

SEA-LEVEL RELATED ENGINEERING GEOLOGY AND INTRINSIC COMPRESSION BEHAVIOUR OF BANGKOK CLAYS

*Krit Saowiang¹ and Pham Huy Giao¹

¹Geotechnical and Earth Resources Engineering Program, Asian Institute of Technology, Thailand

* Corresponding Author, Received: 26 Oct. 2018, Revised: 29 Dec. 2018, Accepted: 20 Jan. 2019

ABSTRACT: All the important infrastructures in Bangkok city are founded in soft, stiff to hard clay layers up to 80 m deep. The engineering properties of these clays depend a lot on their microstructure, which in turns is a result of geological conditions governing the deposition and subsequent geological processes of loading, unloading and weathering. Thus, a study of soil microstructure would help understand better the soil engineering properties to be used in geotechnical analyses. In this paper, a detailed review of sea level-related engineering geology of the depositional environment of Bangkok clays was made. Geotechnical boreholes were drilled at six testing sites as part of a groundwater recovery study project, from which samples of Bangkok clays were collected up to 80 m deep and tested. Based on the results of an integrated geological-geotechnical analysis the microstructure of Bangkok clays was indirectly investigated via their intrinsic compression behavior and in-situ state. It was found that the Soft Bangkok clay at depth 4-11m (SOCL) is a bonding-dominated or cemented clay with a meta-stable structure, whereas stiff clay at depth 12-24m (STCL), the first hard clay at depth 30-50 m (HCL01) and the second hard clay at 50-80 m (HCL02) are fabric dominated with a stable structure. On the plots of void index versus depth the in-situ state the Bangkok soft clay lie in the sedimentation compression range, the stiff clay and the first hard clay lie both in sedimentation compression and overconsolidated clay ranges, while the second deeper hard clay (HCL02) lies only in the overconsolidated clay range.

Keywords: Bangkok clays; Stiff and hard clays; Soil microstructure; Sea level change; Intrinsic compression behavior.

1. INTRODUCTION

In Bangkok city all important infrastructures such as high-rise buildings, tollways, sky trains and bridges, MRT lines etc. have been constructed on piles foundation crossing or resting on the clay layers up to 70 m deep as shown in Fig. 1. The Bangkok clays include soft, medium stiff, stiff and hard clay layers, among which the uppermost 20-m layer of soft Bangkok clay is the most popular one and has been extensively investigated over the past 50 years during the course of development and expansion of the modern Bangkok metropolitan area.

Despite the important role of the stiff and hard clay layers in supporting the increasingly higher and deeper structures in Bangkok studies on characterization of these clays are relatively few due to the difficulties in sampling and testing. The engineering behavior of the stiff & hard clays is also more complex to understand [1]. In the characterization of soft, stiff and hard clays, one often investigates the intrinsic compression to help to assess their natural consolidation and compression.

In addition, a basic understanding of geological controls on the geotechnical properties of soft and stiff clays is much needed. Burland [2], Burland et

al. [3], Cotecchia & Chandler [4], Chandler [5], and Simpson [1] studied the behavior of soft and stiff clays, considering the effect of geological origin and formation. The key characteristics for clays are sedimentation and post-sedimentation structure, which is developed as a result of geological processes occurring during and after normal consolidation. Burland [2] used the dataset from [6] to introduce the concept of compressibility and strength properties of reconstituted clay, which could provide with a useful framework of reference for understanding and interpreting the properties the parent natural clay.

Giao et al. [7] did a study on compressibility behavior of natural Bangkok soft clay, using the intrinsic compression concept. But, for stiff and hard Bangkok clays no study on their intrinsic compression has been done by now.

The purposes of this research are: (i) to investigate the possible relationship between geological history and geotechnical behavior of Bangkok clays; (ii) to study the compressibility behaviour of Bangkok clays based on the intrinsic properties framework and in-situ state pattern proposed by [2] and [8] that might be useful in further studying the possible effect of groundwater drawdown and recovery on Bangkok clay structures.

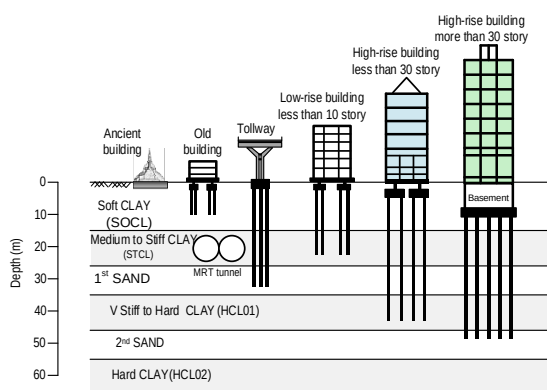


Fig. 1 The uppermost part of the Bangkok subsoil profile and types of common substructures

2. SEA-LEVEL RELATED GEOLOGICAL FORMATION OF BANGKOK CLAYS

The first reference marks for measuring sea level changes were established in 1682 at Amsterdam [9]. During the last glaciation about 21,000 years ago, sea level was much lower than at present, i.e., -120 ± 20 m [10]. The formation and evolution of the Lower Chao Phraya plain (also known as the Bangkok plain) have always been related to the sea level changes throughout geological history. Significant sea-level changes occurred during the Holocene [11]. The indicators of sea level changes from the Gulf of Thailand can be divided into geological and biological indicators such as tidal notches, sea caves, arches, shell and peats etc. The first study of middle Holocene sea-level changes in the Gulf of Thailand was done by [12], who concluded that the fluctuations of the sea level occurred twice, producing two levels of the high stand.

The first level at +5.0 m above the present mean sea level (MSL) was formed about 6,000 years BP (Before Present) and the second level of +3.0 m above the present MSL was about 4,000 years BP. Sinsakul [11] plotted the Holocene sea-level curve as shown in Fig. 2. Choowong [13] revised the middle Holocene sea-level changes in Thailand by a sea level envelop that shows a rapid rise of sea level from about -12 to +3.5 m above the present MSL until the middle Holocene (about 6,500 years ago) and then a gradual fall to the present MSL as seen in Fig. 2. The coastal landform around the Gulf of Thailand is characterized by a distinct sequence of beach ridges, lagoons with broad marsh plains and tidal flats [11]. The soft Bangkok clay had been deposited in a shallow marine environment during the transgression that reached as far as Ayutthaya approximately 70 km north of Bangkok as shown in Fig. 3a.

The low-lying Lower Chao Phraya plain is near featureless with elevation ranging from 0 to 2

meters above the mean sea level (MSL). It merges with a slightly higher alluvial plain at Ayutthaya. In general, topography of the Lower Chao Phraya plain reflects the fact that it was covered by a shallow sea, thus it could be viewed as a large bay fed by estuaries emerging from both the western mountain belt (Kanchanaburi) and the neck of the Lower Chao Phraya plain (at or near Ayutthaya) as shown in Fig. 3a.

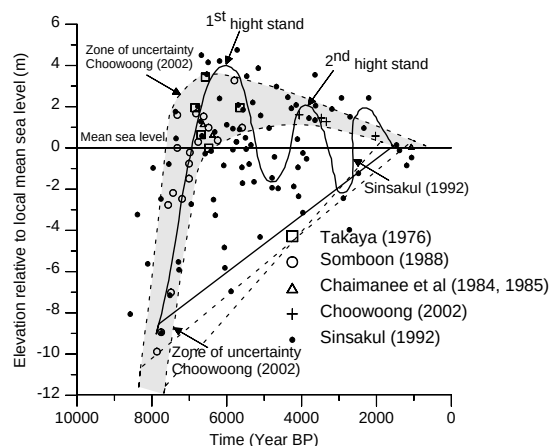


Fig. 2 Holocene sea-level curve for Thailand (Based on [11] & [13])

Bangkok soft clay had been deposited from 5,000 to 3,000 years ago. During most of Mid to Late Holocene, the plain was probably a vast tidal flat that gradually subsided resulting in a thickness of Bangkok clay from 0 to 20 m or so. Subsequently, about 2,700 years ago, the sea withdrew and soft clay was exposed at the surface, which has been little changed since its deposition with only the uppermost 2 m having been weathered [14].

The contour lines of Bangkok soft clay thickness (isopachs) are plotted in Fig. 3a. Underlying this soft clay are medium stiff and stiff clay layers that overlie the first sand layer, which in turn is underlain by another hard clay layer. It was documented that the stiff Bangkok clay had been exposed to the atmosphere and undergone a relatively long period of desiccation during a period of fluctuating sea levels between 75,000 and 25,000 years ago [15,16]. A sketch of landform and stratigraphic sequence of the Lower Chao Phraya plain is presented in Fig. 3b, which shows the Bangkok aquifer system consisting of 8 aquifers named as Bangkok, Phra Pradeang, Nakhon Luang, Nonthaburi, Samkhok, Phayathai, Thonburi and Park Nam, and denoted as BK, PD, NL, NB, SK, PT, TB, PN, respectively [17].

The most important processes controlling the

geometry and landforms in the Lower Chao Phraya plain are climate, water and sediment discharge and the formation of the delta was sensitive to changes in sea level [18]. The stiff and hard clay in Bangkok plain represent the old parts of the Lower Chao Phraya plain during the Late Pleistocene [19-23], whereas the Holocene sequence represents the young delta, i.e., soft clay [20]. The stiff and hard clay sequences are interpreted as a flood plain deposit, following channel migration [20]. The age of stiff clay was determined mainly based on stratigraphic position. However, some absolute age data are available with radiocarbon. Rau & Nutalaya [24] dated the limestone nodules or calcrete in the stiff clay and found the range from $14,700 \pm 2300$ to $45,000 \pm 6,900$ yr BP.

Chaimanee [25] collected the marine shell fragments from the stiff clay at Ban Praksa, Samut Prakarn province and gave a date of $35,460 \pm 1,300$ yr BP. The color of stiff and hard clay layers in the Lower Chao Phraya plain is from light grey, grey, greyish green, olive grey, yellowish brown, greyish brown olive brown, light brown to reddish brown. The wide range of color variation indicates this stiff clay layer must have been exposed to the atmosphere in the geological past and subjected to processes like leaching, precipitation and weathering.

A number of researches into natural processes causing the weathering of clays and the effects on the clay mechanical behavior [8, 26-31] have shown that climatic process can cause permanent modifications of the state and geotechnical properties of clays. For example, the results of drying-wetting cycle tests carried out in the laboratory on undisturbed samples of stiff clays in the Montemesola Basin (Italy) showed that the drying-wetting cycles could produce changes in the grey clay similar to those caused by the present in-

situ weathering [26]. The geological processes that may influence the geotechnical properties of clay sediments in a depositional basin include deposition, consolidation or compaction, diagenesis, tectonic disturbance, weathering and erosion. Some of these processes can occur in parallel and their combined effects control the mechanical behavior of clay sediments [8].

3. GEOTECHNICAL CHARACTERISTICS OF BANGKOK CLAYS

In this paper, the term of “*stiff clay*” in Bangkok plain is used for the clay overlying the first sand layer, while the term of “*hard clay*” for the clay underlying the first sand layer (see Fig. 3b). The soft clay layer at depth 4-11m, the stiff clay layer at depth 12-24m, the first hard clay layer at depth 30-50 m and the second hard clay at 50-80 m are denoted in this study as SOCL, STCL, HCL01 and HCL02, respectively. The index and strength properties of soft, stiff and hard Bangkok clay samples tested in this study are shown in Table 1 and Fig. 4.

The samples were taken from six study boreholes denoted from BH1 to BH6 at six sites in Bangkok central area, and namely, Chatuchak park (BH1), Lumpini Park (BH2), Snam Sua Pa (BH3), Rommaninat park (BH4), Ratchamangala University of Technology Krungtep (BH5) and Kasetsart University (BH6) as seen in Fig. 3a. The samples of soft clay were taken by Shelby tube, while those of stiff and hard clay was taken from 13 to 80 m depth by the Mazier sampler. The cutting shoe and connected inner barrel project ahead of the bit when drilling in stiff and hard clays without affecting the quality of samples. The Mazier core barrel has an inner plastic core liner, which protects the sample during transportation to the laboratory.

Table 1 Geotechnical properties of Bangkok clay

Clay	Depth (m)	w_n (%)	LL (%)	PL (%)	PI (%)	G_s	γ (kN/m ³)	C_u (kN/m ²)
Soft (SOCL)	2.5-11	44-78	25-98	21-48	14-60	2.5-2.7	14-16	9-58
Stiff (STCL)	12-24	15-44	25-89	14-37	8-58	2.6-2.7	17.2-21.7	45-150
Hard (HCL01)	30-50	15.6-27	27.7-71.8	15.4-33.1	12-38.6	2.6-2.7	18.2-21.1	57-225
Hard (HCL02)	50-80	14.3-25	23.8-64.2	13-26	16.1-45.6	2.6-2.7	18.6-21.5	111-394

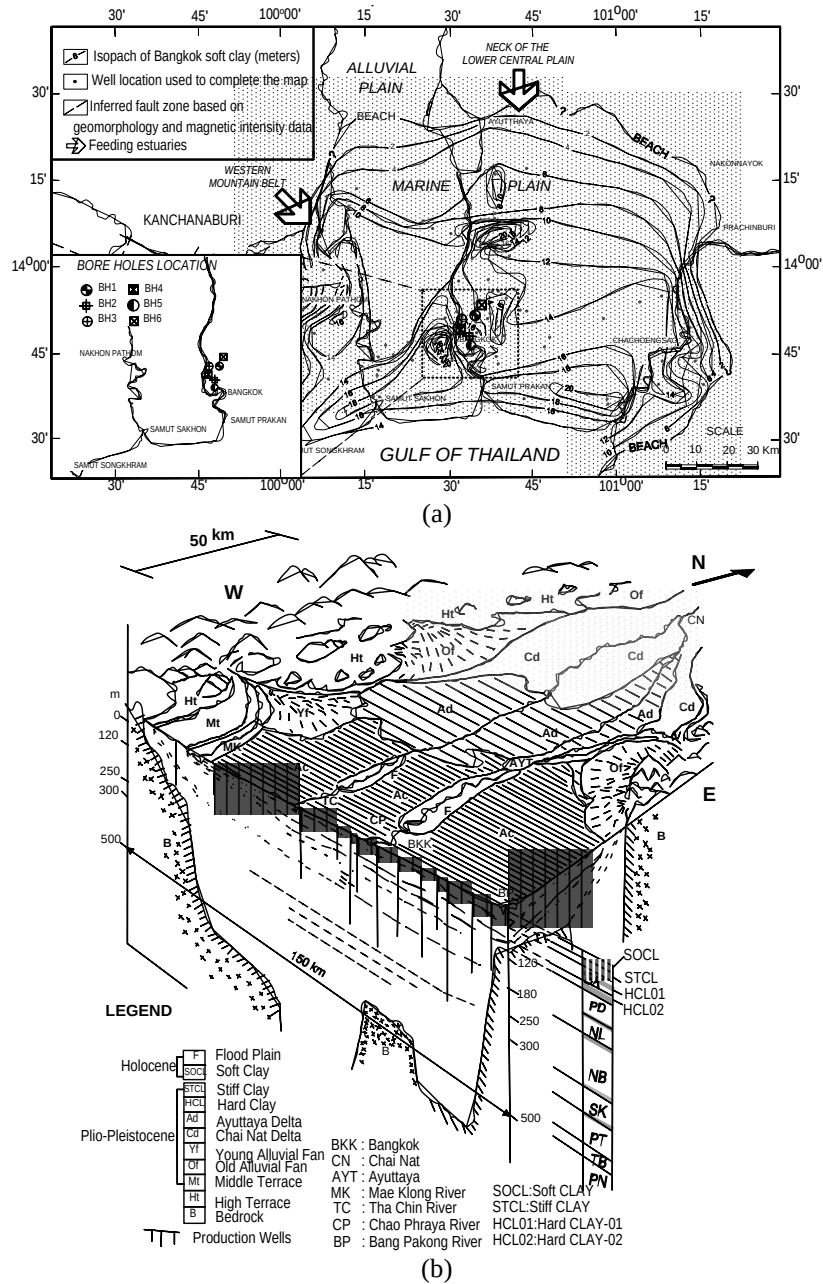


Fig. 3 Distribution of Bangkok soft clay (a) and Sketch of a stratigraphical section of the Lower Central Plain (b) modified from [23]

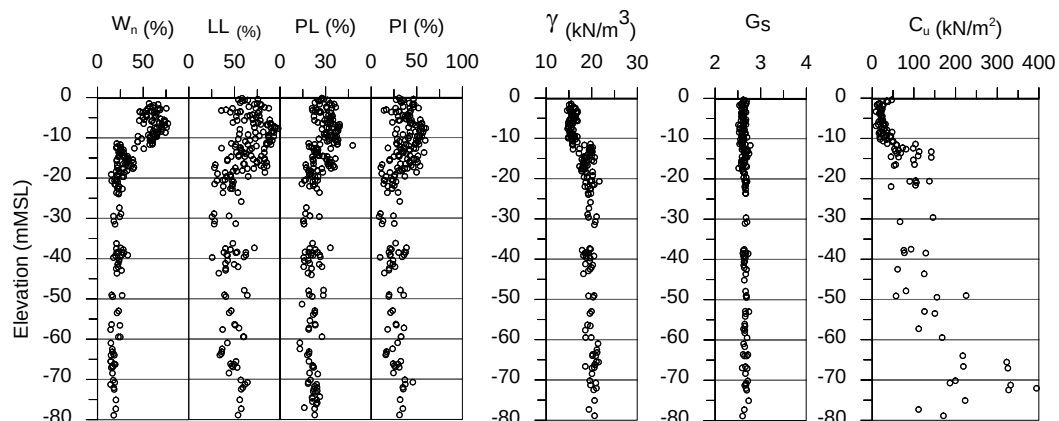


Fig. 4 Geotechnical properties at six study borehole sites

4. INTRINSIC COMPRESSION OF BANGKOK CLAYS

Burland [2] proposed a concept of the intrinsic compression line (ICL) to evaluate the difference in compressibility behavior between natural sedimentary and reconstituted clays, using the normalized void index (I_v). A reconstituted clay is the one that has been thoroughly mixed at a moisture content of between 1 to 1.5 times the liquid limit and then compressed one-dimensionally. The mechanical properties of a reconstituted clay are termed “intrinsic properties” since they are inherent to the material and are independent of its natural state. The void index (I_v) is defined by the following relation

$$I_v = \frac{e - e_{100}^*}{e_{100}^* - e_{1000}^*} = \frac{e - e_{100}^*}{C_c^*} \quad (1)$$

Where e is the void ratio of the reconstituted clay at a consolidation pressure; e_{100}^* and e_{1000}^* are the void ratios on the intrinsic compression line corresponding to the effective stress of $\sigma'_v = 100$ kPa and 1000 kPa, respectively; C_c^* is the intrinsic compression index and defined as $e_{100}^* - e_{1000}^*$.

The void index (I_v) is considered as a measure of the intrinsic compactness of sediment. When I_v is less than zero the sediment is compact, and when I_v is greater than zero the sediment is loose. Based on a study of a number of natural clays, the relationship between the void index and effective overburden stress, σ'_v in kPa, was found by [2] to be a reasonably unique line, known as ICL, as follows:

$$I_v = 2.45 - 1.286 \log(\sigma'_v) + 0.015 \log(\sigma'_v)^3 \quad (2)$$

The intrinsic compression line (ICL) is supposed to represent the compression curve when clays have no structuring due to aging. There are two ways recommended to construct the ICL, i.e., (i) to measure directly e_{100}^* and C_c^* ; and (ii) to construct the ICL using Eq. 2. Skempton [6] conducted a comprehensive study on gravitational compaction of twenty natural clay deposits all over the world and proposed a set of sedimentation compression curves, which represent a relationship between the changes of void ratio against the effective overburden pressure. Burland [2] reanalyzed these curves in the framework of intrinsic compression and transformed them into the so-called Sedimentation Compression Lines (SCL) that represents a relationship between the in-situ void index and the effective overburden for most of the natural clays. To facilitate a fast construction of both ICL and SCL, Burland [2] recommended using

the following relationships:

$$e_{100}^* = 0.109 - 0.679e_L - 0.089e_L^2 + 0.016e_L^3 \quad (3a)$$

$$C_c^* = 0.25e_L - 0.04 \quad (3b)$$

$$e_L = G \cdot LL \quad (3c)$$

Equations (3a) are recommended to be used only for the soils having e_L from 0.6 to 4.5 (corresponding to LL from 25 to 160%) and Atterberg limits lying above the A line in the plasticity chart. These conditions are met by Bangkok clays as seen in Table 1 and Fig. 5.

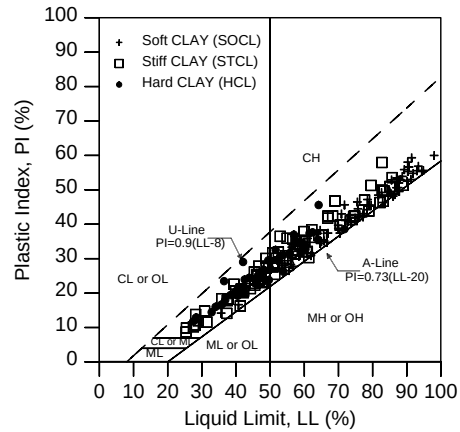


Fig. 5 Plasticity chart of soft, stiff and hard Bangkok clays

As pointed out by [3], the framework including ICL and SCL presented above can be used to assess the compressibility of clays. In this study, the oedometer testing results of clay samples were analyzed. The compression curves of soft, stiff and hard clay are plotted relative to ICL and SCL as shown in Fig. 6a for six study sites from BH1 to BH6, respectively.

To assess soil behavior there are three levels of investigation at the molecular level, the structural level and phenomenological level [32]. This study deals with the structural level. The structure of clays is usually referred to as a combination of fabric (arrangement between particles) and bonding or cementing (forces between particles). The term “soil fabric” basically refers to the orientation and distribution of soil particles in the soil mass. If a consolidation pressure is greater than the apparent maximum past pressure a marked reduction in cohesion may occur due to a rupture of cemented inter-particle bonds [33]. If compression curves are above ICL it indicates a normally consolidated state. On the other hand, the yield point of compression curve shows the breakdown of bonded structure and if the post-yield curves converge to ICL it indicates that the clay in their natural state exhibits significant bonding-dominated behavior.

As seen in Fig. 6a for the compression curves of Soft Bangkok clay at BH1 to BH6 most of the post-yield compression parts converge to ICL and the

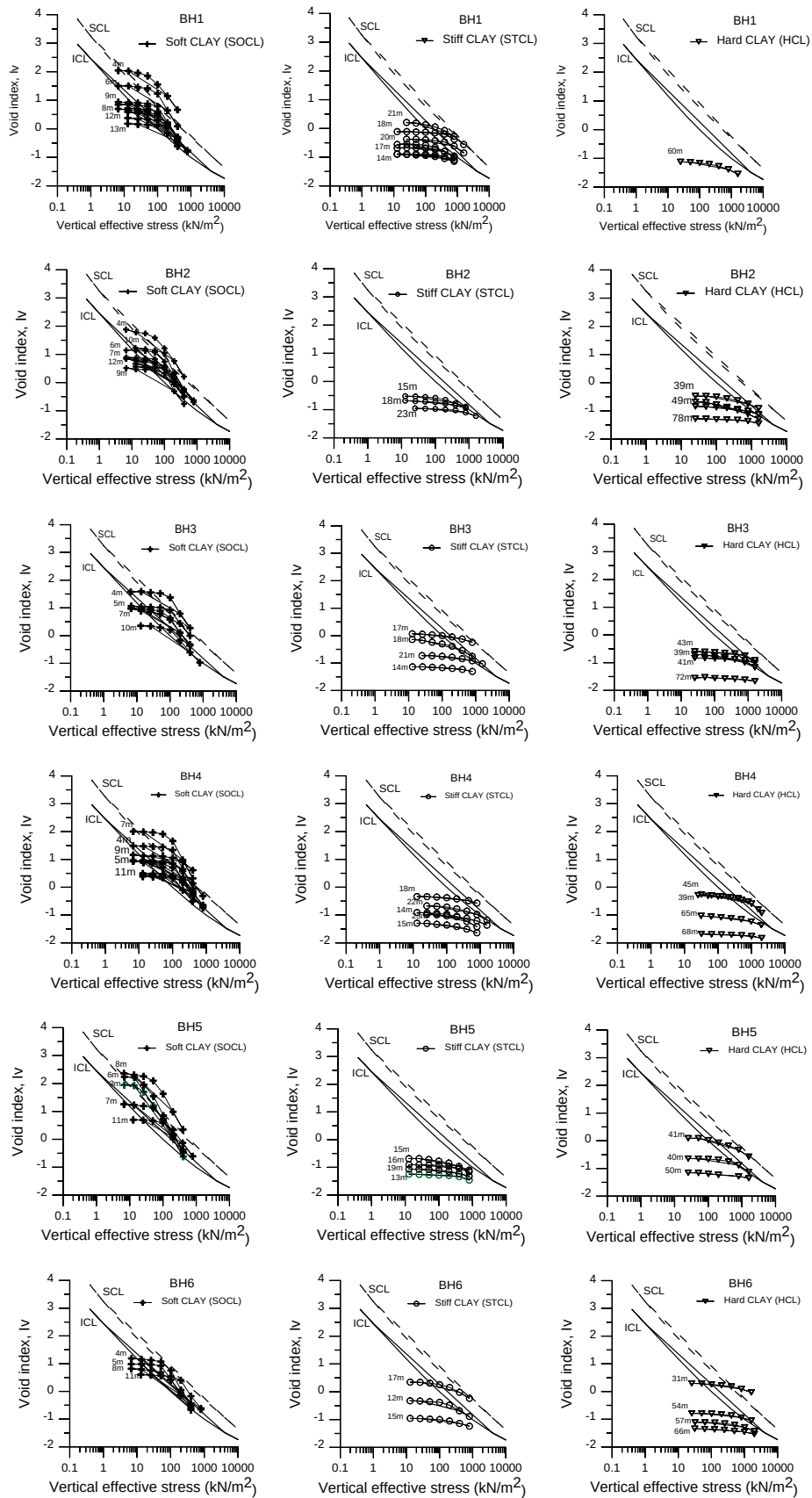


Fig. 6a Intrinsic compression behavior of Bangkok soft, stiff and hard clays

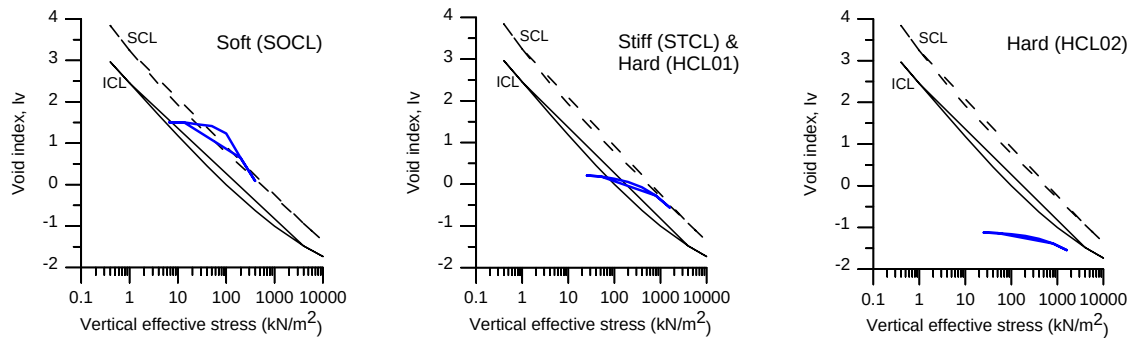


Fig. 6b Typical shape of intrinsic compression curves of Bangkok soft, stiff and hard clays

a clear breakdown of bonding structure implies that soft Bangkok clay is a cemented clay with meta-stable structure.

For the stiff clay majority of the compression, curves cross the ICL, then bend down and slowly converging to ICL, with a few of them totally lying under the ICL. For the first hard clays (HCL01) the compression curves exhibit the same behavior as that of stiff clay, while for the second hard clay (HCL02) most of the compression curves lie under the ICL and yield before reaching the ICL. These results of the intrinsic analysis showed that the structure of stiff and hard Bangkok clay is kind of fabric dominated and stable structure perhaps due to their heterogeneity and complex geological formation comparing to the soft Bangkok clay. Typical intrinsic compression curves for soft, stiff and hard clays are summarized as shown in Fig. 6b.

5. IN-SITU STATE OF BANGKOK CLAYS BASED ON VOID INDEX

Chandler [8] proposed the general pattern of in situ states of natural clays in term of void index based on data from [2], [6], and [34]. According to [8] an interesting group is formed of those clays having sedimentation curves close to the ICL. The present evidence suggests that the relatively dense state of these clays has been influenced either by rapid deposition [2], downslope flow [35], overconsolidation by sea-bed erosion or a consequence of their original depositional environment as tidal flats.

The in-situ state points of Bangkok clays are plotted in Fig. 7a-d. Interpretation of the in-situ state analysis results, however, is not that easy. Fig. 8 shows the concept of stress states framework proposed by [5], which is superimposed with the in-situ state points of Bangkok clays. For any significant degree of overconsolidation, the in-situ state points will lie below of the ICL (See Fig. 8), particularly if quick or moderately sensitive, can lie to the right of the ICL. There will be an overlap zone, within which clays may be either normally consolidated or lightly overconsolidated. The

approximate range within which clays may be referred to as stiff (or stronger) is also shown in the diagram. As seen in Fig. 8, the fact that most of the in-situ state points of soft clay (SOCL) lie above ICL or in the overlap and sedimentation compression ranges would imply that the soft Bangkok clay is a normally consolidated to lightly overconsolidated. As the in-situ state points of Stiff clay (STCL) lie mostly below or above of the ICL with some of them being in the overlap zone (overlapping between the overconsolidated and sedimentation compression ranges) it would indicate a lightly overconsolidated to overconsolidated clay. The points of the first hard clay (HCL01) lie below of the ICL and in the overlap zone, while the points of the second hard clay (HCL02) lies clearly below the ICL. These distributions would imply that the first hard clay (HCL01) exhibits a lightly overconsolidated to an overconsolidated state similar to that of stiff clay (STCL), while the second hard clay (HCL02) exhibits a reasonably well-defined state of an overconsolidated clay.

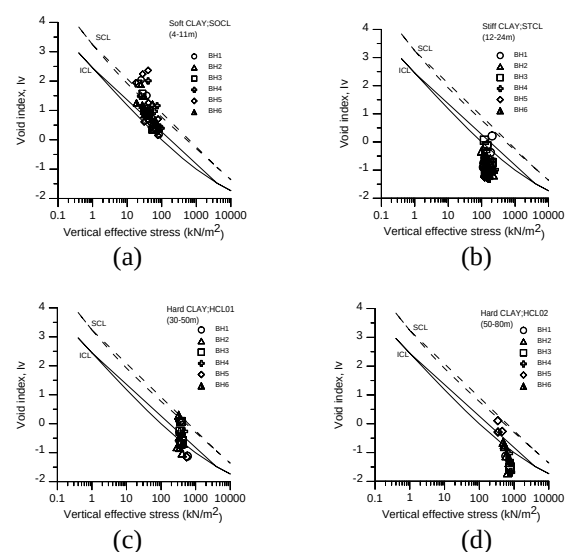


Fig. 7 In-situ state of Bangkok clays: (a) Soft clay (SOCL); (b) Stiff clay (STCL); (c) First Hard clay (HCL01); and (d) Second Hard clay (HCL02)

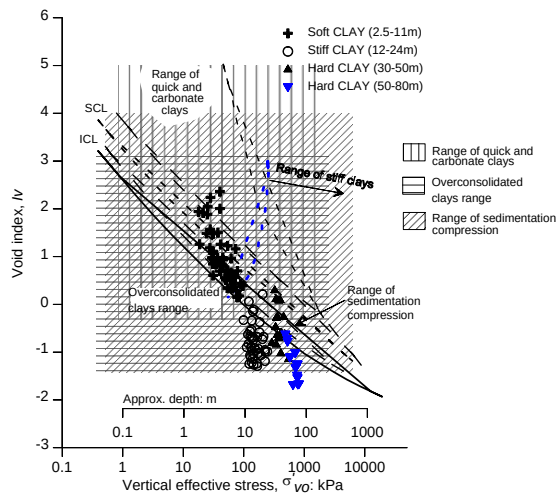


Fig. 8 Stress states of Bangkok clays related to geological history framework proposed by [5]

6. CONCLUSIONS

In this study, an integrated geological-geotechnical analysis was successfully done based on the oedometer testing results for samples taken from six study sites in the central Bangkok area up to 80 m deep to assess the intrinsic compression behaviour and in-situ states of soft, stiff and hard Bangkok clays, which could be linked well with their sea level-related engineering geological aspects such as geological age, depositional environment etc. Some of the conclusions were drawn as follows:

(1) The Bangkok soft clay is a young Holocene soft clay that was formed between 5,000 and 3,000 years, being deposited in the shallow marine environment (tidal flat etc.) when the sea level was 4 to 6 m above MSL. Such marine soft clay is very compressible. From this study it was found that the compression curves of soft clay (SOCL) at depth 4-11m (see Fig. 6a) cross SCL and their post-yield compression parts tend to converge to the ICL line, which in addition to a clear breakdown of bonding structure indicate that soft Bangkok clay is a cemented clay with a meta-stable structure.

(2) For stiff and hard clays belong to the old parts of the Lower Chao Phraya Plain during Late Pleistocene. It has been exposed to the atmosphere and under a long period of desiccation during sea-level fluctuation between 75,000 and 25,000 years ago. Most of the compression curves of stiff clay (STCL) at depth 12 - 24 m and first hard clay (HCL01) at depth 30-50 m cross the ICL and then bend down slowly to converge to the ICL line, only a few of them lie under the ICL and tend to nearly converge to the ICL line (see Fig. 6a). This would imply that the stiff and first hard clay is the type of a fabric dominated with a stable structure. For the second hard clay (HCL02) at depth 50-80m, most

of the compression curves lie under the ICL and yield before reaching the ICL (see Fig. 6a). For some curves, there is a little convergence with ICL even at high stresses, which would imply that the second hard clay is also a type of fabric dominated with a stable structure. The behavior of HCL02 is more complex.

(3) The influence of the structure of Bangkok clay is more significant at shallow depths, i.e., the stiff clay (STCL) and first hard clay (HCL01) are likely to be more structured than the deeper hard clay (HCL02).

7. ACKNOWLEDGMENTS

Sincere thanks are due to the Department of Groundwater Resources of Thailand and Seven Associated Consultants Company for the kind support on geotechnical data used for this research.

8. REFERENCES

- [1] Simpson, B. 2010. Engineering in stiff sedimentary clays. *Géotechnique*, Vol. 60, 2010, pp. 903–911.
- [2] Burland, J.B., On the compressibility and shear strength of natural clays. *Géotechnique*, Vol. 40, Issue 3, 1990, pp. 329–378.
- [3] Burland, J.B., Rampello, S., Georgiannou, V.N. & Calabrese, G., A laboratory study of the strength of four stiff clays, *Géotechnique*, Vol. 46, Issue 3, 1996, pp. 491–514.
- [4] Cotecchia, F. & Chandler, R.J., A general framework for the mechanical behavior of clays, *Géotechnique*, Vol. 50, Issue 4, 2000, pp. 431–447.
- [5] Chandler, R.J., Stiff sedimentary clays: geological origins and engineering properties, *Géotechnique*, Vol. 60, Issue 12, 2010, pp. 891–902.
- [6] Skempton, A.W., The consolidation of clays by gravitational compaction. *Quarterly Journal of the Geological Society*, Vol. 125, 1969, pp. 373–411.
- [7] Giao, P., Phien-Wej, N. & Tanaka, H., An
- [8] Assessment on soil disturbance of Bangkok clay samples in relation to the intrinsic compression behavior. *Lowland technology international: the official journal of the International Association of Lowland Technology / Institute of Lowland Technology*, Saga University, Vol. 6, 2004, pp. 21–31.
- [9] Chandler, R.J., The Third glossop lecture clay sediments in depositional basins: the

- geotechnical cycle, *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 33, Issue 1, 2000, pp. 7–39.
- [10] Van Veen, J., Tide-gauges, subsidence-gauges and flood-stones in the Netherlands, *Geologie en Mijnbouw*, Vol. 16, 1954, pp. 214–219.
- [11] Pluët, J. & Pirazzoli, P., *World Atlas of Holocene sea-level changes*, Elsevier Science, Vol. 58, 1991, pp. 1–299.
- [12] Sinsakul, S., Evidence of quaternary sea level changes in the coastal areas of Thailand: a review, *Journal of Southeast Asian Earth Sciences*, Vol. 7, 1992, pp. 23–37.
- [13] Sinsakul, S., Sonsuk, M. & Hastings, P.J., Holocene sea levels in Thailand: evidence and basis for interpretation, *Journal of Geological Society Thailand*, Vol. 8, 1985, pp. 1–12.
- [14] Choowong, M., The geomorphology and assessment of indicators of sea-level changes to study coastal evolution from the Gulf of Thailand, *International Symposium on Geology of Thailand*, Bangkok, Aug 26–31, 2002, pp. 207–220.
- [15] Nutalaya, P. & Phien-Wej, N., Flooding and Land Subsidence of Bangkok, A chapter in *Physiogeography of South East Asia*, The Physical Geography of Southeast Asia, Oxford University Press, 2002, pp. 358–378.
- [16] Eide, O., Geotechnical problems with soft Bangkok clay on the Nakhon Sawan highway project, *Norwegian Geotechnical Institute Publication*, 1968.
- [17] Neelson, J. D. & Hengchaovanich, D., Effect of overconsolidation on the shear strength characteristics of marine clay, *Proceedings of 2nd Southeast Asian Conference on Soil Engineering*, Singapore, June 11–15, 1970, pp. 1–9.
- [18] Giao, P., Phien-Wej, N., & Honjo, Y., FEM quasi-3D modeling of responses to artificial recharge in the Bangkok multiaquifer system, *Environmental Modelling and Software*, Vol. 14, Issue 2-3, 1999, pp. 141–151.
- [19] Coleman, J.M. & Roberts, H., Deltaic coastal wetlands, In *Coastal Lowlands*, Springer Netherlands, 1989, pp. 1–24.
- [20] Alekseev, M. & Takaya, Y., An outline of the upper Cenozoic deposits in the Chao Phraya Basin, Central Thailand, *Southeast Asian Studies*, 1967, pp.334–352.
- [21] Sinsakul, S., Late Quaternary geology of the lower central plain, Thailand, *Journal of Asian Earth Sciences*, Vol. 18, 2000, pp. 415–426.
- [22] Takaya, Y., Quaternary outcrops in the Central Plain of Thailand, *Geology and mineral resources in Thailand and Malaya*. Kyoto, the Centre for Southeast Asian Studies, Kyoto University, 1968, pp. 8–68.
- [23] Takaya, Y., Physiography of rice land in Peninsular Thailand, *The Southeast Asian Studies*, Vol. 10, 1972, pp. 422–432.
- [24] Takaya, Y. & Thiramongkol, N., Chao Phraya delta of Thailand, *Asian rice-land investigation, A description atlas 1*, Center for Southeast Asian Studies, Kyoto University, Japan, 1982.
- [25] Rau, J. & Nutalaya, P., Geology of the Bangkok clay, *Geological Society of Malaysia Bulletin*, Vol. 16, 1983, pp. 99–116.
- [26] Chaimanee, Y., *Plio-Pleistocene rodents of Thailand*, Ph.D. thesis, Montpellier University, French, 1997.
- [27] Cafaro, F. & Cotecchia, F., Structure degradation and changes in the mechanical behavior of a stiff clay due to weathering, *Géotechnique*, Vol. 51, Issue 5, 2001, pp. 441–453.
- [28] Chandler, R.J., Lias clay: weathering processes and their effect on shear strength, *Géotechnique*, Vol. 22, Issue 3, 1972, pp. 403–431.
- [29] Chandler, R.J. & Apted, J., The effect of weathering on the strength of London clay, *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 21, Issue 1, 1988, pp. 59–68.
- [30] Cooper, M. R., Bromhead, E.N., Petley, D.J. & Grants, D.I., The Selborne cutting stability experiment, *Géotechnique*, Vol. 48, Issue 1, 1998, pp. 83–101.
- [31] Hawkins, A. B., Lawrence, M. S. & Privett, K. D. 1988. Implications of weathering on the engineering properties of the Fuller's Earth formation, *Géotechnique*, Vol. 38, Issue 4, 1988, pp. 517–532.
- [32] Skempton, A.W. Slope stability of cuttings in brown London clay, *Proceeding of the 9th International Conference on Soil Mechanics and Foundation Engineering*, Tokyo, Vol. 3, 1977, pp. 261–270.
- [33] Klausner, Y., *Fundamentals of Continuum Mechanics of Soils*, Springer-Verlag, London, 1991.
- [34] Mitchell, J.K., *Fundamentals of Soil Behaviour*, 1st ed. John Wiley and Sons, Inc., New York,

- 1976, pp. 1-422.
- [35] Buchan, S. & Smith, D.T., Deep-sea sediment compression curves: some controlling factors, spurious overconsolidation, predictions, and geophysical reproduction, *Marine Georesources and Geotechnology*, Vol. 17, Issue 1, 1999, pp. 65–81.
- [36] Paul, M.A., Talbot, L.A., & Stoker, M.S., Shallow geotechnical profiles, acoustic character and depositional history in glacially influenced sediments from the Hebrides and West Shetland Slopes, Geological Society, London, Special Publications, Vol. 129, 1998, pp.117–131.

Copyright © Int. J. of GEOMATE. All rights reserved, including the making of copies unless permission is obtained from the copyright proprietors.
