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

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* 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. Choowoong [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.
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 ± 2300 to 45,000 ± 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 ± 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 underly the first sand layer (see Fig. 3b). The soft clay layer at depth 4-11 m, the stiff clay layer at depth 12-24 m, 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), Samut 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

<table>
<thead>
<tr>
<th>Clay</th>
<th>Depth (m)</th>
<th>w_a (%)</th>
<th>LL (%)</th>
<th>PL (%)</th>
<th>PI (%)</th>
<th>G_s (kN/m³)</th>
<th>γ (kN/m²)</th>
<th>C_a (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft (SOCL)</td>
<td>2.5-11</td>
<td>44-78</td>
<td>25-98</td>
<td>21-48</td>
<td>14-60</td>
<td>2.5-2.7</td>
<td>14-16</td>
<td>9-58</td>
</tr>
<tr>
<td>Stiff (STCL)</td>
<td>12-24</td>
<td>15-44</td>
<td>25-89</td>
<td>14-37</td>
<td>8-58</td>
<td>2.6-2.7</td>
<td>17.2-21.7</td>
<td>45-150</td>
</tr>
<tr>
<td>Hard (HCL01)</td>
<td>30-50</td>
<td>15.6-27</td>
<td>27.7-71.8</td>
<td>15.4-33.1</td>
<td>12-38.6</td>
<td>2.6-2.7</td>
<td>18.2-21</td>
<td>57-225</td>
</tr>
<tr>
<td>Hard (HCL02)</td>
<td>50-80</td>
<td>14.3-25</td>
<td>23.8-64.2</td>
<td>13-26</td>
<td>16.1-45.6</td>
<td>2.6-2.7</td>
<td>18.6-21.5</td>
<td>111-394</td>
</tr>
</tbody>
</table>
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

$$I_v = \frac{e - e_{100}}{e_{100} - e_{1000}} = \frac{e - e_{100}}{C_c}$$  \hspace{1cm} (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, $\sigma_v$, in kPa, was found by [2] to be a reasonably unique line, known as ICL, as follows:

$$I_v = 2.45 - 1.286 \log(\sigma_v) + 0.015 \log(\sigma_v)^3$$  \hspace{1cm} (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:

$$e_{100}^* = 0.109 - 0.679 e_L - 0.089 e_L^2 + 0.016 e_L^3$$ \hspace{1cm} (3a)

$$C_c^* = 0.25 e_L - 0.04$$ \hspace{1cm} (3b)

$$e_L = \frac{\sigma_v}{G}$$ \hspace{1cm} (3c)

Equations (3a) are recommended to be used only for the soils having $e_1$ 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](image)

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 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

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 slightly 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)
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

[8] Chandler, R.J., The Third glossop lecture clay sediments in depositional basins: the


[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.


1976, pp. 1-422.
