Identification of Bangkok Subsoil Parameters for Finite Element Analysis of Excavation and Tunnelling

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ABSTRACT: Finite element method has been widely used in geotechnical practice. In this method, modelling of soil behaviour and its parameters estimation is an important procedure. Over the past decades, enormous efforts have been made to further develop elasto-plastic constitutive models. Nevertheless, the use of these constitutive models in engineering practice is still very limited. The required soil parameters of a particular subsoil condition is a challenging task for geotechnical engineers. Presently, the use of laboratory and in-situ tests, that helps determining the soil parameters, has been highly developed. This paper summaries the results of laboratory, field, and numerical studies related to Bangkok clay behaviour. The stiffness and strength parameters, including small-strain parameters, of Bangkok Clay were main focuses. Anisotropy and non-linearity of Bangkok Clay were also introduced in this paper. The results of deep excavation and tunnelling of the Bangkok MRT were simulated using finite element modelling. The optimal parameters of Bangkok subsoils for deep excavation and tunnelling works, based on Moho-Coulomb and Hardening Soil Models, were finally summarised.

KEYWORDS: finite element analysis, Constitutive model, Soil parameters, Laboratory tests, In-situ tests, Bangkok subsoil

1 INTRODUCTION

Bangkok subsoil is one of the most well-known sedimentary soils and has been extensively studied in the past by many researchers (e.g., Balasubramaniyan et al., 1978; Balasubramaniyan et al., 1980). It consists of a thick soft clay layer on the top deposit called “Bangkok Clay”. This layer is under construction problems such as structural damages during the construction and throughout the lifecycle of structures. Recently, the stiffness and strength parameters of Bangkok Clay have been extensively investigated. Suranak et al. (2012) presented analysed stiffness and strength parameters for hardening soil model of soft and stiff Bangkok Clays. Likitlersuang et al. (2013a) presented geotechnical parameters from preprocessor tests of Bangkok subway project. Likitlersuang et al. (2013b) described the small-strain stiffness and the low-strain deformation curve of Bangkok Clay. Ratannikorn et al. (2013) and Yimsiri et al. (2013) studied anisotropic characteristics and strength characteristics of Bangkok Clay. Ratannikorn et al. (2015) presented relationships among undrained shear strength of Bangkok Clay from various laboratory techniques. Moreover, the applications of soil parameters for finite element analysis were investigated with the case studies of deep excavations or the sugnus sooraw sunayi (t. Jonserup et al., 2012c) and tunnelling of Bangkok subway (Likitlersuang et al., 2013c).

Finite element analysis of geotechnical problems become widely used in practice due to the development of more user-friendly softwares. This paper aims to summarise a set of optimal parameters for Bangkok subsoils to be used in finite element analysis. The hardening soil model and Moho-Coulomb models are recommended for soft to medium stiff Bangkok Clay layers and the sand layer, respectively. The soil parameters were calibrated against the laboratory and in-situ testing results. Case studies of deep excavation and tunnelling of the Bangkok subway project were used to validate the finite element models. Some advanced parameters, such as anisotropy, non-linearity, and small-strain stiffness parameters, of Bangkok Clay for advanced soil models were also discussed.

Figure 1 Geological map of Quaternary deposits in the lower central plains of Thailand (Mitsunari, 2000)

2 BANGKOK SUBSOILS

2.1 Geotechnical conditions

Bangkok is located on the delta of the Chao Phraya River, which traverses the lower central plains of Thailand (Fig. 1). The Quaternary deposits of the lower central plains represent a complex sequence of alluvial, fluvioglacial and marine sediments. The Quaternary strataigraphy consists of many aquifers, which are separated from each other by thick layers of clay or sandy clay. The depth of the bedrock is still undetermined, but its level in the Bangkok area is known to vary between 400 m to 1,800 m depth. Deep well pumping from the aquifers over the last 50 years or so has caused a substantial piezometric drawdown in the upper soft and highly compressible clay layer (Fig. 2).

Figure 1 Geological map of Quaternary deposits in the lower central plains of Thailand (Mitsunari, 2000)
2.2 Typical soil profile

Based on extensive field and laboratory studies carried out in the past by numerous researchers, the following descriptions have been proposed for a typical profile of Bangkok subsols (Fig. 2).

- Weathered crust and backfill (M: Made Ground) – The uppermost layer is the fill material (very loose to dense clayey sand) and weathered crust (medium to stiff silty clay), which is light to yellowish grey in colour. The average thickness is about 1 to 3 m, with the SPT N-value ranging from 2 to 21. The water content is 15 to 35%. The groundwater table is found within this layer. The made ground layer is usually ignored in engineering practice.

- Very soft to medium stiff Bangkok Clay (BSC: Bangkok Soft Clay and MC: Medium Stiff Clay) – The very soft to medium soft Bangkok Clay layer located at depths of 3 to 12 m with medium to dense grey to yellowish grey in colour. The undrained shear strength is ranging from 10 to 30 kN/m² and the natural water content is around 60 to 105%.

3. CONSTITUTIVE MODELS AND PARAMETERS

3.1 Undrained shear strength parameters

The undrained shear strength ($\phi_u$) is an important parameter for describing the consistency of cohesive soils during undrained loading. However, $\phi_u$ is not a fundamental soil property because it is affected by states of loading, boundary conditions, rate of loading, confining stress level, initial stress state, and other variables (e.g., Wroth, 1984). In measuring $\phi_u$, various laboratory tests are used in practice; therefore, correlations of $\phi_u$ measured from various laboratory tests can conveniently help the comparison of results among them.

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The Hardening Soil Model (HSM) developed under the framework of the theory of plasticity was integrated in the Plaxis program as an extension of the Mohr-Coulomb model. Then an additional cap yield surface with a strain hardening factor was added. The SPT N-value varies from 2 to 25, with undrained shear strength of 26 to 160 kN/m², the natural water content is around 15 to 60%.

- Medium dense to dense sand (CS: Clayey Sand) – First medium dense to dense clayey and silty sand, with a yellowish to greyish brown in colour, is present below the stiff clay layer, down to a depth of 30 to 40 m. This sand is fine to medium grained, with fine contents from 17 to 29%. The water content varies from 17 to 25%, with the SPT N value being greater than 25.

- Medium stiff to hard clay (25%: Second Stiff Clay and HC: Hard Clay) – The very stiff hard clay layer is found below the medium dense to dense sand layer, with a thickness of 10 to 12 m, and its colour varies from light grey to greyish brown. The SPT N value is greater than 30, with water content ranging from 15 to 22%. The hard clay may be absent at some locations.

- Very Dense Sand or Second Dense Sand (DS: Dense Sand) – The very dense layer is found below the very stiff hard clay layer until the bedrock, with a thickness of 30 to 60 m. The sand is silty and poorly graded with silt, being yellowish brown to brownish grey in colour. The SPT N values, in general, exceed 50.

The Hardening Soil Model (HSM) developed under the framework of the theory of plasticity was integrated into the Plaxis program as an extension of the Mohr-Coulomb model. Then an additional cap yield surface with a strain hardening factor was added. However, $\phi_u$ is not a fundamental soil property because it is affected by states of loading, boundary conditions, rate of loading, confining stress level, initial stress state, and other variables (e.g., Wroth, 1984). In measuring $\phi_u$, various laboratory tests are used in practice; therefore, correlations of $\phi_u$ measured from various laboratory tests can conveniently help the comparison of results among them.

3.3 Small-strain stiffness parameters

The numerical analysis considering the effect of small strain could yield more realistic ground movements when compared to the field observations, especially in tunnelling and deep excavations (e.g., Addenbrooke et al., 1997 and Kong et al., 2009). In Plaxis, the Hardening Soil Model with Small Strain Stiffness (HSM) is available to model the soil behaviour under small strains. Two parameters, namely small-strain shear modulus ($C_{s0}$) and reference shear strain ($\gamma_0$), are extra requests from the original HSM. The small-strain shear modulus $C_{s0}$ is a material property that relates to the soil's stiffness under small-strain conditions.

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modulus (Gcm) represents the only shear strength modulus of soil as small strain. The reference shear strain (γr) is defined as the shear strain at Gcm = 0.3, in which soils at the strain level below the threshold shear strain behave linear elastic (Vaquer, 1994; and Hu & Vuclier, 2014).

### 3.4 Anisotropy

Most natural soils are deformed through a process of sedimentation followed by postdepositional consolidation under accumulative overburden pressure for a long period of time. It is conceivable that under such condition, soils would be horizontally layered in both heterogeneous and non-homogeneous soils. This leads to anisotropy, called transversely isotropic or cross-anisotropic, in which soils have equal stiffness in all horizontal directions, but have a different stiffness in vertical direction. To develop a simple form of cross-anisotropic soil model that required only three independent parameters. The anisotropy parameter (α) is defined as the ratio between horizontal and vertical moduli (Eh/Eh).

### 4.2 HSM parameters

Ratnamanik et al. (2015) studied the strength and stiffness parameters of Bangkok subsoil for HSM based on unconfined and triaxial compression tests reported from previous literatures. The Mohr-Coulomb strength parameters were calibrated against the isotropically consolidated drained triaxial compression (C1D) and C1D and extension (C1E and C1E) tests. The nonlinear model for HSM and consolidation parameters were determined from oedometer tests. Finally, the sets of HSM parameters (Table 2) were numerically calibrated against undrained and drained triaxial results using a Plaxis finite element software.

### 4.3 Small-strain stiffness parameters

Figure 4 shows a typical soil profile, moisture content, and Atterberg limits, as well as the Gcm parameters from various sites in Bangkok. The trends of the Gcm increase with depth in both the soil and stiff clay. However, the magnitude of Gcm are significantly higher in the stiff clay layers. Lidskasang & Ngarm (2010) reported empirical correlations between undrained shear strength and Gcm from down-hole and multi-channel analysis of surface wave (MAS) in Eqs. (2a) and (2b). However, Lidskasang et al. (2013) proposed a correlation between Gcm and other geotechnical properties of the soil, such as the shear wave velocity. This allows for an easy estimation of the small-strain shear modulus (Gcm) and reference shear strain (γr) of Bangkok subsoil for the HSM as summarised in Table 2. They also suggested that (γr/κ) can be used for embankment stability analysis for Bangkok subsoil without any correction.

Note: α is a reference pressure (100 kN/m²) (n = α) is an asymptotic value of shear strength.

### 4.4 PARAMETERS FOR BANGKOK SUBSOILS

#### 4.4.1 Undrained shear strength

Ratnamanik et al. (2015) presented the values of α of Bangkok Clay are varied from several method of observations. The interrelationships among various α with Gcm (iso) (isotropically consolidated undrained triaxial compression) are presented in Eq. (1). They also suggested that (γr/κ) can be used for embankment stability analysis for Bangkok Clay without any correction.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Parameter Evaluation</th>
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<tbody>
<tr>
<td>d'</td>
<td>Internal friction angle</td>
<td>Slope angle of failure line based on Mohr-Coulomb</td>
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<td>c'</td>
<td>Cohesion</td>
<td>Cohesion-intercept of failure line based on Mohr-Coulomb</td>
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<td>ϕ'</td>
<td>Failure ratio</td>
<td>(n = α)</td>
</tr>
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<td>ε</td>
<td>Relative angle of dilation rate of d', and c'</td>
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<tr>
<td>ε'</td>
<td>Reference secant stiffness</td>
<td>Seismic modulus at 50% stress from drained triaxial test, p'0</td>
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4.4 Anisotropic parameters

Ratananikom et al. (2015) reported the ratio of $s_y$ from triaxial extension to compression, i.e., $s_y/s_y$ = 0.87 and $s_y/s_y = 0.89$, which shows that Bangkok Clay has more isotropic behaviour (in terms of undrained shear strength) than other soils in the area.

Ratananikom et al. (2013) presented an investigation programme of cross-anisotropic elastic parameters of Bangkok Clay. A comprehensive triaxial tests were performed on vertically- and horizontally-oriented undrained Bangkok Clay specimens. The experiments employed local-strain measuring systems and bender elements. Therefore, the soil stiffness at small strains can be measured. The anisotropic stiffness parameters were analysed following the three-parameter cross-anisotropic elastic model proposed by Graham & Holstby (1983). The elastic moduli were assumed as power functions of isotropic confining stress. A complete set of cross-anisotropic elastic parameters of Bangkok Clay was proposed as shown in Eq. (4). The model has an average element size of 2.53 m and a total element number of 449.

\[
\begin{align*}
E_1 &= 231 \quad P_r \\
E_2 &= 200 \quad P_r \\
G_1 &= 123 \quad P_r \\
G_2 &= 139 \quad P_r \\
\nu_1 &= 0.068 \\
\nu_2 &= 0.068
\end{align*}
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Yinwii et al. (2013) investigated the undrained strength-defoarmation characteristics of Bangkok Clay under general stress condition by using torsional shear hollow cylinder (TSHC) apparatus. They proposed the dependency of strength and stiffness on intermediate principal stress parameters and their mesh generation. The model has an average element size of 2.53 m and a total element number of 449.

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The simplified finite element methods were used to model the shield tunnelling of the Bangkok subway blue line project (Likitlersuang et al., 2014). The study focused on the use of three simplified methods, which are contraction ratio method, stress reduction method, and modified gross pressure method, to back-analyse ground settlement due to tunneling works. All the back-analysis results are compared with the field monitoring data in order to assess the validity of the chosen methods.

A section from Khlong Toel to Queen Sirikit twin tunnels, with a side-by-side pattern, was selected. The tunnels of this section are located partially in the stiff clay and partially in the hard clay layers. A high face pressure of 175 and 170 kN/m² was applied to the SB and NB tunnels, along with a penetration rate of 75 mm/min. A high gross pressure of 250 kN/m² was used for great filling of 150%. The maximum surface settlement after both shields had passed was about 25 mm. The soil profile illustrated in Fig. 3 employed the analysis. The soil profile model adopted was the HSM. The input parameters of the HSM finite element analysis study as presented in Table 2 were retained. The tunnel lining was modelled using the plate element with $E = 8000$ MN/m² and $f = 56$ MN/m². Fig. 8 depicts the finite element mesh generation of the section. The number of elements is 1670 with an average element size of 1.2 m.

A modified gross pressure method was applied to the finite element analysis. In this method, the face and gross pressures were modelled by an applied pressure which increased linearly with depth. The unit weight of the earth and muck material were assumed to be 12 and 15 kN/m³, respectively. In the first attempt, the average face and gross pressures, as measured from the earth pressure chamber and the shield cell, were used as the face and gross pressures. These face and gross pressures were averaged from the measuring data. As a consequence, it gave an overestimation of the ground settlement, when compared to the field measurements. Therefore, it was decided that a series of finite element back-analyses were performed in the second attempt and the result is shown in Fig. 9. In general, the predictions of the surface settlement agree well with the field measurements. The ratios of the calculated and measured face pressure were 1.06 and 1.03 for SB and NB, respectively. More details of other cases can be seen in Likitlersuang et al. (2014).

6. CONCLUSIONS
This study aims to identify the set of optimal parameters for Bangkok subsoils, which can be used for the finite element analysis. The following conclusions can be made:
1) To obtain the optimal soil parameters required in advanced constitutive models, the comprehensive experimental results, such as triaxial and consolidation tests, are essentially required. The shear strength parameters shall be determined from the undrained and drained triaxial tests. The non-linear stiffness parameters shall be calibrated against the geodimeter results.
Figure 9: Finite element analysis results of the Bangkok subway twin tunnels (Lichti-erinsang et al., 2014)

2) The small strain shear modulus ($G_{s,t}$) and reference shear strain ($\gamma_{r,s}$) are additionally required for the finite element analysis with considering the small-strain effect. These parameters shall be determined from special tests that can capture the stiffness at small to medium strain ranges. In this study, the small-strain parameters for Bangkok clay were determined from the cycle triaxial tests.

A special triaxial apparatus equipped with local-strain measuring devices and binder elements was successfully used to determine the cross-anisotropic elastic parameters of Bangkok clay. The triaxial test was calibrated with the phial stress increment vectors on the principal stress and strain axes were found to be the Drucker-Prager failure criterion with an associated flow potential.

The finite element analysis employs the HSIM with soil parameters interpreted from laboratory and field tests, provides good agreement with the lateral wall movement and surface settlement field observations of the Bangkok subway.

Simulations of realistic initial stress and pore water pressure conditions as well as construction sequences are crucial for a finite element analysis of excavation and tunnelling.

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8. REFERENCES


