with depth. Their soil behavior types are only clays (type 3) or clays and silt mixtures (type 3 and 4).

The N values of the shallow sediment-sequences are very small and do not increase, or increase with a little quantity. Simultaneously, N values on homogeneous and inhomogeneous soil layers are not clearly different.

The soil-behavior types from the relationship between Q_t and F_R and those from the relationship between Q_t and B_q were almost the same for the shallow sediment sequences. But the soil behavior types based on values of B_q are sometime different with results from the sampling soil specimens. The homogeneous and inhomogeneous characteristics were so clearly identified by the CPTU results. Some small differences about the strength and soil-behavior-types of the shallow sediment sequences can also be confirmed by the CPTU results. Simultaneously, these soil variations exist horizontal direction even in the so small distance, 4 m, at the same site of shallow sediment sequence in the MD are also realized in the CPTU results.

Specially, the surface sublayer at CLM1 site is with very small thickness of overburden layer, but whose states are from firm to stiff, heavy overconsolidation, and the strengths by the CPTU

and UC tests are high. It is not according to the mechanical law.

CHAPTER 5

INFLUENCE OF SEDIMENTARY ENVIRONMENT ON GEOTECHNICAL PROPERTIES AND CONSOLIDATION CHARACTERISTICS

5.1. Introduction

This chapter discusses about relationship between the sedimentary facies and geotechnical properties. The geotechnical sublayer identified by geotechnical results will be collated with the sedimentary facies identified by sedimentary properties that they were presented in chapter 4. Their appeared depth, characteristics, and characteristic-changes of the geotechnical properties and the sedimentary properties will be considered and relationship between the sedimentary facies and geotechnical properties will be realized. From that point, we will define how the sedimentary environment and condition influence on the geotechnical properties of each sedimentary facies. And the delta formation mechanisms influenced on geotechnical property successions at different locations in the late Pleistocene-Holocene progradation of the MRD in the depositional cross-section, ILMN (Fig. 4.8), rebuilt in item 4.4 will be also discussed.

The second content of this chapter is consolidation characteristics of the late Pleistocene-Holocene sediment facies. To consider levels of consolidations through consolidated parameters from the lab consolidation tests and CPTU tests. The levels of consolidation of the sedimentary facies will be analyzed in the context of the sedimentary environment and condition according to the age, space, formation mechanism and development of Mekong Delta, and post-depositional processes. The consolidation processes will also be considered in the structure-condition of soil layers in the soil profile. To interpret development-levels of microstructure of facies' argillaceous soils based on a combination of the consolidated properties, ^{14}C age, and analysis on the images from the PTS and SEM of the selected soil samples of Caolanh, Cantho, and Vinhlong cores. How to choose values of k for estimating OCR values from CPTU test based on the development-levels of microstructure and structure-condition of soil layers in the soil profile for each sedimentary facies will be discussed and suggested.

5.2. Relationship between the sedimentary facies and geotechnical properties

As discussed in 4.4, the sedimentary cross-section from the upper delta plain to the lower delta plain, around the Mekong River and Bassac River, and perpendicular to the present coastline was rebuilt. The cross-section includes the CLM1, VLM1, BT1, BT2, and BT3 cores. The VLM1 and BT2 core sites were located in an incised valley; the CLM1 core site was located in the edge of the incised valley zone; and BT1 and BT3 core sites were located the interfluvies. They includes two sedimentary successions, i.e., (1) transgressive incised-valley fill sediments deposited between 11,500-6,400 yr BP, which include estuarine channel, marsh or marsh/tidal flat, estuarine marine or sub- to inter-tidal flat, and bay or bay/prodelta facies; (2) regressive Holocene delta sediments deposited between 6,400-2,400 yr BP, which include pro-delta, delta front, sub- to inter-tidal flat or inter-tidal flat, flood plain/marsh, natural levee, and sand dune facies.

5.2.1. Transgressive incised-valley fill sediments

5.2.1.1. Estuarine channel facies (Sublayer 1 of VLM1 core)

At the Vinhlong site, the results of the CPTU1-VL(Figs. 4.10b-f) inthe sublayer 1 from -47.8 to -41.5 m showed that the soil-behavior-types vary and that their formation sequences are similar to sedimentary structures of estuary channel facies (Fig. 4.1).The sublayer 1, from -47.8 to -41.5 m, it can be seen that the lowest soil layer, where the materials were cohesive soil, was formed rather early (more than 9,910 yr BP) and under a large effective overburden pressure. The results also showed that the soil layer is from normally to heavily overconsolidated state and that its strength increased highly (Fig. 4.10 and 4.15). From -47 to -45 m, the soil-behavior-type is heavy overconsolidated clays from the CPTU1-VL results (Fig. 4.10b); and the natural water contents, w_n , are nearly equal to the plastic limit, w_p , (Fig. 4.36e). These w_n values are appropriate to firm state with liquidity index LI around zero (Fig. 4.36f). This is probably a result of the sediments containing numerous plant fragments and plentiful organic materials. Especially, in the range of -44.0 to -41.35 m, the w_n is approximately 60% higher than the w_p (Fig. 4.36e) and the soil-behavior-type is normally consolidated clays (Figs. 4.36i and 4.10b). And the undrained shear strengths, S_u , also decrease (Fig. 4.15). The smectite mineral content is highest but the illite mineral content is lowest in comparison with all the facies of both VLM1

and CLM1 cores (Tabs. 4.1 and 4.4).

The sublayer 1 (from -47.8 to -41.5 m) at the Vinhlong site identified by the geotechnical results could seem to coincide to the estuary channel facies on the VLM1 core identified by the sedimentary results presented in 4.2.1 section. The correlation between the sublayer 1 and the estuary channel facies is represented in Figs. 5.1.2 and 5.2.2). The estuary channel facies was formed in the high energy environment; as a result, this facies is characterized by plentiful geotechnical properties.

5.2.1.2. Salt marsh facies (Sublayer 2 of VLM1 core)

At the Vinhlong site, the CPTU1-VL results on the sublayer 2 in the range of -41.5 to -27.8 m indicate that the increase of q_t , u_2 , and f_s are linear with depth (Figs. 5.1.2c-e). Values of Q_t , F_R and B_q are all constant with depth (Fig. 5.2.2). Soil-behavior-type in the sublayer 2 is only clays-clay to silty clay (Fig. 5.1.2b). In the lab geotechnical results, the materials are primarily medium plasticity clay CI, a little high plasticity clay CH, and rarely medium plasticity silt MI (Fig. 4.37a). The marsh facies on the VLM1 core was identified by the sedimentary results presented in 4.2.1 section has characteristics such as: The marsh facies is also in the range of -41.5 to -27.8 m. The marsh facies has the simple structures and materials. Characteristics of sediment are similar with those of geotechnical properties. Namely, the simple sediment properties on the sample at $z = -40.95$ m on the VLM1 core are similar with simple soil-behavior-type of clays-clay to silty clay (Figs. 4.2B and 4.10b); and the increase of q_t , u_2 , f_s , and S_u being linear with depth (Figs. 4.15, and 5.1.2c-e). The clay mineral contents of the three specimens from the sedimentary facies are almost equal and the illite mineral content is highest in comparison with all the facies of the VLM1 core (Tab. 4.1). Hence, the sublayer 2, from -41.5 to -27.8 m, identified by the geotechnical results could seem to coincide to the marsh facies on the VLM1 core identified by the sedimentary results shown in Figs. 5.1.2 and 5.2.2. The salt marsh facies at the Vinhlong site was formed in the low energy environment; as a result, this facies is characterized by the geotechnical properties with a high homogeneity level.

5.2.1.3. Marsh/tidal flat facies (Sublayer 1 of CLM1 core)

At the Caolanh site, the CPTU1-CL results on the sublayer 1, from -36.6 to -32.1 m, indicate soil-behavior-type is commonly clays-clay to silty clay and silt mixtures-clayey silt to silty clay (Fig. 5.1.1b). Moreover, the layers of sand mixture-silty sand to sandy silt insert in the layer of

clays and silt mixtures in the sublayer 1 (Fig. 5.1.1b). The tidal flat/marsh facies on the CLM1 core identified by the sedimentary results presented in 4.2.2 item has characteristics such as: The tidal flat/marsh facies is also in the range of -36.6 to -32.1 m. The tidal flat/marsh facies has the brown seams of very fine sand silt with 8 mm in maximum thickness and gray mud seams alternated rhythmically; the parallel, lenticular beddings and discontinuous very fine sand silt laminae are common. Characteristics of sediment are similar with those of geotechnical properties, namely on the sample at $z = -34.9$ m (Fig. 4.4A). Hence, the sublayer 1 identified by the geotechnical results could seem to coincide to the marsh/tidal flat facies on the CLM1 core identified by the sedimentary results and shown Figs. 5.1.1 and 5.2.1. The structure, material, and geotechnical properties of the marsh/tidal flat facies at the Caolanh site are not highly homogeneous as those of the marsh at the Vinhlong site (Figs. 5.1.1 and 5.1.2.). The marsh/tidal flat facies (around 11,350 yr BP) was formed earlier than the marsh facies (9,910 to 9,090 yr BP) at Vinhlong site. Hence, the undrained shear strengths on the marsh/tidal flat facies are larger than those of the marsh facies at Vinhlong site.

GENERAL SOIL PROFILE CONSISTS OF
THE GEOLOGICAL COLUMNS AND GEOTECHNICAL PROPERTIES
SCALE: 1/130; 1/36,000

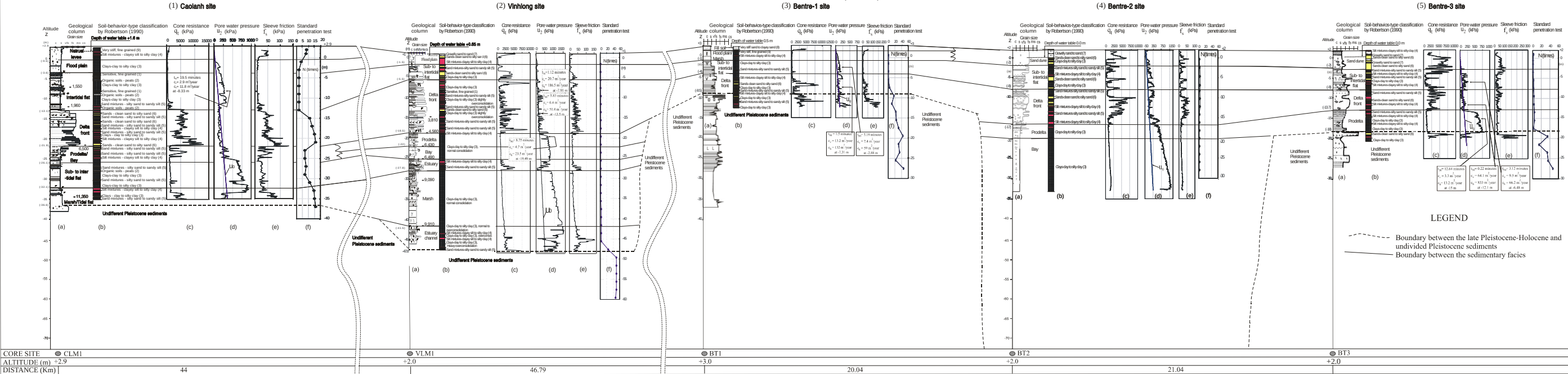


Fig. 5.1. General soil profile consists of investigation sites: (1) Caolanh, (2) Vinhlong, (3) Bentre-1, (4) Bentre-2, (5) Bentre-3; each investigation site displays: (a) Geological columns, (b) Soil-behavior-type classification by Q_i and F_{R_i} , (c) Cone resistance, q_i , (d) Pore water pressure, u_z , and (e) Sleeve friction, f_s , and values of t_{50} was requisite time for dissipating 50% of pore water pressure, values of c_v and c_h were calculated at the each depth of the CPTU tests. And (f) N values from the SPT tests.

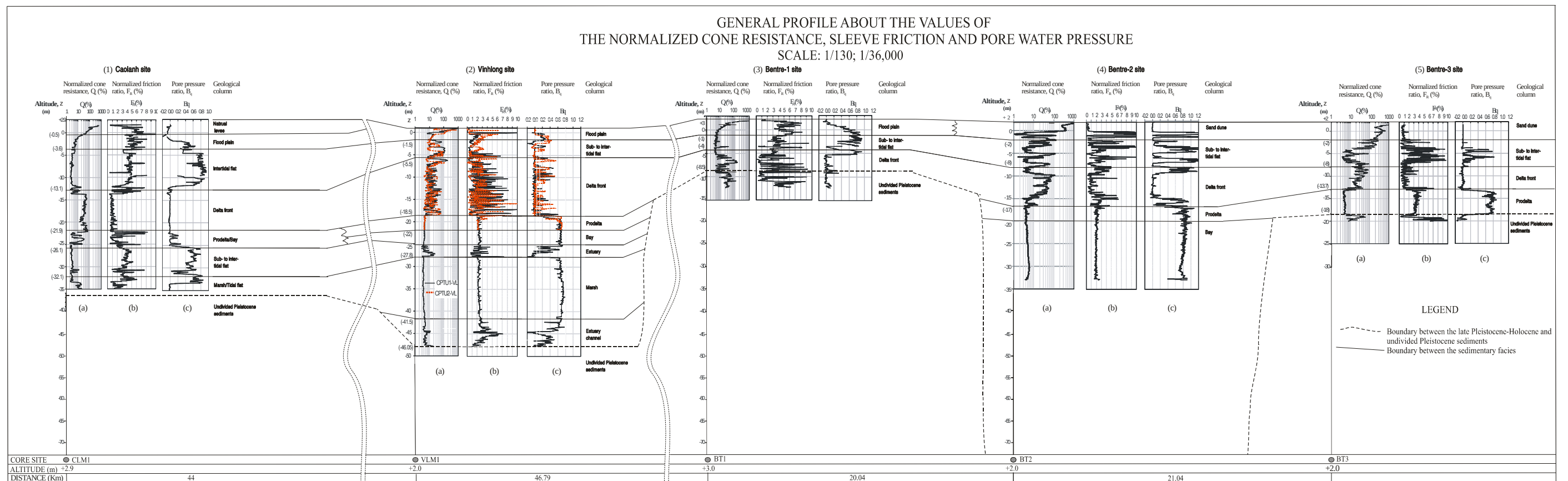


Fig. 5.2. General profile of investigation sites: (1) Caolanh, (2) Vinhlong, (3) Bentre-1, (4) Bentre-2, (5) Bentre-3; each investigation site displays about:
(a) Values of the normalized cone resistance, Q , (b) Sleeve friction, F_R and (c) Pore water pressure, B_q , obtained from the CPTU tests.

5.2.1.4. Estuarine marine facies (Sublayer 3 of VLM1 core)

At the Vinhlong site, the sublayer 3, from -27.8 to -25.0 m, based on the CPTU1-VL results is divided into two parts such as: The lower part in a range of -27.8 to -26.4 m revealed that Q_t increased well beyond the usual increase with depth (Fig. 5.2.2a). The soil-behavior-types are clay to silty clay and silty sand to sandy silt, and the formation sequences are similar to those of sedimentary properties of the lower part of the estuarine marine facies on the VLM1 core (Figs. 5.1.2a-b). The upper part in range of -26.4 to -25 m, the Q_t trend is smaller than those of the lower facies (Fig. 5.2.2a). Soil-behavior-types are most likely clay to silty clay and clayey silt to silty clay (Fig. 5.1.2b) and correlate with the sedimentary properties in the upper part of the estuarine marine facies on the VLM1 core. Namely, we can see on the complex sediment structure on sample at $z = -27.35$ m (Fig. 4.2E) correlate with various soil-behavior-types and changes in the values of q_t , u_2 , f_s , and S_u by the CPTU1-VL (Fig. 5.1.2c-e, 5.2.2, and 4.15). Since there is a mix of sand, silt, and clay, the cohesive soils in the sublayer 3 at the Vinhlong site are only low plasticity clay CL (Fig. 4.37a).

Hence, at the Vinhlong site, the sublayer 3 from -27.8 to -25.0 m identified by the geotechnical results could seem to coincide to the estuarine marine facies identified by the sedimentary results (Figs. 5.1.2 and 5.2.2). The estuarine marine facies was formed in the high energy environment; as a result, this facies is characterized by plentiful geotechnical properties.

5.2.1.5. Sub- to inter-tidal flat facies (Sublayer 2 of CLM1 core)

At the Caolanh site, the sublayer 2, from -32.1 to -25.9 m, the CPTU1-CL results indicate the soil-behavior-types are common cohesive soil with the thin seams of sand mixtures and organic soils-peats (Fig. 5.1.1b). These soil-behavior-types and their formation sequences are similar to sedimentary structures in the range of -32.1 to -25.9 m on the CLM1 core (Figs. 5.1.1a-b). Namely, we can see the peaty seams, organic material on the sample at $z = -28.25$ m on the CLM1 core correlate with type of organic soils-peats by the CPTU1-CL (Figs. 4.4B and 4.17b). Whereby, we can realize that measured quantities of the CPTU show the small changes in sedimentary structure and material which sedimentary environment and condition made them. The cohesive soils in the sublayer 2 are low to medium plasticity silt, ML-I, and low plasticity clay, CL (Fig. 4.41). The sub- to inter-tidal flat facies on the CLM1 core is also in the range of -32.1 to -25.9 m. Hence, the sublayer 2 from -32.1 to -25.9 m at the Caolanh site identified by the geotechnical results could seem to be the geotechnical properties of the sub- to inter-tidal flat

facies on the CLM1 core (Fig. 5.1.1). The homogeneous level of the sub- to inter-tidal flat facies on the CLM1 core is so higher than those of the estuarine marine facies but lower than those of the marsh facies on the VLM1 core (Figs. 5.1.1 and 5.1.2).

5.2.1.6. Open bay mud facies (Sublayer 4 of VLM1 core, Sublayer 1 of BT2 core)

At the Vinhlong site, the Sublayer 4, from -25 to -22 m, the CPTU1-VL results show a main soil-behavior-type of normally consolidated clay to silty clay (Fig. 5.1.2b). The materials are only very high plasticity clay CV (Fig. 4.37a). These materials, and soil-behavior-types and their formation sequences are similar to sedimentary materials and structures in the range of -25 to -22 m on the VLM1 core (Figs. 5.1.1a-b). Namely, we can see the simple sediment structure on the sample $z = -22.15$ m (Fig. 4.2G) on the VLM1 core are similar with soil-behavior-types (Fig. 4.10b); and the increase of q_t , u_2 , f_s , and S_u values are linear with depth (Figs. 4.15, 5.1.2c-e). The sublayer 4 identified by the geotechnical results could seem to coincide to the open bay facies on the VLM1 core identified by the sedimentary results (Figs. 5.1.2 and 5.2.2).

On the other hand, at the Bentre-2 site, the sublayer 1 was identified by the results of CPTU1-BT2, CPTU2-BT2, and CPTU3-BT2, the soil-behavior-types of the sublayer 1 are also only normally consolidated clay to silty clay (Figs. 4.27.1b, 4.27.2b, and 4.27.3b). The values of the q_t , u_2 , f_s , and S_u also regularly increase with depth (Figs. 5.1.4c-e, and 4.31). The bay sediment on the BT2 core (Ta et al. 2001) is characterized by the highly homogeneous materials and simple structures; materials are only clayey silt and sandy silt (Fig. 5.1.4a). These results show that the sublayer 1 identified by the geotechnical results could seem to coincide to the bay facies on the BT2 core (Ta et al. 2001) (Figs. 5.1.4 and 5.2.4).

The geotechnical and sedimentary results at both Vinhlong and Bentre-2 sites indicate that the bay facies was formed in the low energy environment; as a result, this facies is characterized by the geotechnical properties with a high homogeneity level.

5.2.2. Regressive Holocene delta sediments

5.2.2.1. Pro-delta mud facies, and prodelta/bay facies (Sublayer 5 of VLM1 core, Sublayer 3 of CLM1 core, Sublayer 2 of BT2 core, Sublayer 1 of BT3)

At the Vinhlong site, the sublayer 5, from -22.0 to -18.5 m, the CPTU1-VL and CPTU2-VL

results were divided into two parts (Figs. 4.10 and 4.11). The lower part, from -22.0 to -20.0 m, revealed that Q_t , F_R , and B_q are rather constant with depth (Fig. 4.12) and that the soil-behavior-type is only normally consolidated clay to silty clay (Figs. 4.10b and 4.11a). However, the upper part, from -20.0 to -18.5 m, shows small variations in the Q_t , F_R , and B_q values (Fig. 4.12), and the soil-behavior-types are normally consolidated clay to silty clay with the intercalated silt mixtures (Figs. 4.10b and 4.11a). These soil-behavior-types and their formation sequences are similar to sedimentary materials and structures in the range of -22.0 to -18.5 m on the VLM1 core (Figs. 5.1.2a-b). We can see the sediment structure on sample at $z = -21.21$ m on the VLM1 core correlate with soil-behavior-types (Figs. 4.2H and 4.10b); and the increase of the values of q_t , u_2 , f_s , and S_u by the CPTU1-VL are regular with depth (Figs. 5.1.2c-e and 4.15). The cohesive soils are mostly medium plasticity clay CI (Fig. 4.37b) and this differentiates the pro-delta mud facies from the open bay mud facies below, where cohesive soils are very high plasticity clay CV. As a result, the geotechnical properties of the sublayer 5 (from -22.0 to -18.5 m) could be characteristic of the pro-delta mud facies at the Vinhlong site.

At the Caolanh site, the sublayer 3, from -25.9 to -21.9 m, the CPTU1-CL results were divided into two parts (Figs. 5.1.1 and 5.2.1). The lower part, from -25.9 to -24.9 m, revealed that Q_t , F_R , and B_q are rather constant with depth (Fig. 5.2.1) and that the soil-behavior-type is only normally consolidated clay to silty clay and the values of S_u don't largely change (Figs. 5.1.1b and 4.20). But, the upper part, from -24.9 to -21.9 m, shows variations in the Q_t , F_R , and B_q values (Fig. 5.2.1) and the soil-behavior-types of normally consolidated clay to silty clay with intercalated silt mixtures and sand mixtures (Fig. 5.1.1b). Namely, we can see the sediment structure on the sample at $z = -23.8$ m on the CLM1 core correlate with soil-behavior-type by the CPTU1-CL (Figs. 4.4D and 4.17b); and the values of q_t , u_2 , f_s , and u_2 have large changes (Figs. 5.1.1c-e and 4.20). The cohesive soils are mostly low to medium plasticity clay, CL-I, and low plasticity silt, ML (Fig. 4.41). The characteristics of the geotechnical properties in the sublayer 3 are correlative with the sedimentary properties of the prodelta/bay facies on the CLM1 core (Figs. 5.1.1 and 5.2.1). The characteristics of changes about the geotechnical and sedimentary properties of the pro-delta/bay facies at the Caolanh site are rather similar to those of the pro-delta mud facies at the Vinhlong site (Figs. 5.1.1 and 5.1.2).

At the Bentre-2 site, the sublayer 2 identified by the results of the CPTU1-BT2, CPTU2-BT2, and CPTU3-BT2 tests could seem to coincide to the pro-delta facies on the BT2 core (Ta et al. 2001) (Figs. 5.1.4 and 5.2.4). The increase of q_t , u_2 , f_s , and S_u tends to be linear with depth (Figs. 4.27.1c-e, 4.27.2c-e, 4.27.3c-e, and 4.31). Soil-behavior-types classification is general clays-clay to silty clay and silt mixtures-clayey silt to silty clay, and an interference of sand mixtures-silty sand to sandy silt (Figs. 4.27.1b, 4.27.2b, and 4.27.3b). The interference of the sand mixtures-silty sand to sandy silt increases from bottom to top of this sublayer 2. The characteristics of the geotechnical properties of the sublayer 2 at the Bentre-2 site are corresponding with the sedimentary properties of the pro-delta facies on the BT2 core (Ta et al., 2001) (Figs. 5.1.4 and 5.2.4).

In addition, at the Bentre-3 site, the sublayer 1 identified by the CPTU1-BT3 results has characteristics such as: The lower part of the sublayer 1, from -18.0 to -15.0 m, revealed that the soil-behavior-type is commonly normally consolidated clay to silty clay (Fig. 5.1.5b) and that Q_t , F_R , and B_q are constant with depth (Fig. 5.2.5). The upper part, from -15.0 to -13.7 m, of the sublayer 1 at the Bentre-3 site, the values of Q_t , F_R , and B_q have small variations (Fig. 5.2.5). And the soil-behavior-types are also normally consolidated clay to silty clay with the intercalation of silt mixtures and sand mixtures (Fig. 5.1.5b). These characteristics of the geotechnical properties of the sublayer 1 at the Bentre-3 site are corresponding with the sedimentary properties of the pro-delta facies on the BT3 core (Ta et al., 2002a and 2002b) (Figs. 5.1.5 and 5.2.5).

The results of the geotechnical properties and sedimentary properties at four sites (VLM1, CLM1, BT2, and BT3 sites) show that the characteristics of the pro-delta facies are such as: The pro-delta facies was generally formed in the low energy environment, and the energy-levels gradually increased from the lower part to upper part of the facies. The pro-delta facies is general homogeneous, and the homogeneity levels gradually decrease from the lower part to upper part of the facies. The homogeneity level of the pro-delta facies is less than those of the bay facies and the marsh facies.

5.2.2.2. Delta front facies (Sublayer 4 of CLM1 core, Sublayer 6 of VLM1 core, Sublayer 1 of BT1, Sublayer 3 of BT2 core, Sublayer 2 of BT3 core)

At the Caolanh site, the sublayer 4, from -21.9 to -13.1 m, the CPTU1-CL results, which are shown in Figs. 5.1.1b-e. The behavior types tend to be cohesionless soils (Fig. 5.1.1b); Q_t , F_R and B_q varied slightly (Fig. 5.2.1). The q_t and f_s values show saw-tooth graphs with large variations

and the largest magnitudes among all sublayers. We can namely see the sediment structure and material on the sample at $z = -16.23$ m and -15.43 m on the CLM1 core correlate with behavior type of by the CPTU1-CL (Figs. 4.4E-F). Simultaneously, values of N increase relatively regularly from 11 to 16 (Fig. 5.1.1f). The characteristics of the delta front facies at the Caolanh site are it was formed in the high energy environment and the inhomogeneous.

At the Vinhlong site, the sublayer 6, from -18.5 to -5.5 m, in the results of CPTU1-VL and CPTU2-VL, Q_t , F_R , and B_q show saw-tooth graphs with large variations; F_R , Q_t , and B_q are the largest among all the sublayers (Fig. 5.2.2). Soil-behavior-types classification is largely varied (Figs. 4.10b and 4.11a). In general, soil-behavior-types mainly tend to be cohesionless soils. However, cohesive soils are also plentiful and the values of S_u largely vary (Figs. 4.36b, 4.37b, and 4.15). The results are correlative with the sedimentary properties (Figs. 5.1.2 and 5.2.2). Namely, we can see the complex sediment structure and material on the sample at $z = -13.75$ m and -7.7 m on the VLM1 core correlate with various behavior types of by the CPTU1-VL (Figs. 4.2J-K and 4.10b). The marked variation of the soil profiles is a typical characteristic of delta front-mouth bar facies, and deposits near the main Mekong River. The values of N on this facies don't change; they regularly equal 2 at each location of the SPT (Fig. 5.1.2f).

At the Bentre-1 site, the sublayer 1, from -8.5 to -5.0 m, in the CPTU results, q_t and f_s are the largest among all the sublayers (Figs. 5.1.3c and e). Q_t and F_R show saw-tooth graphs with large variations; soil-behavior-types classification is varied (Figs. 5.2.3 and 5.1.3b). In general, soil-behavior-type is commonly cohesionless soils (Fig. 5.1.3b). Values of N from SPT-BT1 results are from 1 to 3 (Fig. 5.1.3f).

At the Bentre-2 site, the sublayer 3, the all results of three CPTU1-BT2, CPTU2-BT2, and CPTU3-BT2 such as: Values of q_t and f_s are so high and the largest in comparison with the other sublayers. In general, soil-behavior-types trend to be cohesionless. Soil-behavior-types classification is common sands-clean sand to silty sand, sand mixtures-silty sand to sandy silt, and an interference of silt mixtures-clayey silt to silty clay and clays-clay to silty clay (Figs. 4.27.1b, 4.27.2b, and 4.27.3b). The interference of the silt mixtures-clayey silt to silty clay and clays-clay to silty clay decreases from bottom to top of this sublayer 3; the changes in the values of S_u largely vary from -17 to -8 m (Figs. 4.31). Values of Q_t , F_R , and B_q indicate the variation of this interference (Figs. 4.28.1, 4.29.1, and 4.30.1). As a result, the values of q_t and f_s trend to increase from bottom to top of the sublayer 3 (Figs. 4.27.1c-e, 4.27.2c-e, and 4.27.3c-e). In addition, the values of N from the SPT-BT2 also trend to increase slightly from the bottom to top

of the sublayer 3 in this case (Fig. 4.27.1a). The sedimentary results at Bentre-2 site by Ta et al. (2001) shown in Fig. 5.1.4a have characteristics such as: The delta front facies was formed in the range of -17 to -8 m and this formed range is around the formed range of the sublayer 3 (-15.0 to -10.0 m) (Fig. 5.1.4). The sandy content and seams increase from the bottom to top of the delta front facies. And the sedimentary materials and structures are similar to the soil-behavior-types and the formation sequences of the geotechnical properties in the sublayer 3 at the Bentre-2 site (Fig. 5.1.4). Based on these results we can suggest that the geotechnical properties of the sublayer 3 is of the delta front facies at the Bentre-2 site; and this correlation is shown in Figs. 5.1.4 and 5.2.4.

At the Bentre-3 site, the sublayer 2, from -13.7 to -7.5 m, the CPTU1-BT3 results: Q_t , F_R and B_q exhibit saw-tooth graphs with large variations (Fig. 5.2.5). Soil-behavior-type mainly tends to be cohesionless soils (Fig. 5.1.5b). The insertion of the cohesive soils decreases from the bottom to top of the sublayer 2 at the Bentre-3 (Fig. 5.1.5b). For this reason, the values of q_t and f_s trend to increase from the bottom to top of the sublayer 2 (Figs. 5.1.5c and e). Simultaneously, the values of S_u vary (Fig. 4.34). The sedimentary results at the Bentre-3 site by Ta et al. (2002a and 2002b) shown in Fig. 5.1.5a have characteristics such as: The delta front facies was formed in the range of -15 to -8 m and this formed range is around the formed range of the sublayer 2 (-13.7 to -7.5 m) (Fig. 5.1.5). The sandy content and seams increase from the bottom to top of the delta front facies at the Bentre-3 site. And the sedimentary materials and structures are similar to the soil-behavior-types and the formation sequences of the geotechnical properties in the sublayer 2 at the Bentre-3 site (Fig. 5.1.5). These results indicate that the geotechnical properties of the sublayer 2 is of the delta front facies at the Bentre-3 site; and this correlation is shown in Figs. 5.1.5 and 5.2.5. Values of N from the SPT results on the sublayer 2 are small, from 2 to 3 (Fig. 5.1.5f).

The all of the geotechnical and sedimentary results at the five investigation sites indicate the general characteristics of the delta front facies in the MRD such as: The insertion of the cohesive soils decreases from the bottom to top of the delta front facies (Fig. 5.1). For this reason, the values of q_t and f_s trend to increase from the bottom to top of the delta front facies (Fig. 5.1). Soil-behavior-types classification is varied (Fig. 5.1). The values of q_t , u_2 , and f_s are large and significantly vary (Fig. 5.1). The values of Q_t , F_R , and B_q show the saw-tooth graphs with large variations (Fig. 5.2). The soil-behavior-types of the delta front facies mainly tend to be cohesionless soils (Fig. 5.1). Simultaneously, there are so cohesive soils in the delta front facies.

Especially, the cohesive soils in the delta front facies at the Vinhlong site are so plentiful (Fig. 5.1.2b); Q_t , F_R , and B_q in the delta front facies at the Vinhlong site are the largest among all the facies (Fig. 5.2.2). And the marked variation of soil profiles is a typical characteristic of delta front-mouth bar facies at the Vinhlong site, and deposits near the main Mekong River. The values of q_t and f_s , and the cohesionless soil-behavior-types on the delta front facies at the Caolanh site are the greatest in comparison with those of the other sites (Fig. 5.1).

The delta front facies were inhomogeneous and formed in the high energy environment; the energy levels increased from the bottom to top of the delta front facies. The inhomogeneous level and the trend of cohesionless soils also increase with the energy-increasing. It means that the soil-mechanical-behavior-types of cohesionless increase according to the tendency of marine regression.

We can easily see the correlation of the geotechnical properties and the sedimentary properties through the results of the CPTU tests.

5.2.2.3. Intertidal flat facies (Sublayer 5 of CLM1 core)

At the Caolanh site, the sublayer 5, from -13.1 to -3.6 m, Q_t , F_R and B_q have saw-tooth graphs with small amplitudes (Fig. 5.2.1). The main soil-behavior-types classification is clays-clay to silty clay with intercalating sensitive fine grained, sand mixtures, silt mixtures, and organic soils-peats (Fig. 5.1.1b). The q_t , u_2 , and f_s values are all linear with depth and the very small magnitudes (Figs. 5.1.1c-e). Characteristics of sediment are similar with those of geotechnical properties, namely on the sample at $z = -8.2$ m and -5.7 m on the CLM1 core (Figs. 4.4G and I).

The cohesive soils are mostly medium plasticity clay, CI, and high plasticity silt, MH (Fig. 4.41). The values of S_u regularly increase with depth except the part below -11 m (Fig. 4.20). This formatted sequence of geotechnical properties is approximate to the sedimentary structure of the intertidal flat facies on the CLM1 core (Fig. 5.1.1). The intertidal flat facies at the Caolanh site is rather homogeneous and formed in the rather low energy environment. But, the homogeneous level of this intertidal flat facies is lower than those of the marsh and bay facies at the Vinhlong and Bentre-2 sites (Figs. 5.1.1, 5.1.2, and 5.1.4).

5.2.2.4. Sub- to inter-tidal flat sandy silt facies (Sublayer 7 of VLM1 core, Sublayer 2 of BT1 core, Sublayer 4 of BT2 core, Sublayer 3 of BT3 core)

At the Vinhlong site, the sublayer 7, from -5.5 to -1.5 m, the CPTU1-VL and CPTU2-VL results such as: The alternation of cohesionless soil layers and cohesive soil layers results in the saw-tooth shape in the overall plot of q_b , u_2 and f_s as a function of depth (Figs. 4.10c-e and 4.11b-d). The variations of values of Q_b , F_R and B_q are all rather regular with depth (Fig. 4.12). Their formatted geotechnical property sequence is approximate to the sedimentary structure with intercalated sandy and silty mud. Namely, we can see the sediment structure on the sample at $z = -2.6$ m approximate to the soil-behavior-types by the CPTU1-VL and CPTU2-VL (Figs. 4.2L and 4.10b). The cohesive soils are commonly medium plasticity clay CI, and a little silt MI (Figs. 4.36b and 4.37b). These features characterize sub- to inter-tidal flat facies at the Vinhlong site.

At the Bentre-1 site, the sublayer 2, from -6.5 to -2.5 m, in the CPTU results, the q_b , u_2 , and f_s values increase with depth with the very small magnitudes. But the q_b , u_2 , and f_s values sometimes have some large changes by appearance of sand mixtures-silty sand to sandy silt and sands-clean sand to silty sand (Figs. 5.1.3c and e). In general, soil-behavior-type is commonly clays-clay to silty clay; the sand mixtures-silty sand to sandy silt and sands-clean sand to silty sand insert the clays (Fig. 5.1.3b). This formatted sequence of the geotechnical properties is approximate to the sedimentary structure and materials of the sub- to inter-tidal flat facies on the BT1 core (Ta et al. 2002a, and 2002b) (Fig. 5.1.3).

At the Bentre-2 site, the sublayer 4, from -10.0 to -2.0 m, in the all results of three CPTUs at the Bentre-2 site such as: The alternation of cohesionless layers and cohesive soil layers results in a rather regular saw-tooth shape in the overall plot of q_b , u_2 and f_s as a function of depth in the sublayer 4 (Figs. 4.27.1b-e, 4.27.2b-e, and 4.27.3b-e). The variations of values of Q_b , F_R and B_q are all rather regular with depth (Figs. 4.28.1, 4.29.1, and 4.30.1). The appearances of the cohesionless soil seams and the cohesive soil seams are in a rather regular alternation (Figs. 4.27.1b, 4.27.2b, and 4.27.3b). These formatted sequences of the soil-behavior-types are approximate to the sedimentary structure and materials of the sub- to inter-tidal flat facies on the BT2 core (Ta et al. 2001) (Fig. 5.1.4).

At the Bentre-3 site, the sublayer 3, from -7.5 to -3.0 m, in the CPTU1-BT3 results: The alternation of cohesionless layers and cohesive soil layers results in a rather regular saw-tooth shape in the overall plot of $f_s q_b$, and u_2 as a function of depth (Figs. 5.1.5b-e). This formatted sequence of the soil-behavior-types is approximate to the sedimentary structure and materials of

the sub- to inter-tidal flat facies on the BT3 core (Ta et al. 2002a and 2002b) (Fig. 5.1.5).

All results of the Vinhlong, Bentre-1, Bentre-2, Bentre-3 sites, indicated that the formatted sequences of geotechnical properties are approximate to the sedimentary structure and materials of the sub- to inter-tidal flat facies (Figs. 5.1.2-5). The rather regular alternations of the cohesionless layers and the cohesive soil layers resemble tidal rhythmites. The features characterize the sub- to inter-tidal flat facies. The sub- to inter-tidal flat facies were formatted in the high energy environment. The homogeneous levels of the sub- to inter-tidal flat facies at the Vinhlong, Bentre-1, Bentre-2, and Bentre-3 sites are so lower than those of the intertidal flat facies at the Caolanh site (Figs. 5.1 and 5.2).

5.2.2.5. Flood plain facies (Sublayer 6 of CLM1 core, sublayer 8 of VLM1 core, sublayer 3 of BT1 core)

At the Caolanh site, the sublayer 6, from -3.6 to -0.5 m, the CPTU1-CL results indicated that the main soil-behavior-type is only clay to silty clay, and correspond with the silty clay and clayey silt mud on the flood plain facies (Figs. 5.1.1a-b). We can namely see on the sample at $z = -2.8$ m and -1.92 m on the CLM1 core correlate the soil-behavior-type by the CPTU1-CL (Figs. 4.4J and K, and 4.17b). The cohesive soils are commonly high plasticity clay, CH, and medium plasticity clays, CI (Figs. 4.40b and 4.41). And the values of S_u on the cohesive soils increase regularly (Fig. 4.20).

At the Vinhlong site, the sublayer 8, from -1.5 to +1.0 m, in the results of the both CPTU1-VL and CPTU2-VL, values of Q_t , F_R and B_q are all rather constant with depth (Fig. 4.12). Soil-behavior-type of the sublayer 8 is a mostly clayey-silt to silty clay (Figs. 4.10b and 4.11a). Characteristics of sediment are similar with those of geotechnical properties. The simple sediment properties on the VLM1 core are similar with simple soil-behavior-type and strength-increase being linear with depth (Figs. 5.1.1a-b). The cohesive soils include medium and high plasticity clays CI, CH (Figs. 4.36b and 4.37b). The sequence of the mechanical behavior was observed by the CPTU1-VL and CPTU2-VL corresponds with the sedimentary properties of the marsh/flood plain facies on the VLM1 core (Figs. 5.1.2 and 5.2.2). The sublayer 8 is homogeneous.

At the Bentre-1 site, sublayer 3, from -2.5 to +1.4 m, the CPTU1-BT1 results also indicated that the main soil-behavior-type is clayey silt to silty clay, and correspond with the silty clay and clayey silt mud of the flood plain/marsh facies on the BT1 core (Ta et al., 2002a) (Figs. 5.1.3a-

b).

In general, the all results at the CLM1, VLM1, and BT1 sites indicated that the formatted sequences of geotechnical properties correspond with the sedimentary structure and materials of the flood plain/marsh facies (Figs. 5.1.1-3). The flood plain/marsh facies was formatted in low energy environment, the sedimentary structure and materials are simple. The soil-behavior-types are cohesive soil and homogeneity and these data characterize the flood plain/marsh facies.

5.2.2.6. Sand dune facies (Sublayer 5 of BT2 core, Sublayer 4 of BT3 core)

At the Bentre-2 site, the sublayer 5, the CPTU1-BT2, CPTU2-BT2, and CPTU3-BT2 results show that the soil-behavior-types are sand mixtures, sands-clean, and clay to silty clay, corresponding to the alternating layers of dark grey sandy mud and well sorted greenish grey fine sand with humus material and mica flakes of the beach ridge facies on the BT2 core (Ta et al., 2001) (Figs. 4.27.1-3, 4.28.2, 4.29.2, 4.30.2, and 5.1.4).

At the Bentre-3 site, the sublayer 4, the CPTU1-BT3 results showed that the soil-behavior-types classification is commonly sands-clean corresponding to the sedimentary properties of the beach ridge facies on the BT3 core (Ta et al., 2002a) (Figs. 5.1.5a-b).

The all results at the Bentre-2 and Bentre-3 sites indicate that the soil-behavior-types are cohesionless soil and homogeneity; and these data characterize the beach ridge facies in the MRD.

5.2.2.7. Natural levee facies (Sublayer 7 of CLM1 core)

At the Caolanh site, the sublayer 7, from -0.5 to +2.9 m, the CPTU1-CL results, the soil-behavior-types are overconsolidated clays-clay to silty clay, silt mixtures-clayey silt to silty clay, and very stiff fine grained (Figs. 4.40a-c, and 5.1.1b). Characteristics of sediment are similar with those of geotechnical properties. Namely, the simple sediment properties on the sample at $z = -0.27$ m on the CLM1 core are similar with soil-behavior-type and high values of q_u and S_u by the UC and CPTU1-CL (Figs. 4.4L and 4.17b). The S_u , q_u , N , q_t , and f_s by the SPT-CL and CPTU1-CL increased highly upward and greater than those of the sublayer 5 and sublayer 6 below (Figs. 4.20 and 5.1.1b-f). The compression strength for undisturbed sample, q_u , and yield stresses σ'_{y-IL} and σ'_{y-CRS} are notably large (Figs. 4.40g and f). The illite contents in the natural levee facies are more than 70% (Tab.4.4). The illite content in the natural levee facies is the

largest in comparison with the illite contents in the other facies (Tabs.4.1 and 4.4). Cause may be due the specific gravity of illite ($G_s=2.8$) are greater than those of the others; for this reasons, the illite settled on the area around the banks. The natural levee sediment often existed along the two sides of rivers with large elevations, as at the CLM1 core site +2.9 m a.p.s.l (Figs. 3.1 and 5.1.1). It is due to the existence of the natural levee facies. The natural levee sediments were often above the ground water table (Fig. 5.1.1), and contacting with the sun energy and air. Simultaneously, the dehydrating and shrinking processes occurred. The $\text{Fe}(\text{OH})_3$ was dehydrated during the 6 months of the dry season in the tropical area; and the trivalent iron oxides, Fe_2O_3 , was produced in the sediment as in Equations (5.1) and (5.2). The iron hydroxyls appeared during the depositional process. And the iron-hydroxyl was carried from underlying sediments into the natural levee sediment by an oscillation of the ground-water table and capillary water. The Fe_2O_3 is strong cement and made the soils be in reddish, yellowish, and brownish color (Fig.4.4L). It is called the laterization. Hence, the q_u , σ'_{y-IL} and σ'_{y-CRS} , q_b , f_s , N by the SPT, and γ_{sat} increased highly; and the w_n , LI , S_t were low (Figs. 4.40 and 5.1.1). The Fe_2O_3 is durable and cannot be extracted by 0.1 N H_2SO_4 , so the contents of exchangeable trivalent iron in the natural levee sediment are lower than those in the others. And the bivalent iron content is notably low and even equal to zero (Table 5.1a) but the total contents of Fe and Al are the highest (Table 5.1b). The dehydrating process also produced free sulfate, so the natural levee sediment has the lowest pH values, around 4.6 (Table 5.1a). The exchangeable ion contents and the total contents of Ca^{2+} and Mg^{2+} are small (Table 5.1a). These results characterize the natural levee facies.

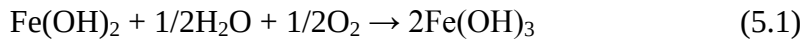


Table 5.1a

Exchangeable-ion content in the argillaceous sediments from the CLM1 and VLM1 cores.

Information of the cores and the facies associations		Exchangeable ions						Total percentage of dispersive carbon	pH
Facies association	Altitude	Fe ²⁺	Fe ³⁺	Fe ²⁺ / (Fe ²⁺ +Fe ³⁺)	Al ³⁺	Ca ²⁺	Mg ²⁺	TOC	
	(m)	equivalent milligram/100g		(%)	equivalent milligram/100g			(%)	
Caolanh core									
Natural levee	0.28	0.00	54.10	0.00	1.55	1.65	1.82		4.7
	-0.41	2.30	77.30	2.89					4.3
	-0.48	8.01	217.55	3.55	0.20	1.30	2.2	6.31	4.8
Flood plan	-0.78	401.95	488.17	45.16	0.72	4.10	5.91	9.41	6.1
	-1.50	102.02	747.82	12.00	1.43	5.37	5.94	11.15	5.7
	-4.50	449.80	956.26	31.99	0.53			12.03	7.3
Inter-tidal flat	-4.81	1438.26	233.81	86.02	1.11	1.78	3.2	10.05	6.9
	-5.70	1141.28	294.15	79.51	1.18	4.52	3.86	12.33	7.6
	-8.10	1346.71	605.19	68.99	0.10	2.78	2.12	10.32	7.2
	-8.20	583.64	984.71	37.21	1.03	6.87	4.03	11.96	6.7
	-13.02	266.62	398.11	40.11	0.21	2.3	2.47	11.65	6.2
Delta front	-14.03	20.88	745.65	2.72	0.40	2.19	4.06	12.58	7.4
	-15.23	46.68	285.27	14.06	0.25	1.14	3.26	1.38	7.3
	-15.33	167.42	501.10	25.04	0.30	1.22	2.77	2.39	7.5
Prodelta	-23.70	280.43	169.85	62.28	0.42	0.82	3.78	2.35	7.2
	-24.20	455.43	143.70	76.01	0.20	5.19	1.78	6.36	7.7
	-25.50	511.75	122.44	80.69	0.00	1.46	2.43	3.81	7.5
	-26.10	139.25	270.36	34.00	0.20	0.98	1.95	6.69	6.8
Vinhlong core									
Flood plain	-0.80	62.00	18.40	77.11	1.51	1.89	6.11	13.90	6.4
	-1.31	1206	57.50	95.45	0.50	1.48	4.13	9.40	6.7
Sub- to intertidal flat	-3.40	2.00	195.00	1.02	0.85	0.96	2.45	8.00	6.3
Delta front	-11.50	343.43	650.38	34.56	0.05	1.89	3.21	7.94	7.5
Prodelta	-21.01	471.41	392.48	54.57	0.05	1.89	3.86	7.04	7.9
Marsh	-37.30	448.37	609.20	42.40	0.05	2.31	2.97	7.98	7.5

Table 5.1b

Total ion content in the argillaceous sediments from the CLM1 and VLM1 cores.

Caolanh core		Total ion and element contents in the argillaceous sediments						
Facies association	Altitude	Total [Fe]	Al ³⁺	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	[Si]
	(m)	(%)						
Natural levee	0.29	5.93	4.58	0.19	0.46	0.47	1.79	29.82
	0.28	5.26	4.39	0.18	0.48	0.33	1.96	28.00
Flood plain	-0.78	4.92	3.39	0.14	0.41	0.39	1.25	24.41
Vinhlong core								
Flood plain	-0.80	2.95	1.79	0.33	0.47			24.10
	-1.30	3.01	1.81	0.27	0.49			24.07
	-1.50	2.06	1.77	0.29	0.52			28.20
Sub- to intertidal flat	-5.10	4.13		0.29	0.56			27.70
Delta front	-11.50	4.85	4.29	0.25	0.55	0.40	1.91	28.00
Marsh	-33.40	4.81	4.87	0.28	0.59	0.84	2.78	26.61
	-37.30	5.10	4.93	0.30	0.64	0.55	2.26	27.40

5.2.3. Relationship between the delta formation mechanism and geotechnical property sequence

We consider the sedimentary geology column and the geotechnical property succession at each core site and compare them with the different locations in the sedimentary cross-section, ILMN, was rebuilt in item 4.4. Each sedimentary geology column was produced in the typical delta formation mechanism as presented in item 4.4. And then, the delta formation mechanisms influenced on geotechnical property successions at different locations in the late Pleistocene-Holocene progradation of the MRD will be realized.

The mechanical behaviors on the delta front and prodelta/bay facies of the CLM1 core site trend to be cohesionless soils and the values of q_t and f_s more than those of the VLM1, BT1, BT2, and BT3 core sites (Fig. 5.1). As presented in item 4.4: The VLM1, BT1 core sites were in the region of the tide-dominated-delta (Ta et al., 2005) (Fig. 3.1). The BT2, BT3 core sites were in the region of the tide- and wave-dominated delta (Ta et al., 2005) (Fig. 3.1). The CLM1 core site was possibly in the fluvial-dominated delta (Fig. 3.1). According to the morphology and sedimentary environment of the fluvial-dominated delta, the delta front platform is short in Fig.

2.11c (Hori and Saito, 2003). The CLM1 core site was closer to and received the plentiful source of material supply of the large streams (Mekong River system). And the material-source at the riverhead of Mekong River system was normally coarser than those lower of Mekong River system. As a result, the geotechnical properties sequence at the CLM1 core site is almost cohesionless soils and coarser size of grains. Especially for the delta front facies of the CLM1 core is almost cohesionless soils and the highest strength in comparison with all facies of other sites. Except, the intertidal flat, flood plain, and natural level facies of the CLM1 core because at the period of time and where the CLM1 core site was not in a subaqueous region i.e. in the region of tidal and flood influence (Fig. 2.11c). Hence, the materials are commonly fine and an insertion of the thin fine sand seams in the intertidal flat facies; and its mechanical behaviors generally trend to be cohesive soils and an insertion of the cohesionless soils (Fig. 5.1.1).

The BT2 and BT3 core sites in the tide- and wave-dominated delta, their materials are coarse size of grains and sedimentary structures are almost sand layers with an insertion of thin clayey and silty seams (Figs. 2.13b and 5.1.4-5) (Ta et al., 2002 and 2005). These sedimentary characteristics are displayed in whose mechanical behaviors trend to be cohesionless soils and the values of q_t and f_s more than those of the BT1 and VLM1 core sites in the tide-dominated delta (Figs. 2.13a and 5.1.2-5). Especially, for the BT3 core site was in the tide- and wave-dominated delta but it was significantly dominated by wave; as a result, the geotechnical properties sequence trend to be almost cohesionless soils from the prodelta to sand dune.

The mechanical behaviors and strengths of the prodelta/bay facies in the CLM1 core site are more cohesionless soils and greater than those of the bay facies in the VLM1 and BT2 core sites as shown in Figs. 5.1.1-2 and 5.1.4. This change is similar with the typical coarsening-upward succession from the open to inner bay existed in the bay facies in the VLM1 and BT2 core sites to the prodelta/bay facies in CLM1 core site as presented item 4.4.

In general, the plasticity of the cohesive soils of the sedimentary facies at the Cantho and Vinhlong core sites are commonly medium, high, low, and very high plasticity; but, the plasticity of the cohesive soils of the sedimentary facies at the Caolanh core site are commonly medium, high, and low plasticity and none of very high plasticity (Figs. 4.37 and 4.41). As presented in item 4.5, the contents of illite, kaolinite, and chlorite minerals of the all sedimentary facies of the CLM1 and VLM1 cores are large; especially, the illite contents are the largest, over 44%, in comparison with the other mineral contents in the all sedimentary facies. The thicknesses of these minerals are large; but specific surface and reciprocal of average surface densities of

charges are so small (after Braja, 1998). Conversely, the contents of smectite are so low from 0.0 to 13% (Tabs. 4.1 and 4.4), however the thickness of this mineral is small and specific surface and reciprocal of average surface densities of charges are so large (after Braja, 1998). So, the illite, kaolinite, and chlorite minerals dominated in the microstructure and mechanical behavior. Accordingly, it is not so high possibility to keep water on the surface of these minerals; hence, the screen-water covering the mineral particles is not so large. As a result, the plasticity of the cohesive soils of the late Pleistocene-Holocene sediments is not extremely high and lower than those of the Tanan clay (Fig.5.3). The origin of the Tanan sediments is from the Saigon river system.

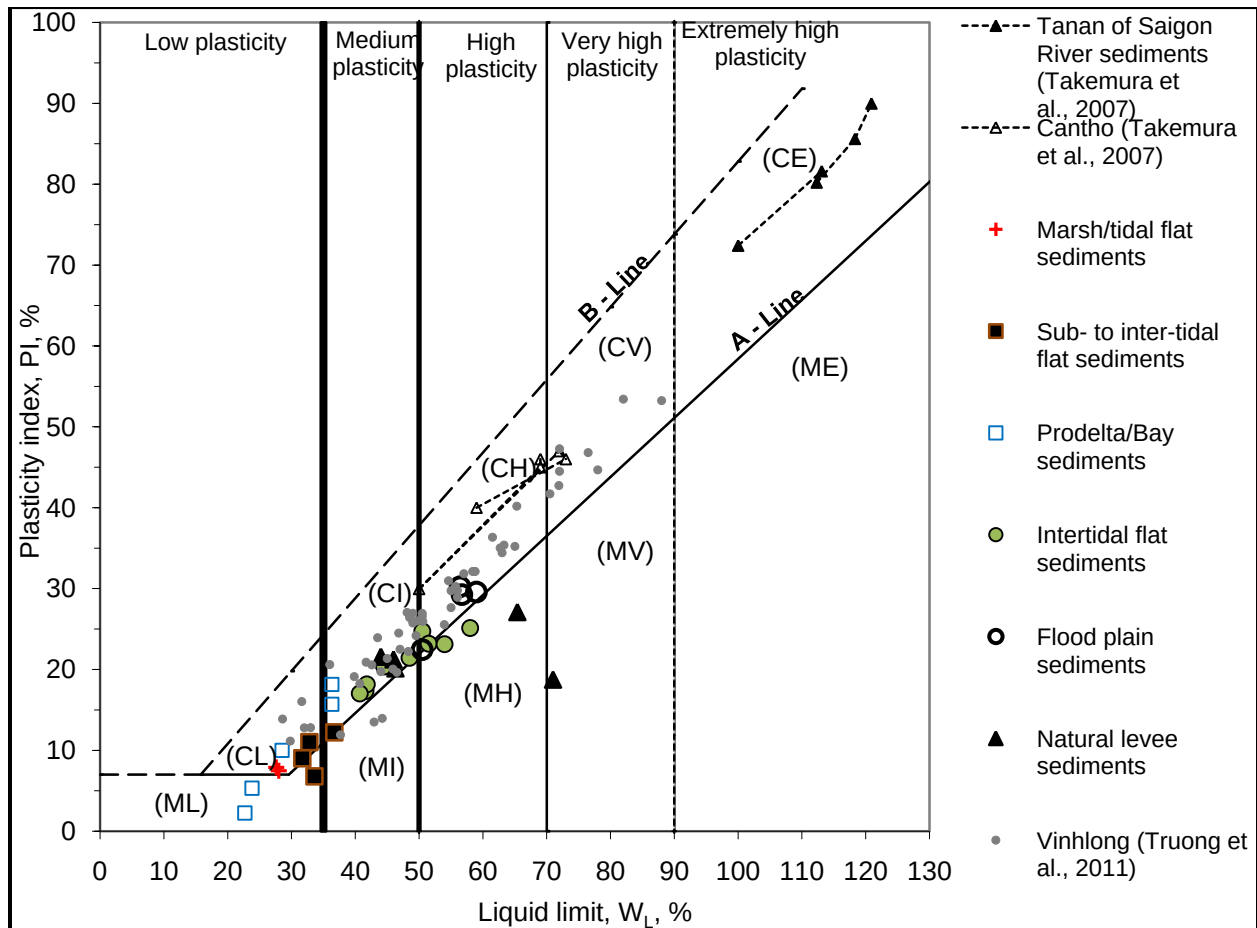


Fig. 5.3. Plasticity chart of deposits of the CLM1 core, VLM1 (Truong et al., 2011), and TAS1 and CTM1 (Takemura et al., 2007) cores.

The contents of illite and of mixture of illite and smectite of the CLM1 core are larger than those of VLM1 core, but the smectite contents in the VLM1 core are larger than. The illite content in the natural levee facies is largest in comparison with the illite contents in the other facies, and they are more than 70% (Tabs 4.1 and 4.4). In addition, the sand contents in the CLM1 core trend to be larger than those in the VLM1 core (Figs. 4.36c and 4.40c). So, in general, the plasticity of the cohesive soils of the sedimentary facies at the Vinhlong core sites is a little greater than those of the sedimentary facies at the Caolanh core site (Fig. 5.3).

5.2.4. Undifferentiated Pleistocene sediment-basement

As above discussion in 4.4 item, the Vinhlong and Bentre-2 sites located in the incised-valley-zone, and Caolanh sites located in the edge of the incised-valley-zone (Fig. 2.6) which sufficiently had the late Pleistocene-Holocene sedimentary facies of the MRD (Fig. 5.1). The lower part of the earliest facies of the late Pleistocene-Holocene sediments at these three sites commonly contains materials of the undifferentiated Pleistocene sediments as presenting in the above part in Section 4.4 (Fig. 5.1). The N values are fairly large on the lower parts of the earliest facies at the Vinhlong and Caolanh sites (Figs. 5.1.1f and 5.1.2f). The Bentre-1 and Bentre-3 sites located the interfluvies (Ta et al., 2002a), where the Pleistocene basement coastal to fluvial sediments were subaerially exposed and weathered at the time of the last glacial maximum. As a result, the undifferentiated Pleistocene sediments are characterized by the stiff to hard, slightly oxidized, yellowish gray silty sand and fine-medium sand bearing scattered quartz pebbles 0.5-1 cm in diameter, and laterite. The weathered soil layer is called the lag deposit. The thickness of the lag deposit is commonly a few meters (Ta et al., 2002a). Obviously, the materials of the lag deposit were the Pleistocene basement coastal to fluvial sediments. The late Pleistocene-Holocene sedimentary facies directly overlay the lag deposit and/or the undifferentiated Pleistocene sediment-basement with the age over 43,400 yr BP (Ta et al., 2002a, 2002b). As a result, values of N , q_b , and f_s suddenly shift from the late Pleistocene-Holocene sediments to the lag deposit and then the undifferentiated Pleistocene sediment-basement (Fig. 5.1). Namely: At the Caolanh site, the N value is 26 that can find at -37.0 m at the boundary between the late Pleistocene-Holocene sediments and undifferentiated Pleistocene sediment-basement (Fig. 5.1.1f). At the Vinhlong site, N value is 25 at -47.8 m; and then from -49.6 to -60 m in the undifferentiated Pleistocene sediment-basement, N values suddenly increased to over 50

(Fig. 5.1.2f). At the Bentre-1 site, N value suddenly increased to 18 at -9.45 m and continuously increased to 48 at -48.0 m in the undifferentiated Pleistocene sediment-basement (Fig. 5.1.3f). At the Bentre-3 site, N value suddenly increased to 38 at -19.45 m and then continuously increased from 38 to 47 from -18.0 to -28.0 m in the undifferentiated Pleistocene sediment-basement (Fig. 5.1.5).

5.3. Conclusions about influence of sedimentary environment on geotechnical properties from upper to lower Mekong Delta

The investigation results indicate that there is a close relationship between the sedimentary facies and geotechnical properties. Therefore, it can be concluded that the sedimentary environments significantly affect the formation of materials, macro- and micro-structure, and orientation of properties in each sedimentary facies.

The results allow the identification of soil properties and estimation of the general tendencies of the mechanical behavior of soils of the MD region in the context of geotechnical engineering. From previous sedimentary profiles, we can infer the mechanical behavior of the sediments. The particular sedimentary conditions in the late Pleistocene-Holocene deposits can be reasonably estimated by the CPTU.

We can say that the soil variations exist horizontally even in very small distance (4 m) in the MD late Pleistocene-Holocene sediments. The soil behavior types at the same altitude in the facies estimated by CPTU are quite different. But, the main characteristics of the general tendencies of the mechanical behavior of each specific facies are quite specific. Especially, the marked variation of soil profiles is a typical characteristic of delta front facies, and deposits near the main Mekong River. The N values by SPT cannot represent such variation accurately and continuously, which can be made by the CPTU on the MD late Pleistocene-Holocene sediments. The N values have only clear differences between the late Pleistocene-Holocene sediments with the undifferentiated Pleistocene sediments.

However, each sublayer has specific features estimated by CPTU, from which good correlation can be obtained between geological sedimentary environment and geotechnical properties. It can be reconfirmed from the above facts that CPTU could be used for geological investigation, especially for the sediment with very complication and heterogeneous conditions

of the MD.

Changes in the MD late Pleistocene-Holocene sedimentary facies are sedimentary successions with trends of fining upwards in the transgression and coarsening upwards in the regression. The estuarine channel, estuarine marine, delta front or delta front-mouth bar, and sub- to inter-tidal flat facies, which were formed under strong hydrodynamic conditions, have various sedimentary structures and material. As a result, their soil-behavior-types have various types and their sequences of the geotechnical properties are similar to the characteristics of sedimentary structures with inhomogeneity. Especially, the delta front and delta front facies were formed under extremely strong hydrodynamic conditions and their sedimentary properties are so inhomogeneous. And as a result, the mechanical behavior of the delta front facies shows great variability, as shown by the CPTU results. The delta front facies dominant in entire delta.

The marsh, marsh/tidal flat, sub- to inter-tidal flat (in the transgression), bay, pro-delta, intertidal flat, and flood plain facies were formed under low hydrodynamic conditions. They have faint sedimentary structures of uniform clay and silty layers, and their strengths increase linearly with depth. Specially, the marsh, bay, and flood plain facies are highly homogeneous. In this case, the plasticity chart may be used in identifying characteristics of sedimentary facies because each sedimentary facies has typical components of clay mineral species. Dominant facies depends on the location of delta.

Each delta formation mechanism has a typical geotechnical property sequence which can be observed by the CPTU results. The BT2 and BT3 core sites in the tide- and wave-dominated delta whose mechanical behaviors trend to be cohesionless soils and strengths more than those of the BT1 and VLM1 core sites in the tide-dominated delta from the prodelta to sand dune facies. Especially, for the BT3 core site significantly dominated by wave; as a result, the geotechnical properties sequence trends to be almost cohesionless soils from the prodelta to sand dune facies. The mechanical behavior of the CLM1 core site trends to be cohesionless soils and the strengths are larger than those of the VLM1 core sites in the tide-dominated delta and even the BT3 core site, especially the delta front facies of the CLM1 core. Because the CLM1 core site was possibly in the fluvial-dominated delta, and close to and received the abundant source of material supply of the large streams (Mekong River system). Furthermore typical coarsening-upward succession from the open to inner bay is also displayed, with increasing trend about the mechanical behavior of cohesionless soils and the strength in the bay facies in the VLM1 and BT2 core sites to the prodelta/bay facies in CLM1 core site.

As for the clay mineral, illite mineral content is high (over 44%) in all the facies. The contents of clay mineral types of the all sedimentary facies of the cores were generally in descending order from the illite, kaolinite, chlorite, smectite. The illite content in the natural levee facies is largest (over 70%) in comparison with the illite contents in the other facies. The contents of illite and sand trend to decrease and the smectite contents trend to increase from the CLM1 core site in the fluvial-dominated delta to the VLM1 core site in the tide-dominated delta. These characteristics of the clay minerals and sizes of the source of material supply from the Mekong River system and their move-possibility have produced the plasticity with being not extremely high and slightly increasing according to the reduction of the illite and sand contents.

5.4. Consolidation characteristics

5.4.1. Results of consolidation tests

5.4.1.1. Vinhlong site

The curves of the $e - \log \sigma'_v$ relationship of the loading and unloading stages, and c_v against vertical effective stress were given by the IL and CRS tests on the undisturbed and reconstituted cohesive soil specimens of Vinhlong core shown in Fig. 5.4. The curves of the $e - \log \sigma'_v$ relationship and c_v against vertical effective stress on the cohesive soil specimens from -47.8 to -18.5 m of the VLM1 core are presented in Fig. 5.4.1-3. The curves of the $e - \log \sigma'_v$ relationship and c_v against vertical effective stress on the cohesive soil specimens from -14.5 to -6.5 m of the VLM1 core are presented in Fig. 5.4.4-5. The curves of the $e - \log \sigma'_v$ relationship and c_v against vertical effective stress on the cohesive soil specimens from -6.5 to +1 m of the VLM1 core are presented in Fig. 5.4.6.

The Coefficients c_v with t_{50} against the vertical effective stress by the IL and CPTU at the same depth and same type of soil at Vinhlong site were presented in Fig. 5.5.

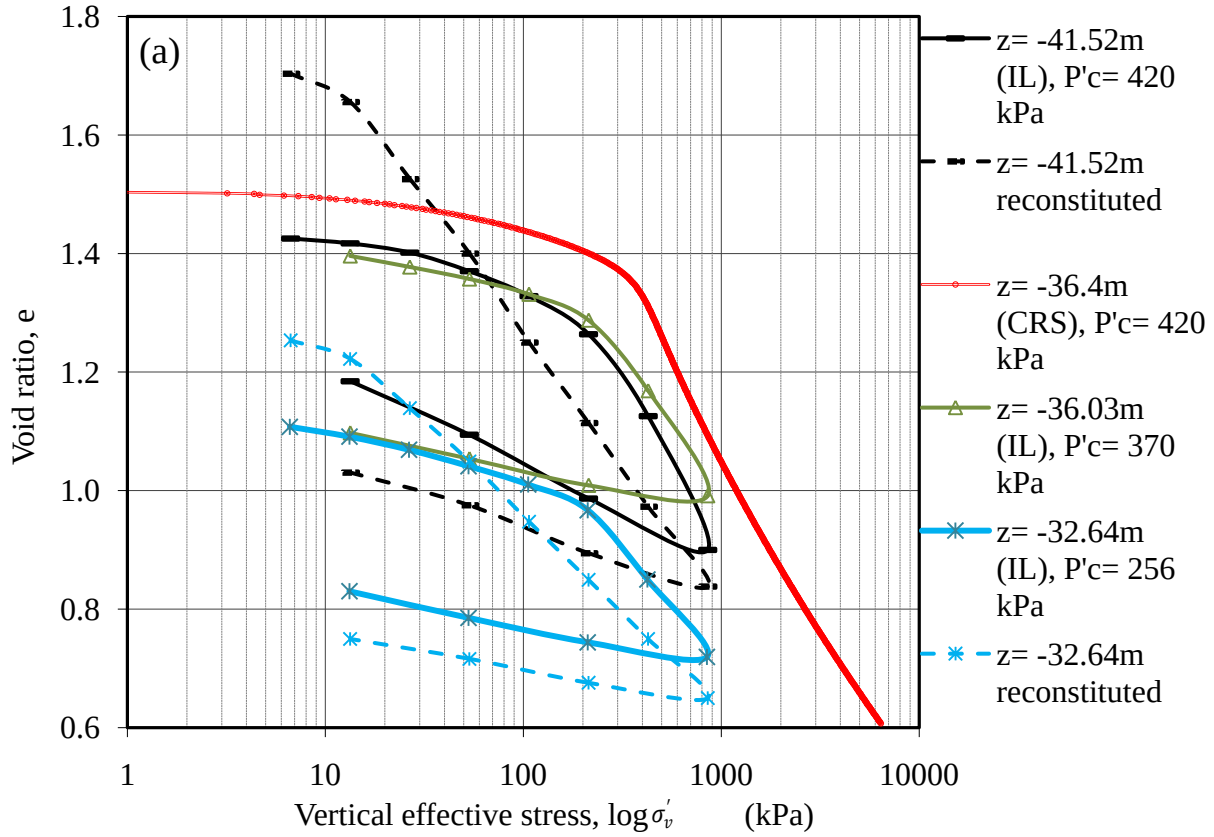


Fig. 5.4.1a. Curves of $e\text{-}\log \sigma'_v$ on sediment specimens from -41.52 to -32.64 m.

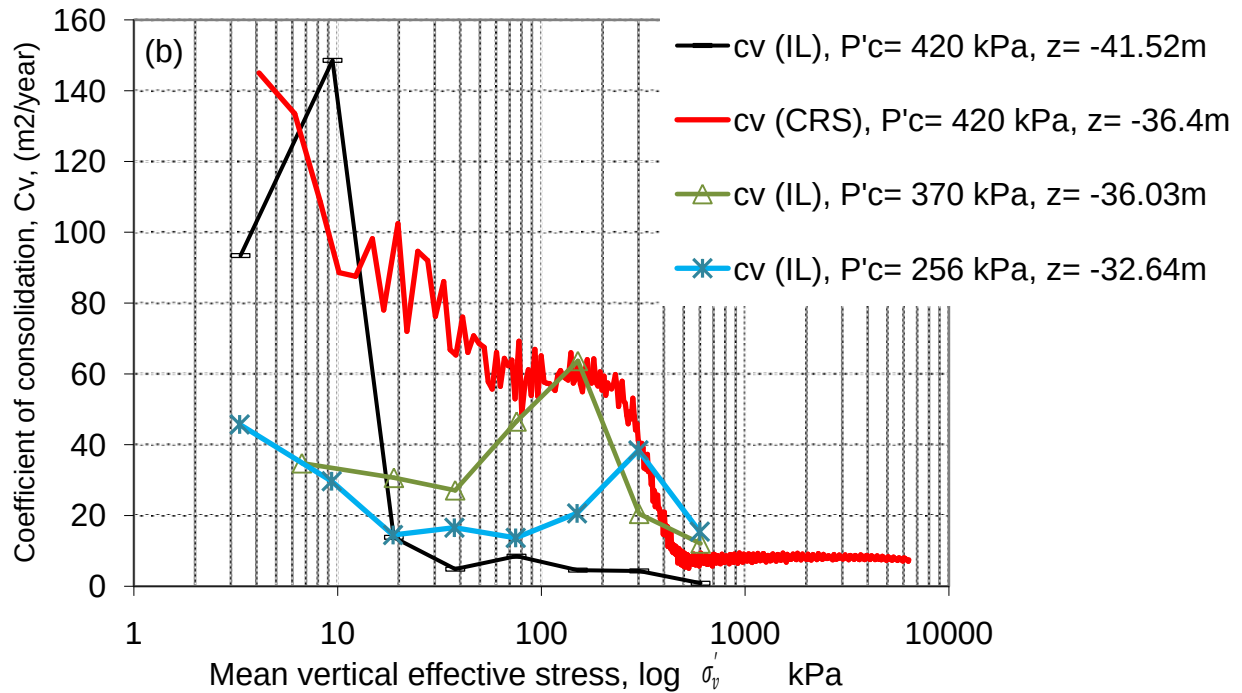


Fig. 5.4.1b. C_v vs. vertical effective stress on sediment specimens from -41.52 to -32.64 m.

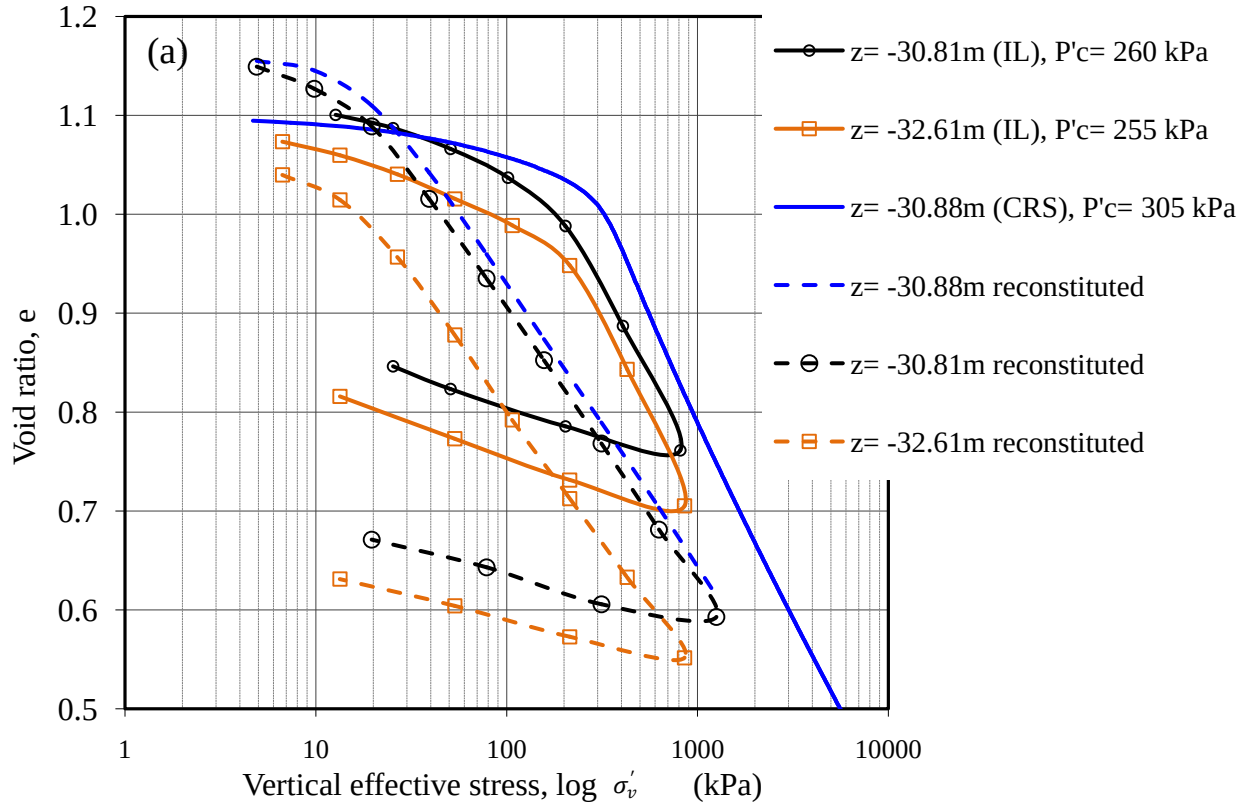


Fig. 5.4.2a. Curves of e - $\log \sigma'_v$ on sediment specimens from -32.61 to -30.81 m.

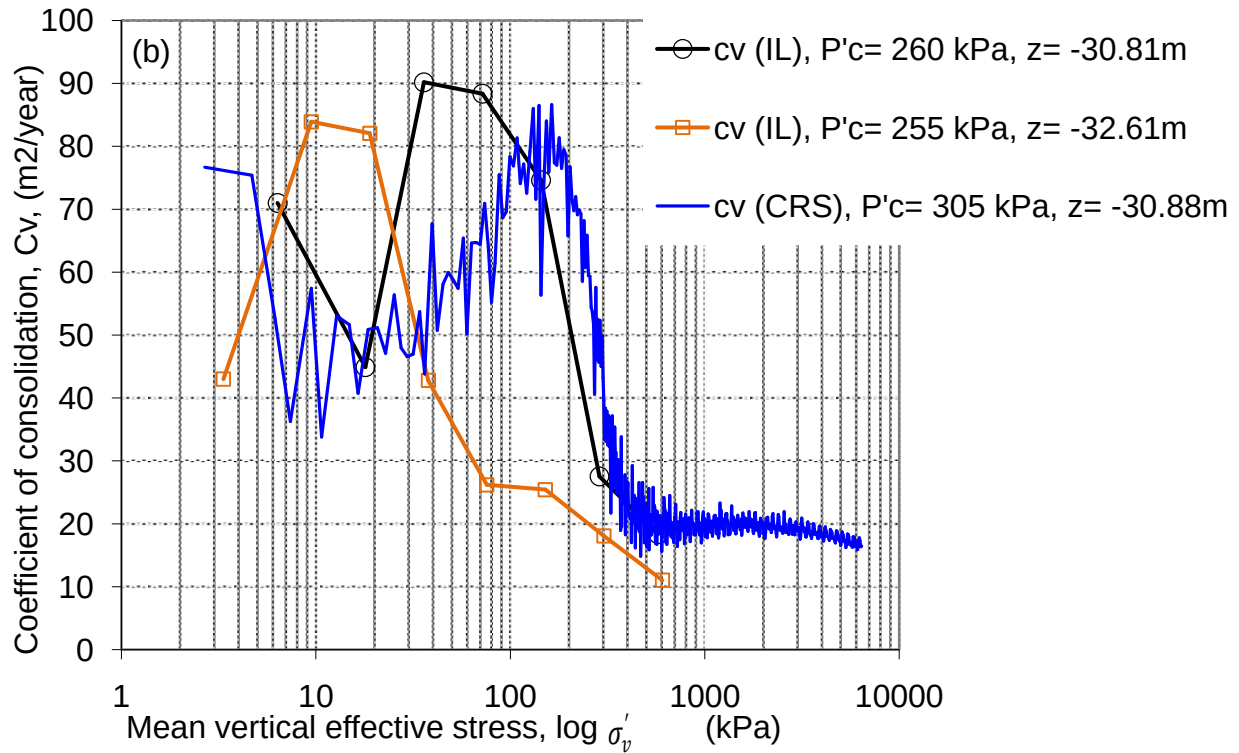


Fig. 5.4.2b. c_v vs. vertical effective stress on sediment specimens from -32.61 to -30.81 m.

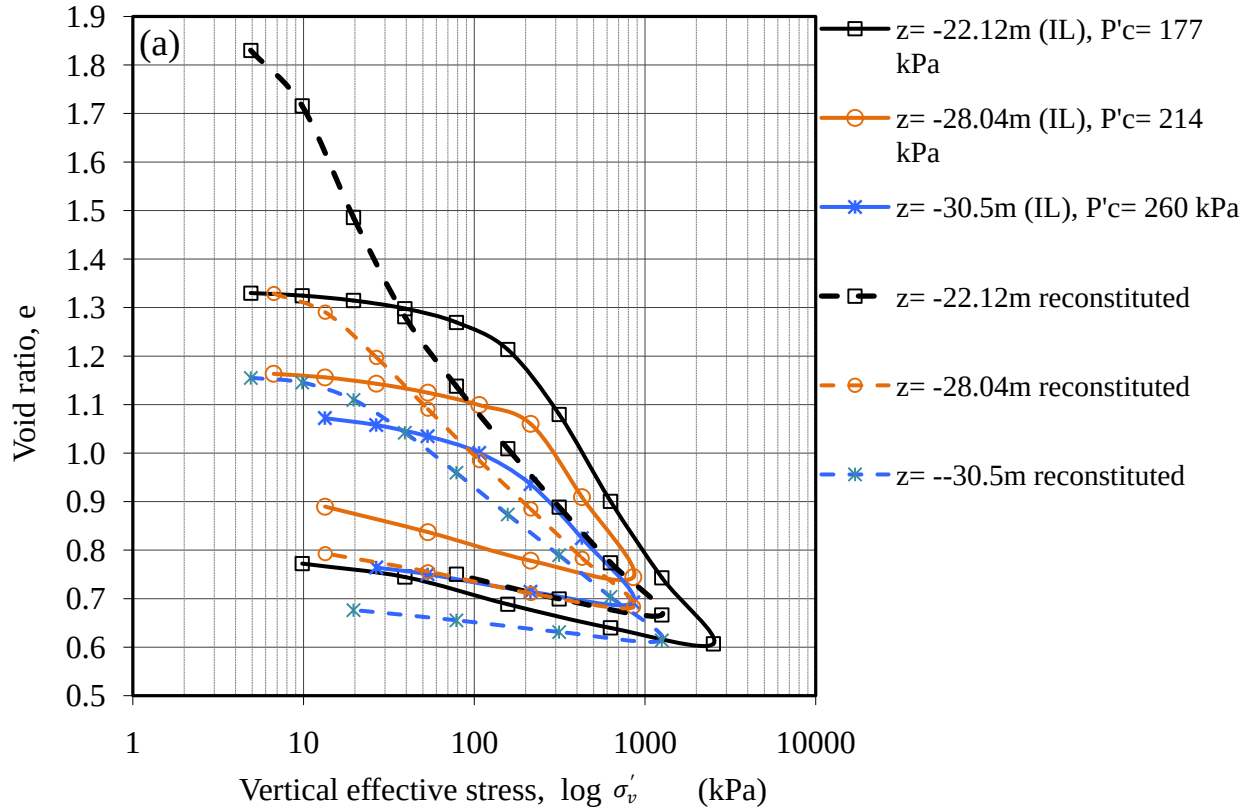


Fig. 5.4.3a. Curves of e - $\log \sigma'_v$ on sediment specimens from -30.5 to -22.12m.

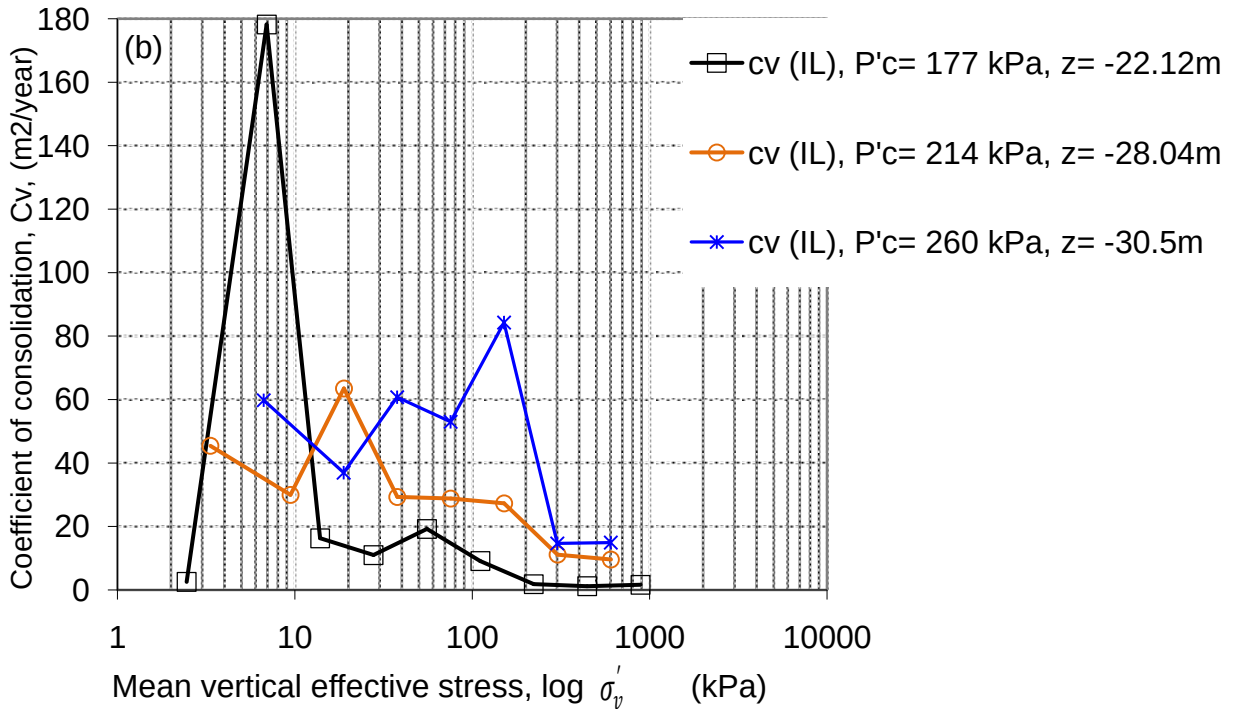


Fig. 5.4.3b. c_v vs. vertical effective stress on sediment specimens from -30.5 to -22.12 m.

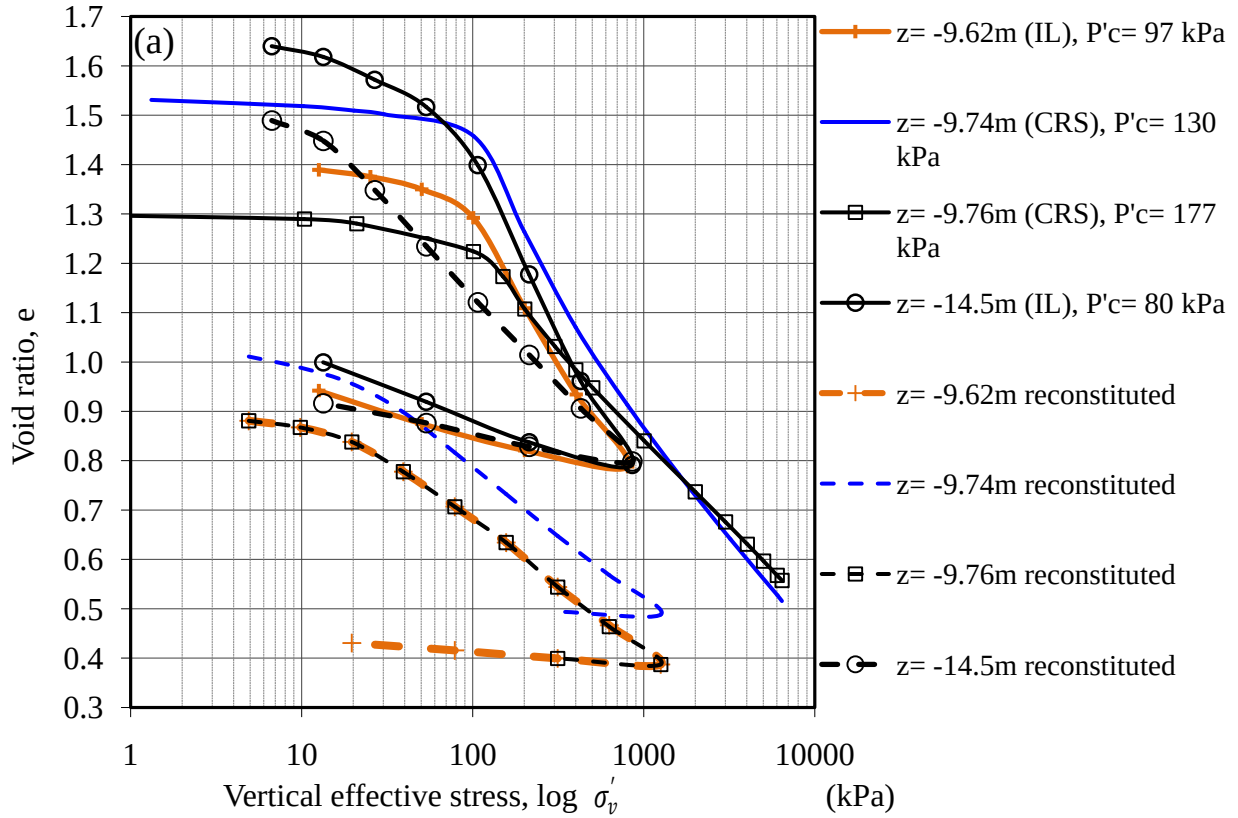


Fig. 5.4.4a. Curves of $e-\log \sigma'_v$ on sediment specimens from -14.5 to -9.62m.

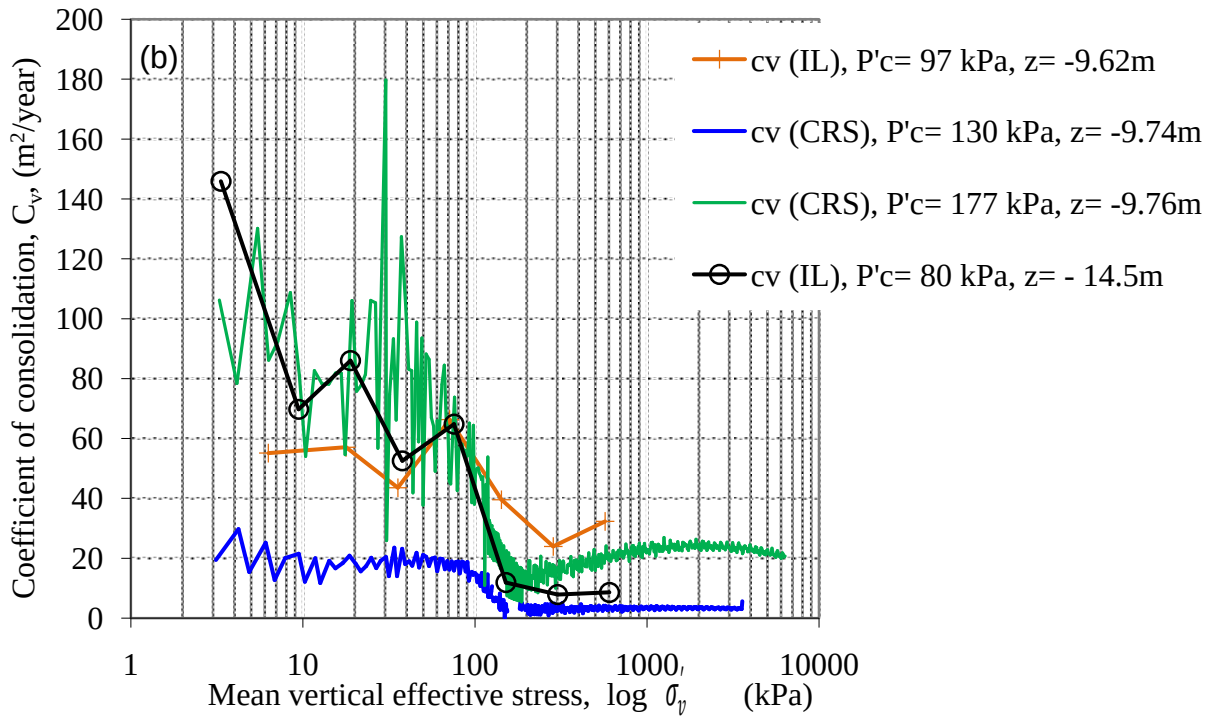


Fig. 5.4.4b. c_v vs. vertical effective stress on sediment specimens from -14.5 to -9.62 m.

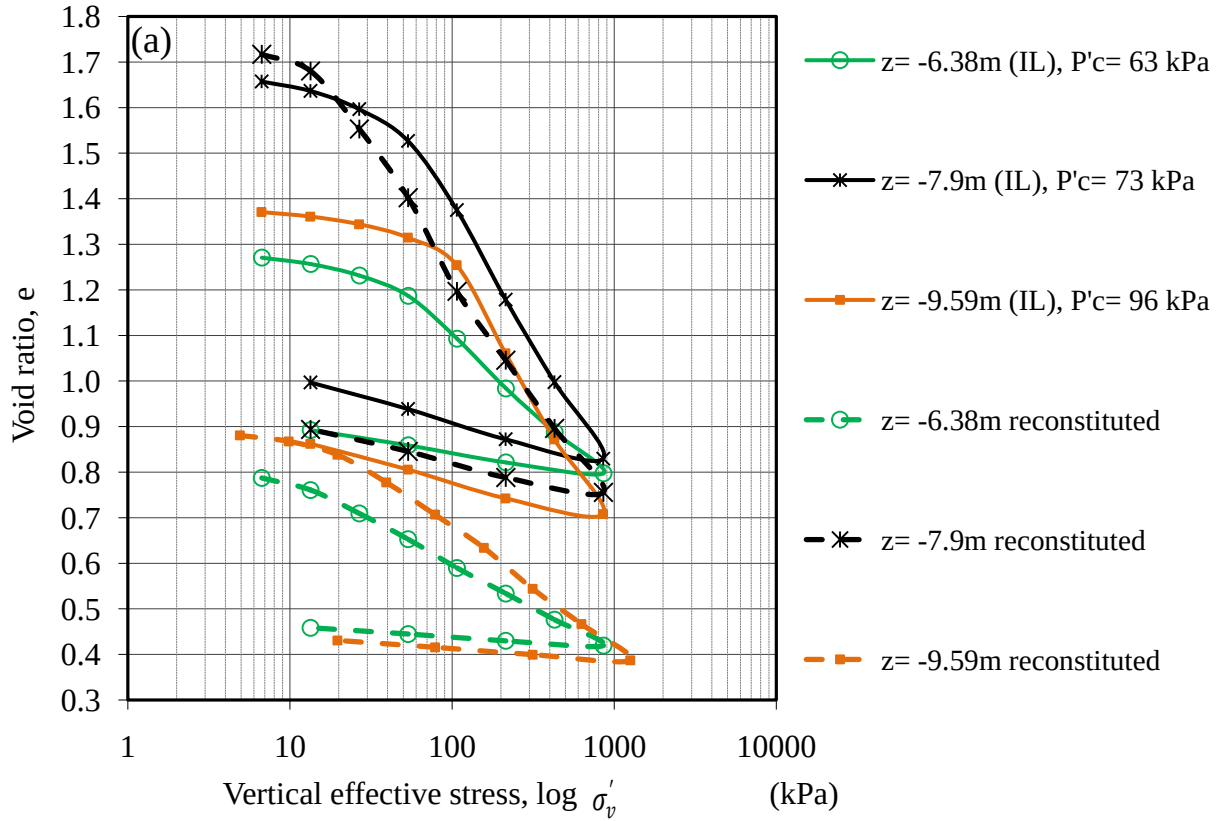


Fig. 5.4.5a. Curves of $e\text{-}\log \sigma'_v$ on sediment specimens from -9.59 to -6.38 m.

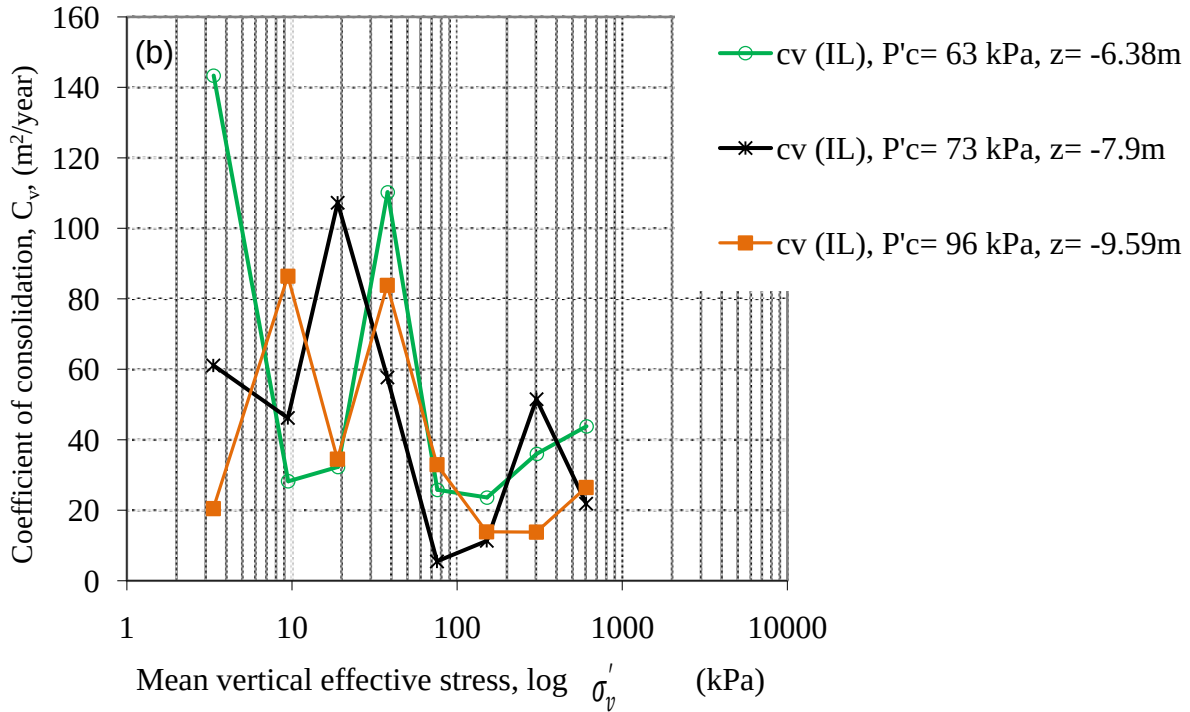


Fig. 5.4.5b. c_v vs. vertical effective stress on sediment specimens from -9.59 to -6.38 m.

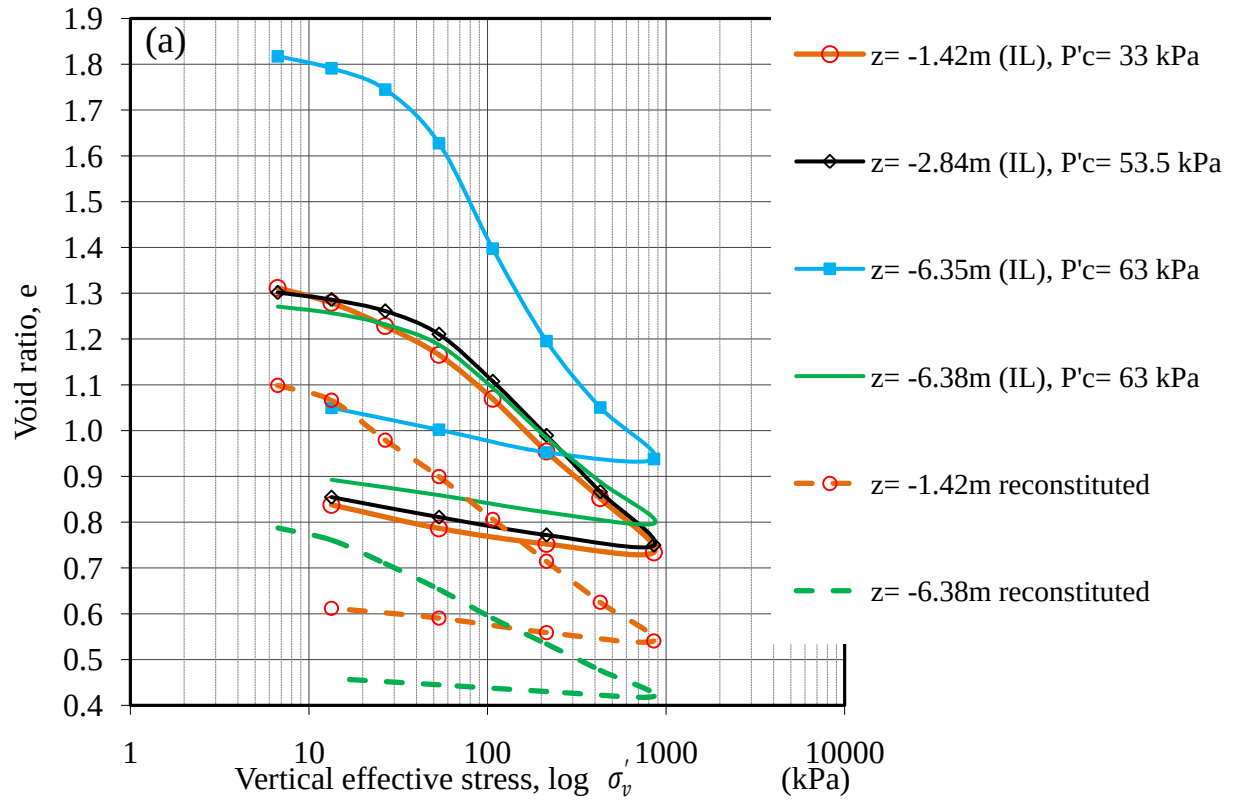


Fig. 5.4.6a. Curves of $e\text{-}\log \sigma'_v$ on sediment specimens from -6.38 to -1.42 m.

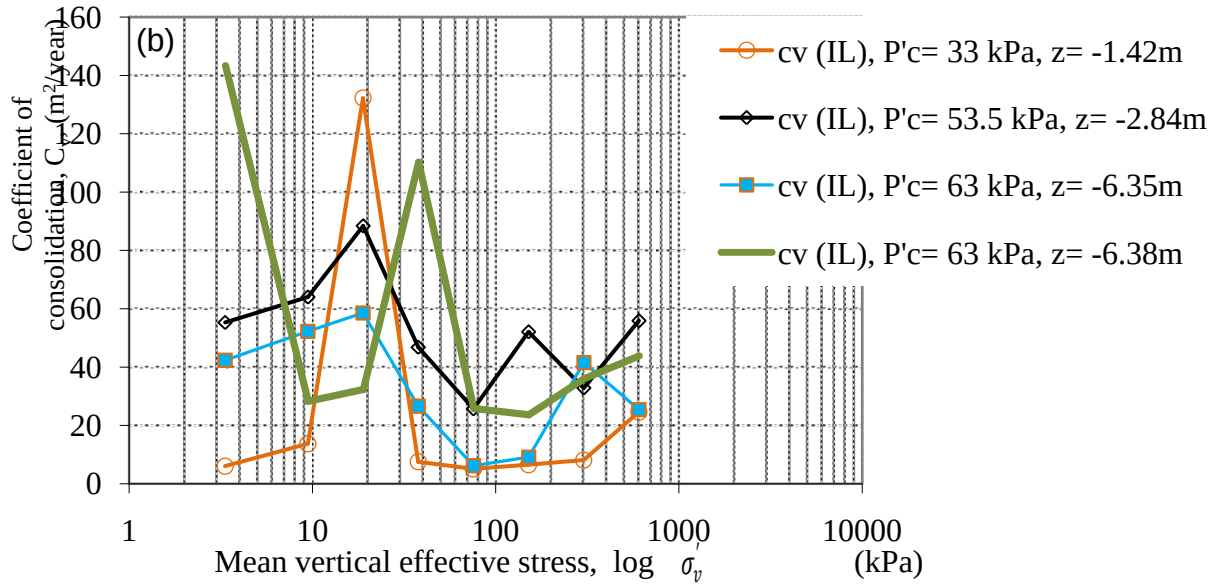


Fig. 5.4.6b. c_v vs. vertical effective stress on sediment specimens from -6.38 to -1.42 m.

Fig. 5.4. Curves of $e\text{-}\log \sigma'_v$ of loading & unloading stages, & c_v vs. vertical effective stress from IL & CRS tests on undisturbed and reconstituted cohesive soil specimens of Vinhlong core.

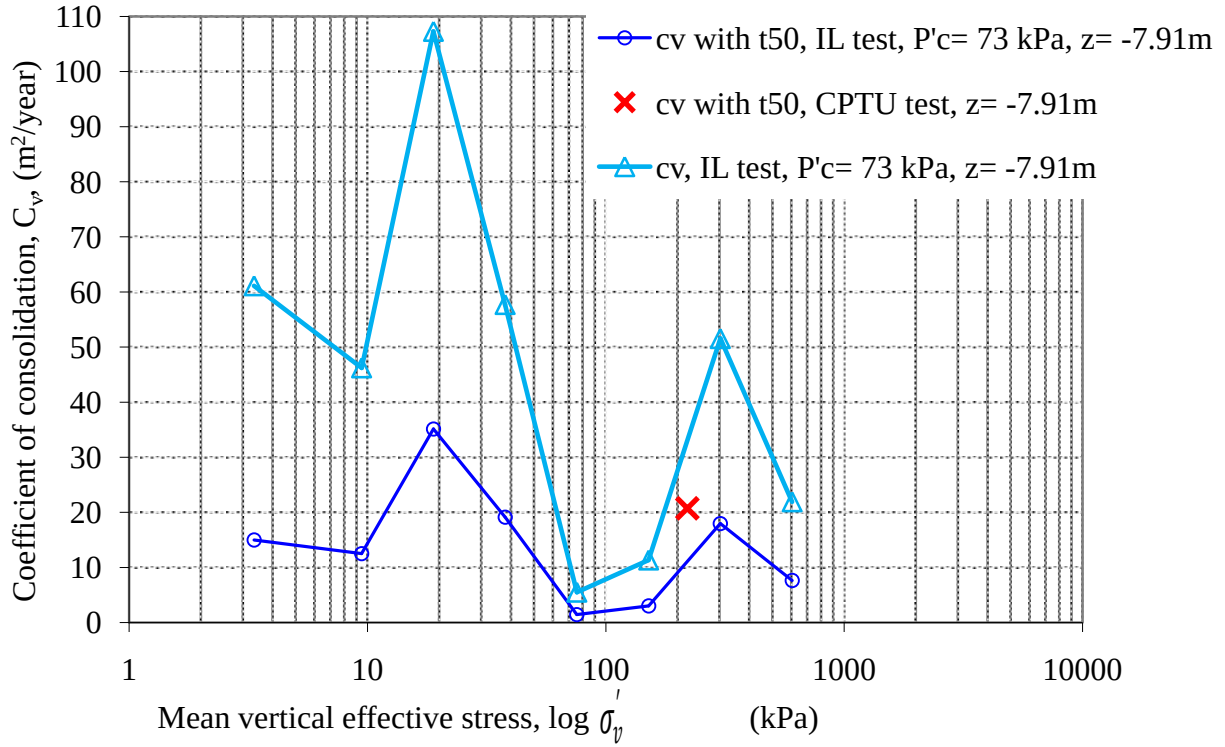


Fig. 5.5. Coefficients c_v vs. vertical effective stress on type 4, silt mixtures-clayey silt to silty clay (Robertson, 1990) at $z = -7.91$ m by IL & CPTU tests at Vinhlong site.

5.4.1.2. Caolanh site

The curves of the $e - \log \sigma'_v$ relationship of the loading and unloading stages, and c_v against vertical effective stress were given from the IL and CRS tests on the undisturbed and reconstituted cohesive soil specimens of Caolanh core shown in Fig. 5.6. The curves of the $e - \log \sigma'_v$ relationship and c_v against vertical effective stress on the cohesive soil specimens from -36.6 to -21.9 m of the CLM1 core are presented in Fig. 5.6.1. The curves of the $e - \log \sigma'_v$ relationship and c_v against vertical effective stress on the cohesive soil specimens from -7.8 to -1.68 m of the CLM1 core are presented in Fig. 5.6.2-3. The curves of the $e - \log \sigma'_v$ relationship and c_v against vertical effective stress on the cohesive soil specimens from +0.98 to +0.25 m of the CLM1 core are presented in Fig. 5.6.4.

The Coefficients c_v with t_{50} against the vertical effective stress by the IL and CPTU at the same depth and same type of soil at Caolanh site were presented in Fig. 5.7.

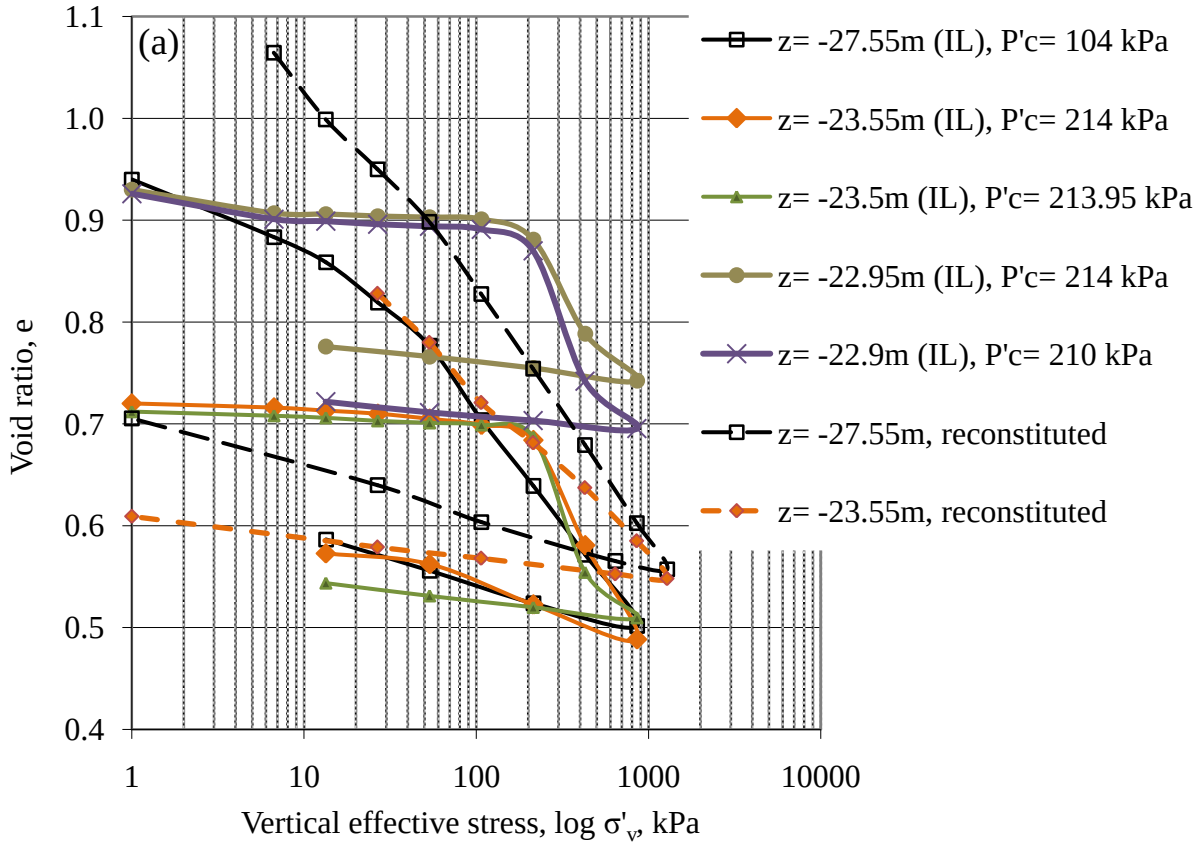


Fig. 5.6.1a. Curves of e - $\log \sigma'_v$ on sediment specimens from -27.55 to -22.9 m.

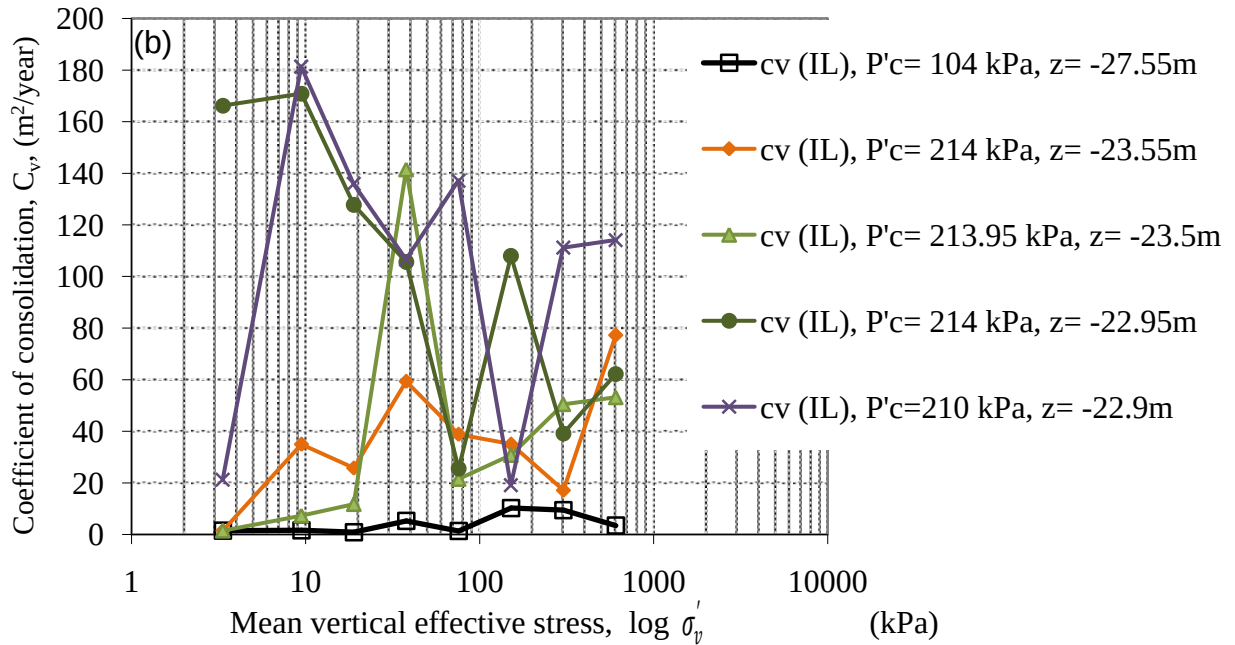


Fig. 5.6.1b. c_v vs. vertical effective stress on sediment specimens from -27.55 to -22.9 m.

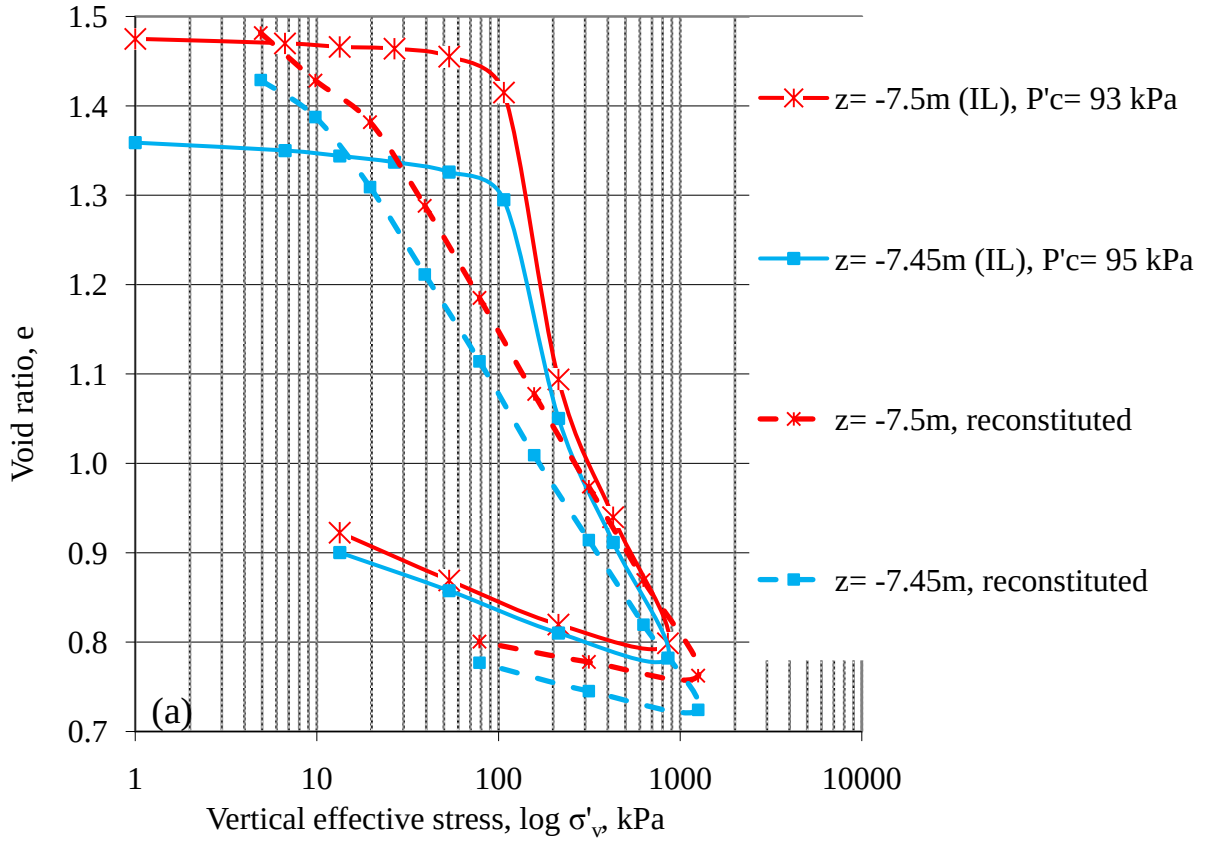


Fig. 5.6.2a. Curves of $e\text{-}\log \sigma'_v$ on sediment specimens from -7.5 to -7.45 m.

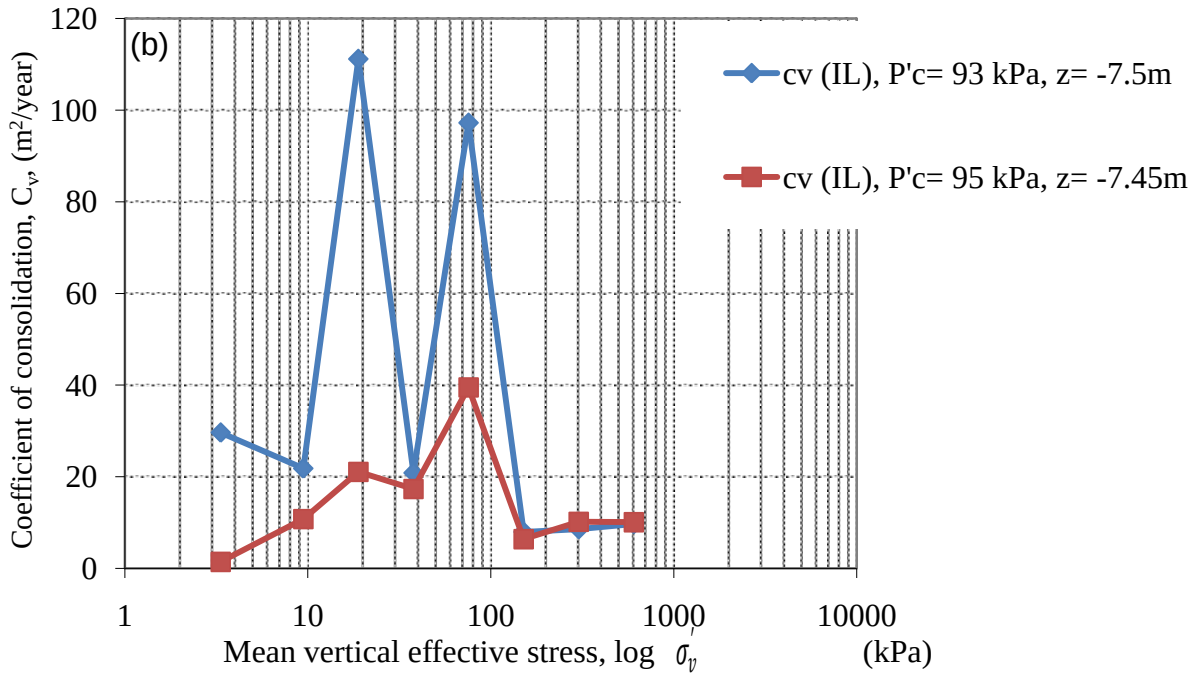


Fig. 5.6.2b. c_v vs. vertical effective stress on sediment specimens from -7.5 to -7.45 m.

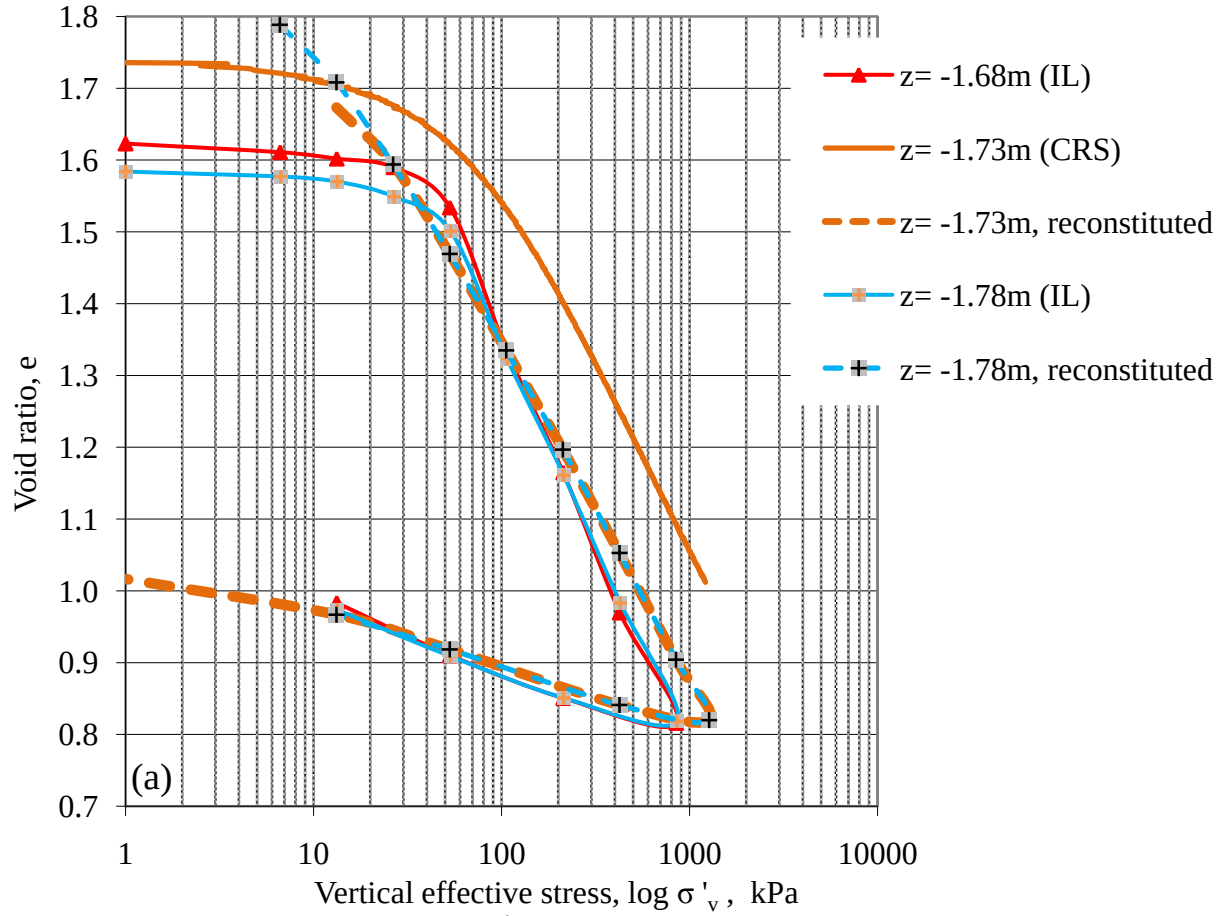


Fig. 5.6.3a. Curves of e - $\log \sigma'_v$ on sediment specimens from -1.78 to -1.68 m.

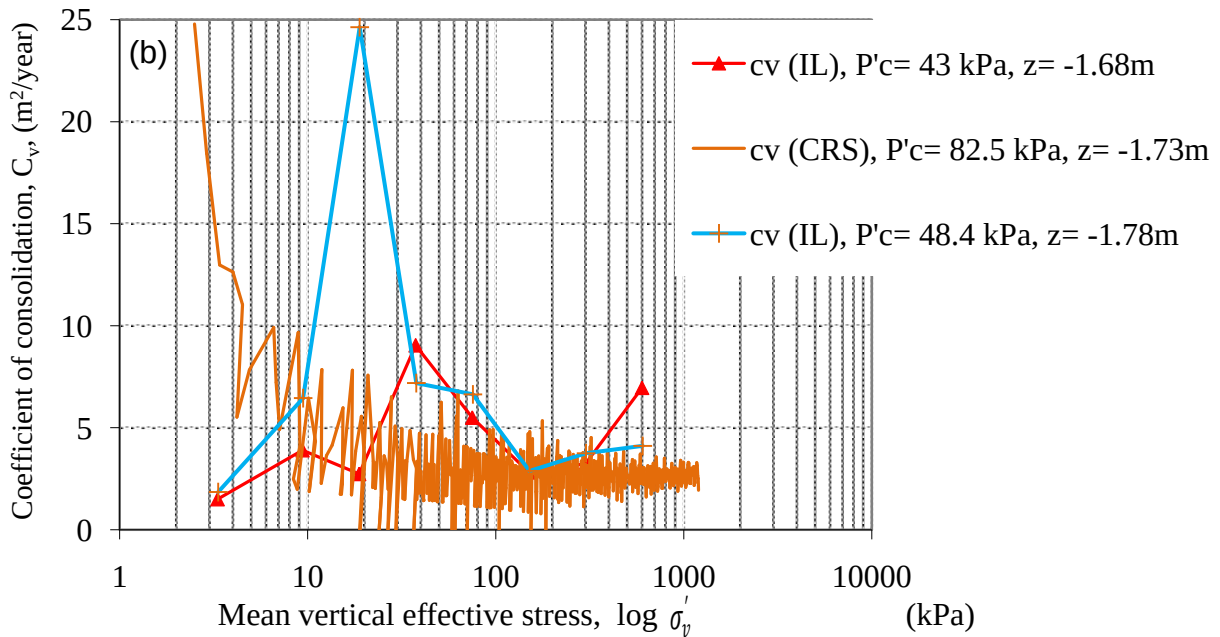


Fig. 5.6.3b. c_v vs. vertical effective stress on sediment specimens from -1.78 to -1.68 m.

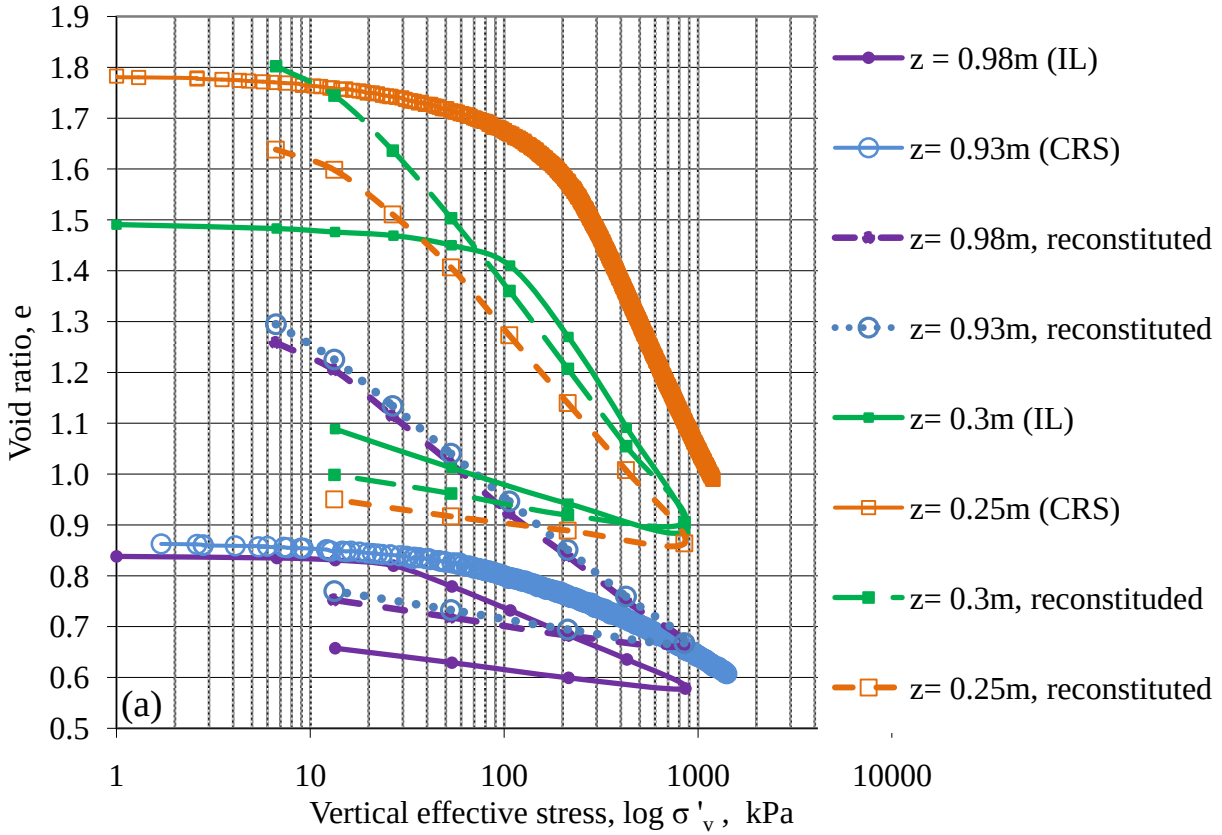


Fig. 5.6.4a. Curves of e - $\log \sigma'_v$ on sediment specimens from 0.25 to 0.98 m.

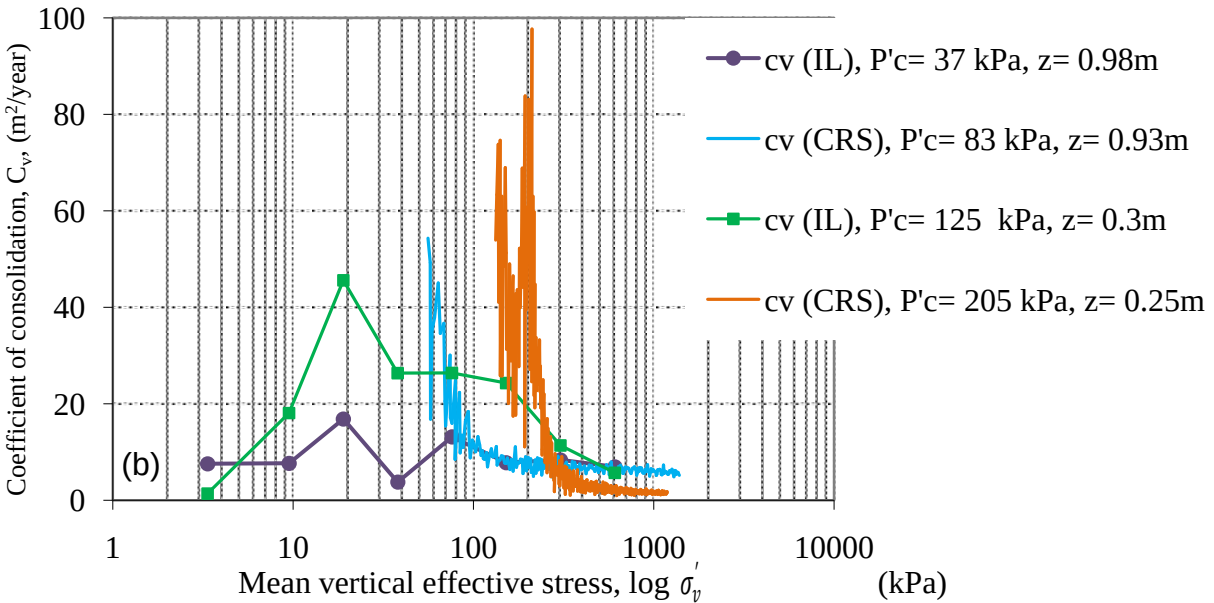


Fig. 5.6.4b. c_v vs. vertical effective stress on sediment specimens from 0.25 to 0.98 m.

Fig. 5.6. Curves of e - $\log \sigma'_v$ of loading & unloading stages, & c_v vs. vertical effective stress from IL& CRS tests on undisturbed and reconstituted cohesive soil specimens of Caolanh core.

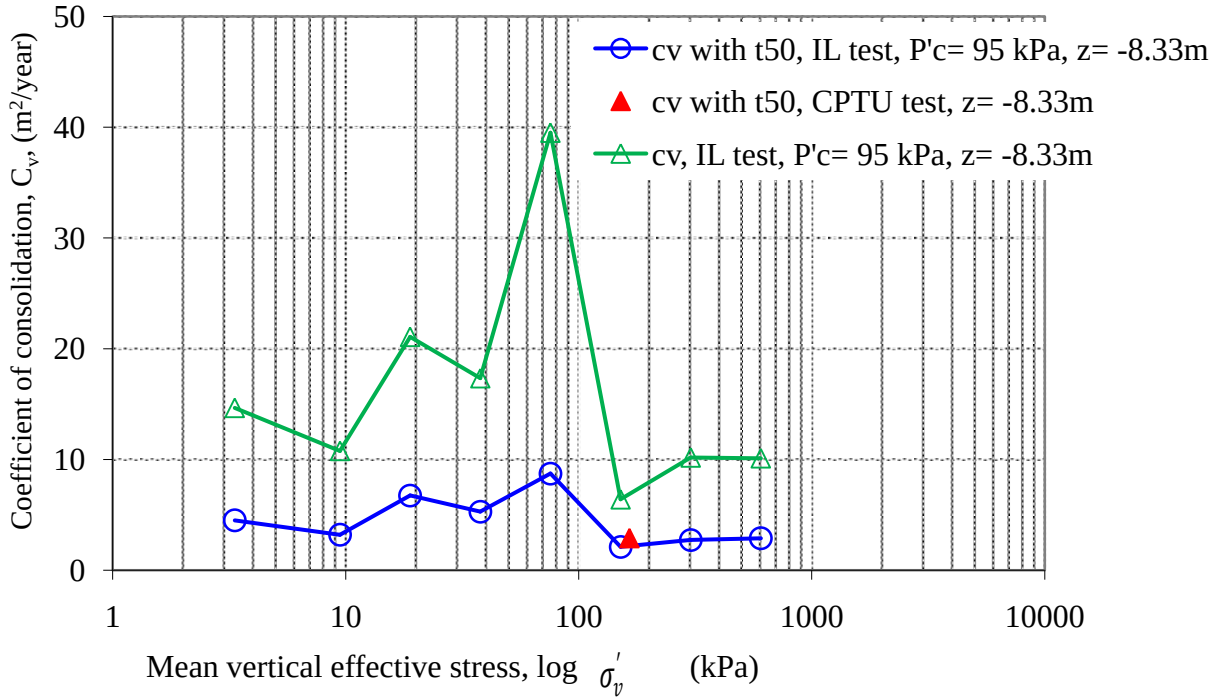


Fig. 5.7. Coefficients c_v vs. vertical effective stress on type 3, Clays-clay to silty clay (Robertson, 1990) at $z = -8.33$ m by IL & CPTU tests at Caolanh site.

We realize that the e - $\log \sigma'_v$ curves from the CRS test are sharper than those from the IL test; and the vertical yield stresses, σ'_{vy} , are also identified so easily and precisely (Figs. 5.4 and 5.6). The vertical yield stresses from the CRS test are often greater than from the IL test (Figs. 4.36i and 4.40i).

5.4.1.3. Void index

Void indices I_{v0} for in situ void ratio e_0 were estimated using above Equation 3.8 (Burland, 1990) for the Vinhlong and Caolanh argillaceous soils from the IL and CRS tests on undisturbed and reconstituted argillaceous soil specimens, they are presented in Tab. 5.2 Fig.5.8. Values of I_{v0} on the sedimentary facies formed in the high energy condition such as the delta front facies (from -5.5 to -18.5m) of the VLM1 core largely vary from between the SCL and ICL to well above the SCL (Fig. 5.8). This characteristic of the delta front facies of the VLM1 core is also realized the I_{v0} values on a range of -4.3 to -11.3 m of the Cantho cohesive soil (Takemura et al., 2007) (Tab. 5.2 and Fig. 5.8). Values of I_{v0} on the sedimentary facies formed in the low energy condition are almost between the SCL and ICL and around the SCL, such as the bay facies (from -22 to -25 m) and marsh facies (from -27.8 to -41.5 m) of the VLM1 core (Tab. 5.2 and Fig. 5.8).

Values of I_{vo} on the surface sediment facies are almost below and around the ICL, such as the natural levee facies (+2.9 to -0.5 m) and flood plain facies (-0.5 to -3.6 m) of the CLM1 core; especially, those of the natural levee facies are very low (Tab. 5.2 and Fig. 5.8).

Table 5.2

Void indices, I_{vo} , in situ void ratio, e_o , and void ratios, e^*_{100} , e^*_{1000} , at vertical stresses 100 kPa and 1000 kPa on e -log σ'_v of remold specimens, of cohesive soils of Caolanh and Vinhlong cores

Altitude	γ	w_n	w_p	w_L	G_s	OCR	σ'_{vo}	e_o at σ'_{vo}	e^*_{100}	e^*_{1000}	I_{vo}
(m)	(g/cm ³)	(%)	(%)	(%)	(g/cm ³)		(kPa)				
Caolanh cohesive soil											
0.080	1.95	29.43	24.75	46.00	2.76	1.5	30.65	0.825	0.930	0.640	-0.36
0.075	1.94	29.32	26.17	46.30	2.76	2.0	31.50	0.830	0.956	0.647	-0.41
-0.620	1.62	49.65	52.26	71.00	2.60	4.2	35.85	1.470	1.420	0.870	0.09
-0.660	1.70	51.80	38.31	65.40	2.59	2.7	36.50	1.200	1.287	0.830	-0.19
-2.660	1.63	59.11	27.46	56.70	2.66	1.0	48.40	1.530	1.345	0.870	0.39
-8.300	1.69	44.96	23.65	41.80	2.69	1.2	85.10	1.320	1.080	0.750	0.73
-8.340	1.67	48.29	25.76	42.90	2.73	1.2	85.40	1.450	1.150	0.800	0.86
Vinhlong cohesive soil											
-1.416	1.70	47.49	26.86	46.50	2.66	1.1	29.42	1.220	0.815	0.510	1.33
-6.38	1.72	45.50	20.19	33.00	2.70	1.1	62.21	1.169	0.600	0.414	3.06
-7.9	1.61	62.24	28.57	63.00	2.65	1.0	71.94	1.470	1.215	0.715	0.51
-9.735	1.64	59.34	21.07	48.11	2.58	1.1	90.51	1.430	0.790	0.520	2.37
-9.765	1.69	58.79	28.39	53.94	2.61	1.1	90.70	1.320	0.687	0.412	2.30
-14.5	1.59	55.79	26.69	58.80	2.65	1.0	114.69	1.382	1.130	0.790	0.74
-22.05	1.67	56.93	28.59	82.00	2.72	1.1	167.60	1.363	1.300	0.800	0.13
-28.05	1.76	42.93	24.66	50.60	2.63	1.0	219.18	1.060	0.990	0.665	0.22
-30.95	1.81	36.31	20.71	39.83	2.68	1.2	246.60	0.990	0.930	0.644	0.21
-30.98	1.81	38.62	21.08	40.12	2.68	1.2	246.84	1.030	0.905	0.621	0.44
-32.62	1.78	39.29	24.28	44.00	2.67	1.1	254.82	0.920	0.800	0.545	0.47
-32.65	1.77	42.41	23.28	43.00	2.68	1.1	255.06	0.940	0.960	0.630	-0.06
-41.52	1.70	52.40	29.16	71.90	2.67	1.3	317.69	1.190	1.260	0.810	-0.16

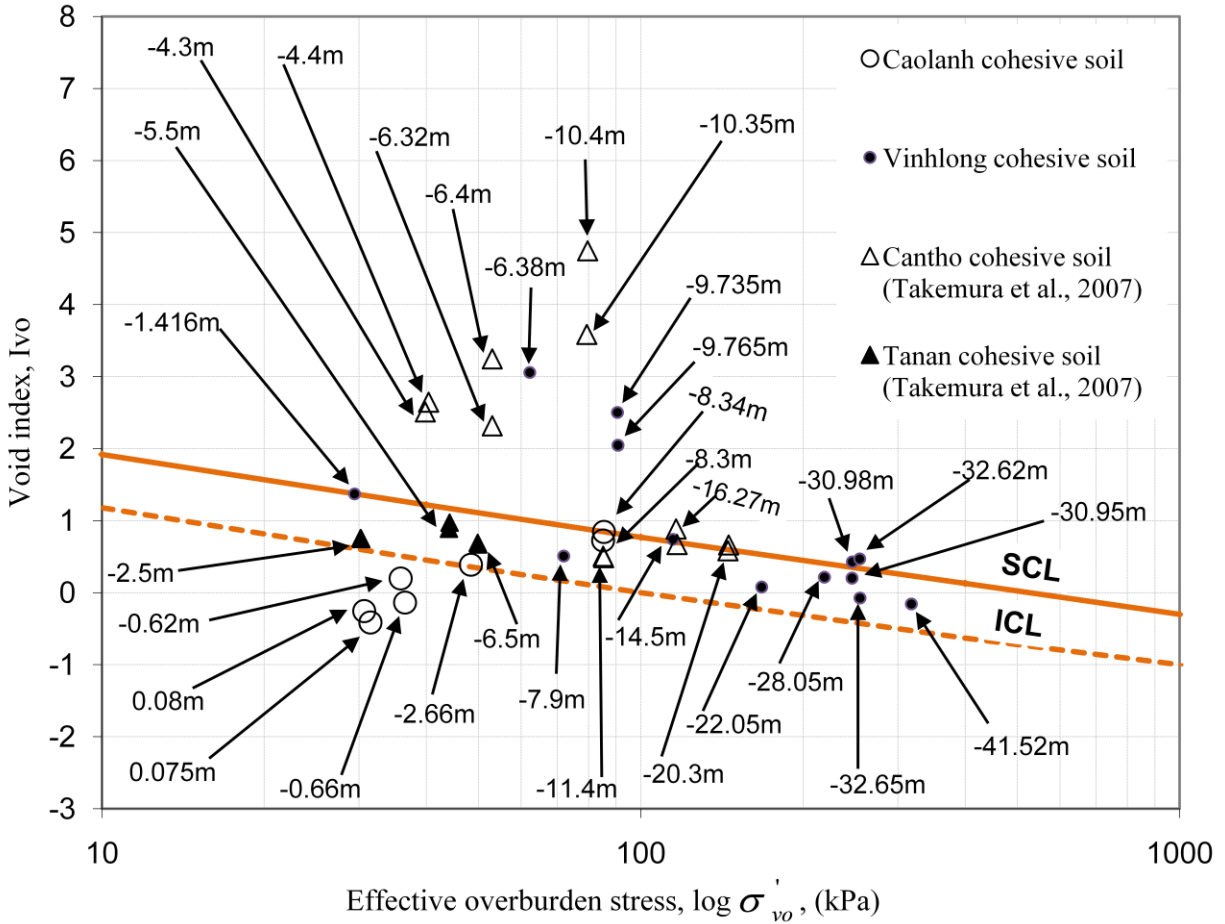


Fig. 5.8. Relationship between void indices I_{vo} and effective overburden stress σ'_{vo} on the Caolanh, Vinhlong cohesive soils, Cantho and Tanan cohesive soils (Takemura et al., 2007).

5.4.1.4. Swelling sensitivity

The values of the swell sensitivity ratios, C_s^*/C_s , from the IL tests of both Caolanh and Vinhlong cores are shown in Tab. 5.3, they obtain less than or equal 0.9. Values of C_s^*/C_s on the sedimentary facies formed in the high energy condition largely vary; such as, those of the intertidal flat facies of the CLM1 core are from 0.44 to 0.8, and those of the delta front facies of the VLM1 core are from 0.19 to 0.82 (Tab. 5.3). Values of C_s^*/C_s on the sedimentary facies formed in the low energy condition don't largely vary; such as the flood plain, bay, and marsh facies (Tab. 5.3). Especially, the values of C_s^*/C_s on the marsh facies of the VLM1 core vary in a small range of 0.69 to 0.79 (Tab. 5.3). Values of C_s^*/C_s on the natural levee facies of the CLM1 core are a range of 0.48 to 0.6 and general a little less than those of the other facies (Tab. 5.3). Simultaneously, values of C_c on the natural levee facies of the CLM1 core are also a little small, in a range of 0.48 to 0.16, and less than those of the other facies (Tab. 5.3). And values of OCR

by the IL test on the natural levee facies of the CLM1 core are the largest, in a range of 1.5 to 3.5 (Tab. 5.3). It shows the natural levee facies of the CLM1 core are heavy overconsolidation. Values of OCR by the IL test on the delta front facies of the VLM1 core are low and around unity (Tab. 5.3).

5.4.1.5. Coefficients of consolidation

The values of coefficients of consolidation in vertical direction, c_v , and horizontal direction, c_h , are shown in Tab. 5.4, we can realize that values of c_v obtained in the both CPTU and IL are approximately equal in the same stress (same depth) on the same sediment. Values of c_v and c_h on the delta front facies at the VLM1, BT1, and BT3 core sites are so high, and can be the highest in comparison with other facies, and change largely from 64.1 to 6.4 m^2/year (Tab. 5.4). Values of c_v and c_h on the sub- to intertidal flat facies at the BT1 and BT3 core sites are the second high in comparison with other facies from 7.4 to 9.5 m^2/year (Tab. 5.4). Values of c_v and c_h on the flood plain, prodelta facies at the VLM1, CLM1, and BT3 core sites are so low in a range of 2.9 to 4.7 m^2/year ; especially, those in the flood plain facies are the lowest (Tab. 5.4).

Table 5.3.

Swell sensitivities, C_s^*/C_s , yield stress ratio, OCR, virgin compression index, C_c , from IL tests and
Atterberg limits of facies' argillaceous sediments of the CLM1 and VLM1 cores.

Facies	Altitude, m	w _l	w _p	w _n	Undisturbed soil				Disturbed soil		C [*] / _s
					OCR	Virgin compression Index	Swell Index, C _s		Compre- -ssion Index C [*] _c	Swell Index, C [*] _s	. C [*] _s : at OCR=10 . C _s : at 215-13 kPa
		%					C _c	860 to 215 kPa			215 to 13 kPa
Caolanh site											
Natural levee	0.88	46.30	26.17	29.32	3.5	0.18	0.03	0.05	0.31	0.03	0.60
	0.3	71.00	52.26	49.65	3.5	0.48	0.09	0.12	0.50	0.06	0.52
	0.2	65.40	38.31	51.80	2.2	0.44	0.05	0.10	0.46	0.05	0.48
	0.08	46.00	24.75	29.43	1.5	0.16	0.03	0.05	0.41	0.03	0.60
Flood plain	-1.78	56.70	27.46	59.11	1.0	0.58	0.05	0.10	0.475	0.07	0.69
Intertidal flat	-7.45	44.50	24.13	43.14	1.2	0.55	0.05	0.07	0.33	0.06	0.80
	-7.55	41.80	23.65	44.96	1.2	0.64	0.03	0.09	0.35	0.04	0.44
Vinhlong site											
Flood/ marsh	-1.41	46.50	26.86	47.49	1.1	0.38	0.03	0.07	0.30	0.04	0.56
Delta front	-6.39	33.00	20.19	45.50	1.0	0.33	0.04	0.06	0.19	0.04	0.64
	-7.92	63.00	28.57	62.24	1.0	0.76	0.07	0.10	0.50	0.09	0.82
	-9.57	48.11	21.07	59.34	1.1	0.73	0.07	0.12	0.27	0.02	0.19
	-9.60	49.11	20.73	58.79	1.1	0.64	0.06	0.10	0.30	0.03	0.28
	-14.5	58.80	26.69	55.79	1.1	0.82	0.08	0.13	0.34	0.04	0.29
Bay	-22.14	72.00	24.72	46.81	1.2	0.60	0.07	0.09	0.40	0.08	0.90
Marsh	-28.05	50.60	24.66	42.93	1.2	0.60	0.06	0.09	0.33	0.07	0.76
	-30.76	40.12	21.10	38.21	1.3	0.58	0.04	0.06	0.28	0.04	0.69
	-30.83	39.80	20.71	37.23	1.3	0.53	0.04	0.07	0.29	0.05	0.79
	-38.90	44.20	30.28	49.30	1.1	0.83	0.05	0.07	0.33	0.06	0.76
Estuary channel	-41.52	71.90	29.20	52.40	1.7	1.13	0.14	0.16	0.45	0.11	0.67

Table 5.4.

Values of coefficients of consolidation in direction: vertical, c_v , and horizontal, c_h , from CPTU and IL at the sites.

Facies (1)	Altitude (2)	Soil behaviour type classification (3)	CPTU Test					IL Test		
			Maximum excess hydrostatic pressure (4)	Time for 50% pore pressure dissipation (5)	Possible field values of k_h/k_v for soft clays (6)	Coefficients of consolidation in		Under increase of total stress (9)	Time for 50% pore pressure dissipation (10)	Vertical (11)
						Vertical direction (7)	Horizontal direction (8)			
	Δu_2	t_{50}	(Jamiołkowski et al., 1985)	c_v	c_h	$\Delta\sigma$	t_{50}	c_v		
m			kPa	minutes		m ² /year	m ² /year	kPa	minutes	m ² /year
Vinhlong site, from CPTU1-VL										
Delta front	-7.91	Clayey silt to silty clay (4)	<u>220</u>	1.12	9	20.73	186.5	<u>214</u>	2.645	3.02
	-13.50	Clay to silty clay (3)	185	5.83	8	6.4	51.4			
prodelta	-19.49	Clay to silty clay (3)	460	8.75	5	4.7	23.5			
Caolanh site, from CPTU-CL										
Flood plain	-8.33	Clay to silty clay (3)	<u>165</u>	19.5	4	2.9	11.8	<u>214</u>	4.061	2.11
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Bentre-1 site, from CPTU-BT1										

Sub- to intertidal flat	-2.88	Clay to silty clay (3)	80	5.19	8	7.4	59			
Delta front	-7.1	Clay to silty clay (3)	112	1.5	10	13.2	132			
Bentre-3 site, from CPTU-BT3										
Sub- to intertidal flat	-6.48	Clay to silty clay (3)	161	3.12	7	9.5	66.2			
Delta front	-12.1	Clayey silt to silty clay (4)	145	0.22	13	64.1	833			
Prodelta	-15	Clay to silty clay (3)	474	12.64	4	3.3	13.2			

5.4.1.6. Overconsolidation ratio

To substitute values of normalized cone resistance, Q_t , from the CPTU results and k values being 0.2, 0.3, 0.4, and 0.5 into formula (3.4). We obtain OCRs with different values of k from CPTU results at the investigation sites. The OCRs by CPTU, IL and CRS, and Q_t at each investigation site are presented as follows.

a. At Caolanh site

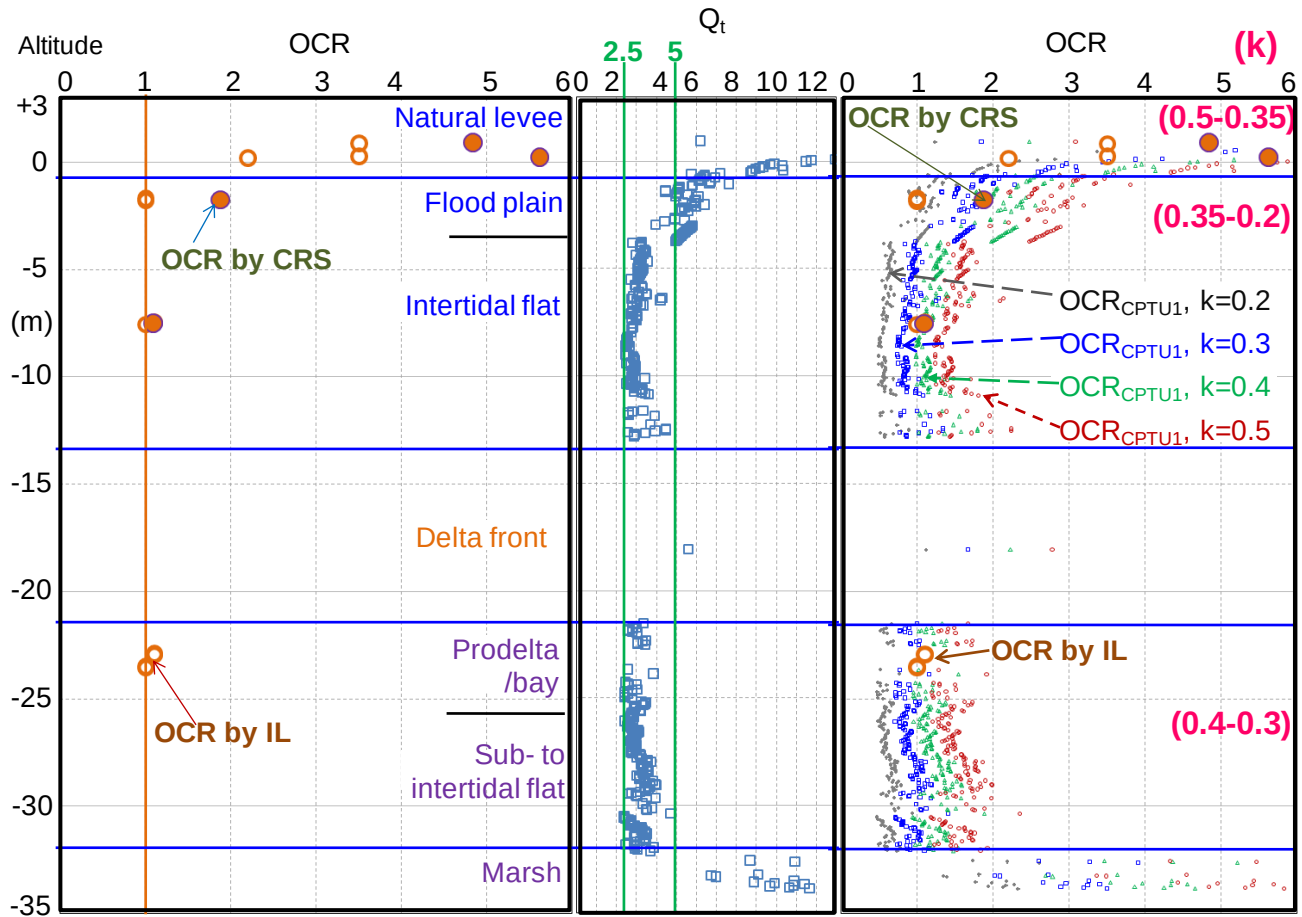


Fig. 5.9. OCRs by IL, CRS, and CPTU with values of k being 0.2, 0.3, 0.4, and 0.5, and normalized cone resistance, Q_t on the cohesive soil at Caolanh site.

At the Caolanh site, values of OCR by IL and CRS more than 1. OCRs of the surface sediments are so more than one (Fig. 5.9). All values of Q_t are more than 2.5 (Fig. 5.9). These values of Q_t indicate that the Caolanh cohesive soils are overconsolidation (Lunne et al., 1997). Especially, for the surface and marsh sediments are more than 5 (Fig. 5.9). Values of Q_t tend to decrease from the nature levee to delta front sediments. And then, Q_t values tend to increase

again from prodelta to marsh sediments (Fig. 5.9). It implies that OCRs also change like values of Q_t .

We realized that for the natural levee sediments, OCR by IL and CRS are within lines of OCR by CPTU with k from 0.5 to 0.35 (blue line and red line) (Fig. 5.9). For the flood plain and intertidal flat sediments, OCR from IL and CRS lie within lines of OCR with k being 0.4 to 0.2 (back line and green line) (Fig. 5.9). For the prodelta and bay sediments, OCRs by IL test are within lines of OCR with k being 0.4 to 0.3 (blue line and green line).

b. At Vinhlong site

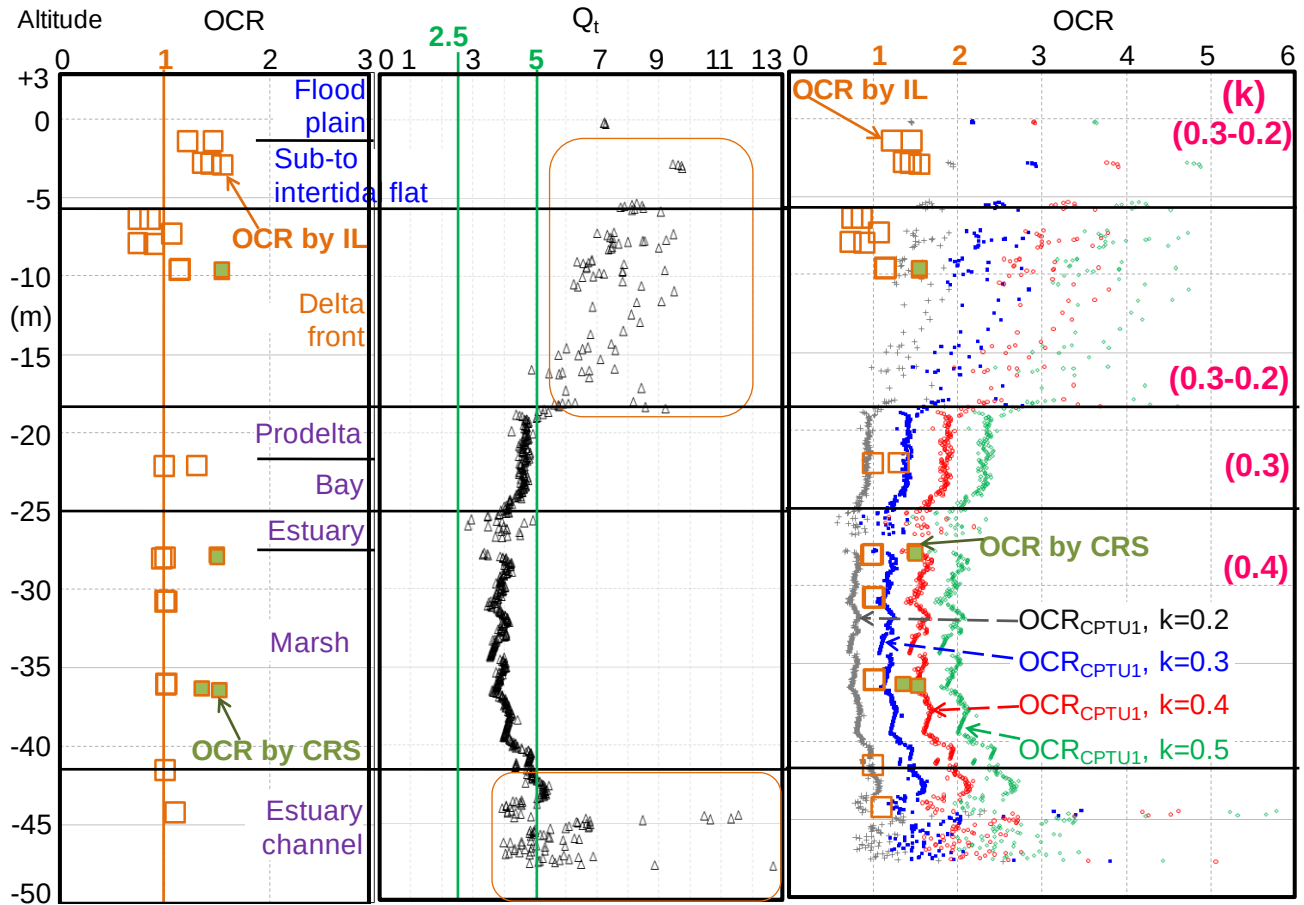


Fig. 5.10. OCRs by IL, CRS, and CPTU with values of k being 0.2, 0.3, 0.4, and 0.5, and normalized cone resistance, Q_t on the cohesive soil at Vinhlong site.

At the Vinhlong site, values of OCR by IL and CRS are almost more than one except OCR by IL on the specimens at greater than -25 m in the depth and the delta front sediment because of

the low quality (Fig. 5.10). Values of Q_t are so more than 2.5 (Fig. 5.10). Values of Q_t on the delta front sediments are large and vary largely because they contain high sand contents. Values of Q_t of estuary channel sediments are more than 5 (Fig. 5.10); and they have big variation because the estuary channel sediments contain high organic materials. These Q_t values also indicate the Vinhlong cohesive soils are slight overconsolidation to overconsolidation (Lunneet al., 1997).

For the flood plain and sub to intertidal flat sediments, OCRs from IL and CRS are around line of OCR with k being 0.3 (blue line) (Fig. 5.10). For the delta front sediment, OCRs from IL and CRS are within lines of OCR with k being 0.3 to 0.2 (blue line and back line) (Fig. 5.10). For the prodelta and bay sediments, OCRs from IL test are close to line of OCR with k being 0.3 (blue line) (Fig. 5.10). For the marsh sediment, OCRs from CRS are around to line of OCR with k 0.4 (red line) (Fig. 5.10). Values of Q_t on the estuary channel sediment are more than 5; hence, they are overconsolidation.

5.4.2. Development-levels of microstructure

Coinciding with the rise and reduction of sea level, the high and stable sediment-discharge created the late Pleistocene-Holocene sedimentary facies as presenting in Section 4.4. As a result, the altitude of the Mekong Delta during the late Pleistocene-Holocene period continuously increased; namely, the typical investigation sites in Fig. 4.8. Therefore, the effective overburdened pressure (vertical effective over stress, σ'_{vo}) in the field from the late Pleistocene-Holocene to present in the MRD has not reduced by the natural geologic processes. The results of the IL, CRS, and CPTU tests showed that the late Pleistocene-Holocene sediments are normal consolidation and slight to high overconsolidation. All OCR values are equal and greater than one (Figs. 5.11.1-2 and Tab. 5.5). Hence, a mechanical overconsolidation (gravitational compaction) could not occur in the late Pleistocene-Holocene sediments. The causes of the overconsolidation may be by cementation and ageing. The evidence which can be clearly seen is calcareous concretion and incipient in the marsh or marsh/tidal flat, sub- to inter-tidal flat, bay, and prodelta or prodelta/bay facies of the VLM1 and CLM1 cores (Figs. 4.2I & 4.4K). The calcareous concretion and incipient also occurred in the marsh, bay, and prodelta facies of both BT2 and BT3 cores presented by Ta et al. (2005). Takemura (2007) also indicated that the

development-level of microstructure is high through the results of CRS tests on the clay samples in the Cantho province, MRD. The OCRs of equivalent sediment-facies tend to reduce slightly from the CLM1 core site to the VLM1 core site (Figs. 5.11.1.1-2 and Tab. 5.5). As presented in items 4.5 and 5.2.3, because the CLM1 core site was possibly in the fluvial-dominated delta, and close to and received the abundant source of material supply of the large streams. And there are also the change of materials from the upper to lower delta plain by their move-possibility and the influence of the delta formation mechanism. Imply that the changes of material and the delta formation mechanism are also causes of the different levels of overconsolidation and produced the typical sedimentary sequences with different characteristics of consolidation. Therefore, we should use terms the yield stress ratio for the overconsolidation ratio, OCR, and the yield stress for the preconsolidation pressure for the MRD late Pleistocene-Holocene sediments. And we

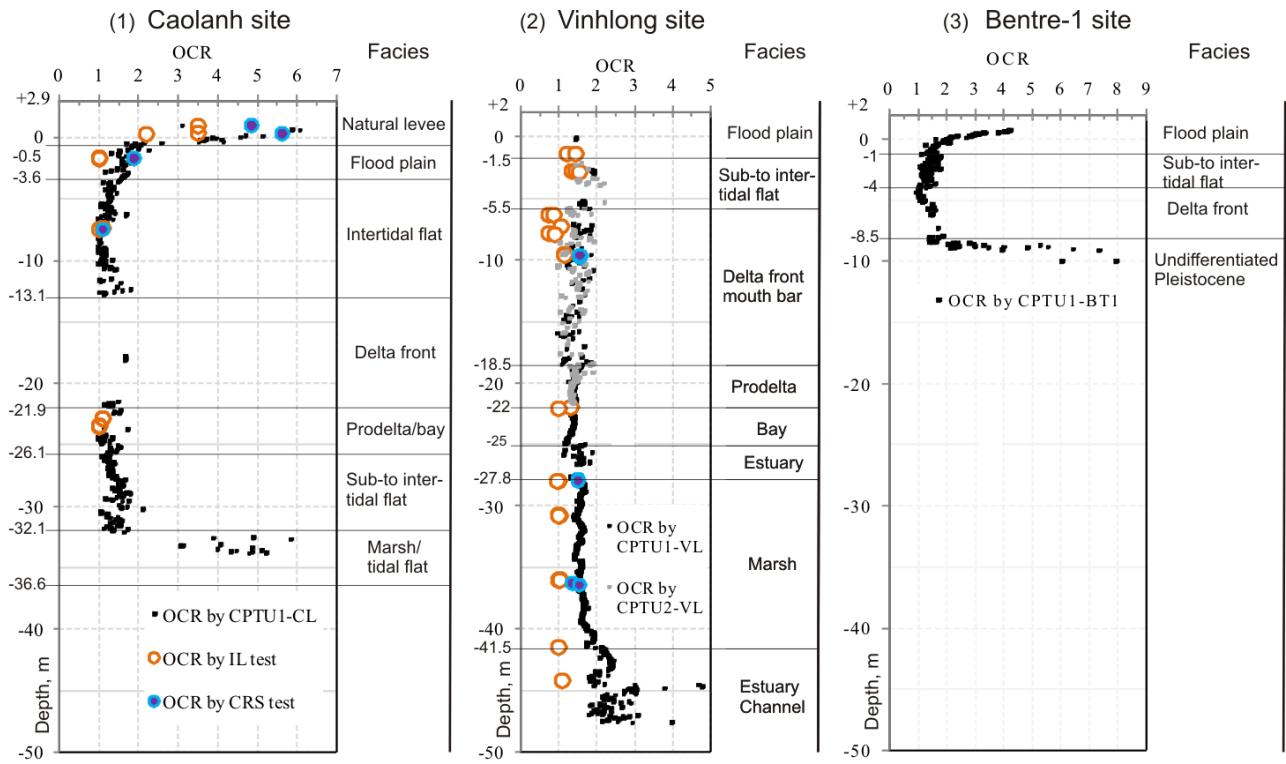


Fig. 5.11.1. Values of OCRs with depth from IL, CRS and CPTU tests for the cohesive soils at Caolanh, Vinhlong, and Bentre-1 sites.

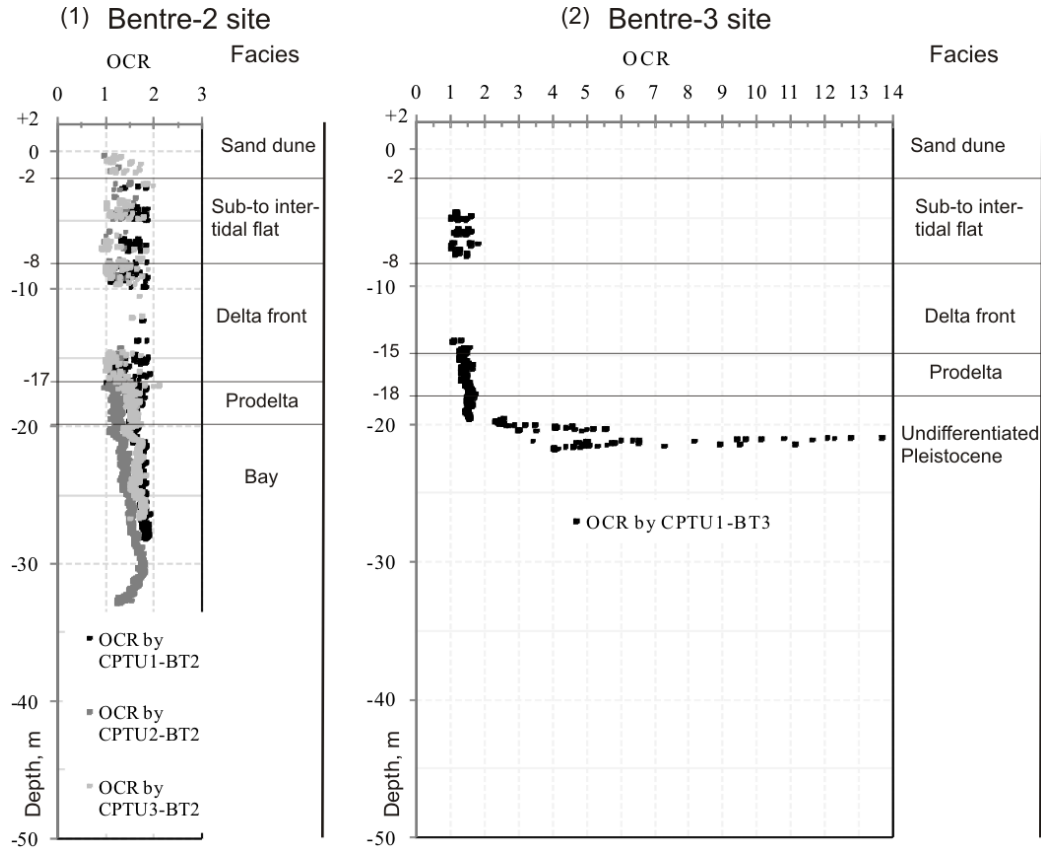


Fig. 5.11.2. Values of OCRs with depth from CPTU tests for the cohesive soils at Bentre-2, Bentre-3 sites.

could say that the age-reduction of these equivalent sediment-facies in the regressive marine stage from the upper delta to the lower delta do not significant influence on the consolidation-level like the changes of material and the delta formation mechanism.

To carefully consider the microstructures through the results of the consolidation tests and the images of PTS and SEM, and mechanism of the consolidation process based on the depositing process and post-depositional processes. The development-levels of microstructure of the argillaceous sediments in each facies are interpreted by a combination of the geotechnical and consolidation properties, ^{14}C age, and analysis on the PTS and SEM images (Figs. 5.13 and 5.14). We can directly observe the development-levels of microstructure of the MD late Pleistocene-Holocene sediments on the PTS and SEM images in Figs. 5.13 and 5.14. The development-levels of microstructure of the argillaceous sediments in each facies are summarised in Tab. 5.6. The development-levels of microstructure of the MD late Pleistocene-Holocene sediments can be divided into three main broad cases. These three cases correspond to

three broad soil layers. The general soil profile simplified in Fig. 5.12 includes three main broad soil layers with isochrones. Three main broad soil layers are surface sediment facies, shallow sediment facies, and deep sediment facies. The characteristics of consolidation of the each case in the simplified profile in Fig. 5.12 are presented as follows.

5.4.2.1. Surface sediment facies

Case 1 includes natural levee, flood plain, intertidal flat, and sub- to intertidal flat facies.

a. Natural levee facies

For the natural levee facies at the Caolanh site, the OCR values are notably large, from 6.1 to 2.2 and the largest in comparison with those of the all facies (Fig. 5.11.1.1 and Tab.5.5).

The values of I_{vo} of the natural levee sediment of the CLM1 core lie well below the corresponding ICL, around and so less than zero despite the notably small values of σ'_{vo} : 30 to 40 kPa (Tab. 5.2 and Fig. 5.8). Because, the natural levee sediment with oxidization & dehydration by the solar energy and air exposure, in situ void ratios, e_o , become small. In addition, when reconstituting specimen was prepared to mix water resulting in expanded material, which result in relatively large (e^*_{100} - e^*_{1000}). Then I_{vo} from equation (3.9) locates below ICL. All indicate the natural levee sediment is compact. The e - $\log \sigma'_v$ cures on the undisturbed soil specimens are compared with those of reconstituted soil specimens at $z = 0.98$ and 0.93 m on the natural levee facies of the CLM1 core from the IL and CRS tests (Fig. 5.6.4a). They have a remarkable characteristic is the e - $\log \sigma'_v$ cures on the undisturbed soil specimens (at $z = 0.98$ and 0.93 m) quite lie under those of reconstituted soil specimens. And then, they together converge at the late part with large vertical effective stress (Fig. 5.6.4a). The slopes of the parts after the yield stress point on the e - $\log \sigma'_v$ cures are smaller than those on all of the other sedimentary facies (Figs. 5.4 and 5.6). This means that the values of the compression indexes, C_c , on the natural levee sediment are less than those on the underlying sediments (Table 5.3).

A reason of this matter is the location of the natural levee facies which lies just on the top of the ground, none of overburdened soil layer. We consider the depositing process and post-depositional process: In the flood season (the rainy season) the water level rose highly and overflowed the banks of rivers. Simultaneously, the materials settled on the area around the banks and created the top sediment layer. The materials with large sizes and specific gravity

often settled down at there. So, the quartz fragments (Q) with large sizes and the illite content in the natural levee sediment are plentiful than those of the march/flood plain facies; we can see them in Figs. 5.13a-b and Tab. 4.4. During a long time (about 6 months) of the dry season in the tropical area, the groundwater level was approximately -0.76 m (Nguyen, N. T., 1990). At the same time, the top sediment layer perfectly lay above the surface water level. And then, dehydrating and shrinking processes occurred in the top sediment by contacting with the solar energy and air and the Fe_2O_3 was produced such as the above presentation in item 5.2.2.7).

The formation-cycle of the iron oxides and sediments would continuously occur every year and produced the natural levee facies. These iron oxides existed in the formation as discrete particles (Fig. 4.4L). The trivalent iron oxides also enclosed and bonded the soil minerals and quartz particles, and are counted an iron-cement (Figs. 5.13a-b and 5.14a). As a result, values of swell sensitivities (C_s^*/C_s) are large, from 0.48 to 0.6 (Tab. 5.3); they indicate the bonds in the natural levee sediments are so steady. The petrography-images in the thin section of the natural level sediment were dyed in the blue color (Fig. 5.13b), the blue color is light and the distribution is thinly populated in the sediment sample on the petrography-images. It shows that the density and size of space pores are small and the smallest in comparison with those the other facies (Fig. 5.13). The initial void ratio, e_0 , is so small, 0.838, shown in Tab. 5.6. Simultaneously, values of liquidity indexes, LI, are so small and lower than those of the other facies except the marsh/tidal flat facies of the Caolanh site and the estuary channel facies of the Vinhlong site (Figs. 4.36f and 4.40f). This is a reason why values of I_{v0} of the natural levee sediment of the Caolanh site lower than the ICL despite the very small effective vertical overburdened stress (from 30 to 40 kPa) (Tab. 5.2 and Fig. 5.8). And the $e\text{-log}\sigma'_v$ curves of the natural levee sediment lie below those of the flood plain sediment (Fig. 5.15). Consequently, the consolidation of the natural-levee sediment was a special consolidation process that was not caused by the gravitational compaction. This consolidation process resulted in the unusual geotechnical properties; the OCRs are the greatest in comparison with the other facies and the values of S_u , q_t , f_s , and N are higher than those of the underlying sediment facies (Figs. 5.11.1-2, 4.20 and 5.1).

Typically, the values of OCR (Fig. 5.11.1), stiff state, and reddish and yellowish brown color of the natural levee sediments gradually decrease from the upper part to the lower part of the natural levee facies on the CLM1 core. From these above analyses, it can say that the development-level of microstructure of the natural levee sediments is high to so high. Hence,

values of k should be 0.5 to 0.35 for calculating OCRs from CPTU in Equation (3.4) shown in Tab. 5.6. And values of k should choose in the gradual decrease from the upper part to the lower part of the natural levee facies. These OCRs from the CPTU results estimated by the k inferred-values are highly agreed with those from the CRS results in comparison with those by k values from $k = 0.5$, and $k = 0.35$, for the natural levee sediments of the CLM1 site from -0.5 to +2.9 m (Fig. 5.9).

Please, permit me to display that all the values of OCR from CPTU results presented in the above Fig. 5.11.1-2 were estimated by the k inferred-values in these discussions.

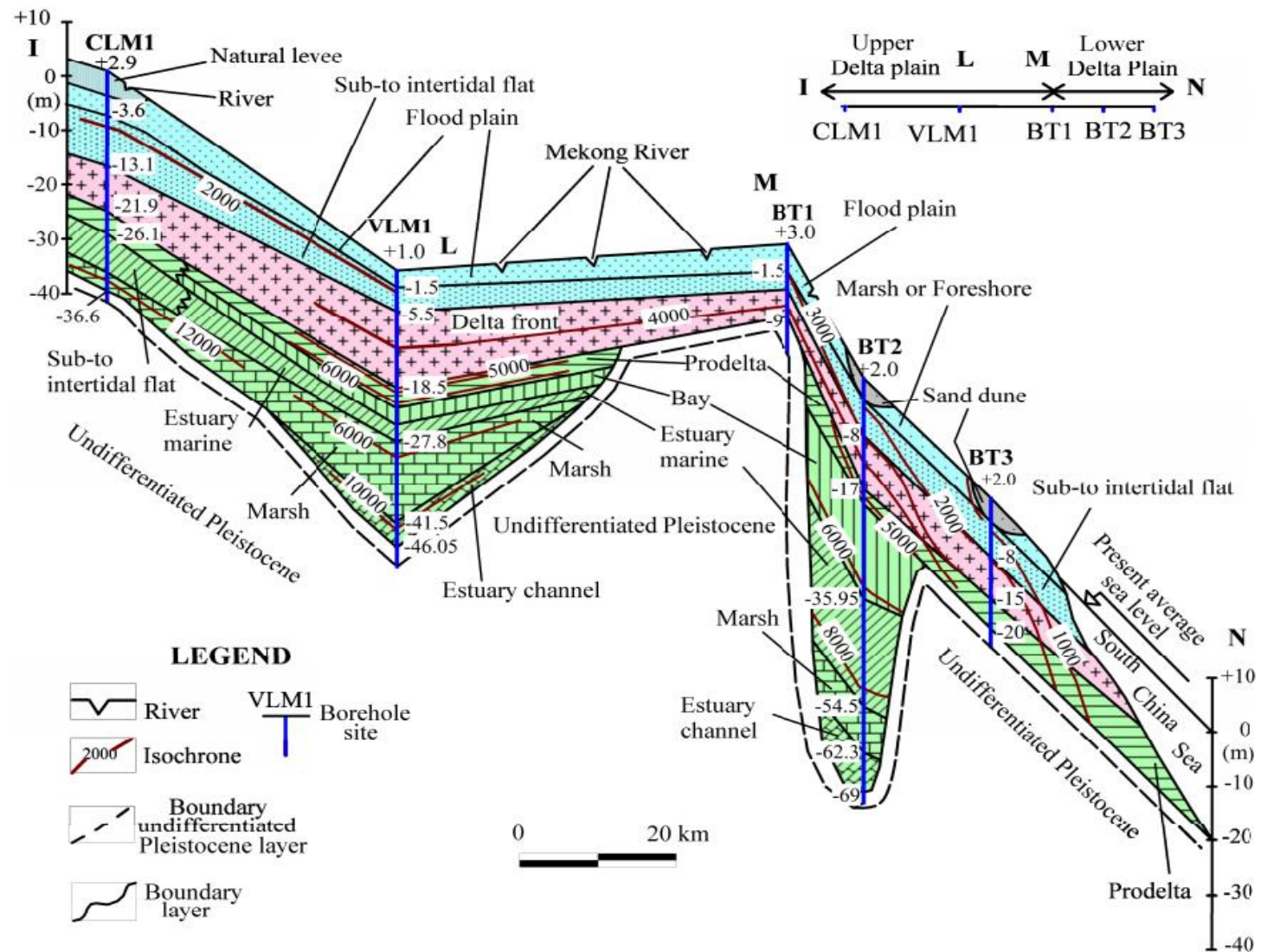


Fig. 5.12. Simplified geotechnical profile with three main broad soil layers on the plan layout of the core sites in Fig. 3.1.

Table 5.5.

Values of k and OCR by the CPTU at the Caolanh, Vinhlong, Bentre-1, Bentre-2, and Bentre-3 sites.

		Information of sites Facies	Upper delta			Lower delta				Values of k for calculating OCR by CPTU		
			CLM1	VLM1		BT1	BT2			BT3	Upper delta	Lower delta
				CPTU1-VL	CPTU2-VL	CPTU1-BT1	CPTU1-BT2	CPTU2-BT2	CPTU3-BT2	CPTU1-BT3		
Late Pleistocene-Holocene sediments	Surface sediments	Natural levee	6.1 - 2.2								0.5 to 0.35	
		Beach ridge/marsh						1.74 - 1				0.25 to 0.2
		Marsh/flood plain	2.7 - 1.4	1.45 - 1.46		4.3 - 1.3					0.35 to 0.2	
		Sub- to intertidal flat/intertidal flat	2.1 - 1	1.95 - 1.58	2.2 - 1.47	1.8 - 1.1	2.1 - 1	1.97 - 1	2.08 - 1.22	3.1 - 1	0.35 to 0.2	0.25 to 0.2
	Shallow	Delta front	1.7 - 1	1.9 - 1	1.95 - 1	1.9 - 1	1.6 - 1	1.86 - 1	2.1 - 1	2.1 - 1.1	0.3 to 0.2	0.2
	Deep sediments	Prodelta	2.3 - 1	1.63 - 1.28	1.92 - 1.29		1.4 - 1	2.12 - 1.28	1.76 - 1.41	2.6 - 1.3	0.4 to 0.3	0.3
		Bay		1.44 - 1.17			1.8 - 1.1	1.86 - 1.37	1.93 - 1.49		0.4 to 0.3	0.3
		Estuary/ sub-to intertidal flat	2.1 - 1.1	1.87 - 1.14							0.45 to 0.4	
		Marsh/tidal	2.7 - 5.2	1.98 - 1.39							0.4 to 0.45	
		Estuary channel		5.7 - 1.77							0.45 to 0.5	

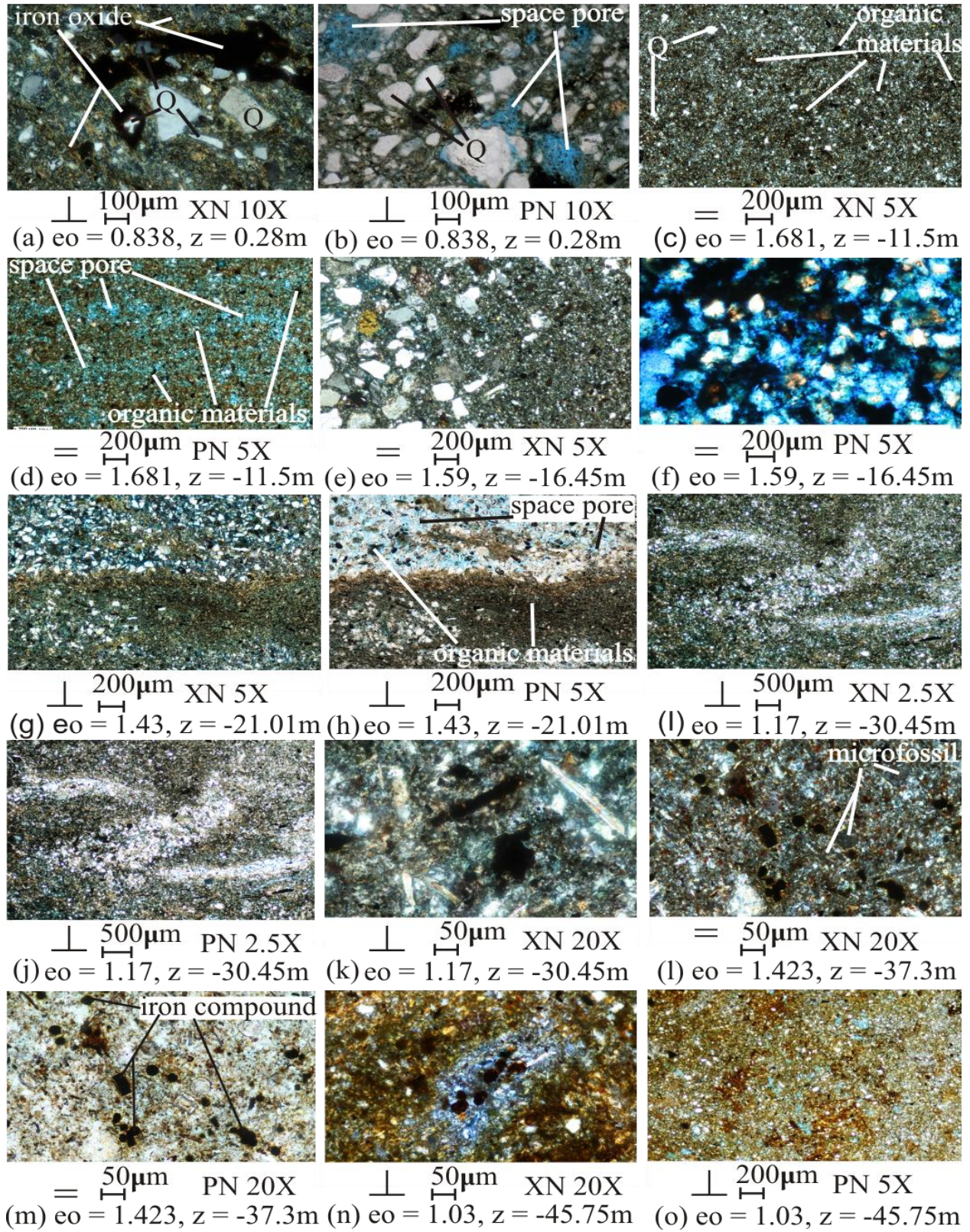


Fig. 5.13. Selected petrography-images in thin sections of Caolanh core: **a, & b**) clay-specimens in the natural levee facies, iron and calcium cements significantly joined in bond. Large angular

quartz fragments (Q) obtained 0.35 mm length and distributed chaotically and plentifully; Q were completely enclosed by iron oxide. Density of space pores is so small. Sizes of space pores are general small through blue color. Other images of Vinhlong core: **c & d**) in the delta front, Q with even sizes, and organic materials are plentiful with general greenish gray and black joining in bond, e_0 increased highly; **e & f**) in the delta front, contiguous zone between sandy and clayey parts; **g & h**) in prodelta, clayey seams plainly divided, e_0 decreased. **i, j & k**) in marsh, clayey seams and hydromica sticks arranged clearly parallel together, the matrix between the sand grains contains opaque iron oxide and calcites, e_0 significantly decreased; **l & m**) in marsh, calcite, iron compound and diatoms are plentiful, but e_0 unusually increase; **n, o**) in estuary channel, iron cements and pyrites and calcites abundantly crystallized, e_0 and size of e_0 decreased, well compacted.

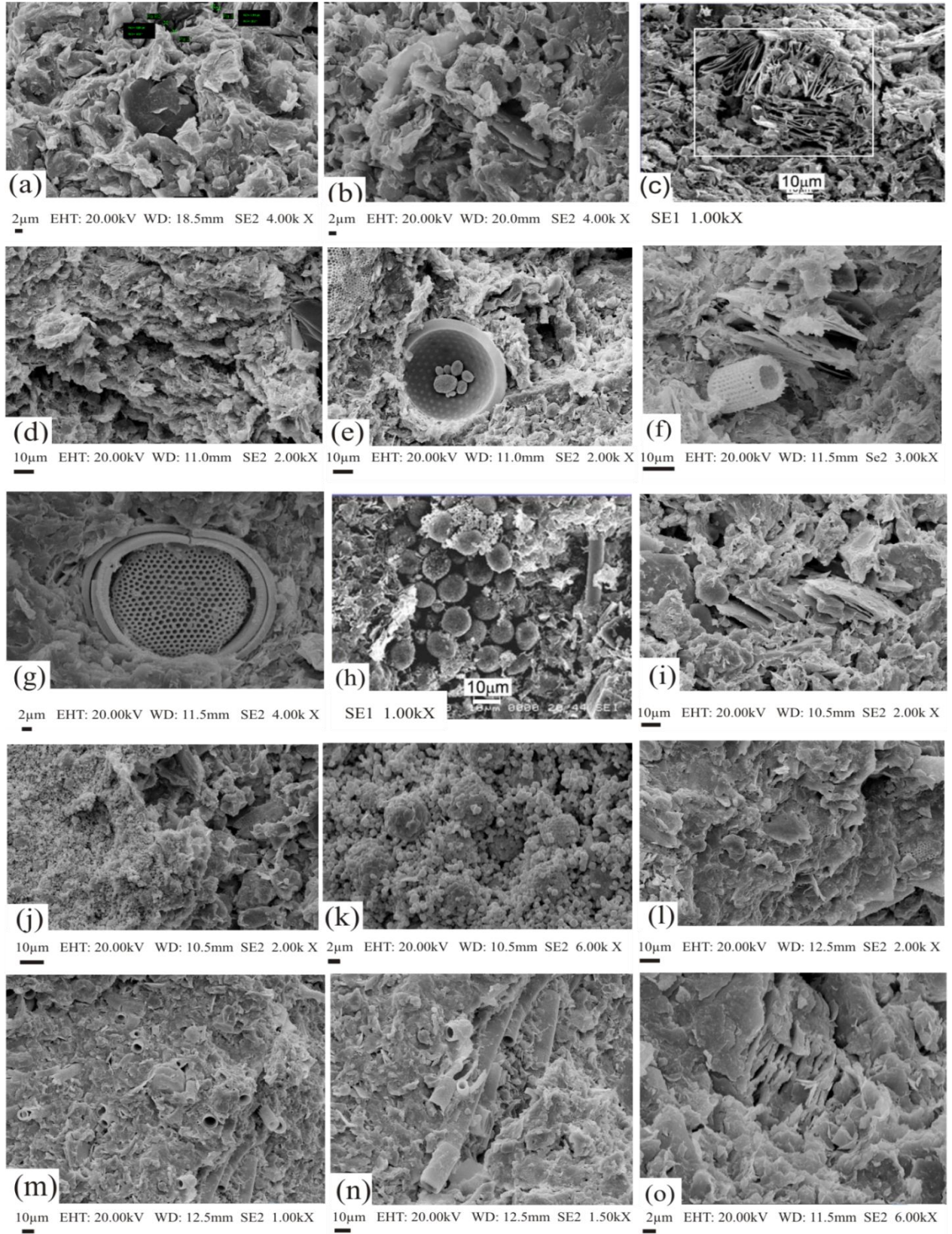


Fig. 5.14. Selected SEM images of Caolanh core: a) in natural levee $z = 0.28\text{m}$, clay-minerals

arranged chaotically, clay particles aggregated and generally bond well, sizes and density of space pores are so small; **b)** in flood $z = -4.81$ m, clay-minerals arranged chaotically, clay particles aggregated, sizes of space pores are greater than those of the natural levee sediment. Cantho core: **c)** in delta front at $z = -11.1$ m (Takemura et al., 2007), salt flocculation and large space pore, clay particles weakly bond. Vinhlong core: **d)** in prodelta $z = -21.01$ m, clays arrange in parallel seams; **e, f, & g)** in prodelta $z = -21.01$ m, shapes of the diatoms are petri dish and tubular, pyrites crystallized in space pore of the petri dish diatom, the matrix of fine clay-particles around the diatoms is not well compacted. Cantho site: **h)** in open bay $z = -20.1$ m (Takemura et al., 2007), pyrite-sizes are greater than those of delta front sediment and more plentiful than, petri dish diatom fragments. Vinhlong core: **i, j & k)** in marsh $z = -30.45$ m, clays clearly arranged in seams, pyrites plentifully crystallized, sizes of space pore decreased; **l, m & n)** in marsh $z = -37.3$ m, clays so clearly arranged parallel, tubular diatoms are extremely plentiful, the matrix around the tubular diatoms is quite compacted, but the clear open cycles of the tubular diatoms are large with $10 \mu\text{m}$ in diameter and $150 \mu\text{m}$ on the exposed surface; **o)** in estuary channel $z = -45.75$ m, clays with large sizes arranged parallel, sizes of space pore decreased, and well compacted.

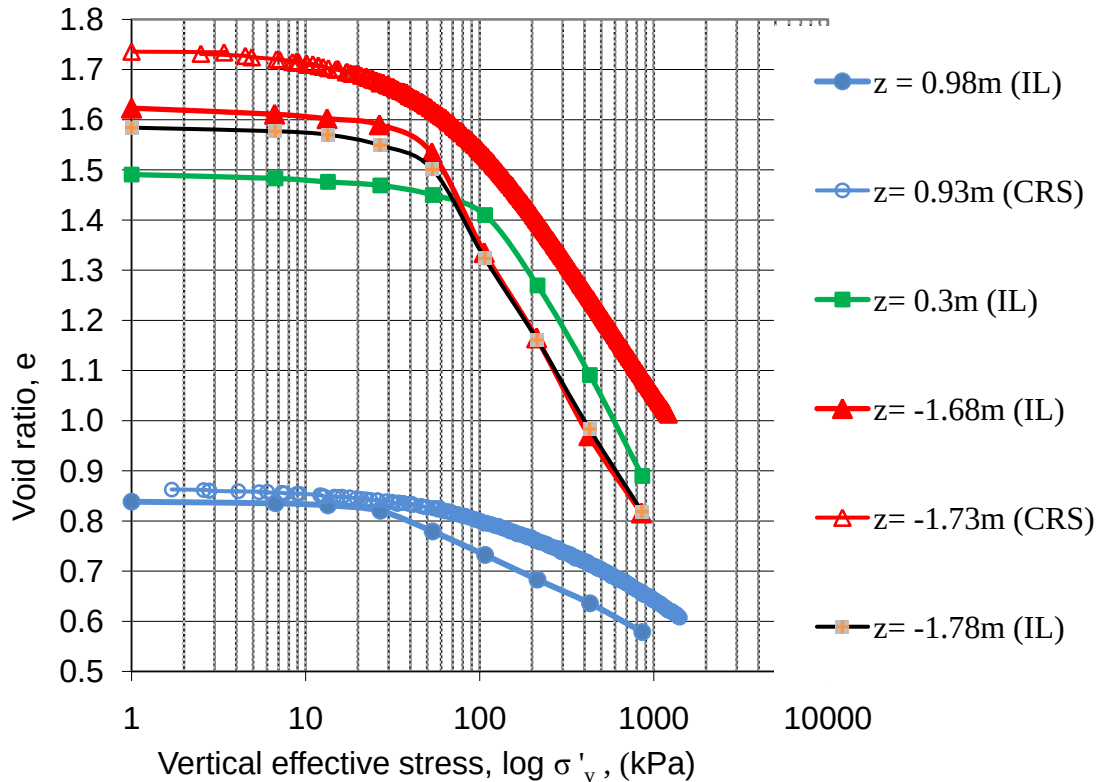


Fig. 5.15. Comparison of curves of e - $\log \sigma'_v$ given by IL and CRS tests on undisturbed cohesive soil specimens of natural levee facies ($z = 0.98$ m, 0.93 m, & 0.3 m) with those of flood plain facies ($z = -1.68$ m, -1.73 m, & -1.78 m) of CLM1 core.

Table 5.6.

To interpret development-levels of microstructure of facies' argillaceous sediments based on a combination of the consolidated properties, ^{14}C age, and analysis on PTS and SEM in Figs. 4.6, and 4.7 of CLM1, VLM1, and CTM1a cores. Values of k suggested for calculating OCR from CPTU

Facies	Petrography-images in thin section (PTS)		Scanning electron micrograph (SEM)		^{14}C age (yr BP)		Initial void ratio, e_0	Development -level of micro-structure: bonding, aging, and crystallizing	k suggested for calculating OCR, CPTU
	Fig.	Note	Fig.	Note	Upper delta plain *	Lower delta plain **			
Natural levee	4.6. .a .b	Iron and calcium cements significantly joined in bond. Large angular quartz fragments (Q) obtained 0.35 mm length and distributed chaotically and plentifully; Q were completely enclosed by iron oxide. Density of space pores is so small. Sizes of space pores are general small through blue colour.	4.7. .a	Clay-minerals arranged chaotically. Clay particles aggregated and generally bond well. Sizes and density of space pores are so small.	less than 3,000		0.838	High to so high	0.5 to 0.35
Flood/Beach ridge, Marsh or Foreshore			.b	Clay-minerals arranged chaotically. Clay particles aggregated.	around 3,425	less 2,500	1.1-1.62	Medium to high	*: 0.35 to 0.2 **: 0.25-0.2
Delta-front	.c .d .e .f	Q with silty- to sandy-sizes and organic materials are plentiful. The organic materials with black color joined in the bond between soil particles. Density and sizes of space pore increased highly.	.c	Salt flocculation or called flocculent structures. Sizes and density of space pore are so large.	4,000 to 7,000	less 4,000	1.2-1.9	Low to medium	*: 0.3 to 0.2 **: 0.2
Prodelta	.g .h	Clayey and silty seams plainly divided Density and sizes of space pore decreased with light blue under PN. Organic materials are plentiful in greenish gray and black.	.d .e .f .g	Clayey seams so plainly divided. Pyrites crystallized in space pore of diatom. Marine microfossils are very plentiful.	5,000 to 8,880	5,000 to 2,500	1.43	Medium to high	*: 0.4 to 0.3 **: 0.3
Bay			.h	Pyrites strongly crystallized with big sizes	5,658 to 8,880	less 5,658	1.1-1.33	Medium to high	*: 0.4 to 0.3 **: 0.3
Marsh/tidal flat	.i .j .k .l .m	Clayey seams and hydromica sticks arranged clearly parallel together. The matrix between the sand grains contains opaque iron oxide and calcites. Density and sizes of space pore strongly decreased at -30.45m. At -37.3m, calcite, iron compound and microfossil are plentiful.	.i .j .k .l .m .n	Clay clearly arranged parallel with big sizes and formed parallel seams. Pyrites so strongly crystallized. Microfossils are extremely plentiful. Density and sizes of space pore decreased at -30.45m, but at -37.3m they unusually increase by the microfossils.	8,880 to 13,258		1.17 and 1.423	High to so high	0.4 to 0.45
Estuary channel	.n .o	Iron cements and calcite strong developed. Density and sizes of space pore significantly decreased.	.o	Clays with large sizes arranged parallel. Density and sizes of space pore decreased.	more than 9,910		1.03	So high	0.45 to 0.5

b. Flood plain facies

A formation-mechanism of the flood plain sediment is similar with those of the natural levee sediment, but the positions of the flood plain facies were farther than those of the natural levee facies from the waterways (Fig. 3.1). So, the grain sizes and illite content of the flood plain sediment are often smaller than those of the natural levee sediment. The altitudes of the flood plain are lower than those of the natural levees, and the flood plain sediment is always so close to the ground water table. The carbon with very small sizes dispersed a clay-water suspension in the sedimentary process; these carbons joined to form cements within bonding between particles. This is also one of the causes lead the sediments in the case 1 are often dark or greenish dark color.

c. Intertidal flat facies and sub- to intertidal flat facies

For the intertidal flat facies and sub- to intertidal flat facies, when the tide went up, materials were settling down; these materials became the initial sediment seam. And then, when the tide went down, this sediment seam directly contacted with sunshine and air. Simultaneously, the lightly oxidizing and dehydrating processes would occur in the initial sedimentary seam. The cycle would continue per day and formed the sub- to inter-tidal or intertidal facies.

Values of swell sensitivities (C_s^*/C_s) on the flood plain, intertidal flat, and sub- to intertidal flat sediments in both Caolanh and Vinhlong cores are large, from 0.44 to 0.8 (Tab. 5.3). They indicate the bonds in the sediments are relatively steady. The sediments are somewhat overconsolidation (Tab.5.5). From the analyses, the development-levels of microstructure in the flood plain, intertidal flat, and sub- to intertidal flat sediments are medium to high. As presenting in sections 4.4, there are differences about the source of material supply, tidal influence, and age between the upper delta plain and lower delta plain. The illite contents in the upper delta plain are higher than those in the lower delta plain; the specific gravity of the illite mineral is higher than the others. The sizes of particles of the sediments in the upper delta plain are slightly greater than those in the lower delta plain. The ages of sediments in the upper delta plain are also higher than those in the lower delta plain. Therefore, the development-levels of microstructure of the sediments in the upper delta plain are higher than those in the lower delta plain. So, how to select values of k for calculating OCRs in Eq. (3.4) for each sedimentary facies is also divided two

different ways. The values of k for sedimentary facies in the upper delta plain will be higher than those in the lower delta plain. For the flood plain, intertidal flat, and sub- to intertidal flat sediments, values of k should be 0.35-0.2 around CLM1 and VLM1 core sites in the upper delta plain. And values of k should be 0.25 to 0.2 around BT1, BT2, and BT3 core sites in the lower delta plain (Tab. 5.6). These OCRs from the CPTU results estimated by the k inferred-values are equal to those from the CRS and IL results in comparison with those by k values in the lower limit, $k = 0.2$, and the upper limit, $k = 0.35$, for the flood plain, intertidal flat, sub- to intertidal flat sediments of the CLM1 from -13.1 to -0.5 m and VLM1 sites from -5.5 to -1.5 m (Fig. 5.9 & Fig. 5.10).

5.4.2.2. Shallow sediment facies

Case 2, the delta front facies with alternation of clay-seams and sandy seams was created in the marine environment with high energy as above presentation. The alternation of clay-seams and sandy seams in the inhomogeneous delta front facies can be called “alternate-structure”. We can realize that a salt flocculation structure with the particle-orientation in a high parallelism on the SEM image of the Cantho delta front clay at $z = -11.1$ m taken by Takemura et al. (2007) in Fig. 5.14c. Sizes and density of space pore are large that we can see through the blue color by dyeing in the Petrography-images in thin sections (PTS) shown in Figs. 5.13c, e, and f. These sizes and density of space pore are also directly seen in the SEM image (Fig. 5.14c). The initial void ratios, e_0 , are from 1.2 to 1.9 (Tab. 5.6). In truth, according to Braja (1998) for the sediments in this salt flocculation structure, they are somewhat overconsolidated. Therefore, the values of OCRs from results of the IL, CRS, and CPTU tests of delta front sediments at the VLM1, CLM1, BT1, BT2, and BT3 core sites are somewhat greater than one shown in Figs. 5.11.1-2 and 5.12. Simultaneously, the shape of the e - $\log \sigma'_v$ curves from the results of the IL and CRS tests has a characteristic of the curve of clay in the flocculent structure; the lower part of the e - $\log \sigma'_v$ curves (behind curvature-point) is with large concave-level. These e - $\log \sigma'_v$ curves were called the S-shape curves with clear bent by Takemura et al. (2007). For examples, the e - $\log \sigma'_v$ curves at $z = -9.76$ m, -9.74 m, -9.59 m, and -6.35 m of the VLM1 core are shown in Fig. 5.16. The influence of the alternate-structure is significant for draining water of the cohesive soil seams during the consolidation tests. In the results of the CPTU and IL tests, the time for 50%

pore water pressure dissipation is small on the delta front cohesive soils at the investigative sites

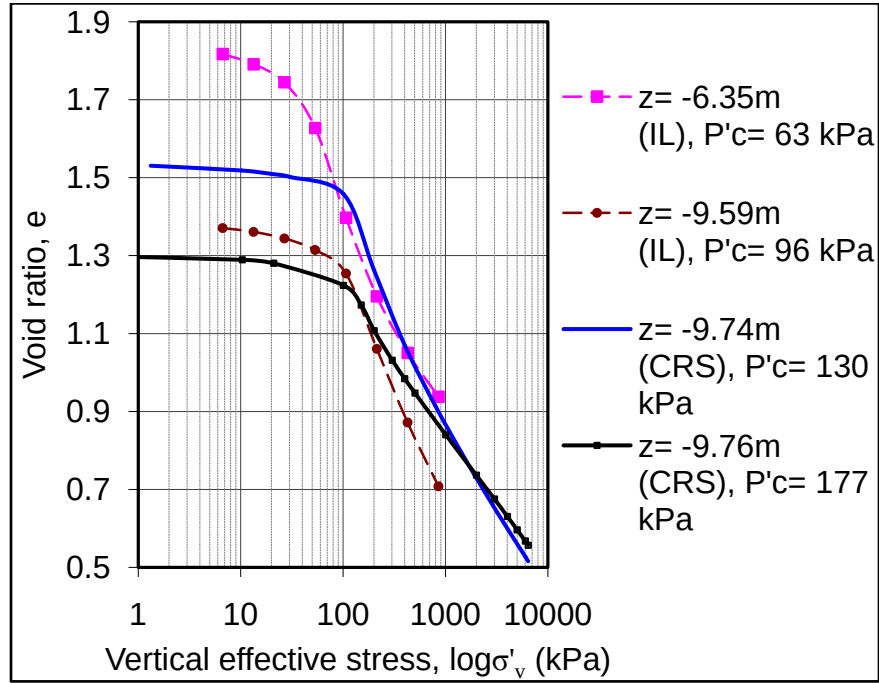


Fig. 5.16. S-shape of $e\text{-}\log \sigma'_v$ curves from the IL and CRS tests with characteristic of curve of clay in the flocculent structure at $z = - 9.76\text{ m}$, -9.74 m , -9.59 m , and -6.35 m of VLM1 core.

(Tab. 5.4). At same position in the cohesive soil of the delta front facies, the coefficients of consolidation in horizontal direction, c_h , are greater many times than the coefficients of consolidation in vertical direction, c_v , from the CPTU and IL results (Tab. 5.4). As shown in Fig.5.16, the shape of the compression curves, initial void ratios and yield stresses change significantly with depths. The void indices, I_{v0} , are plotted against the logarithm of in situ effective overburden stress in Tab. 5.2 and Fig.5.8, together with data on Cantho cohesive and Tanan cohesive soils (Takemura et al, 2007). The I_{v0} values on the delta front cohesive soils at the Vinhlong (from 0.51 to 3.06 in Tab. 5.2) and Cantho sites (Takemura et al., 2007) largely varied and laid well above the Sedimentary Compression Line, SCL, (Burland, 1990) (Fig. 5.8). Conversely, for the homogenous cohesion soils in the other facies, the I_{v0} values are close to or below the SCL for the most of the plots (Fig. 5.8). The cohesive soils in the delta front facies (Unit 6) of the Vinhlong site are somewhat overconsolidated, though their ages are less than 4,560 yr BP. These results show the development-level of microstructure during the post-

depositional processes depends on sedimentary structures and materials. It is possible to measure the sedimentary conditions of natural cohesive soils in MRD using I_{v0} values, as long as the test

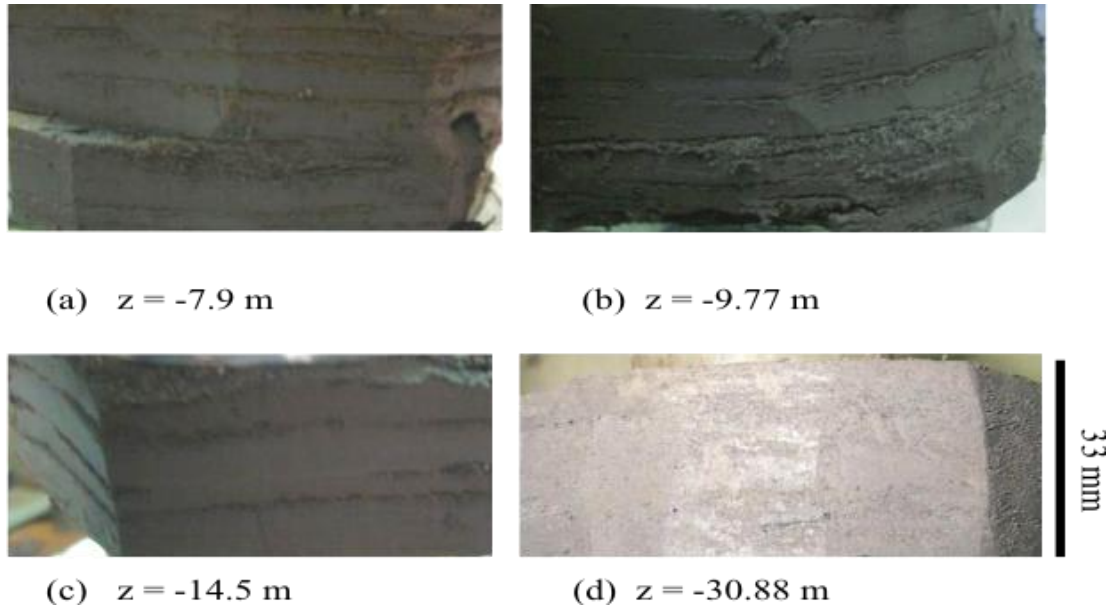


Fig. 5.17. Observed cross section of test specimens for oedometer and CRS tests.

specimen is homogeneous, as shown in Figs. 5.17a, c, and d. judging from Fig. 5.8, it can be said that the microstructure or fabric of Mekong delta soils is typical of that of relatively young natural deposits. However, some of the observed I_{v0} values are well above SCL for some samples in the delta front-mouth bar facies; this is attributed to inhomogeneity of specimens with a number of thin sand seams (Fig. 5.17b). The sand in the thin layers becomes mixed with clay when the reconstituted sample is prepared, resulting in well-sorted material that may not represent intrinsic properties of the sample. Hence, $(e^*_{100} - e^*_{1000})$ become small, then I_{v0} as eq. (3.9) will be largely. There are some thin sand seams with different thicknesses & seam-amount in clay (Fig. 5.17). Difference of sand seams made initial void ratio, e_0 , and OCRs of specimens are different. Simultaneously, sand in thin seams mixed with clay when reconstituted specimen was prepared resulting in well-sorted material with different sand contents. It leads curves of $e - \log \sigma'_v$ on reconstituted specimens largely vary. Finally, curves of $e - \log \sigma'_v$ of undisturbed and reconstituted specimens of the delta front facies are very different (Fig. 5.4.4a & 5.4.5a), and I_{v0} largely vary (Tab. 5.2 and Fig. 5.8). This should be noted in the application of I_{v0} , as discussed

by Takemura et al. (2007) for Cantho and Tanan cohesive soils, similarly in the case of Atterberg limits.

The values of C_s^*/C_s of the delta front cohesive soil on the VLM1 core also vary largely from 0.19 to 0.82 shown in Tab. 5.3. It is also attributed to inhomogeneity of specimens with a number of thin sand seams of the delta front facies of the VLM1 core like above presented. For this reason, values of C_s^*/C_s are large, from 0.64 to 0.82 (Tab. 5.3). For the homogeneous specimens, values of C_s^*/C_s are small, from 0.19 to 0.29, and the smallest in comparison with the others (Tab. 5.3); these values just indicate the true level of bonding in the delta front cohesive specimens. This should be careful in the application of C_s^*/C_s for measuring the bonding-level of the cohesive soil of the delta front facies. These cases often occur in the delta front facies. Simultaneously, to carry out the UC test on the remolded specimens were so difficult; so, q_{ur} values are very low and sensitivities, S_t , are so high (Fig. 4.36h). Even, we cannot conduct the UC test for remolded specimens which the initial undisturbed specimens contained many thin sand seams. So, the sensitivities of delta front sediments are from medium to extra quick (Fig. 4.36h). Therefore, the soil samples may be easily disturbed by sampling, transporting, and preparing for tests. Especially, the soil samples may be broken at the sand seams. If the delta front soil samples are saved for a long time after the sampling and transportation to the lab, water in the sandy seams may easily go out of soil sample by the temperature difference and atmospheric pressure between the below condition and the above condition of the grown surface. These all are causes of change of OCRs differently with true values. The strange change of OCRs was commonly less than one as report of Man (2003).

The combination of all the analyses about the above results of the geotechnical properties, sedimentary geology, and microstructure through the PTS and SEM images, allows us to infer that the development-levels of microstructure of the delta front sediments are low to medium (Tab. 5.6). The microstructure-development of the delta front facies is lower than those of other facies. As a result, for the case 2, the delta front sediment in the lower delta plain (beach-ridge delta plain) with age less than 4 ka BP, k values should be 0.2 for calculating OCRs from CPTU test in Equation 3.4. For the delta front sediment in the upper delta plain with age 4 to 7 ka BP (Fig. 5.12), k should be 0.3 to 0.2 for calculating OCRs from CPTU test in Eq. 3.4 (Tab. 5.6). These OCRs from the CPTU results estimated by the k inferred-values are similar to those from

the CRS results in comparison with those by k values in the limit, $k = 0.2$, and the upper limit, $k = 0.3$, for the delta front sediments of the VLM1 site from -18.5 to 5.5 m (Fig. 5.10).

5.4.2.3. Deep sediment facies

Case 3 includes prodelta, bay, estuarine marine, sub- to intertidal flat, marsh, marsh/tidal flat, and estuary channel facies.

All facies except the estuarine marine and estuary channel facies were formed under relatively quiet hydrological conditions (low energy environments). They were created in the marine transgression, i.e. the salt water environment. This was a good condition for clay sediments to flock in the deposited process. The sedimentary facies in case 3 have been being at greater depth and forming in earlier stage than those of the sedimentary facies in case 1 and 2. An ageing strongly occurred in the case 3. The calcareous nodules and incipience plentifully presented in the facies of the case 3 with large size and obtained 3 cm in diameter (Fig. 4.2I) and they were also popular in other core sites of Ta et al. (2005) as in the above representation. The clay minerals and cohesive soil seams were arranged again that they became more parallel and closer together by the overburden pressure in the post-depositional processes (Figs. 5.13g, k, and 5.14d). The clay minerals in the prodelta sediments were arranged in the parallel seams shown in Fig. 5.14d. Simultaneously, the pyrites significantly recrystallized. Especially, the pyrites recrystallized inside the void pores of the petri dish diatom (Fig. 5.14e). The recrystallization of the pyrites tended to increase from the prodelta to marsh facies (in corresponding depth from -18.5 m to -41.5 m) that can be seen on the PTS and SEM images (Figs. 5.13g-o, and 5.14d-o). These features of recrystallization of the pyrites in the case 3 of the MRD late Pleistocene-Holocene sediments are similar with those of the Osaka Bay clay (in depth from -130 to -170.4 m) reported by Tanaka et al. (1999) (Figs. 5.18a-c). Values of C_s^*/C_s of the sedimentary facies in case 3 are so large, from 0.67 to 0.9 (Tab. 5.3); these values indicated the bonds in the sedimentary facies in case 3 are so steady. These values of C_s^*/C_s vary very small, they indicate that the sedimentary facies in case 3 except the estuarine marine facies are rather homogenous. Values of C_s^*/C_s of the estuary channel sediments in the range of -44 to -41.35 m with plentiful organic materials decrease; namely, values of C_s^*/C_s of the specimen at $z = -41.52$ m is 0.67 (Tab. 5.3). The bonding- and compacting-levels in the sediments in case 3 increased from the prodelta

to estuary channel; especially, for the marsh and estuary sediments, can be clearly seen in Figs. 5.13g-o and 5.14d-o. All results show that the structure-development-levels of the sedimentary facies in case 3 are from medium to so high and are presented in Tab. 5.6. The cohesive soils in the sedimentary facies of the case 3 are slight overconsolidation to overconsolidation. The OCR values from the CRS test are nearly equal with those from the CPTU test with k inferred-values from -18.5 to -47.8 m the VLM1 core in Fig. 5.10. Values of k for calculating OCR for each specific sediment facies of case 3 are represented such as:

For the prodelta and bay facies of case 3 in the upper delta plain as at the Caolanh and Vinhlong sites (Figs. 3.1 and 5.12), values of k should be 0.4-0.3 for calculating OCR in Equation 3.4 (Tab. 5.5). For the prodelta and bay facies in the lower delta plain as at the Bentre-1, Bentre-2, and Bentre-3 sites (Figs. 3.1 and 5.12), values of k should be 0.3 for calculating OCR in Equation 3.4 (Tab. 5.6).

The marsh and marsh/tidal flat facies have been at the great depth and great age from 8.88 to 13.258 ka BP as the Caolanh, Vinhlong, and Bentre-2 sites (Fig. 5.12). The recrystallizations of pyrites and hydromicas in the marsh and marsh/tidal flat sediments are so high (Fig. 5.13k). These results allow us to infer the microstructure-development in the marsh and marsh/tidal flat sediments is from high to so high. Hence, values of k should be 0.4 to 0.45 for calculating OCRs in Eq. 3.4 (Tab. 5.6).

For the estuary channel sediments at the VLM1 core site, values of k should be 0.5 to 0.45 (Tab. 5.6) because they have been existing at the greatest depth and with age being more than 9,910 yr BP. The pyrites and calcites in the estuary channel sediments abundantly crystallized (Fig. 5.13n). The estuary channel sediments are well compacted (Fig. 5.14o). The iron cements with reddish brown to dark color distribute throughout in the sediment (Figs. 5.13n-o), it indicate that the bonds well develop.

One interesting point, during observing the sediments of case 3 under the electron microscope, to surprisedly see *diatoms* with large void pores joined significantly in the microstructure in the prodelta, bay, and marsh sediments. The shapes of the diatoms found are general petri dish and tubular (Figs. 5.14e-n). The tubular diatoms in the marsh sediment are plentiful (Figs. 5.14m-n). The tubular diatoms in the MRD late Pleistocene-Holocene sediments are more plentiful than those of the Osaka Bay sediments (Tanaka et al., 1999) but the petri dish

diatoms are lower than (Figs. 5.14e-n and 5.18d-e). In the MRD, the clay matrixes around the diatoms in the prodelta and bay sediments (Figs. 5.14e-h) were compacted lower than those of the marsh sediment (Figs. 5.14m-n). The diatoms in the MD late Pleistocene-Holocene sediments were compacted lower than those of the Osaka Bay sediments. The pore spaces and shapes of diatoms in the MD late Pleistocene-Holocene sediments have not yet changed (Figs. 5.14e-n). Conversely, the pore spaces and shapes of the diatom in the Osaka Bay sediments fully filled by pyrite and have changed (Figs. 5.18c, and 5.18f-g) (Tanaka et al., 1999).

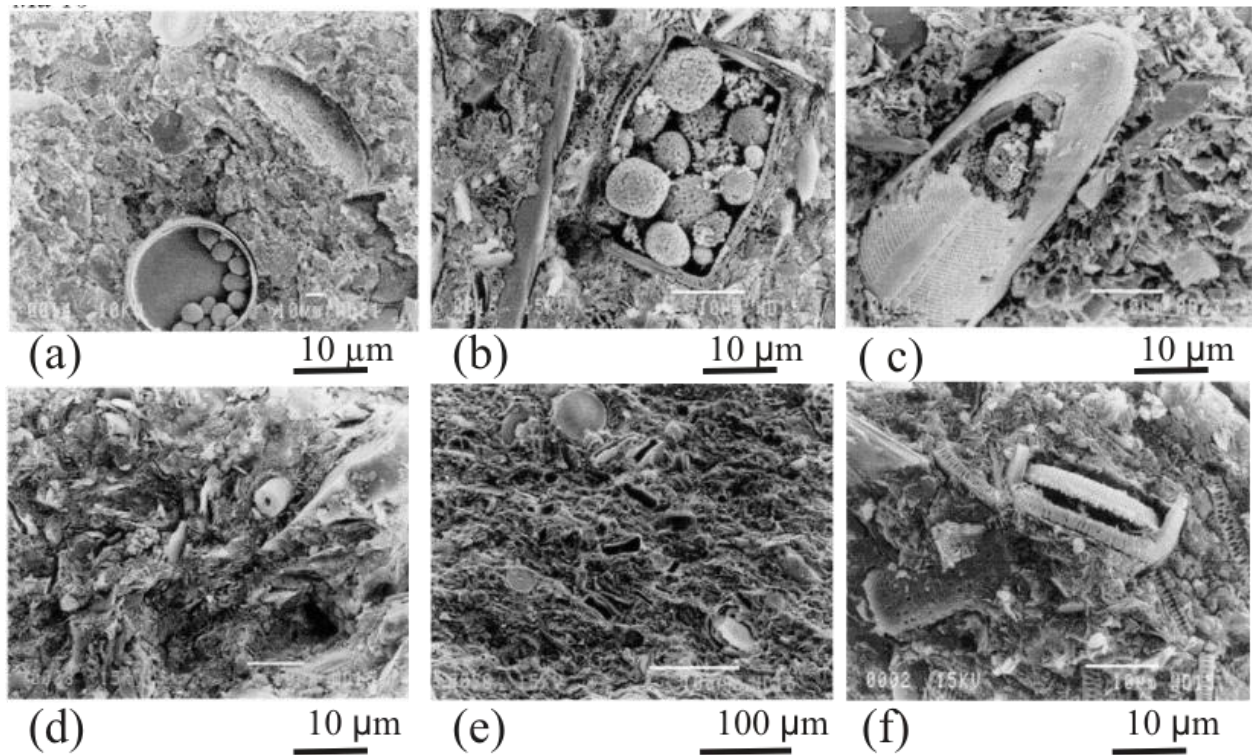


Fig. 5.18. SEMs of Osaka Bay clay: **a)** Marine clay $z = -144.1$ m, petri dish diatom contains some framboidal pyrite particles and compacted aggregates; **b)** Marine clay $z = -162.2$ m, framboidal pyrites particles increase in amount and size, the pore spaces and shape of diatoms have changed; **c)** Marine clay $z = -164.4$ m, diatom fills with framboidal pyrite particles and aggregated structure; **d)** Marine clay $z = -274.8$ m, compacted microfabric with clay particles moulding microfossil elements, tubular diatom; **e)** Marine clay $z = -383.7$ m, petri dish diatom cover about 1/3 of the exposed surface, no pyrite filling the pore space, clay matrix is so compressed and pore space has vanished, shape and pore space of petri dish have been changing; **f)** Diluvial clay $z = -181.4$ m, shape and pore space of petri dish diatom have been changing, no pyrite filling the pore space, clay matrix is so compressed and pore space has vanished, and

abundant microfossil fragments, oriented by Tanaka et al. (1999) and Locat et al. (2001).

Because, the MD late Pleistocene-Holocene sediments (from -18.5 to -41.5 m in depth) are under an effective overburden pressure less than those of the Osaka Bay sediments (from -70.7 to -383.7 m in depth) (Tanaka et al., 1999). The sizes of tubular diatoms are large; the clear open cycles of the tubular diatoms are 10 μm in diameter and 150 μm in length on the exposed surface of the MRD late Pleistocene-Holocene sediments (Figs.5.14n). The open cycles of the tubular diatoms have still opened clearly.

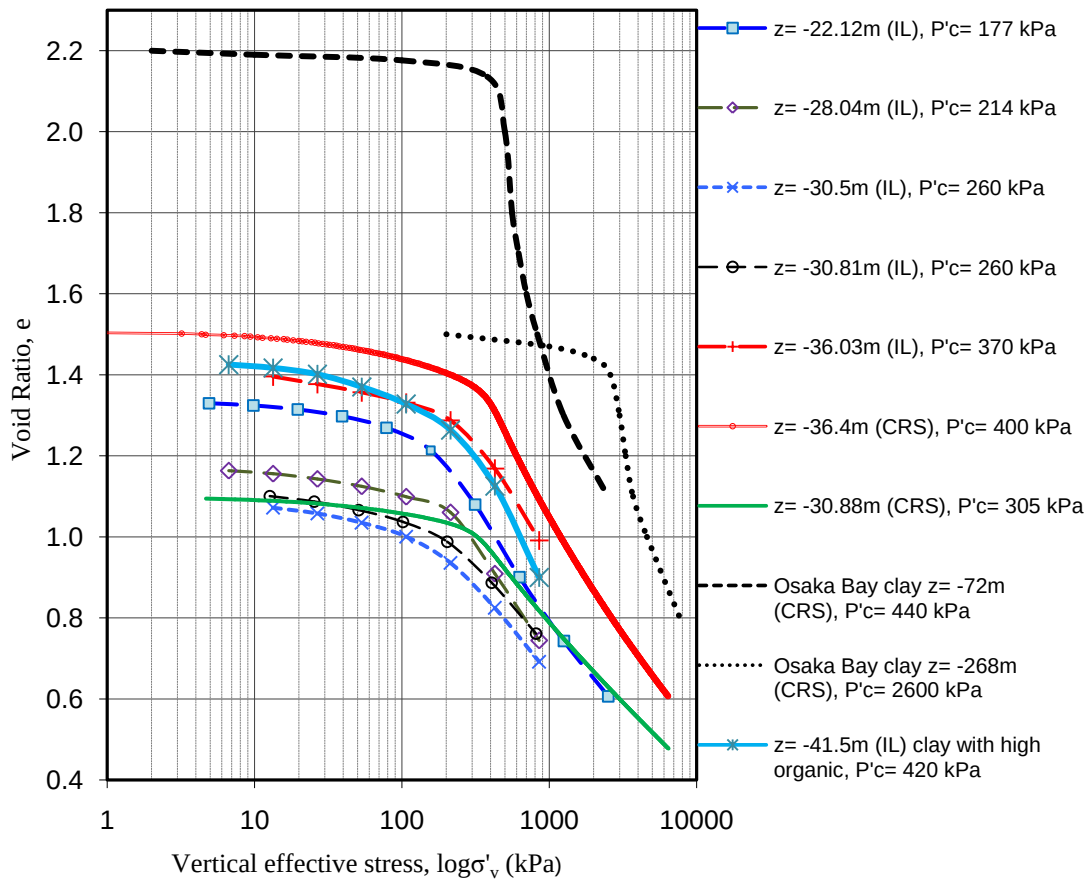


Fig. 5.19. Compression curves, $e - \log \sigma'_v$ relationship, and yield stresses (P'_c) obtained from IL loading oedometer tests and CRS tests for cohesive soils of case 3 of VLM1 core contained microfossils and high organic material, data of Osaka Bay cohesive soils (Tanaka et al., 1999).

Specially, the tubular diatoms in the marsh sediment in the part from -33 to -41.5 m in the VLM1 core are so plentiful, about 1/3 of the exposed surface (Figs. 5.14m-n). These tubular diatoms

made the void ratio of the marsh sediment in the part from -33 to -41.5 m amazingly increased. They are cause: The $e\text{-log}\sigma'_v$ curves of the specimens in the part from -33 to -41.5 m of the marsh facies lie well above those of the specimens in the part from -27.8 to -33 m of the marsh facies (Fig. 5.19). Even, the $e\text{-log}\sigma'_v$ curves of the specimens in the part from -33 to -41.5 m of the marsh sediment lie well above those of the specimen at -22.12 m of the bay sediment of the VLM1 core (Fig. 5.19). Whereas: The yield stresses of the sediments in case 3 still increased with the depth (Fig. 4.36i). Namely, the yield stresses of the specimens in the part from -33 to -41.5 m of the marsh facies are greater than those of the specimens in the part from -27.8 to -33 m of the marsh facies and of the specimen at -22.12 m of the bay facies of the VLM1 core (Fig. 4.36i). And the bond, C_s^*/C_s , of the specimens in the part from -33 to -41.5 m of the marsh facies is still large (Tab. 5.3). Hence, the microfossils are also a deep cause to create unusual changes in the consolidated properties of the MRD late Pleistocene-Holocene sediments. The $e\text{-log}\sigma'_v$ curves of the specimens from -33 to -41.5 m of the marsh facies in the MD late Pleistocene-Holocene sediments lie well under those of the specimens at $z = -72$ m and -268 m, of the Osaka Bay sediments (Fig. 5.19) (Tanaka et al., 1999). It indicates that the microfossil in the Osaka Bay sediments influences on their consolidated properties very more than those of the MD late Pleistocene-Holocene sediments.

In case 3, the concave-level of the lower parts of the $e\text{-log}\sigma'_v$ curves (the S-shape curves) are gradually fading from the prodelta facies to the estuary channel facies at the VLM1 core site by the increase of depth and age (Fig. 5.4). The microfossils also make the concave-level increase. The S-shape of $e\text{-log}\sigma'_v$ curves by the CRS test are clearer than those by the IL test.

The other point, which is the organic materials were plentiful in soil-structure in range of -44 to -41.5 m at the VLM1 core (Fig. 4.36b) that they also significantly made the geotechnical properties unusually change such as: The water content, w_n , and sensitivity, S_t , increased (Figs. 4.36e and h). The $e\text{-log}\sigma'_v$ curve of specimen at -41.53 m lies well above those of the specimens at -22.12 m and in the range of -33 to -27.8 m of the VLM1 core (Fig. 5.19).

To base on the values of the coefficients of consolidation from the IL, CRS, and CPTU results in Tab. 5.3, the rates of primary consolidation of the sediment facies are in descending order: the delta front, sub- to intertidal flat, prodelta, and marsh/flood plain sediments. Generally, the rates of primary consolidation of the MD late Pleistocene-Holocene sediments are not so slow (Tab.

5.3); and the plasticity is not extremely high plasticity (Figs. 4.37 and 4.41). These matters may be due to: The clay mineral contents of illite, kaolinite, and chlorite are so high but the contents of smectite are so low from 0.0 to 13% in the MD late Pleistocene-Holocene sediments (Tab.5.7). The truth, the natural properties of the clay minerals are such as: For the illite, kaolinite, and chlorite minerals, whose thicknesses are large; but, whose specific surface and reciprocal of average surface densities of charges are so small (after Braja, 1998). Conversely, for the smectite mineral, whose thickness is small, and whose specific surface and reciprocal of average surface densities of charges are so large (after Braja, 1998). So, the illite, kaolinite, and chlorite minerals dominated in the structure and mechanical behavior. Accordingly, it is propitious for drainage and leads to the consolidation rate being relatively rapid. It is also deep cause that the plasticity of the late Pleistocene-Holocene sediments is relatively low and lower than those of the Tanan clay (Figs. 4.37 and 4.41). The origin of the Tanan sediments is from the Saigon river system.

The other cause is an insertion of sand seams in the clay seam; the sand seams help the water in the clay seams to flow out. The insertion of sand seams in the clay seam is commonly in sub- to intertidal flat, delta front, and the upper part of the prodelta facies. Specially, the alternate-structure in the delta front facies, the value of t_{50} is so small; hence, c_h is so many times greater than c_v . But, the values of c_h and c_v in the prodelta facies are approximately equal, and in the marsh/flood plain facies are so approximately equal, and t_{50} are so large (Tab. 5.4).

Table 5.7.
Summary of clay mineral content analysis of argillaceous sediments
of Vinhlong and Caolanh cores.

Illite (%)	Kaolinite (%)	Chlorite (%)	Smectite (%)	Mixture of Illite and Smectite (%)
max - min *rarely	max - min *rarely	max - min *rarely	max - min *rarely	max - min *rarely
72.1-54.2 *44.7	21.8-12.1 *9.6	18.6-10.4 *8.1	13.0-0.0 *26.4	9.8 - 1.3

The values of OCRs decrease in order from the natural levee, sub- to intertidal flat or intertidal flat, marsh/flood plain, and delta front sediments. Subsequently, the values of OCRs

tend to increase in order of the prodelta, bay, sub- to intertidal flat (in the marine transgression), marsh or marsh/tidal flat, and estuary channel sediments. OCRs of the natural levee sediment are the largest; values of OCR of the delta front sediment are the lowest. The OCR values of the MD late Pleistocene-Holocene sediments generally varied but still equal to greater than unity.

According to Mitchell (1976), the term “structure” implies a combination of “fabric” (arrangement of particles) and interparticle “bonding”. Not only the fabric and bonding but also recrystallizing of minerals such as the calcite and pyrite significantly joined that we can see them in the structure in the PTS and SEM images (Figs. 5.13 and 5.14). As a result, the term “structure” should be a combination of “fabric”, “bonding”, and “recrystallizing”.

5.5. Conclusions about consolidation characteristics

Since overconsolidation (OCR) of the MD late Pleistocene-Holocene sediments is influenced by the cement, ageing, and recrystallization of minerals; consequently, it is appropriate to use the term *yield stress ratio* for OCR and *yield stress* for preconsolidation pressure. Their microstructure is a combination of “fabric”, “bonding”, and “recrystallization”.

The post-depositional processes influence significantly on the consolidation process. Especially, the dehydrating and oxidizing processes by contacting the solar energy and air are the strongest. The characteristics of change of OCRs depending on facies could be summarized as follows. 1) Gradual reductions of OCRs (from 6.1 to 1.0) from the natural levee sediment to delta front sediment coincided with increase of depth. 2) Subsequently, the gradual increase of OCRs (from 1.0 to 5.7) from the prodelta to estuary channel sediments. The almost shapes of e - $\log \sigma'_v$ curves more or less have typical character of the flocculent structures except those of the natural levee and flood plain facies. The consolidation was defined the three typical consolidation cases.

Case 1 is the surface sediment facies from slightly overconsolidation to heavy overconsolidation by the dehydrated and oxidization processes by contacting the solar energy and air. Especially, the natural levee sediment is heavy overconsolidated, which are made by the high to very high development-level of microstructure. The yield stresses, σ'_{y-CPTU} , σ'_{y-IL} , and σ'_{y-CRS} are highly and the largest in comparison with the other facies; the sedimentation compression

curves lie well below the corresponding ICL and I_{v0} values are less than zero. Hence, k values are recommended to be 0.5 to 0.35 for calculating OCRs from CPTU test for the natural levee sediment. A formation-mechanism of the flood plain sediment is similar with those of the natural levee sediment. But the grain sizes and illite content of the flood plain sediment are often smaller than those of the natural levee sediment. As a result, the development-levels of microstructure of the flood plain sediment are medium to high. The intertidal flat facies and sub- to intertidal flat facies, the lightly oxidizing and dehydrating processes occurred in them. As a result, their development-levels of microstructure are medium to high. The development-levels of microstructure of the sediments in the upper delta plain are slightly higher than those in the lower delta plain by the differences in the source of material supply, fluvial and tidal and wavy influences, and age between them. So, k values for the flood plain/marsh, intertidal flat, and sub- to intertidal flat sediments in the upper delta plain are recommended to be 0.2 to 0.35 and in the lower delta plain 0.2 to 0.25.

Case 2 is shallow sediment facies, the delta front facies with “alternate-structure”. The cohesive soil in the delta facies has salt flocculation structure and somewhat overconsolidated. The shape of the $e\text{-log}\sigma'_v$ curve has typical character for the flocculent structures, lower part of the $e\text{-log}\sigma'_v$ curves behind curvature-point with clear bent. The influence of the alternate-structure is such as: the c_h is many times greater than c_v , which hastens primary consolidation. Values of C_s^*/C_s are very low; I_{v0} values varied largely and well above the SCL. The microstructure development-levels of the case 2 are such as: The sediments in the lower delta plain with age less than 4 ka BP are low and k values are suggested to be 0.2. The sediments in the upper delta plain with age 4 to 7 ka BP are medium and relatively low k values of 0.2 to 0.3 are recommended.

Case 3 is deep sediment facies. The development-levels of microstructure are from medium to so high in ascending the prodelta, bay, sub- to intertidal flat, marsh/tidal flat, and estuary channel sediments. Pyrites and calcites are significantly recrystallized. The recrystallization tends to increase from the prodelta to estuary channel facies. Microfossils significantly join in the microstructure and make the void ratio increase with unusually highly value. The k values of 0.3 to 0.4 are recommended for the prodelta and bay sediments in the upper delta, and 0.3 for the prodelta and bay sediments with age less than 5.6 ka BP in the lower delta plain. For the marsh and marsh/tidal flat facies at the great depth, from 8.88 to 13.258 ka BP, strong recrystallization

results their microstructure-developments from high to very high. Hence, 0.40 to 0.45 are recommended for the k value of these facies. For the estuary channel sediments, microstructure-developments are very high because they have been at the greatest depth, more than 9,910 yr BP, and strongest recrystallization. The k values inferred for the sediments are 0.45 to 0.5.

It should be also concluded that the void index (I_{v0}) and swelling sensitivity (C_s^*/C_s) could be related to sediment conditions of the MD natural soils.

CHAPTER 6

CONSIDERATION OF SOIL STRUCTURE AND SOIL CHARACTERIZATION FOR THE INFRASTRUCTURE CONSTRUCTION IN MD

6.1. Introduction

This chapter 6 will present about a soil structure model which be rebuilt based upon the results of the sedimentary geology and the geotechnical properties and the characteristics of consolidation of the sedimentary facies as presented in chapters 4 and 5. Each sedimentary facies was formed under a different environment and revealed typical geotechnical properties (Truong et al., 2011). Based upon these results the identification of soil properties and estimation of the general tendencies of the mechanical behavior of soils of the MRD region in the context of geotechnical engineering will be applied on the previous sedimentary profiles (Fig. 4.9 and Tab. 4.6), we will guess the mechanical behavior of them. And the particular sedimentary conditions in the late Pleistocene-Holocene deposits will be also estimated by the CPTU and lab results. All these points allow us to establish a soil structure model. And based on thicknesses and arrangement of the surface sediment facies, shallow sediment facies, and deep sediment facies, the soil structure model will be divided into typical soil structure types. Advantages and disadvantages of each typical soil structure type and soil characterization for the infrastructure construction in the MRD will be presented.

Difficulty in soil characterization about large sensitivity and depths of the MRD late Pleistocene-Holocene sediment facies, and alternation of clay-seams and sandy seams for the sampling for lab tests, CPTU and SPT tests, and represent-ability about testing results of methods will be discussed. Simultaneously, from this discussion a rational investigating procedure for the MRD late Pleistocene-Holocene sediments will be rebuilt.

The geotechnical properties of the MRD late Pleistocene-Holocene sediment facies will be compared with those of other deltas in the world for further clearly understanding about them.

6.2. Soil structure model and their advantages and disadvantages for highway and railway construction

6.2.1. Soil structure model

As presented in item 5.4.1 and reported by Truong et al. (2011), the sublayers are homogeneous and their strengths increase linearly with depth; they could be the marsh, marsh/tidal flat, sub- to inter-tidal flat (in the transgression), bay, pro-delta, intertidal flat, and flood plain facies. Especially, the sublayers are highly homogeneous and their strengths strictly increase linearly with depth, they could be the marsh, bay, and flood plain facies. The sublayers are inhomogeneous and their soil-behavior-types vary largely; they could be the estuarine channel, estuarine marine, delta front or delta front-mouth bar, and sub- to inter-tidal flat facies. Especially, the sublayers are so inhomogeneity and their mechanical behavior shows great variability, as shown by the CPTU results, they could be the delta front and delta front-mouth bar facies. The typical geotechnical properties of each sedimentary facies in the MD were summarized in Tab. 6.1. Therefore, the particular sedimentary environments and conditions in the late Pleistocene-Holocene deposits can be reasonably estimated by the CPTU results or combine with lab geotechnical results. It is further clearly and exactly we can combine the geotechnical results with ages and collate them with the geological column in the MRD region. Accordingly, we can get the particular sedimentary conditions and geological sections from the CPTU results and geotechnical profiles such as: At the Cantho site, we estimated a geological section (designed CTM1) from the results of *CPTU-CT and lab geotechnical tests of Takemura et al. (2007).

Also, as represented in item 5.4.1 and reported by Truong et al. (2011), the estuarine channel, estuarine marine, delta front or delta front-mouth bar, and sub- to inter-tidal flat facies, their soil-behavior-types vary largely and their sequences of the geotechnical properties are similar to the characteristics of sedimentary structures with inhomogeneity. Especially, the delta front and delta front-mouth bar facies are so inhomogeneity and the mechanical behavior of the delta front and delta front-mouth bar facies shows so great variability in the CPTU results. And the marsh, marsh/tidal flat, sub- to inter-tidal flat (in the transgression), bay, pro-delta, intertidal flat, and flood plain facies are homogeneous, and their strengths increase linearly with depth. Specially, the marsh, bay, pro-delta, and flood plain facies are so highly homogeneous, and their strengths

Tab. 6.1. Summary the typical geotechnical properties of each facies in the MD.

Facies	Altitude of appearance	Thick of facies	Soil classification	Homogeneous levels	Consolidated levels	Physical characteristics		State parameters						Mechanical parameters		C^*/C_s
	(m)	(m)				w_L (%)	w_p (%)	w_n (%)	S_r (%)	e_0	γ_n (g/cm ³)	I_p (%)	I_c	c_c	q_c (MPa)	
Natural levee	2.9	3.4	CH, CL, MH-V	Medium	Heavy overcons	44-79	22-52	29-52	98	0.84	1.62-1.95	18-30	0.3-0.7	0.3 to 0.5	0.7-1.1	0.5-0.6
Sand dune															0.1-9.3	
Flood plain	from +2 to -0.5	2-4 Max: 32	CH, CL	Homogeneous	Normal, slight overcons	46-63	25-29	31-70	99-100	1.1-1.62	1.5-1.75	19-35	from -1 to 0.1	0.3 to 0.5	0.1-2.52 surface: 0.9-1.2	0.4-0.8
Sub-to intertidal flat or Intertidal flat	from 0 to -3.6	3-9.5	CL, MI-H	Low-medium	Normal, slight overcons	40-58	19-32	29-71	98-100	1.2-1.5	1.6-1.76	11-25	from -0.6 to 0.1	0.27-0.43	0.1-0.3 Sand: 4.6-6.25	
Delta front (Upper delta)	from -4 to -13.1	from 4.5 to 13.9	Almost cohesionless	Unhomogeneity											0.8-13	
Delta front (Middle delta)			CL, CL, CH, CV,	High unhomogeneity	Normal, slight overcons	48-63	21-28	43-72	100	1.2-1.9	1.54-1.75	25-35	from -0.7 to 0.1	0.34-0.48	0.23-0.78 Sand: 9.7	0.19-29
Delta front (Lower delta)				Unhomogeneity											0.5-9.3	
Prodelta	from -13.7 to -21.9	from 3 to 10	CL-I, MI	Homogeneous	slight overcons	22-50	18-29	18-52	98-100	1.43	1.65-1.97	2 to 27	from -0.1 to 0.9	0.11 to 0.36	0.33-0.85 Sand: Max 7.15	
Bay	from -20 to -24.5	3 to 15.95	CV	High homo.	overcons	72-82	24-28	16-42	98-100	1.1 to 1.33	1.73 to 1.78	47 to 53	1.0 to 0.2	0.56 to 0.65	0.53-0.9	0.9
Estuary	-25	2.8 to	CL	Unhomogeneity	slight overcons	29-43	15-22	17-42		1.3	1.73				0.8-5.3	
Marsh	-27.8	7.8-13.7	Most: CL, CH	High homo.	overcons	40-65	21-25	37-60			1.68-1.78			0.53 to 0.91	0.7-1.6	0.9-0.67
Estuary channel	-41.5	4.5-6.7	Most: CV; CL, CH	High unhomogeneity	overcons	36-80	16-27	19-66		1.48	1.7-2			1-1.16	1.3-7.1	>0.67

strictly increase linearly with depth. For this reason, we can do the identification of soil properties and estimation of the general tendencies of the mechanical behavior of soils of the MRD region in the context of geotechnical engineering. Accordingly, we can guess the typical general tendencies of their mechanical behavior from the late Pleistocene-Holocene depositional facies of the DT1, VL1, TC1, TV1, VC1, CD1, GC1, and CM1 cores in the MRD on the sedimentary research results of Ta et al. (2005) and Nguyen et al. (2004) (Tab. 4.6 and Fig. 4.9).

All allow us to infer a generally preliminary soil structure model with three main broad soil layers corresponding with three consolidation cases as presented in item 5.3. The generally preliminary soil structure model includes the core sites in this study and collected core sites in Tab. 4.6. The generally preliminary soil structure model is drawn in Fig. 6.1.

As pointed out in section 5.3, the sedimentary facies in the general soil profile (Fig. 5.7) were divided into three consolidation cases corresponding to three main soil layers including the

surface sediment facies, the shallow sediment facies, and the deep sediment facies. Based on thickness and arrangement of the sediment facies, and the typical geotechnical properties of each facies (Tab. 6.1), the soil structures of the MD late Pleistocene-Holocene sediments may be divided into six typical soil structure types (Fig. 6.2 and Tab. 6.2). The six typical soil structure types are presented such as:

(1) Type 1

The first type has sufficiently presented the eight successive facies of the MRD late Pleistocene-Holocene sediments with more than 40 m in thickness and the sand dune facies, as at the BT2 core site with 71 m in thickness (Fig. 6.2 and Tab. 6.2).

(2) Type 2

The second type has sufficiently presented the eight successive facies with more than 40 m in thickness, for example at the VLM1 core site with 47 m in thickness (Fig. 6.2 and Tab. 6.2).

(3) Type 3

The third type has presented from six to eight successive facies and the natural levee facies in thickness 20-40 m, as at the CLM1 core site with 39.5 m in thickness (Fig. 6.2 and Tab. 6.2).

(4) Type 4

The fourth type, which has presented from six to eight successive facies and none of the natural levee facies, in thickness between 20-40 m, as at the CTM1 core site (Fig. 6.2 and Tab. 6.2).

(5) Type 5

The fifth type has four facies including sand dune, sub- to intertidal flat, delta front, and basal prodelta facies with thickness being less than 20 m and unconformably overlay on the undifferent Pleistocene sediments, as at the BT3 with 20 m in thickness (Fig. 6.2 and Tab. 6.2).

(6) Type 6

The sixth type, which has presented three facies including the flood plain/marsh, sub to intertidal flat, and basal delta front facies with thickness being less than 20 m and unconformably overlay on the undifferent Pleistocene sediments, as at the BT1 core site with 12 m in thickness (Fig. 6.2 and Tab. 6.2).

The second main soil layer (shallow sediment facies is delta front facies) almost appeared in the all soil structure types (Fig. 6.2 and Tab. 6.2).

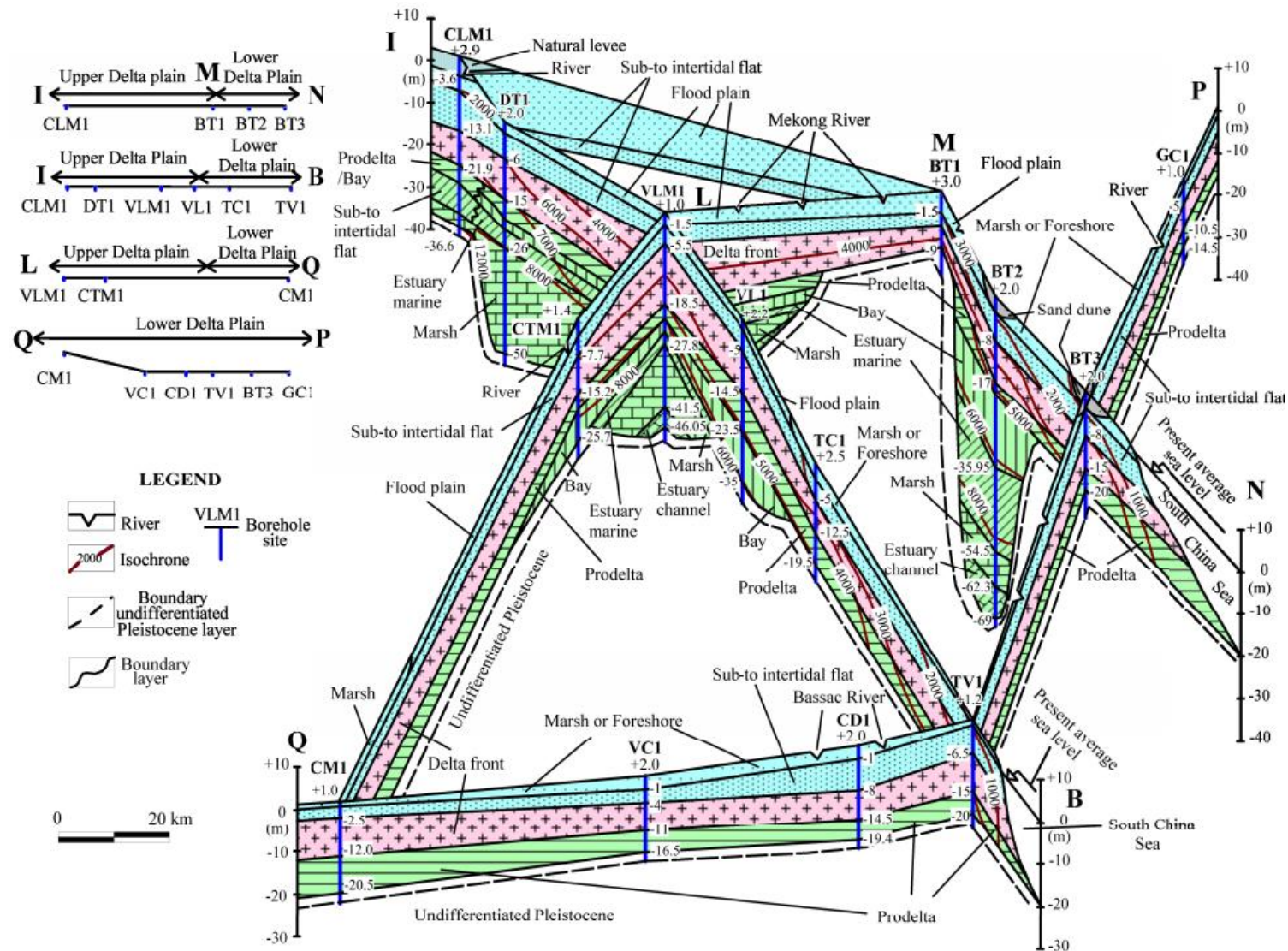


Fig. 6.1. Generally preliminary soil structure model with three main broad soil layers based on geotechnical and sedimentary properties of core sites (simplified after Truong et al., 2011; Ta et al., 2005 and Nguyen et al., 2004; Takemura et al., 2007). The plan layout of the core sites in the model is in Fig. 4.9.

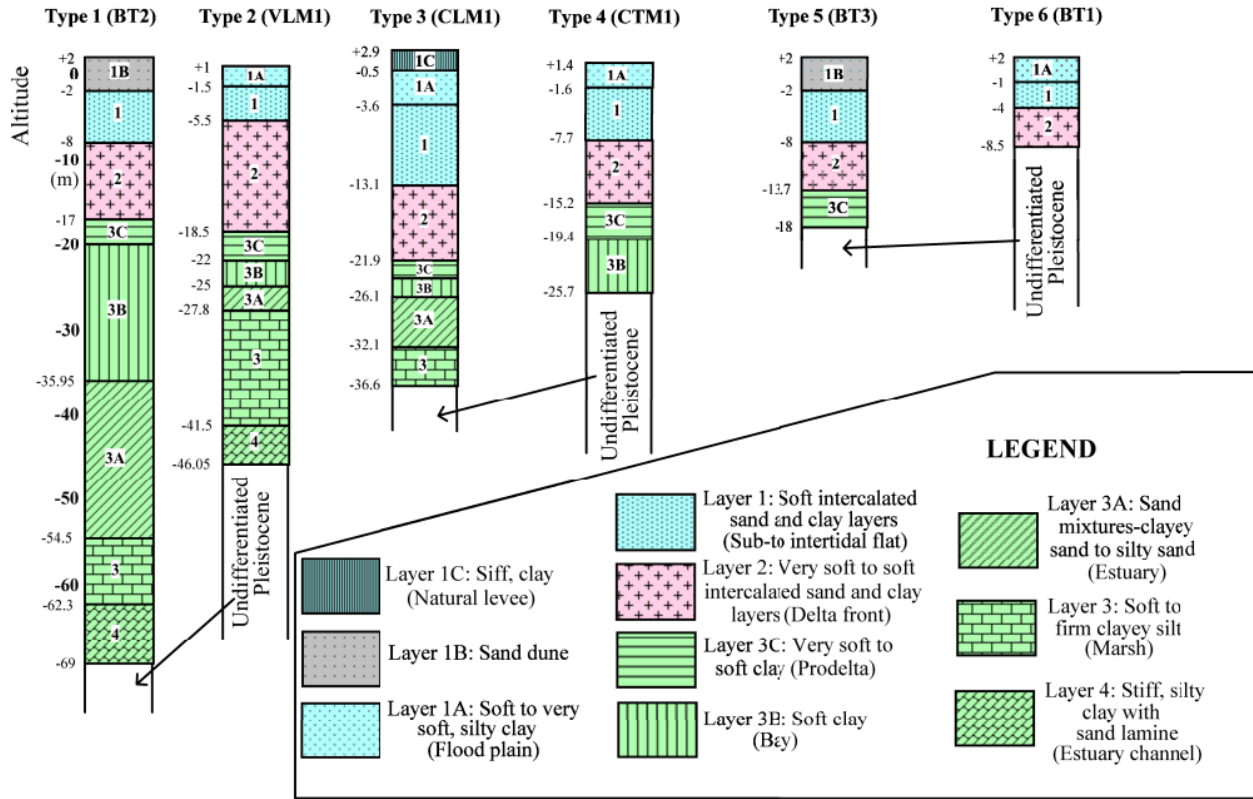


Fig. 6.2. Six typical soil structure types base on the thickness and arrangement of three main broad layers.

6.2.2. Advantages and disadvantages for highway and railway

The highway and railway are considered two construction-structures including light structure and heavy structure. The light structure is embankments built on the surface ground of the late Pleistocene-Holocene sediments. The heavy structure is bridges with foundation load being more than 5000 kPa. For heavy structure the foundation load are transmitted to the below soil layers. Especially, these large loads are transmitted to the undifferentiated Pleistocene sediments. The advantage and disadvantage of the six types of soil structure will be considered for these two construction-structures.

In general, the consolidation characteristics of the MD late Pleistocene-Holocene sediments include three broad cases as presented in 5.4. The consolidation characteristics of each sedimentary facies in each case varied according to vertical direction and horizontal direction (Tab. 6.3). Especially the second case-delta front facies the consolidation characteristics have big variation caused by the thin sand seams in the clay layer with very different thicknesses and

Table 6.2.

Amount of sediment facies, thicknesses of late Pleistocene-Holocene sediments, top facies, and appearance-depth of undifferent Pleistocene sediments in each type of soil structure and typical core site; Levels of advantage and disadvantage of them for construction of structures.

		Type	1	2	3	4	5	6	
Soil structure	Amount of facies		8	8	from 6 to 8	from 6 to 8	4	3	Late Pleistocene-Holocene sequence
	Thickness (m)		>40	>40	20-40	20-40	<20	<20	
	Top facies		Sand dune/beach ridge	Flood plain /Marsh	Natural levee	Flood plain /Marsh	Sand dune/beach ridge	Flood plain /Marsh	Top facies of sequence
	Thickness (m)		<5	<5	<5	<5	<5	<5	
	Appearance -depth of undifferent Pleistocene (m)		<-40	<-40	from -20 to -40	from -20 to -40	>-20	>-20	Undifferent Pleistocene
Typical core site			BT2	VLM1	CLM1	CTM1	BT3	BT1	
Soil structure	Amount of facies		8	8	7	6	4	3	Late Pleistocene-Holocene sequence
	Thickness (m)		71	47	39.5	27.1	20	11.5	
	Top facies		Sand dune	Flood plain	Natural levee	Flood plain	Sand dune	Flood plain	Top facies of sequence
	Thickness (m)		4	2.5	3.4	5	3	3	
	Appearance -depth of undifferent Pleistocene (m)		-69	-46	-36.6	-25.7	-18	-8.5	Judgement
Structure in construction	Light	Low	Low	Very low	Medium	Low	Medium	Medium	
		High	High	Very high	Medium	High	Low	Low	Disadvantage
	Heavy	Very high	Very high	Very high	High	High	Medium	Medium	Disadvantage

seam-amounts. The coefficients of consolidation, c_v , at same range of pressures are very different in the delta front facies (Tab. 6.3). In addition, according to the location in the MD the consolidation characteristics equivalent sediment-facies are also different. For example, the delta front facies at the Caolanh site are almost cohesionless behavior types, while at the Vinhlong site the alternation of the clay seams and sand seams (Figs. 5.1.1-2 and Tab. 6.1). The consolidation characteristic of each sedimentary facies is different i.e. the consolidation settlement and time are also different. On the other hand, the poor geotechnical investigation practice leads to be significantly underestimated or overestimated the consolidation settlements and time for the embankment in the MD. If the thicknesses of the late Pleistocene-Holocene sediments increase, the disadvantage for both two construction-structures will increase.

The levels of advantage and disadvantage of six types of soil structure for the construction of structures are classified based upon the facies' geotechnical properties (Tab. 6.2), soil structures, and appearance-depth of the undifferentiated Pleistocene sediments. In general, the undifferentiated Pleistocene sediments have very high strength and compression resistance potentials, and the late Pleistocene-Holocene sediment sequence is generally soft. The levels of advantage and disadvantage are divided into 4 in degree including low, medium, high, and very high. The constructions of structures include the heavy structure as elevated bridges and light structures as embankments (roads).

The first to fourth types are in a high to very high disadvantage for the heavy structure; specially, the first type is in a very high disadvantage (Fig. 6.2 and Tab. 6.2). The fifth and sixth types with thicknesses of the late Pleistocene-Holocene sediment sequence being less than 20 m are in a medium disadvantage for the heavy structure. The top soil sublayer in the first type is sand dune facies with about 4 m in thickness; it is in a low advantage for the road. But, the sand dune facies is not popularly in the MRD, they only scattered in the lower delta plain shown in Fig. 4.9 (Ta et al., 2005). The second type is in a very high disadvantage for the road and elevated bridge. The third type is in a medium advantage for the road because the natural levee facies with about 3.4 m in thickness is high strength and compression resistance potentials (Figs. 4.9 and 6.1-2, and Tab. 6.2). The fourth type with the top flood plain/swamp facies is in a high disadvantage for the road (Figs. 4.9 and 6.1-2 and Tab. 6.2); but, the top fine grain flood plain/swamp facies are very popularly in the upper delta plain of the MRD shown in Fig. 4.9 (Ta et al., 2005). The fifth type is in a medium advantage for the road because the top soil sublayer is

Tab. 6.3. Summary the typical consolidation properties of each facies at Vinhlong site.

Altitude (m)	Facies	Yield stress, σ'_y		Coefficients of consolidation, c_v	Maximum pressure of c_v	Cc	Cs	e_0
		IL (kPa)	CRS (kPa)	IL (m ² /year)	IL (kPa)	IL	IL	IL
-1.4	Flood plain		67.8					
-1.416		33		5.1	107	0.379	0.057	1.36
-1.447		40		18	107	0.419	0.052	1.39
-2.815	Sub- to intertidal flat	50		40.8	107	0.371	0.050	1.20
-2.845		53		25.6	107	0.431	0.065	1.33
-3.45		58		27.2	101	0.379	0.061	1.25
-6.365	Delta front	43		6.2	107	0.671	0.082	1.87
-6.395		54		25.8	107	0.328	0.063	1.30
-7.315		73		25.7	107	0.704	0.094	1.63
-7.90			83					
-7.915		53		5.5	107	0.760	0.110	1.69
-7.985		65		18.5	107	0.549	0.094	1.51
-9.57		95		23	107	0.732	0.125	1.53
-9.59		96		32	107	0.639	0.105	1.40
-9.635		96		66.3	101	0.777	0.090	1.41
-9.65			130					
-14.51	Bay	80		64.8	107	0.650	0.136	1.68
-22.065		168		5.85	78.5	0.685	0.116	1.55
-26.4	Estuary marine	177		9.1	157	0.599	0.093	1.33
-27.95	Marsh		327					
-28.015		219		30.5	107	0.547	0.077	1.13
-28.045		214		29	107	0.603	0.098	1.18
-32.615		255		26	107	0.532	0.069	1.12
-36.05		320		46.6	107	0.832	0.076	1.42
-36.3			370					
-36.4			420					
-41.51	Estuary channel	318		10.5	107	1.058	0.186	1.43
-41.535		420		8.5	107	1.166	0.179	1.48
-42.8			473					1.43
-44.2			349					1.48

sand dune facies and thickness of the Holocene sediment sequence is less than 20 m. The sixth type is in a low disadvantage for the road because thickness of the Holocene sequence is less than 20 m and the basal soil sublayer is the delta front facies overlies directly on the undifferentiated Pleistocene sediments (Figs.4.9 and 6.1-2 and Tab. 6.2).

As shown in Figs. 4.9 and 6.1, thicknesses of the MRD late Pleistocene-Holocene sediments overlay on the undifferentiated Pleistocene sediments with general tendency such as: The large

and varied thicknesses may be in the center area locating between the Mekong and Bassac Rivers in the IMN and ILB sections (Figs. 4.9 and 6.1). Especially, the incised-valley zone (Nguyen et al., 2010) within the center area includes the VLM1, CLM1, DT1, and BT2 core sites (Figs. 4.9 and 6.1). A maximum thickness found is 71 m at the BT2 core site. This center area seems like high to very high disadvantage for the heavy structure like elevated bridges. Thicknesses of the late Pleistocene-Holocene sediments tend to decrease in the perpendicular directions with both Mekong and Bassac Rivers, from their banks into the inners. For specific examples as the direct from the Mekong River to the BT1 core site, and the direct from the Bassac River to CM1 core site (Figs. 4.9 and 6.1). Thicknesses of the late Pleistocene-Holocene sediment in the QP section in the coast area are relative small and regular, thicknesses in range of 15.12 to 22 m, shown in Figs. 4.9 and 6.1. In the QP section, the types of soil structure are only 5 and 6. The QP section may be medium disadvantage for heavy structure but in the seashore, many large estuaries, high ground water table, and exists in the part of the incised-valley which causes the difficulty in construction work (Figs. 4.9 and 6.1).

In general, six types of soil structures are from medium to very high disadvantage for the heavy structure. The heavy structures require the use of pilings. Specially, the center areas locating between the Mekong and Bassac Rivers need to use the deep pilings. The areas having the natural levee facies or sand dune facies are low to medium advantage for the light structure but they are not popular in the MRD.

6.3. Difficulty in soil characterization of MRD

6.3.1. Sensitivity of MRD soils

The most of the values of sensitivities, q_u/q_{ur} , of the sediments in both Vinhlong and Caolanh sites except the natural levee, flood plain, and estuary channel facies are more than 8; they are from slightly quick to extra quick according to the classification of Rosenqvist (1953) (Figs. 6.3 and 6.4). Specially, for the cohesive soils of the delta front facies, values of q_u/q_{ur} are very high, more than 64 (Fig. 6.3). The alternate-structure of the delta front facies easily makes the soil samples break during sampling, transporting, and preparing for tests. Pore water pressure was lost when these soil samples were taken out of the soil ground and tube sampler.

Fig. 6.3. Sensitivity, ration of compression strength for undisturbed sample, q_u , to remold sample, q_{ru} , on the Vinhlong core according to the classification of Rosenqvist (1953).

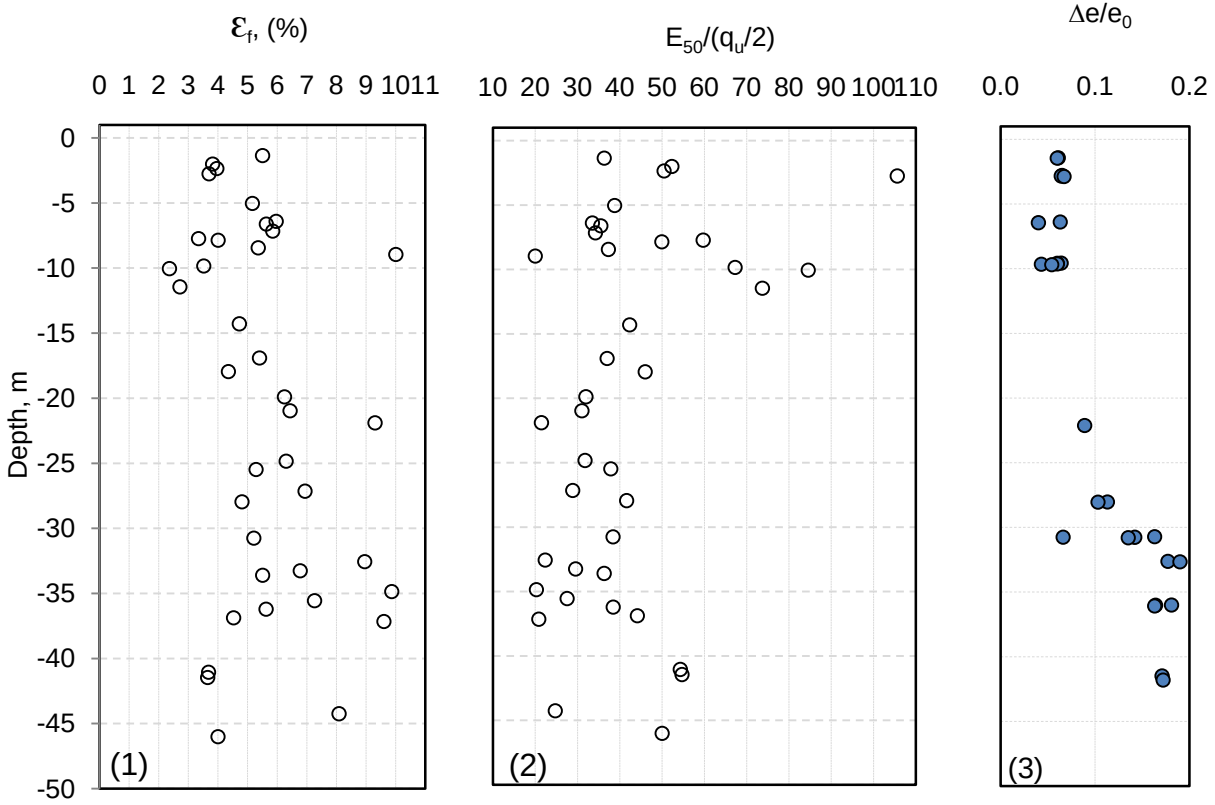


Fig. 6.5. Sample quality in terms of (1) failure strains, ε_f , (2) secant moduli divided by the undrained shear strength, $E_{50}/(q_u/2)$, from UC tests, and (3) $\Delta e/e_0$ from IL tests on Vinhlong core.

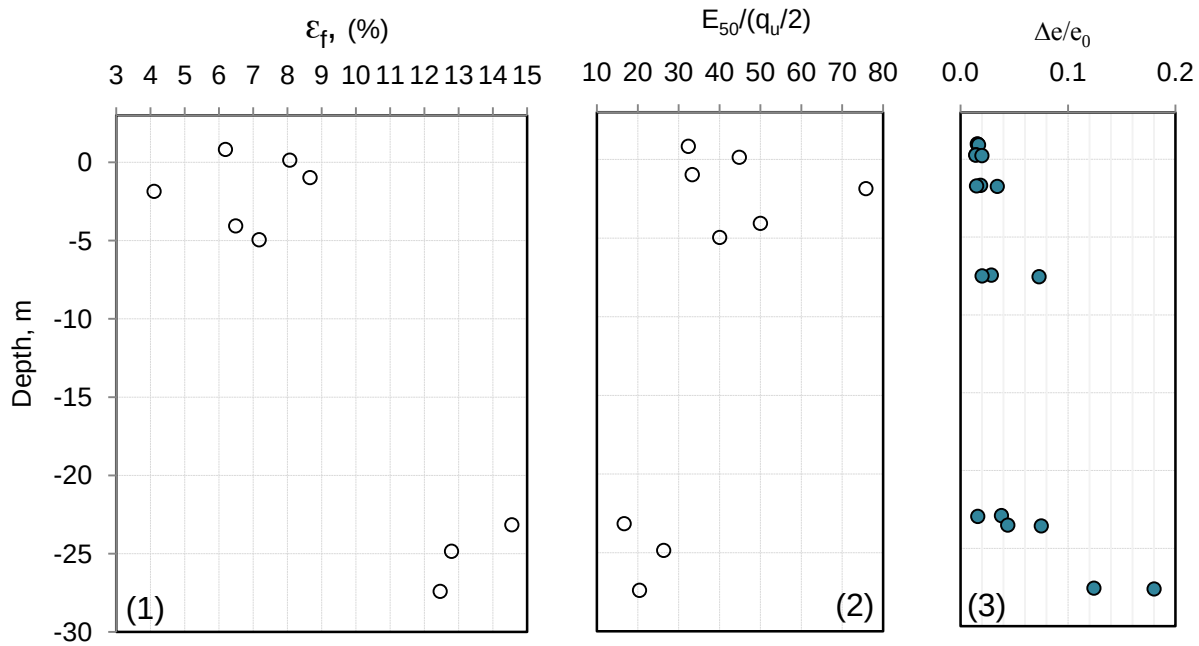


Fig. 6.6. Sample quality in terms of (1) failure strains, ε_f , (2) secant moduli divided by the undrained shear strength, $E_{50}/(q_u/2)$, from UC tests, and (3) $\Delta e/e_0$ from IL tests on Caolanh core.

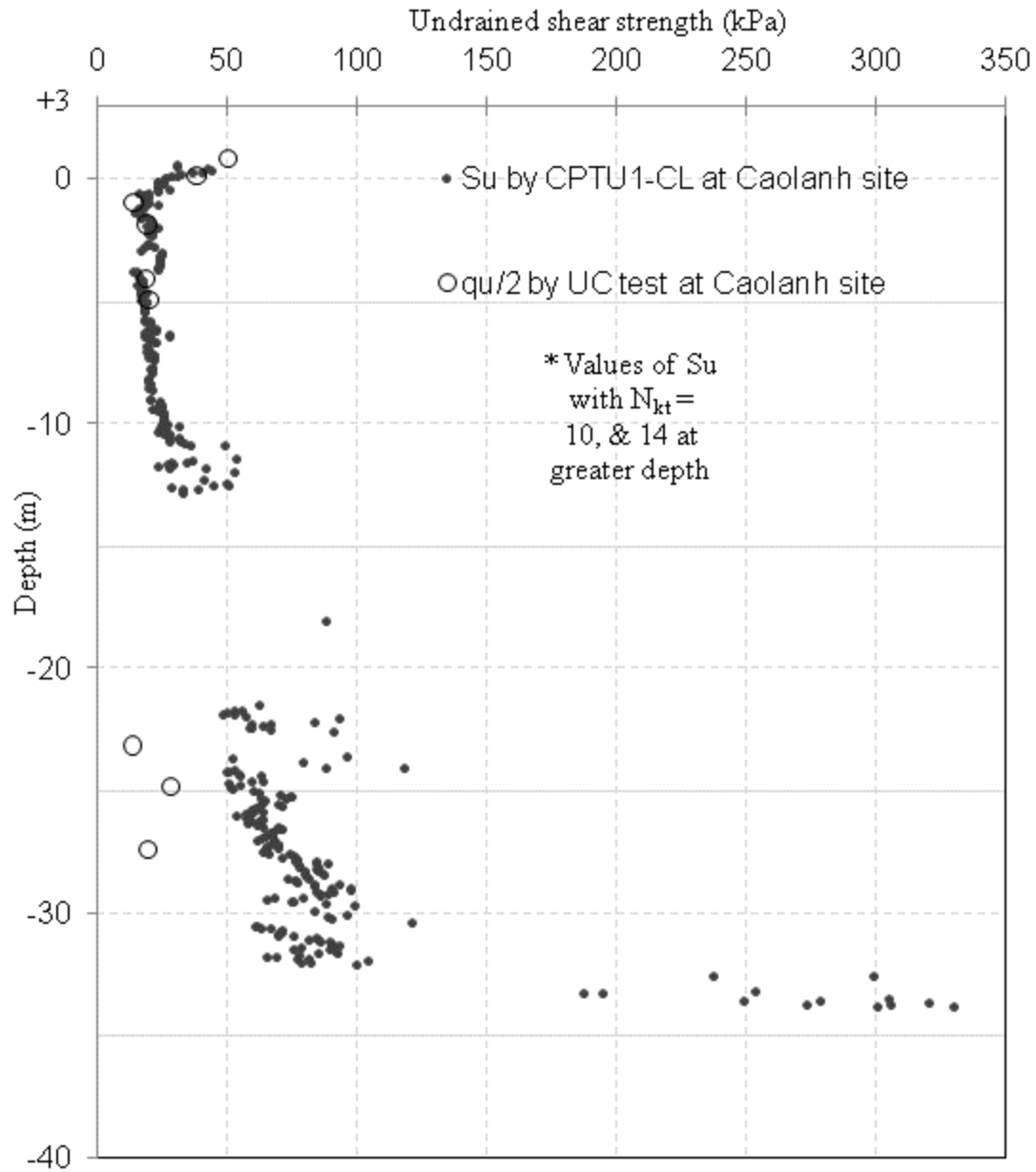


Fig. 6.7. Comparisons of undrained shear strength obtained from CPTU with those by UC tests at Caolanh site.

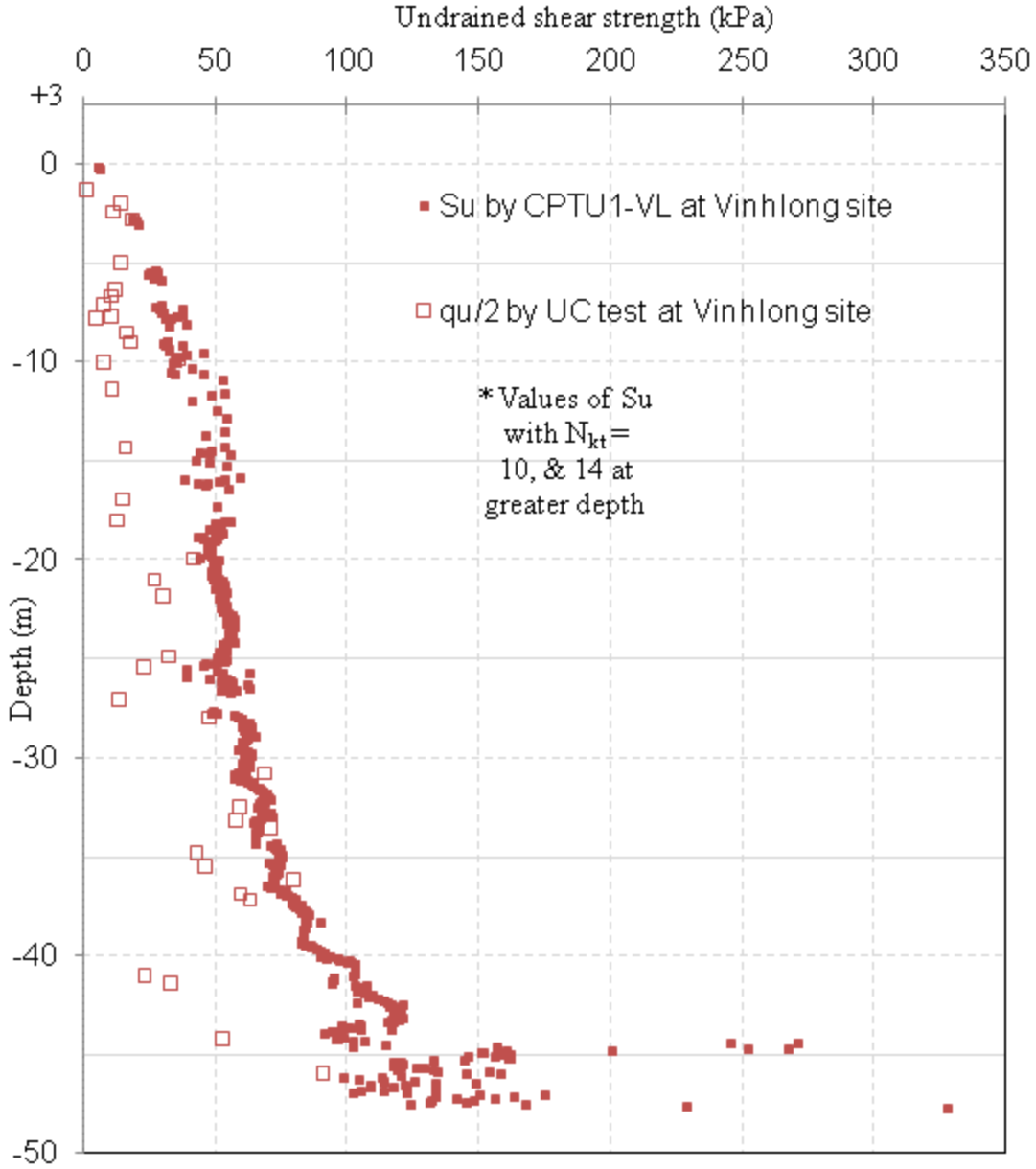


Fig. 6.8. Comparisons of undrained shear strength obtained from CPTU with those by UC tests at Vinhlong site.

The failure strains, ε_f , and changes of void ratio, $\Delta e/e_0$ increase with depth; especially, the values of the sub- to intertidal flat and delta front facies vary largely (Figs. 6.5.1, 6.5.3, 6.6.1, and 6.6.3). Simultaneously, these cant moduli divided by the undrained shear strength, $E_{50}/(q_u/2)$, decrease with depth; and the values of the sub- to intertidal flat and delta front facies also vary largely (Figs. 6.5.2 and 6.6.2). The values of $E_{50}/(q_u/2)$ are almost less than 100 (Figs. 6.5.2 and 6.6.2). In addition, distance between values of $q_u/2$ by UC and values S_u by CPTU increase with

depth and in soil specimens with alternated-sand-seams (Figs. 6.7 and 6.8). It implies the parameters also indicate that the sample quality decrease with depth; especially, for the sub- to intertidal flat and delta front facies vary largely. The undrained strength tends to be significantly underestimated by unconfined compression tests for the delta front facies and deep sediment, e.g., estuary channel, due to high sensitivity and low sample quality respectively.

The excessive disturbance affects the $e\text{-log}\sigma'_v$ plot and tend to obscure the influence of development history of stress in the natural soil. The curvature-point on the $e\text{-log}\sigma'_v$ curve becomes to obscure and seem like the straight line of the $e\text{-log}\sigma'_v$ curves of the reconstituted specimens results to difficulty in the determination of consolidation properties. In addition, the microstructure development-levels of the delta front facies are low to medium as above discussion in item 5.3. The delta front facies in the MRD commonly appear from -4 to -21.9 m (Fig. 6.1 and Tab. 4.6). In general, the depths of the soft Pleistocene-Holocene sediment facies as delta front, prodelta, bay, and marsh facies with high sensitivities and normal consolidation-slight overconsolidation are from -4 to -62.3 m (Fig. 6.1 and Tab. 4.6).

6.3.2. Influence of alternation-sand-seams

The alternation-sand-seams also influence the coefficients of consolidation (c_v). Especially, the delta front facies, the c_v values are the biggest variation in comparison with other facies, from 66.3 to 5.5 m^2/year at the same range of pressures as shown in Tab. 6.3. The big variation was due to the thin sand seams with different thicknesses and amounts as shown in Fig. 5.16.

In addition, the influence of sand seams with large scale in the surrounding environment in the nature ground which the lab consolidation tests cannot capture them. But, CPTU can capture the effect of sand seam for large scale. The influence of alternation-sand-seams on the primary consolidation, in the same soil behavior type in the same facies but times for dissipating pore water pressure are very different when there are different alternation-sand-seams about thickness and seam-amount in the surrounding environment in the nature ground. We consider the clays-clay to silty clay (the soil behavior type classification is (3) (Robertson, 1990)) in the delta front and prodelta facies, but the times for dissipating pore water pressure from the CPTU test are very different shown in Fig. 5.1 and Tab. 5.3. And the times for dissipating pore water pressure from the CPTU test are very different those of the IL test at the same soil type and the same depth

shown in Figs. 5.5 and 5.7 and Tab. 5.3. Therefore, c_v , obtained from CPTU will be truer than those from the lab consolidation tests. This cause is to lead the c_v from CPTU are different with those from IL as shown in Tab. 5.3. We realize that the sedimentary structure also significantly influence the rate of primary consolidation. The piezocone dissipation-test of pore water pressure during the CPTU test can present the influence of the sedimentary structure.

The sedimentary structures of the Mekong Delta late Pleistocene-Holocene sediment facies significantly vary in the horizontal and vertical. Such as above discussion in item 5.2 at the Vinhlong and Bentre-2 sites, the soil variation exist horizontally even in the small distance being 4 m that the CPTU results showed it. The appearances of the same sedimentary facies are at very different depths (Fig. 6.1 and Tab. 4.5). The thicknesses of the late Pleistocene-Holocene sediments largely change like at the BT1 being 10 m and at the BT2 being 71 m. These things are causes of the geotechnical problems if the investigation results do not reported clearly.

6.4. Poor geotechnical investigation practice

On the other hand, the Shelby tube sampler has popularly been using by Vietnamese firms. As a result, the microstructures of these sediments are easily broken, and lead to the low quality of soil samples. The final results, the quality of soil samples decreased with depth; the values of OCR are small and often less than one as report of Man (2003). The results of IL and CRS tests indicate the soil sampling method with type thin-walled tube sampler with fixed piston getting the highest quality soil samples by Takemura (2007). But the maximum depth of the type thin-walled tube sampler with fixed piston inserted by the water pump used is 26 m. The thicknesses of the MRD late Pleistocene-Holocene sediments are too large, from 12 to 71 m; and the thicknesses greater than 26 m are common (Fig. 6.1). It shows that the sampling with the depths greater than 26 m for the high quality soil samples is also a difficulty for investigating the geotechnical and consolidation properties of the MD late Pleistocene-Holocene sediments on the soil sample in the present technique condition.

The MD in the tropics climate, the temperatures are from 18 to 40 degrees. For this reason, soil sample is easily shrunk by dehydration at the field. Therefore, the preservation for the soil samples during the awaiting time for the transport to lab test should be careful. And the decrease of amount of soil samples is also needed. The best solution could be to combine the CPTU test

and the soil sampling for the lab tests.

The CPTU test can well represents the characteristics of the MD late Pleistocene-Holocene sediments; especially, for the small variations and the various soil behavior-types in the prodelta, delta front, and sub- to intertidal flat sediments, will be represented with high precision and continuousness. The CPTU test can conduct easily, quickly; it can give different parameters about the strength and consolidation properties such as the value of N (like the SPT test) and undrained shear strength, S_u . Simultaneously, it is easily to move and carry out quickly in the condition of the MRD. The values of OCR from the CRS and CPTU tests are approximated. These OCRs obtained from the CRS and CPTU tests are always greater than these from the IL tests (Fig. 5.14.1-2). The OCRs from the CRS and CPTU tests may be so close to the truth. The vertical yield stresses from the CRS test are often more than from the IL test. The compression curves (e - $\log \sigma'_v$) from the CRS test is sharper, and identifies vertical yield stress, σ'_{vy} , more easily and precisely (Figs. 5.4 and 5.6).

However, the CPTU test has notes for conducting on the Mekong Delta late Pleistocene-Holocene sediments. The soil behaviors type classification of the deep sediment facies (case 3) based on values of B_q are sometimes different with results from the sampling soil specimens because the normalized values of B_q slightly increase. The conditions of formation and existence of the deep sediment facies presented as the above item 5.3 were very difficult for pore water drainage. Hence, the natural pore water pressure increase lightly, so the measuring quantities of pore water pressure from CPTU test is sometimes high. Accordingly, we should care for using the values of B_q . The other point is about the state of the stiff clays (3); the results based on B_q will be more actually than those of F_R about state for the Mekong Delta late Pleistocene-Holocene sediments. For an example, the estuary channel sediment, the state based up F_R was sensitivity but B_q was high consolidation.

At beginning of the load of the IL test, the consolidation process occurred rapidly. It is too difficult to estimate a time of primary consolidation from the plot of deformation against log-time because the plot of log-time/deformation cannot represent the primary consolidation stage, for a typical example at the VLM1 core shown in Fig. 6.9.1. Hence, we should use the plot of deformation against the square-root-time for calculating a time of primary consolidation, t_{100} , shown in Fig. 6.9.2. The log-time/deformation curves from the IL tests should be used to define the secondary compression index for estimating the secondary consolidation settlement.

The CRS test help to estimate with high precision, so the loading in the CRS test is with very small and continuous steps. The c_v values from the IL and CRS tests from the results of the VLM1 and CLM1 cores show that the values of c_v in the overconsolidation range largely vary, but in the normally consolidation range small vary in the both tests (Figs. 5.4 and 5.6). The coefficient c_v by the IL test are higher than those by the CRS test. The cause can be a large load-difference of loading steps. In the overconsolidation range, a larger compression can be easily observed than on the high quality soil samples at the vertical stresses less than the yield stress, being a gradual bent in the e - $\log \sigma'_v$ (Takemura et al., 2003). Especially, for the low quality sample, the larger compression in recompression process indicates the higher disturbance and higher value of c_v in overconsolidation range from the IL test.

According to the Vietnamese conventional criterion, the sampling is at 2 m per soil sample, the soil samples aren't continuously taken in the investigation. For the sub- to inter-tidal flat and delta front sediments, how many thin sand seams insert into the clayey layer, and how many millimeters are their thicknesses. Thereby, the rate of consolidation settlement estimated by the Vietnamese conventional standard oedometer consolidation test, IL, cannot be accurately assessed. Therefore, it needs to study larger sizes of specimens for this matter; this way may be to appreciably suffer fewer disturbances to the microfabric than do small specimens (60 mm diameter and 20 mm thickness).

All the N values of the SPT results on homogeneous and inhomogeneous soil layers are not clearly different at the Vinhlong, Caolanh, Bentre-1, Bentre-2, and Bentre-3 sites as discussed in 5.2 (Fig. 5.1). The N values cannot represent the small variations of the strengths accurately, precisely and continuously observed by the CPTU on the late MD Pleistocene-Holocene sediments. The SPT tests are always alternated with sampling in the same borehole at per 1 m in distance. The falling of the hammer with 63.6 kg in weight will disturb the soil

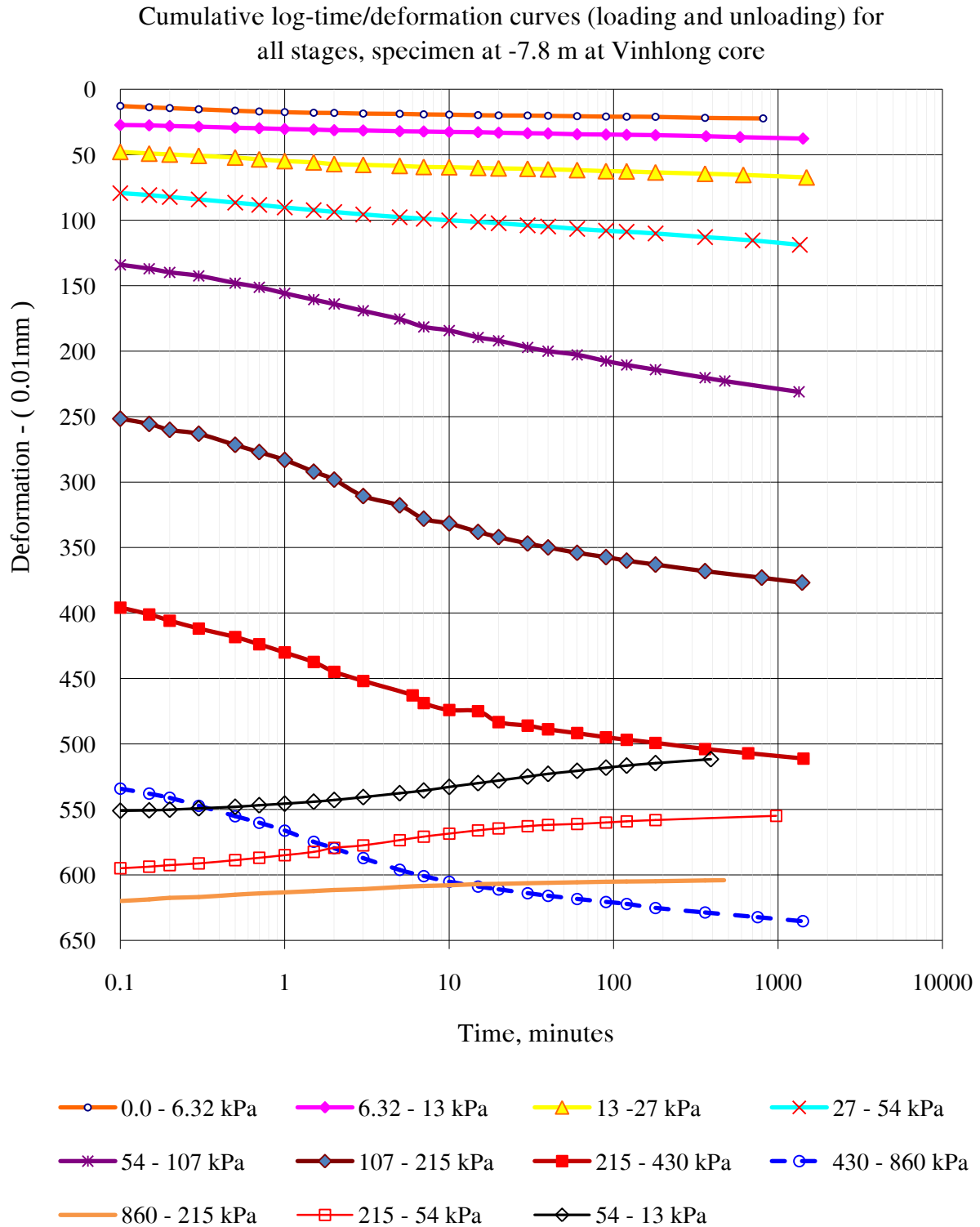


Fig. 6.9.1. Cumulative log-time/deformation curves for all stages
from IL test of typical clay specimen at – 7.8 m Vinhlong core.

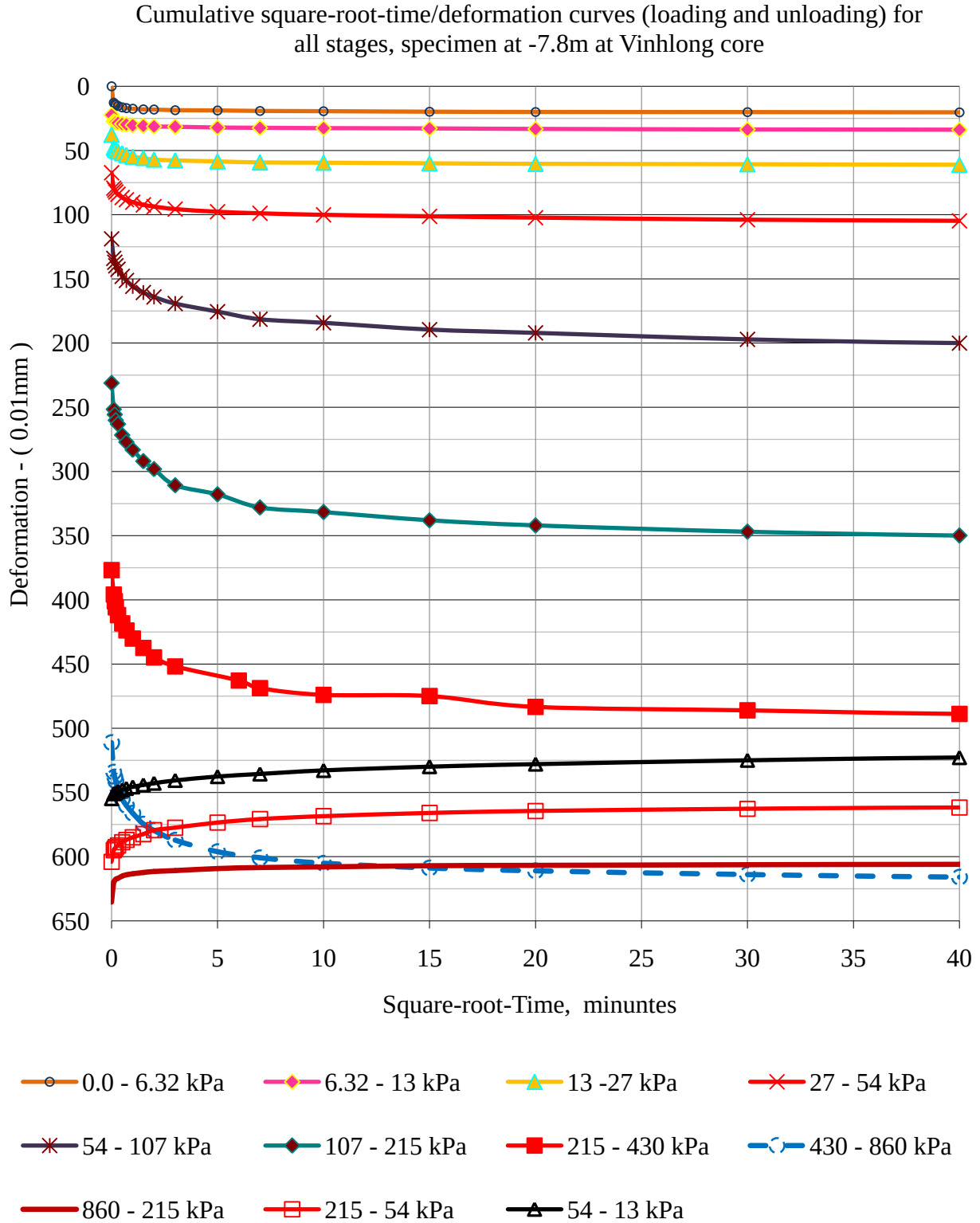


Fig. 6.9.2. Square-root-time/deformation curves for all stages
from IL test of typical clay specimen at – 7.8 m Vinhlong core.

sublayer and lead the low quality of soil samples. Specially, for the delta front and sub- to inter-tidal flat sediments, it is easily to phenomenon of flowing sand and disturbance caused by influence of the hammer blows. In addition, the SPT test is difficultly carried out and it takes much time in the MRD condition. For these reasons, the SPT test shouldn't be used for the MRD late Pleistocene-Holocene sediments.

6.5. Rational investigation procedure

The investigation procedure should be as: To draw up an investigative plan layout with small scale based on the construction-position and the collecting data of geotechnical engineering, engineering geology, and sedimentary geology. The CPTU tests should be firstly conducted to define the geotechnical structure types in the investigative zone. After the first investigation, to modify again the investigative plan layout with a greater scale. To add positions of sampling boreholes, CPTUs, and pore pressure dissipation tests into the investigative plan layout. And then, to define amount and kinds of lab consolidation test for each soil sublayer in the specific geotechnical structure type based upon the results of the CPTU in the first investigation.

Sampling method, which should be used, is the hydraulic type thin-walled tube sampler with a fixed piston. The soil samples should be contained in the wooden boxes with soft materials and keeping in the moisture condition. Both IL and CRS tests should be used. The IL tests should be begun with a minimum incremental load in range of 3.2 to 6.32 kPa.

The in situ- and lab-consolidation tests with large size of specimen should be further studied for MRD sediments.

6.6. Comparison with other deltas about geotechnical properties

As presented in item 2.3.2 about the late Pleistocene-Holocene sediment facies of the MRD, the Mississippi delta (Heinrich, 2005) and Arno delta (Giovanni et al., 2012).

The geotechnical properties of the late Pleistocene-Holocene sediment sequences of the MRD in this study will be compared with those of the Mississippi delta (Heinrich, 2005) and Arno delta (Giovanni et al., 2012). The geotechnical results of the MRD of this study and the geotechnical data of the Mississippi delta(Heinrich, 2005) and the Arno delta (Giovanni et al.,

2012) are summarized in Tab. 6.3. Values of compression indexes, C_c , are estimated based upon the expression of Terzaghi and Peak (1967): $C_c = 0.009 (w_L - 10)$ for the sediments of the MRD and Mississippi delta (Heinrich, 2005) in this item. Since the compression indexes of the Arno delta sediments were estimated according to this expression by Giovanni et al. (2012).

The content of this part is to discuss about (1) characteristics of physics, state, and mechanical properties, (2) compressibility and settlement, and (3) soil structures and foundations, of the transgressive incised-valley fill sediment succession including bay facies, and the Holocene delta sediment succession including prodelta, delta front, sub- to intertidal flat/intertidal flat, flood plain/marsh, and natural levee facies.

(1) Bay facies

The bay facies in the MRD and Arno delta (Giovanni et al., 2012) are relatively similar about thickness, high homogeneity, and mechanical parameters that represented in Tab. 6.3. The period of appearance of them are close, from 8,500 to 5,000 yr BP. Values of cone resistance, q_c , are low, from 0.5 to 0.9 MPa; compressibility potentials, C_c , are high, from 0.56 to 0.65 (Tab. 6.3). Evidently, there are slightly differences between them; it is due to source of materials and condition. The geotechnical properties of the bay facies in the Mississippi delta are so different with those of the bay facies in the MRD and Arno delta (Giovanni et al., 2012) (Tab. 6.2). The clay of the bay facies in the Mississippi delta are underconsolidated; and the liquid limit, w_L , plasticity index, PI, and compression index, C_c are too high, from 0.45 to 1.35. But, values of q_c are commonly too low, from 0.15 to 0.3 MPa and maximum value is rarely 0.5 MPa (Heinrich, 2005). The causes may be due to the bay facies in the Mississippi delta were formed in the latest period (less than 4,800 yr BP), in the interdistributary bays, and so close to the ground surface (Heinrich, 2005) in comparison with the bay facies of the MRD and Arno delta (Giovanni et al., 2012).

In general, the bay facies in three deltas have high deformability and low strength, especially in the Mississippi delta. And their thicknesses are too large and vary largely (Tab. 6.3). So the bay facies are unsuited for foundation or pilings of heavy structures.

Table 6.4.

Comparison the geotechnical results of the MRD and data of Mississippi (Paul, 2005) and Arno deltas (Giovanni et al., 2012).

	Facies	Deltas	Ages	Altitude of appearance	Thick of facies	Soil classification	Homogeneous levels	Consolidated levels	Physical characteristics		State parameters						Mechanical parameters	
			(yr BP)	(m)	(m)				w _L (%)	w _p (%)	w _n (%)	S _r (%)	e ₀	γ _n (g/cm ³)	I _p (%)	I _c	c _c	q _c (MPa)
Holocene delta sediments	Natural levee	MRD	< 2,000	2.9	3.4	CH, CI, MH-V	Medium	Heavy overcons.	44-79	22-52	29-52	98	0.84	1.62-1.95	18-30	0.3-0.7	0.3 to 0.5	0.7-1.1
		Arno																
		Mississippi	< 1,800	from +3.6 to +11	3.6-6	CH, CL, ML	Medium	Heavy overcons.	35-75		20-30						0.2 to 0.6	0.8-1.2
	Flood plain/ Marsh	MRD	< 3,500	from +2 to -0.5	2-4 Max: 32	CH, CI	Homogeneous	Normal, slight overcons.	46-63	25-29	31-70	99-100	1.1-1.62	1.5-1.75	19-35	from -1 to 0.1	0.3 to 0.5	0.1-2.52 surface: 0.9-1.2
		Arno	< 2,000	from 0 to -2	1.5-7	CI, rarely MI	Homogeneous	Slight-medium overcons.	29-52	22-28	23-31		0.79-0.81	1.32-2.52	6.5-26.5	0.6-1	0.1-0.3	0.9-3
		Mississippi	< 4,000		1.5-3; 2.4-3.6	OH; PT, OH	Homogeneous		60-150 70-250		60-200 80-800				30-60	0 to -0.6	0.45-1.3 0.6-7.1	0.2-0.68
	Sub-to intertidal flat or Intertidal flat	MRD	3,500-800	from 0 to -3.6	3-9.5	CI, MI-H	Low-medium	Normal, slight overcons.	40-58	19-32	29-71	98-100	1.2-1.5	1.6-1.76	11-25	from -0.6 to 0.1	0.27-0.43	0.1-0.3 Sand: 4.6-6.25
		Arno	< 4,000	from -1 to -3	3.5	CI-H, MI rarely: ML	Low-medium	Slightly overcons.	32-52	21-28	23-35	99.7	0.5-0.7	1.5-2.1	8.9-26.9	0.4-1	0.22-0.4	0.5-1.3 sand: 1.5-2
		Mississippi																
	Delta front	MRD	6,800-1,100	from -4 to -13.1	from 4.5 to 13.9	CL, CI, CH, CV,	Unhomogeneity	Normal, slight overcons.	48-63	21-28	43-72	100	1.2-1.9	1.54-1.75	25-35	from -0.7 to 0.1	0.34-0.48	0.23-0.78 Sand: 9.7-13
		Arno	< 6,000	from -2 to -6	from 1 to 8	Sand	Unhomogeneity				22-38	87.86	0.5-1.7	1.65-1.93				1.5-3, rarely: >3
		Mississippi	< 4,800	from -4 to -8	from 2 to 11.3	CH, CL: ML:	Unhomogeneity	Normal consolid.	35-110 30		30-40 15-30				15-60 10		0.23-0.9 0.18	
	Prodelta	MRD	8,000-4,000	from -13.7 to -21.9	from 3 to 10	CL-I, MI	Homogeneous	Normal, slight overcons.	22-50	18-29	18-52	98-100	1.43	1.65-1.97	2 to 27	from -0.1 to 0.9	0.11 to 0.36	0.33-0.85 Sand: Max 7.15
		Arno	5,000-2,000	from -5 to -9	from 2 to 5	CI-H, rarely: CL, CV, MH	Homogeneous	Normal, slight overcons.	38-63	21-31	29-55	100.6	0.82-0.98	1.6-1.84	16.5-34.3	0.4-0.8	0.3-0.5	< 0.8 rarely: < 1
		Mississippi	< 4,800	from -14 to -21.3	from 4 to 9.1	CH	High homo.	Normal, slight over.	70-120	25-80	40-80				30-40		0.54 to 0.99	0.2-0.6 0.9-1.3
Transgressive incised-valley fill sediments	Bay	MRD	8,500-5,000	from -20 to -24.5	3 to 15.95	CV	High homo.	Normal, slight over.	72-82	24-28	16-42	98-100	1.1 to 1.33	1.73 to 1.78	47 to 53	1.0 to 0.2	0.56 to 0.65	0.53-0.9
		Arno	8,000-6,000	from -8 to -15	from 3 to 12	CV, CH, MH, rarely: MV	High homo.	Normal, slight over.	59-78	26-38	40-64	96.5-103.3	1.2-1.6	1.4-1.75	30-44	0.2-0.6	0.4-0.6	0.5-0.8
		Mississippi	< 4,800	from -2.4 to -6	from 9 to 15	CH	Highhomo.	Undercon.	60-160		50-160				30-75		0.45-1.35	0.15-0.3 Max: 0.5

(2) Prodelta facies

The prodelta facies in the MRD, Mississippi delta (Heinrich, 2005), and Arno delta (Giovanni et al., 2012) are similar about normal consolidation to slight overconsolidation and homogeneity (Tab. 6.3). However, the prodelta facies of these deltas were interrupted by the thin sand or silt layers, especially in the upper part of the prodelta facies. Therefore, the homogeneous level of the prodelta facies is less than those of the bay facies of these deltas. The prodelta facies of the MRD and Arno delta are so similar. The values of cone resistance, q_c , of the prodelta facies in the MRD and Arno delta are generally regular and low. The q_c values of the cohesive soils of the prodelta facies in the MRD and Arno delta are from 0.2 to 0.85 MPa (Tab. 6.3). The maximum values of q_c of the thin sand or silt layers of the prodelta in the Arno delta are lower than 1 MPa. But, the maximum values of q_c of the silt or sand layers of the prodelta facies in the MRD can obtain 7.15 MPa. The q_c values of the cohesive soil of the deeper part of the prodelta facies in the Mississippi delta can obtain from 0.9 to 1.3 MPa, which are so greater than those of the MRD and Arno delta. The compressibility potentials of the prodelta facies of these three deltas are generally high. And they increase in ordering from the prodelta facies in the MRD (C_c : 0.11-0.36), the prodelta facies in Arno delta (C_c : 0.3-0.5), and the prodelta facies in Mississippi delta (C_c : 0.54-0.99) (Tab.6.3). It means the settlements of the prodelta facies of these three deltas are high, and also increase in this ordering.

As the above discussions in items 4.4, 4.5, and 5.2.2.1, and based upon the data of the Mississippi delta (Heinrich, 2005) and Arno delta (Giovanni et al., 2012), we can also realize that an influence of the marine regression on the geotechnical properties of the prodelta facies in these two deltas is rather clear. It is indicated the increase of the strengths and cohesionless soil-behavior seams by the increase of the thin sand layers and grain size with altitude-increase in the Arno delta and Mississippi delta. The thicknesses of the prodelta facies of these deltas are relatively large (Tab. 6.3). Simultaneously, they appeared close to the ground surface in sphere of activity of foundations of structures and roads. Therefore, the prodelta facies of these three deltas are not good condition for floating foundations or pilings of heavy structures.

(3) Delta front facies

The delta front facies in the MRD, Mississippi delta (Heinrich, 2005), and Arno delta (Giovanni et al., 2012) are similar, all of them are normal consolidation and unhomogeneity

(Tab. 6.3). The q_c of the cohesive soil in the delta front facies of three deltas are low and also lower those of the cohesive soil in the prodelta (Tab. 6.3). The characteristics of geotechnical structure of the delta front facies at the VLM1 core site in the MRD and Mississippi delta are so similar about intercalation of the thin cohesive soil layers. The delta front facies at the VLM1 core site in the MRD and Mississippi delta (Heinrich, 2005) are high inhomogeneity. Because they occurred in the river-mouth environment that created the silty sand mouth bars in the delta front facies. The characteristics of structure of the delta front facies at the CLM1 core site in the MRD and Arno delta are so similar about an increase of sand content and grain size. The mechanical behaviors of the delta front facies of the CLM1 core site in the MRD and Arno delta are almost sand and more homogeneity than those of the delta front facies of the VLM1 core site in the MRD and Mississippi delta (Tab.6.3).

In general, the mechanical behavior types of the delta front facies of three deltas tend to be cohesionless soils. The cohesive soils in the delta front facies are large deformability and low strengths. The geotechnical properties of the delta front facies vary complexly. The delta front facies are too unhomogeneous.

(4) Sub- to intertidal flat or intertidal flat facies

The sub- to intertidal flat or intertidal flat facies was only found in the MRD and Arno deltas (Giovanni et al., 2012). This facies of these two deltas are very similar about homogeneity level, physical characteristics, and compression indexes, C_c , (Tab. 6.3). The period of appearance of them is in same time, from 4,000 to 800 yr BP. Obviously, there are still slightly differences between them. Values of cone resistance, q_c , of cohesive soil in these facies of the MRD are very low, from 0.1 to 0.3 MPa, but those of the Arno delta are high, from 0.5 to 1.3 (Giovanni et al., 2012). In sharp contrast, values of cone resistance, q_c , of sand soil on these facies of the MRD are very high, from 4.6 to 6.25 MPa, but those of the Arno delta are too low, from 1.5 to 2 MPa (Giovanni et al., 2012) (Tab. 6.3). In general, the mechanical behaviors of these facies in the MRD and Arno deltas (Giovanni et al., 2012) are also similar with rhythmical alternation of the cohesion and cohesionless soil-layers. Their deformability potential and geotechnical strength are intermediate features.

(5) Flood plain/marshfacies

The flood plain/marsh facies of the MRD, Arno delta (Giovanni et al., 2012), and Mississippi delta (Heinrich, 2005) have general characteristics about homogeneity. The mechanical behavior types of the flood plain/marsh facies of three deltas are cohesive soils. They contain high organic contents. Specially, the organic contents of this facies in the Mississippi delta are so large (Heinrich, 2005). As a result, the natural water contents are the highest, 60-200% for the swamp sediments which border the natural levees of the Mississippi River and Bayou La Loutre, and 80-800% for the marsh sediments within the delta plain between Lake Borgne and the natural levees of the Mississippi River and Bayou Loutre (Heinrich, 2005). Values of cone resistance on the flood plain/marsh facies are greater than those of the underlay sub- to intertidal flat/intertidal flat facies in the three deltas (Tab. 6.3). The q_c values of the flood plain/marsh facies in the Mississippi delta are the lowest, from 0.2 to 0.68 MPa. The q_c values of the flood plain/marsh facies in the MRD are intermediate; they increase regularly with depth, from 0.1 to 2.52 MPa; and on the upper part of the flood plain/marsh facies are from 0.9 to 1.2 MPa. The q_c values of the flood plain/marsh facies in the Arno delta are the largest, from 0.9 to 3 MPa. The physical characteristics (w_L and w_L) and compression indexes (C_c) of the flood plain/marsh facies in the MRD and Arno deltas are similar but those of the Mississippi delta are very large (Tab. 6.3). The high organic-matter contents can make the values of q_c of the facies in the MRD and Mississippi delta (Heinrich, 2005) be low. In contrast, the flood facies in the Arno delta contained the calcareous pedogenic nodules, iron and manganese oxides, and low organic-matter content are to cause the largest values of q_c (Giovanni et al., 2012). Simultaneously, w_n and e_0 decrease, and γ_n increases in the flood facies in the Arno delta (Giovanni et al., 2012) (Tab.6.3). This phenomenon also occurred in the upper part of the flood plain/marsh facies in the MRD but weaker than those of the Arno delta. The flood plain/marsh facies in the Arno delta are classified as sediments with low deformability potential and high geotechnical strength (Giovanni et al., 2012). The strength of the flood plain/marsh facies in the MRD is intermediate. And the strength of the flood plain/marsh facies in the Mississippi delta reveal too low and the deformability potential is high (Heinrich, 2005).

(6) Natural levee facies

The geotechnical properties (Tab. 6.3) and spatial distribution of the natural levee facies in the MRD and Mississippi delta are similar. The natural levees present along the Mekong and

Mississippi rivers. Typically, these natural levee sediments are heavy overconsolidation, strengths are high, and compressibility potentials, C_c , are relatively low (Tab. 6.3) (Heinrich, 2005). The natural levee facies provide relatively favorable foundation conditions for light structures as roads. The strengths, grain size, and thickness of the natural levee facies decrease away from it crests towards where they merges with surrounding delta plain and depth. It means the advantage for the construction of structures and reconstruction of critical infrastructure will also decrease this way. The natural levees in the MRD cover on the flood plain and intertidal flat cohesive sediments with low strengths. The arrangement of these soil layers is not good conditions for heavy foundation that will likely require the use of pilings, floating foundations or other engineering techniques. This geotechnical structure is similar with those within St. Bernard Parish in the Mississippi delta. In contrast, the natural levees with 6 m in thickness overlie the sandy point bar deposits within La Loutre of the Mississippi River; where provide the relatively stable locations for the construction of the heavy structures and reconstruction of critical infrastructure (Heinrich, 2005).

* In general, the geotechnical properties of the late Pleistocene-Holocene sediment sequence in the MRD, Arno delta (Giovanni et al., 2012), and Mississippi delta (Heinrich, 2005) have same changes. These changes of the geotechnical properties are also according to the changes of sedimentary environment. Namely:

The incised-valley fill sediment succession formatted in the marine transgression environment with low energy revealed the mechanical behavior of the cohesive soils. The mechanical behavior of the cohesionless soil began to appear in the upper part of the prodelta facies; which indicate the gradual change from the marine transgression to the marine regression environment. The clearest appearance of the mechanical behavior of cohesionless soil is in the delta front facies formatted in the marine regression with high energy.

The maximum values of q_c in the late Pleistocene-Holocene sediment sequence in the MRD, Arno delta (Giovanni et al., 2012), and Mississippi delta (Heinrich, 2005) are such as: The maximum values of q_c of the cohesive soil obtained 3 MPa in the flood plain facies in the Arno delta (Giovanni et al., 2012). And the maximum values of q_c of the cohesionless soil obtained 13 MPa in the delta front facies in the MRD.

The geotechnical characteristics and the stratigraphy including five upper sediment facies in the MRD and Arno delta (Giovanni et al., 2012) are so similar; which the matter was also

confirmed by Giovanni et al. (2012). The complex levels of the geotechnical properties and structure of the MRD late Pleistocene-Holocene sediment sequence could be higher than those of the Arno delta (Giovanni et al., 2012).

The all sedimentary facies in these three deltas, only bay facies in the Mississippi delta is underconsolidation (Heinrich, 2005). The liquid limits of the Mississippi delta except the natural levee sediments are very high (Heinrich, 2005) (Tab. 6.3).

6.7. Conclusion of chapter 6

The general preliminary soil structure model was constructed with three main broad soil layers including the surface sediment facies, shallow sediment facies, and deep sediment facies corresponding with three consolidation-cases. The soil structure model was divided into six typical soil structure types based upon the thickness and arrangement of three main layers.

In infrastructure construction the specific consideration of six soil structure types is required for medium to very high for the heavy structure. The heavy structures need the use of pilings for six soil structure types. Especially, the first to fourth types of soil structure need deep pile foundation.

The zones between the Mekong and Bassac Rivers and center area of the MRD like the IMN and ILB sections have all six soil structure types; the thicknesses of the late Pleistocene-Holocene sediments are large and varied, and the mechanical behavior changes complexly. These areas may need more care about the construction for the heavy structure.

In the coast zone like QP section: the thicknesses of the late Pleistocene-Holocene sediments are relative small and regular (from 15 to 22 m); and there are only two soil structure types (types 5 and 6). The coast zone has some concerns for heavy structure construction, in the seashore, large estuaries, high ground water table, and exists in the part of the incised-valley which causes the difficulty in construction work.

The areas having the natural levee facies or sand dune facies has some advantage for the light structure but they are not popular in the MRD. The mechanical behavior of the late Pleistocene-Holocene sediment ground may decrease in complexity according to the perpendicular directions with both Mekong and Bassac Rivers, from their banks into the inners.

Consolidation settlements and time are very different depending on the type of facies.

Therefore soil structure model of MD can be used for predicting potential problems at a particular construction site.

As a rational geotechnical investigation procedure for the MRD late Pleistocene-Holocene sediments, the following are recommended: 1) to draw up an investigative plan layout with a small scale based on the construction-position and collected data of geotechnical profile, engineering geology, and sedimentary geology of the MRD late Pleistocene-Holocene sediments. 2) To Conduct preliminary CPTU tests to define the concretely geotechnical structure types. 3) After the first investigation, to modify the investigative plan layout with a greater scale, and added positions of sampling boreholes, CPTUs and pore pressure dissipation tests. 4) And then, to define kinds of the lab consolidation tests for each sublayer in the specific geotechnical structure type in the geotechnical profile by the CPTU tests in the first investigation. The sampling method is the hydraulic type thin-walled tube sampler with a fixed piston. Special care should be made in the entire process of soil investigation to secure the quality of test results. For example, the hammering in the sampling should be avoided for the deep stiff layer. But it is unavoidable, it should be reported. The soil samples should be contained in the wooden boxes with soft materials and watering. Not only IL tests but also CRS tests are recommended for the consolidation tests, which begin from a small pressure so that the effects of structure can be examined more precisely.

The undrained strength tends to be significantly underestimated by unconfined compression tests for delta front facies and deep sediment, e.g., estuary channel, due to high sensitivity and low sample quality respectively.

The geotechnical properties of the late Pleistocene-Holocene sediment sequence in the MRD, Arno delta (Giovanni et al., 2012), and Mississippi delta (Heinrich, 2005) have same changes. These changes of the geotechnical properties are also according to the changes of sedimentary environment. The incised-valley fill sediment succession formatted in the marine transgression environment with low energy revealed the mechanical behavior of the cohesive soils. The mechanical behavior of the cohesionless soil began to appear in the upper part of the prodelta facies; which indicates the gradual change from the marine transgression to the marine regression environment. The clearest appearance of the mechanical behavior of cohesionless soil is in the delta front facies formatted in the marine regression with high energy. The q_c maximum value of the cohesive soil obtained 3 MPa in the flood plain facies in the Arno delta (Giovanni et

al., 2012), and of the cohesionless soil obtained 13 MPa in the delta front facies in the MRD.

The geotechnical characteristics and the stratigraphy including five upper sediment facies in the MRD and Arno delta (Giovanni et al., 2012) are so similar. The complex levels of the geotechnical properties and soil structure of the MRD late Pleistocene-Holocene sediment sequence could be higher than those of the Arno delta (Giovanni et al., 2012). The liquid limits of the MRD late Pleistocene-Holocene sediments are very less than those of the Mississippi delta except the natural levee sediments and only bay sediment in the Mississippi delta is underconsolidation (Heinrich, 2005).

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

The sedimentary section was rebuilt in the evolving-direction of the Mekong Delta in two main types of delta formation mechanisms being the tide-dominated delta and tide- and wave-dominated delta. The core sites in this study sufficiently presented the sedimentary facies of the MD region. The successive sediment facies were identified based upon sedimentary properties. The characteristics of the unit showed development of sedimentary facies. Each sedimentary facies was formed under a different environment and condition. On the other hand, the geotechnical profiles at these sites were also identified and divided into the sublayers based on the geotechnical results of the in-situ tests and the lab tests. The characteristics of the geotechnical properties of the sublayers were collated with the sedimentary facies.

The changes in the MD late Pleistocene-Holocene sedimentary facies are sedimentary successions with trends of fining upwards in the transgression and coarsening upwards in the regression. The late Pleistocene-Holocene sediments unconformably overlay the undifferentiated Pleistocene sediments with over 40,000 yr BP.

They concretely consisted of (1) the transgressive incised-valley fill sediments deposited between 13,300-6,400 yr BP, which included estuarine channel, salt marsh/tidal flat, estuarine marine, sub- to inter-tidal flat and bay facies; and (2) the regressive Holocene delta sediments deposited between 6,400-0,0 yr BP, which include pro-delta, delta front-mouth bar or delta front, sub- to inter-tidal flat or intertidal flat facies, and flood plain or marsh, and sand dune, and/or natural levee facies.

The following conclusions are derived from this study

7.1.1. Influence of sedimentary environment on geotechnical properties

The results indicate that there is a close relationship between the sedimentary facies and

geotechnical properties. Therefore, it can be concluded that the sedimentary environments significantly affect the formation of materials, macro- and micro-structure, and orientation of properties each sedimentary facies.

The results allow the identification of soil properties and estimation of the general tendencies of the mechanical behavior of soils of the MD region in the context of geotechnical engineering. From previous sedimentary profiles, we can guess the mechanical behavior. The particular sedimentary conditions in the late Pleistocene-Holocene deposits can be reasonably estimated by CPTU.

Not only the vertical direction but also horizontal direction, the significant change of soil profile is one of main geological features of MD. The soil behavior type at the same altitude in the facies appeared quite different by CPTU. But, the main characteristics of the general tendencies of the mechanical behavior of each specific facies still don't change. The N by SPT cannot represent the small variation of the penetration resistance precisely, accurately, and continuously which can be observed by CPTU on the MD late Pleistocene-Holocene sediments. The N values have only clear differences between the late Pleistocene-Holocene sediments with the undifferentiated Pleistocene sediments.

However, each sublayer has specific features estimated by CPTU, which show the better correlation between geological sedimentary environment and geotechnical properties than other words. CPTU could be used for geological investigation, especially for the sediment with very complicated and heterogeneous conditions of the MD.

The estuarine channel, estuarine marine, delta front or delta front-mouth bar, and sub- to inter-tidal flat facies, which were formed under strong hydrodynamic conditions, have various sedimentary structures and material. As a result, their soil-behavior-types vary largely and their formed sequences of the geotechnical properties are similar to the characteristics of sedimentary structures with inhomogeneity. Especially, the delta front and delta front-mouth bar facies were formed under extremely strong hydrodynamic conditions, near the main Mekong River; hence, their sedimentary properties are so inhomogeneity. As a result, the mechanical behavior of the delta front and delta front-mouth bar facies shows great variability, as shown by CPTU results.

The marsh, marsh/tidal flat, sub- to inter-tidal flat (in the transgression), bay, pro-delta, intertidal flat, and flood plain facies were formed under low hydrodynamic conditions. They are homogeneous, and their strengths increase linearly with depth. Specially, the marsh, bay, and

flood plain facies are highly homogeneous. In this case, may combine with the plasticity chart in identifying exactly characteristics of sedimentary facies because each sedimentary facies has typical components of clay mineral species.

7.1.2. Influence of delta formation mechanism on geotechnical property sequence

Each succession of sedimentary facies was formed under a different delta formation mechanism and revealed a typical geotechnical property sequence from the prodelta to sand dune facies. The particular tendency of the mechanical behavior of the sedimentary succession can be reasonably estimated from the delta formation mechanism. The sediments are in the tide- and wave-dominated delta whose mechanical behavior sequence tends to be more cohesionless soils than those in the tide-dominated delta. And the coastal sediment significantly dominated by wave its mechanical behavior sequence tends to be almost cohesionless soils. The delta front facies in the tide-dominated delta with significant fluvial-activity and material-supply its mechanical behavior sequence is cohesionless soils but the mechanical behavior sequences of the surface facies are cohesive soils.

The illite mineral content is the highest (over 44%) in all the facies. The contents of clay mineral types of the all sedimentary facies were generally in descending order from the illite, kaolinite, chlorite, smectite. The illite content in the natural levee facies is largest (over 70%) in comparison with the illite contents in the other facies. These characteristics of the clayey minerals and grain-sizes of the source of material supply from the Mekong River system and their move-possibility produced the plasticity with being not extremely high.

7.1.3. Characteristics of consolidation

The consolidation characteristics can be relative to the microstructure development-levels. In general, the MD late Pleistocene-Holocene sediments are normal consolidation to overconsolidation. The overconsolidations were by the cement, ageing, and recrystallization of minerals; consequently, we should use the terms the *yield stress ratio* for OCR and *yield stress* for preconsolidation pressure. Their microstructure is a combination of “fabric”, “bonding”, and “*recrystallization*”. The microstructure development-levels at surface and deep depth sediments

are medium to very high, while at shallow depth (delta front facies) the level is low to medium. Which level can be correlated to k values for estimating OCR by CPTU.

Furthermore consolidation properties in the MD late Pleistocene-Holocene sediments can reasonably be estimated by CPTU. The void index and the swelling sensitivity can be related to sediment conditions of the MD natural soils.

The surface sediment facies including natural levee, flood plain, intertidal flat, and sub- to intertidal flat facies are from slightly overconsolidated to heavy overconsolidated by the dehydrating and oxidizing processes by contacting the solar energy and air. Especially, the natural levee sediment is heavy overconsolidation; the development-level of microstructure is high to very high. Hence, k values should be 0.5 to 0.35 for calculating OCRs from CPTU test for the natural levee sediment. A formation-mechanism of the flood plain sediment is similar with those of the natural levee sediment. But the grain sizes and illite content of the flood plain sediment are often smaller than those of the natural levee sediment. As a result, the development-levels of microstructure of the flood plain sediment are medium to high. For the intertidal flat facies and sub- to intertidal flat facies, the materials were settling down in the tide went up. And then, when the tide went down this sediment seam directly contacted with sunshine and air; the lightly oxidizing and dehydrating processes would occur in them. As a result, the development-levels of microstructure in the intertidal flat and sub- to intertidal flat sediments are medium to high. The development-levels of microstructure of the sediments in the upper delta plain are slightly higher than those in the lower delta plain by differences about the source of material supply, fluvial and tidal and wavy influences, and age between them. So, k values for the flood plain/marsh, intertidal flat, and sub- to intertidal flat sediments in the upper delta plain should be 0.35-0.2 and in the lower delta plain 0.25 to 0.2.

The shallow sediment facies is the delta front facies with “alternate-structure of cohesionless seam and cohesive seam”. The microstructure development-levels of the shallow sediment in the lower delta plain with age less than 4 ka BP are low and k value should be 0.2. The sediments in the upper delta plain with age 4 to 7 ka BP are medium and k values should be $0.2 \div 0.3$.

The deep sediment facies include the prodelta, bay, estuarine marine, sub- to intertidal flat, marsh, marsh/tidal flat, and estuary channel facies. The development-levels of microstructure are from medium to very high in ascending the prodelta, bay, sub- to intertidal flat, marsh/tidal flat, and estuary channel sediments. The recrystallization of minerals tends to increase from the

prodelta to estuary channel facies. The k values should be $0.4 \div 0.3$ for the prodelta and bay sediments in the upper delta, and 0.3 for the prodelta and bay sediments with age less than 5.6 ka BP in the lower delta plain. The marsh and marsh/tidal flat facies at the great depth, from 8.88 to 13.258 ka BP, and strong recrystallizations resulted their microstructure-developments are from high to so high; hence, k values should be 0.45 to 0.4. For the estuary channel sediments, k values should be 0.5 to 0.45 because they have been at the greatest depth, more than 9,910 yr BP, and the strongest recrystallization.

7.1.4. Soil structure models and advantage and disadvantage for infrastructure construction

The soil structure model includes 6 typical soil structure types, which could provide a first estimation of potential geotechnical problems in the infrastructure construction in the MD.

The most common and dominant facies in the MD soil structure model is delta front. As the mechanical properties of the soil in this facies is very complicated, there need a special care for the soil investigation on the soils in this facies.

The general preliminary soil structure model is with three main broad soil layers including the surface sediment facies, shallow sediment facies, and deep sediment facies. The soil structure model was divided into six typical soil structure types based upon the thickness and arrangement of three main layers.

In general, the disadvantages of six soil structure types are from medium to very high for the heavy structure. The heavy structures require the use of pilings for six soil structure types. Especially, the first to fourth types of soil structure need to use the deep pilings.

The zones between the Mekong and Bassac Rivers and center area of the MD have sufficiently six soil structure types; the thicknesses of the late Pleistocene-Holocene sediments are large and varied; and the mechanical behaviors change complexly. These areas could seem like high to very high disadvantage for the heavy structure.

In the coast zone: the thicknesses of the late Pleistocene-Holocene sediments are relative small and regular (from 15 to 22 m); and there are only two soil structure types (types 5 and 6). The coast zone may be medium disadvantage for heavy structure but in the seashore, large estuaries, high ground salt water table, and exists in the part of the incised-valley which causes

the difficulty in construction work.

The areas having the natural levee facies or sand dune facies have low to medium advantage for the light structure but they are not popular in the MD. The mechanical behaviors of the late Pleistocene-Holocene sediment ground may decrease in complexity according to the perpendicular directions with both Mekong and Bassac Rivers, from rivers' banks into the inners.

7.1.5. Rational investigation procedure

As a rational geotechnical investigation procedure for the MRD late Pleistocene-Holocene sediments, the following are recommended: 1) To draw up an investigative plan layout with a small scale based on the construction-position and collected data of geotechnical profile, engineering geology, and sedimentary geology of the MRD late Pleistocene-Holocene sediments. 2) To Conduct preliminary CPTU tests to define the concretely geotechnical structure types. 3) After the first investigation, to modify the investigative plan layout with a greater scale, and added positions of sampling boreholes, CPTUs and pore pressure dissipation tests. 4) And then, to define kinds of the lab consolidation tests for each sublayer in the specific geotechnical structure type in the geotechnical profile by the CPTU tests in the first investigation. The sampling method is the hydraulic type thin-walled tube sampler with a fixed piston. Special care should be made in the entire process of soil investigation to secure the quality of test results. For example, the hammering in the sampling should be avoided for the deep stiff layer. But it is unavoidable, it should be reported. The soil samples should be contained in the wooden boxes with soft materials and watering. Not only IL tests but also CRS tests are recommended for the consolidation tests, which begin from a small pressure so that the effects of structure can be examined more precisely.

7.2. Recommendations for future study

Based upon the discussions in this study some matters have not still been pointed out clearly. They may be suggested to be made in the future study such as:

1) Integrated investigation of the geotechnical engineering, sedimentary geology, and geophysics for finding their relationship on the MD late Pleistocene-Holocene sediments: The

aim of the integrated investigation is to apply their relationship for the identification of soil properties and estimation of the general tendencies of the mechanical behavior of soils of the MD region in the context of geotechnical engineering through the geophysical results. This application may decrease works in the geotechnical tests that the investigation report will be clearer than.

2) The geotechnical investigation with a larger scale for the preliminary soil structure model: The zones in the north, northwestern, and western parts of the MD should further be studied. Then, we will have a full geotechnical structure model for the entire MD region.

3) The lab-consolidation tests with large size of specimen, specially, for the sub- to intertidal flat and delta front sediments in the MD.

4) Study about exact amounts of diatoms joined in the microstructure and influence-levels on the consolidation properties according to variations of amounts of diatom in the MD late Pleistocene-Holocene sediments.

5) Further study about the sizes of space pore and exchangeable ions in soil for improving for the MD late Pleistocene-Holocene soil ground.

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