Advanced soil parameters determination for Ho Chi Minh city soft clay to predict ground movements in deep excavations and tunneling

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ABSTRACT: The Hardening Soil model (HSM), an advanced soil model, is acknowledged as the suitable soil constitutive law for deep excavation analyses. In this paper, the HSM parameters of Ho Chi Minh (HCMC) soft clay were determined in a high-quality laboratory test program and are recommended for local design practice. The undisturbed clay samples were collected from two sites in the city central soft ground zone. The test program includes: (i) Oedometer tests for investigating the consolidation characteristics i.e. compression and swelling indices and oedometric moduli, and (ii) Isotropically consolidated both undrained and drained triaxial tests (CID and CIU tests) for investigating strength parameters and stress-strain characteristics including loading and unloading-reloading moduli.

1. INTRODUCTION

To estimate the specific strength and deformation parameters of HCMC Soft clay for numerical analysis of deep excavations, a high-quality and well-controlled laboratory testing program were performed on undisturbed samples collected from two sites located in the city central soft ground. The program includes: (i) Oedometer tests for investigating the consolidation characteristics of the clays and the oedometric moduli, and (ii) Isotropically consolidated triaxial both undrained and drained tests (CID and CIU tests) for investigating the undrained and drained stress-strain characteristics and stress path to estimate strength parameters and the loading and unloading-reloading stiffness moduli. The set of HSM parameters of the clay is estimated from the laboratory testing. The realistic oedometric/triaxial moduli ratios are also accordingly recommended for the local design practice.

2. SUBSOIL STRATIGRAPHY OF HCMC AND HCMC CENTRAL LOWLAND

The city center lowland zone is located adjacent to the Saigon River. Generalized subsoil profiles and soil properties (Hung and Phienwej, 2015) reveal the dominant soil strata in this area as: (i) fill, (ii) stratum 1: soft to very soft organic clay (hereinafter called 'HCMC Soft clay"), (iii) stratum 2: loose fine sand, (iv) stratum 3: medium to stiff clay, (v) stratum 4: fine sand - loose to medium dense may be encountered in between the above strata, (vi) stratum 7: medium to stiff clay, (vii) stratum 8: fairly dense medium sand and (viii) stratum 10: dense, fine to coarse sand.

3. SITES AND TESTED MATERIAL-TARGETS AND TESTS CONDUCTED

The soil profile to a depth of 70 m of the two sites where the undisturbed samples were taken is shown in Fig. 1. Thirty-three samples by piston samplers for the Soft clay/Lower soft clay were taken at Site 1 from 4.5 m to 12.5 m depth and at

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Table 1. Main tests of the laboratory testing program

Site	Type of test	Soft clay: Confining pressure (kPa)	Soft clay: No.	Lower soft clay: Confining pressure (kPa)	Lower soft clay: No.	Main soil parameters to be obtained
1	OED		11			$\lambda, \lambda^*, \kappa, \kappa^*, E_{oed}^{ref}, E_{ur,oed}^{ref}$
	CIU	30, 100, 200 50, 100, 200 24, 50, 100 100, 150, 200	2 1 1 1			$c', \varphi', E_{iu}^{ref}, E_{50u}^{ref}$
	CID	50, 100, 200 50, 100, 150	4 2			$c', \varphi', E_{i}^{ref}, E_{50}^{ref}, E_{ur}^{ref}$
	CRS		2			For comparison with OED
2	OED				3	$\lambda, \lambda^*, \kappa, \kappa^*, E_{oed}^{ref}, E_{ur,oed}^{ref}$
	CIU			50, 100, 200	3	$c', \varphi', E_{iu}^{ref}, E_{50u}^{ref}$
	CID			50, 100, 200	2	$c', \varphi', E_{i}^{ref}, E_{50}^{ref}, E_{ur}^{ref}$

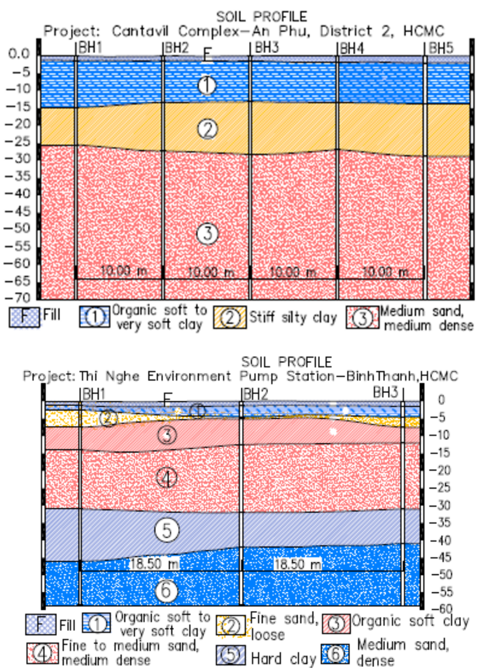

Figure 1. Geotechnical soil profile at Site 1 (CDCo, 2006) and Site 2 (from UGEFEM 2003)

Site 2 from 13 m to 17 m depth for carrying out necessary laboratory tests as listed in Table 1 for obtaining the following relationship and parameters: (1) Oedometer (OED) tests: Compression index C_c, Swelling index C_s, original Cam-clay parameters λ and κ, Modified Compression index λ^*, Modified Swelling index κ^*, Overconsolidated ratio OCR, Loading oedometric modulus at reference confining pressure p^{ref}=100 kPa E_{oed}^{ref} and Unloading-reloading oedometric modulus at p^{ref} $E_{ur,oed}^{ref}$. Two Constant Rate Strain Consolidation test with vertical drainage (CRS) were also performed for comparison of the results of the OED tests. (2) CIU and CID tests: Undrained/Drained stress-strain relationship, the pore pressure-strain relationship and the stress path for the strength parameters, volume change-strain relationship, Undrained / Drained strength c'/c' and φ/φ', the Undrained / Drained initial tangent modulus at p^{ref} E_{iu}^{ref}/E_i^{ref}, the Undrained/Drained secant modulus at 50% shear strength $E_{50u}^{ref}/E_{50}^{ref}$ and Unloading-reloading stiffness moduli at p^{ref} E_{ur}^{ref}.

4. PROCEDURES OF THE TESTS

4.1 The consolidation tests

Humboldt system (USA) is used. The standard applied is ASTM D2435: Standard Test Method for One-Dimensional Consolidation Properties of Using Incremental Loading. All specimens are 63.5 mm diameter x 25.4 mm length and vertically oriented. The load increment ratio of 1 is applied. The time required for primary consolidation is 24 hours.

4.2 The triaxial tests

Load Trac-II/Flow Trac-II system of automatically controlled Geocomp (USA) is used. The standards for reference include: (i) ASTM D4767-11- Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils; (ii) ASTM D7181-11- Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils; (iii) BS 1377-8-1990 Methods of test for Soil for civil engineering purposes – Part 8: Shear strength tests (effective stress). All specimens are 38 mm diameter x 76 mm length and vertically oriented. 15% strain is adopted as limiting strain for the test (ASTM-D7181). The limited maximum rate of strain d_r is estimated from BS 1377-8-1990 as: $d_r = e_f L_c / t_f$.

Where: ε_f: the estimated strain at which failure will occur; L_c: length of the consolidated specimen; $t_f = Ft_{100}$; t_f: significant testing time; F: a coefficient which depends on the drainage conditions and the type of compression test, i.e. undrained or drained. During consolidation, the drainage condition applied is radial boundary and one end: F = 14 in case of drained test and F = 1.8 in case of undrained test. Typical values of t_{100} of the drained tests on the Soft clay are 68, 150, 301 and 501 min. The minimum time to failure should not be less than 120 min (Head 1986); therefore, with the strain at failure of 15%, L_c ranging from 72-75 mm, d_r is 0.002-0.01 mm/min for drained tests. Typical values of t_{100} of the undrained tests 30-1147 min and d_r to be applied are 0.01-0.026 mm/min. For specimen with initial diameter of D_0, the membrane of t_m total thickness surrounding a membrane correction σ_{mb} is multiplied by $38t_m/0.2D_0$ (BS 1377-8-1990). In case of applying vertical side drains, a drain correction σ_{dr} shall be applied for strains of more than 2%. The drain correction for the case of this laboratory program with the specimen diameter of 38 mm is 10 kPa. The corrected deviator stress $(\sigma_1 - \sigma_3)$ is given by $(\sigma_1 - \sigma_3) = (\sigma_1 - \sigma_3)_m - \sigma_{mb} - \sigma_{dr}$. In the triaxial tests, confining pressures of $0.5\sigma_v$, σ_v and 2 σ_v (σ_v is vertical in-situ stress at the sample location) might be appropriate (Head and Epps, 2011). Hence, cell confining pressure selected for three trial tests is from 25-200 kPa.

5. CONSOLIDATION PARAMETERS FROM OEDOMETER TESTS

Fig. 2 shows the graphs of typical *OED* test results and the comparison between the stress-strain curve of a typical *OED* test on a Soft clay sample and the one of *CRS* test on another Soft clay sample taken at the same place and depth. Table 2 shows the data from the *OED* tests. The values of the Preconsolidated pressure σ_p' are estimated with Casagrande's method and then corrected to the in-situ condition. It is seen that the soft clays are Lightly OC (1.2 < *OCR* < 2.5).

6. RESULTS OF THE UNDRAINED TRIAXIAL TESTS

The B-values from 0.95 to 0.99 are used. All specimens are 95% to 100% saturated. The range of effective consolidation pressure applied is from 50 kPa to 300 kPa. The undrained stress-strain response, excess pore water pressure during loading or unloading/reloading at effective confining pressures σ_3' = 30-200 kPa are shown in Fig. 3 for the five Soft clay samples and in Fig. 4 for the three Lower soft clay samples. The effective strength parameters from stress path using both failure criteria, maximum effective stress ratio $(\sigma_1'/\sigma_3')_{max}$ and maximum deviator stress $(\sigma_1'-\sigma_3')_{max}$, are very similar (Fig. 7). This similarity is acknowledged as typical for NC to Lightly OC soft soils. The CIU test results are summarized in Table 3.

Table 2. Compression and consolidation parameters from the OED tests

Samples	Depth	e_0	C_c	C_{s1}/C_{s2}	λ^*	κ_1^*/κ_2^*	σ'_{v0}	σ'_p	OCR
	m	[-]	[-]	[-]	[-]	[-]	kPa	kPa	[-]
Soft clay- Site 1									
OED-1-2	5.3	2.11	1.124	0.143	0.157	0.040	43.7	90	2.05
OED-1-3	6.2	2.24	1.024	0.059/ 0.097	0.137	0.016/0.026	48.6	62	1.27
OED-1-4	7.8	2.07	0.969	0.061/0.095	0.137	0.017/0.027	57.4	63	1.09
OED-1-5	7.0	2.12	0.945	0.114	0.132	0.032	53.0	91	1.71
OED-1-6	5.4	2.45	1.197	0.177	0.151	0.024	44.2	58	1.31
OED-1-7	5.4	2.37	1.017	0.115/0.121	0.131	0.030/0.031	44.2	67	1.51
OED-1-8	7.5	1.93	1.017	0.177/0.212	0.121	0.049/0.077	55.7	72	1.29
OED-1-9	6.1	2.06	0.837	0.169/0.236	0.119	0.048/0.067	48.1	68	1.41
OED-1-10	4.5	2.62	1.197	0.177	0.151	0.024	39.3	51	1.29
OED-1-11	8.5	2.04	1.125	0.144	0.161	0.041	61.2	73	1.19
OED-1-12	12.5	1.50	0.578	0.131	0.101	0.046	83.3	74.8	0.90
Average			0.910	0.133/0.152	0.136	0.033/0.045		70	1.36
Lower soft clay- Site 2									
OED-2-1	14.3	1.77	0.778	0.122	0.122	0.038	121.7	182.5	1.50
OED-2-2	12.9	1.67	0.733	0.096/0.149	0.119	0.031/0.049	113.2	174.3	1.54
OED-2-3	14.3	1.80	0.762	0.120	0.081	0.026	121.7	183.7	1.51
Average			0.757	0.112/0.149	0.107	0.032/0.049		180.0	1.52

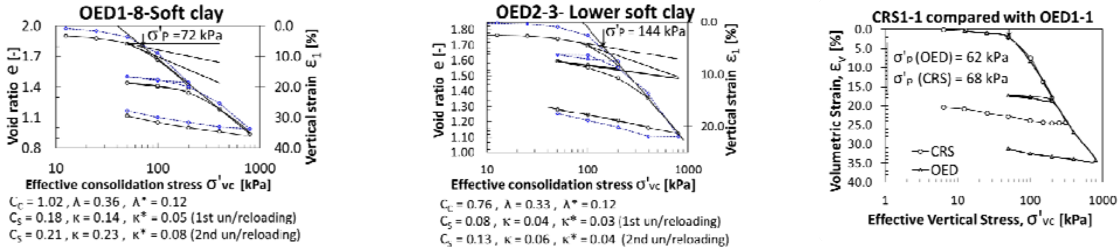

Figure 2. Typical OED test result on the Soft clay (Site 1), Lower soft clay (Site 2; Comparison between OED and CRS test result of Soft Clay at 6.2 m depth (Site 1)

Table 3. Summary of CIU test results

Tests	Depth	Confining pressures	e_0	Strength parameters/ Failure criteria			
				$(\sigma_1' - \sigma_3')_{max}$		$(\sigma_1' / \sigma_3')_{max}$	
				c'	φ'	c'	φ'
	m	kPa	[-]	kPa	[°]	kPa	[°]
Soft clay- Site 1							
CIU1-1	6	30, 100, 200	2.02	9.5	23.9	8.0	25.6
CIU1-2	6	30, 100, 200	1.86	9.6	23.7	7.5	25.9
CIU1-5	5.4	50, 100, 200	2.60	4.5	21.7	6.2	21.6
CIU1-6	6.1	24, 50, 100	2.01	7.5	19.2	9.0	19.2
CIU1-9	12.5	100, 150, 200	2.07	6.3	20.0	7.7	19.6
Lower soft clay- Site 2							
CIU2-1	13.6	50, 100, 200	1.85	8.4	21.2	3.9	24.1
CIU2-2	15.1	50, 100, 200	1.80	9.0	20.0	6.5	21.8
CIU2-3	13.3	50, 100, 200	1.67	3	22.0	0	24.9

7. RESULTS OF THE DRAINED TRIAXIAL TESTS

Seven CID tests on the Soft clay and two CID tests on the Lower soft clay are performed under the σ_3' = 50 kPa, 100 kPa, 200 kPa (or 150 kPa). Like the CIU tests, back pressure of 200 kPa and saturation at 95 to 100% are applied. The correlation between stress-strain, volume strain-axial strain of the specimens (Figs. 5 and 6) shows that, during the increase of the deviator stress, the soil specimen reduces almost linearly in volume and then at the axial strain of about 5%, the volume strain starts to reduce slower and non-linearly. The basically hyperbolic stress-strain relationships are observed, and the volume strain-axial strain curves tend to be congruent with the stress-strain curves. The CID test results are summarized in Table 4.

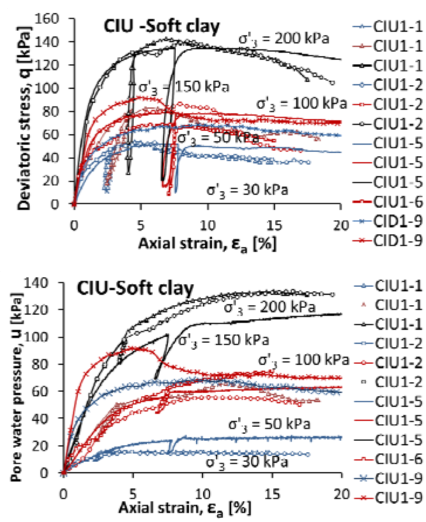

Figure 3. CIU tests on the Soft clay: q versus ε_a and u versus ε_a

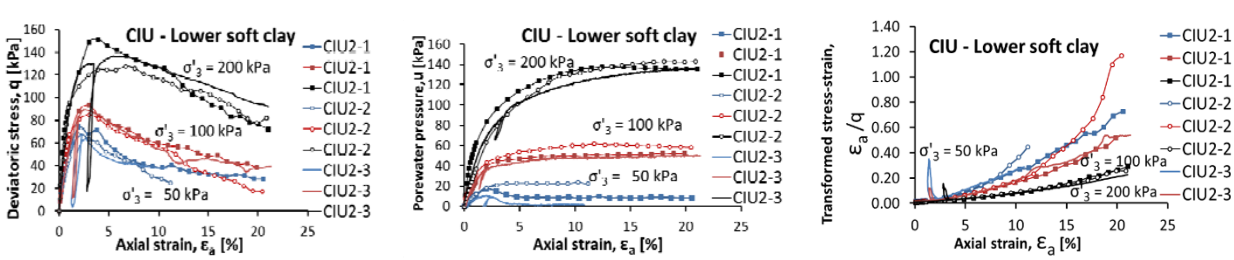

Figure 4. CIU tests on the Lower soft clay: q versus ε_a and u versus ε_a

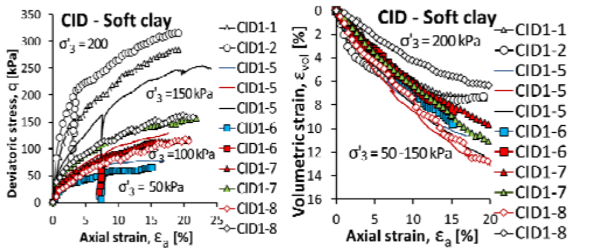

Figure 5. Curves of Stress – strain, Volume change – strain &Transformed hyperbolic stress – strain from the CID tests on the Soft clay

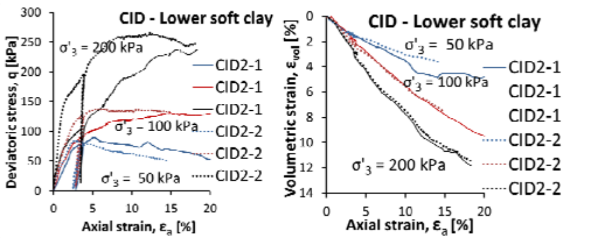

Figure 6. CID tests on the Lower soft clay: Stress-strain/ Volume change - strain relationships

Table 4. Summary of CID test results

Samples	Depth	Confining pressure	c'	φ'	ν
	m	kPa	kPa	[°]	[-]
Soft clay- Site 1					
CID-1-1	6	50, 100, 200	14.9	22.3	0.380
CID-1-2	6	50, 100, 200	12.9	24.1	0.366
CID-1-5	6.8	50, 100, 200	9.0	19.6	0.529
CID-1-6	7.9	50, 100, 200	6.0	18.4	0.586
CID-1-7	4.5	50, 100, 150	15.1	16.3	0.533
CID-1-8	9	50, 100, 150	8.7	18.5	0.531
Lower soft clay- Site 2					
CID2-1	14.6	50, 100, 200	14	18.8	0.529
CID2-2	14.6	50, 100, 200	8	21.6	0.526

8. STRENGTH PARAMETERS RESULTED FROM THE TRIAXIAL TESTS

The stress path and the accordingly estimated c' and φ' of HCMC Soft Clay resulting from the CID tests and the CIU tests using both failure criteria, $(\sigma_1'/\sigma_3')_{max}$ and $(\sigma_1'-\sigma_3')_{max}$ are shown in Fig. 7 and summarized in Table 5.

9. OEDOMETRIC MODULI FROM THE OEDOMETER TESTS

$E_{oed} = \sigma_1'/\lambda^*$ (according to PLAXIS) can also be estimated from the field virgin compression curve with void ratio e^{ref} at a reference compression pressure:

$$E_{oed} = \left(\frac{1+e^{ref}}{C_c}\right)\sigma^* = \left(\frac{1+e^{ref}}{C_c}\right)\frac{\Delta\sigma'}{\log_{10}\left(\dfrac{\sigma_{oed}^{ref}+\Delta\sigma'}{\sigma_{oed}^{ref}}\right)} \quad (1)$$

$E_{ur,oed}$ can be similarly estimated with void ratio e_{vm} at the effective maximum pressure σ_{vm}':

$$E_{oed} = \left(\frac{1+e_{vm}}{C_s}\right)\sigma^* = \left(\frac{1+e_{vm}}{C_s}\right)\frac{\Delta\sigma'}{\log_{10}\left(\dfrac{\sigma_{oed}^{ref}+\Delta\sigma'}{\sigma_{oed}^{ref}}\right)} \quad (2)$$

For the stress dependency of the constraint modulus, Ohde (1939) and Janbu (1963) proposed the relationship $E_{oed} = E_{oed}^{ref}(\sigma_1'/p^{ref})^m$. Brinkgreve et al., (1998) proposed the empirical correlations showing the dependency on the soil compression and swelling characteristics: $E_{oed}^{ref} = p^{ref}/\lambda$ and $E_{ur,oed}^{ref} = 3p^{ref}(1-2\nu_{ur})/\kappa^*$. The reference E_{oed} and $E_{ur,oed}$, m, λ^*, κ^* are examined by both graphical and empirical methods and summarized in Table 6. E_{oed} and $E_{ur,oed}$ are estimated by the axis y-intercept of their linear trendlines from the double log scale graph plotting normalized E_{oed} and $E_{ur,oed}$ versus normalized effective vertical stress $\sigma_{vc}' = \sigma_1'$. The slope of these linear trendlines is computed for m.

10. STIFFNESS PARAMETERS FROM THE TRIAXIAL TESTS

According to the nonlinear stress-strain hyperbola relationship (Duncan and Chang 1970):

$$\left(\sigma_1' - \sigma_3'\right) = \frac{\varepsilon}{1/E_i + \varepsilon\left(\sigma_1' - \sigma_3'\right)_{ult}} \quad (3)$$

The correlation between E_{50} and the Initial stiffness modulus E_i is $E_{50} = E_i(1-R_f/2)$. Janbu (1963) expressed the variation of E_i with σ_3' as: $E_i = Kp_a(\sigma_3'/p_a)^m$; where, K is modulus number and p_a is atmospheric pressure. Ohde (1939) proposed: $E_i = k.p^{ref}(\sigma'/p^{ref})$; where, k is a dimensionless modulus number. The value of k and m can be estimated by the slope of the effective consolidation stress-tangent modulus curve. The undrained or drained stiffness parameters are estimated from the stress-strain curves according the Equation 3. E_{iu}, E_{50u}, or E_{50} is directly determined by plotting a tangent at the origin of the stress-strain curve or plotting a tangent from the origin through the point corresponding to 50% shear strength on the curve, respectively.

Table 5. Strength parameters resulting from CIU and CID tests

Type of clay	$CIU/(\sigma_1'/\sigma_3')_{max}$		$CIU/(\sigma_1'-\sigma_3')_{min}$		*CID*		*Average*	
	c' (kPa)	φ' (^{0})	c' (kPa)	φ' (^{0})	c' (kPa)	φ' (^{0})	c' (kPa)	φ' (^{0})
Soft clay	10.03	20.8	9.38	20.6	5.8	21	10.2	19.2
Lower soft clay	3.17	23.5	6.74	21.2	9.2	19.6	10.9	19.3

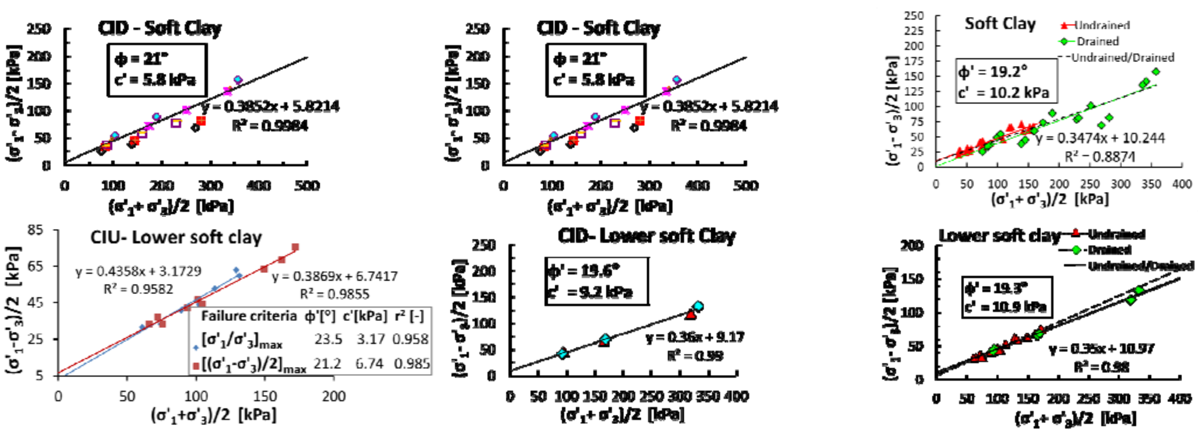

Figure 7. Strength envelope/ strength parameters of all Triaxial tests on the Soft clay/Lower soft clay

Table 6. Oedometric Moduli at reference confining pressure p^{ref}

Test samples	E_{oed}^{ref}				$E_{ur,oed}^{ref}$					
	From e versus σ_1'		From $\frac{p^{ref}}{\lambda^*}$ (m=1)		From e versus σ_1': 1st un/reload		From e versus σ_1': 2nd un/reload		$=3p^{ref}(1-2\nu_{ur})/\kappa^*$ (ν_{ur}=0.20, m=1)	
	m	E_{oed}^{ref}	λ^*	E_{oed}^{ref}	m	$E_{ur,oed}^{ref}$	m	$E_{ur,oed}^{ref}$	κ^*	$E_{ur,oed}^{ref}$
	[-]	kPa	[-]	kPa	[-]	kPa	[-]	kPa	[-]	kPa
Soft clay- Site 1										
OED1-2	0.90	549	0.157	637	0.98	4596			0.040	4500
OED1-3	0.89	624	0.137	730	0.99	5111			0.016	11250
OED1-4	0.89	683	0.137	730	0.98	4922	0.98	5212	0.017	10588
OED1-5	0.93	690	0.132	757	0.98	4410	0.99	9274	0.032	5625
OED1-6	0.89	836	0.151	662	0.99	6010			0.024	7500
OED1-7	0.89	641	0.131	763	0.98	5384			0.031	5806
OED1-8	0.90	709	0.121	826	0.98	3472	0.98	4183	0.049	3673
OED1-9	0.89	693	0.119	840	0.98	4864	0.96	3222	0.048	3750
OED1-10	0.88	588	0.151	662	0.98	4499	0.97	3519	0.024	7500
OED1-11	0.90	633	0.161	621	0.97	3538			0.041	4390
Average	0.90	670	0.140	650	0.98	4680	0.98	5082	0.032	6460
Lower soft clay- Site 2										
OED2-1	1,21	575	0.122	819	1.22	3601			0.038	4736
OED2-2	1.22	612	0.119	840	1.21	4808	1.19	3087	0.031	5806
OED2-3	1.12	589	0.081	1234	1.21	5678	1.19	3509	0.026	6923
Average	1.18	592	0.107	964	1.21	4695	1.19	3298	0.031	5821

Table 7. Deformation Moduli from CIU tests at reference confining pressure p^{ref}

Test Samples	Undrained Tangent Modulus		Undrained Secant Modulus		$E_{iu}^{ref} / E_{50u}^{ref}$	R_f
	m	E_{iu}^{ref}	m	E_{50u}^{ref}		
	[-]	kPa	[-]	kPa	[-]	[-]
Soft clay						
CIU1-1	0.79	6244	0.67	3858	1.62	0.94
CIU1-2	0.80	8265	0.67	5314	1.55	0.96
CIU1-5	1.00	9428	0.96	4854	1.94	0.97
CIU1-6	0.55	1499	0.58	937	1.60	0.92
CIU1-9	0.77	8495	0.95	4637	1.83	0.97
Average	0.78	6786	0.78	3920	1.71	0.95
Lower soft clay						
CIU2-1	0.61	12308	0.52	9057	1.36	0.95
CIU2-2	0.71	11324	0.48	8312	1.36	0.94
Average	0.66	11816	0.50	8684	1.36	0.94

E_{iu}^{ref}, E_{50u}^{ref} or E_{50}^{ref} and m from the CIU tests are estimated by the graph of normalized E_{iu} and E_{50u} versus normalized σ_3', i.e., the correlation between E_{ui}/p^{ref} and E_{50u}/p^{ref} with σ_3'/p^{ref}, in the double log scale. Similarly, the values of E_i^{ref}, E_{50}^{ref} and m from the CID tests are also estimated by the correlation between E_i/p^{ref} and E_{50}/p^{ref} with σ_3'/p^{ref}. The variation of E_{ui}/p^{ref} and E_{50u}/p^{ref} or E_i/p^{ref} and E_{50}/p^{ref} with σ_3' from all CIU tests or CID tests are described in Figs. 9 & 10. Tables 7 & 8 summarize E_{iu}^{ref}, E_{50u}^{ref}, m and R_f from the CIU tests and E_i^{ref}, E_{50}^{ref} or E_{ur}^{ref}, m and $R_f$from CID tests. The moduli from the triaxial tests tend to increase with the increasing confining pressure in accordance with Janbu (1963)'s suggestion.

11. THE HSM PARAMETERS ESTIMATED FROM THE LABORATORY TESTING

The set of values of soil parameters in average of HCMC Soft Clay is estimated for soil modeling using HSM as shown in Table 9. The realistic oedometric/triaxial moduli ratios is about 2.5.

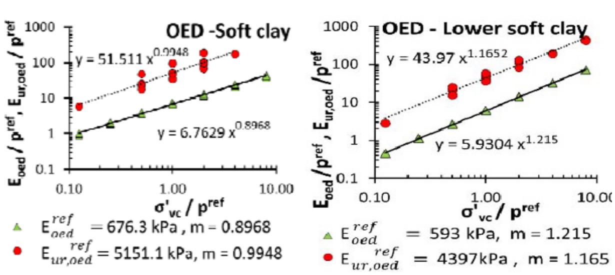

Figure 8. Oedometric Moduli versus Consolidation pressure of all OED tests

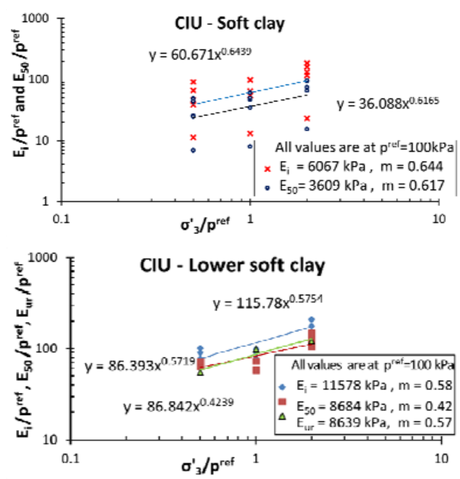

Figure 9. Variation of Deformation Moduli with Confining pressure from all CIU tests

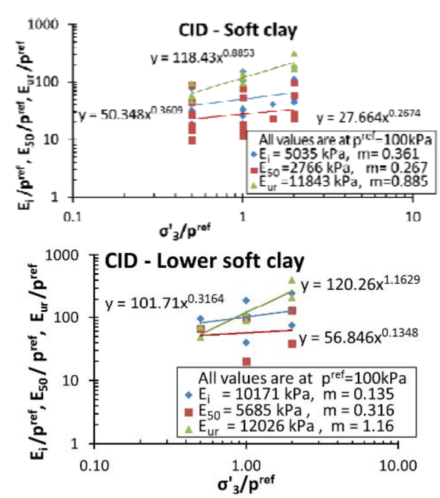

Figure 10. Deformation Moduli versus Confining pressure from all CID tests

Table 8. Deformation Moduli from CID tests at reference confining pressure p^{ref}

Test Samples	Drained Tangent Modulus		Drained Secant Modulus		Drained Un/ reloading Modulus		R_f	$\frac{E_i^{ref}}{E_{50}^{ref}}$	$\frac{E_{ur}^{ref}}{E_{50}^{ref}}$
	m	E_i^{ref}	m	E_{50}^{ref}	m	E_{ur}^{ref}			
	[-]	kPa	[-]	kPa	[-]	kPa	[-]	[-]	[-]
Soft clay									
CID1-1	0.66	8024	0.55	4346			0.86	1.84	
CID1-2	0.77	12934	0.57	6873			0.93	1.88	
CID1-5	0.30	3865	0.36	2050	0.62	11222	0.85	1.88	1.63
CID1-6	0.62	2824	0.62	1412	1.39	11278	0.86	2.00	5.50
CID1-7	0.60	3201	0.71	1685	0.50	13125	0.87	1.90	9.29
CID1-8	0.36	2932	0.38	1616			0.91	1.81	
Average	0.55	*3205*	0.53	*1690*	0.94	11875	0.87	1.88	7.4
Lower soft clay									
CID2-1	0.91	3990	0.94	2013	0.80	11062	0.88	1.98	5.50
CID2-2	0.69	16522	0.48	9427	1.53	13074	0.94	1.75	1.39
Average	0.80	*3990*	0.71	5720	1.16	12068	0.91	1.86	3.45

Table 9. Average value of HSM parameters from the laboratory testing results

HCMC Soft clay strata	E_{oed}^{ref}	$E_{ur,oed}^{ref}$	E_{50}^{ref}	E_{ur}^{ref}	$\frac{E_{50}^{ref}}{E_{oed}^{ref}}$	$\frac{E_{ur,oed}^{ref}}{E_{oed}^{ref}}$	$\frac{E_{ur}^{ref}}{E_{ur,oed}^{ref}}$	$\frac{E_{ur}^{ref}}{E_{50}^{ref}}$	c'	φ'	m	R_f
	kPa	kPa	kPa	kPa	[-]	[-]	[-]	[-]	kPa	[°]	[-]	
Soft clay	670	5570	1690	11875	2.52	8.31	2.13	7.02	9	19.2	0.9	0.9
Lower soft clay	780	4560	2013	12026	2.58	5.85	2.63	5.97	9.9	19.7	0.9	0.9

12. CONCLUSIONS & RECOMMENDATION

The main conclusions can be drawn:

(i) The strength properties show very good consistent values with small variation from CIU or CID data. This shows high quality of undisturbed samples and testing done;

(ii) The average values of Hardening Soil model parameters are determined for design practice of deep excavations and tunneling;

(iii) In case of a safe and conservative design, it can accept that the value of the ratio of unloading/reloading modulus to primary loading modulus is about the same value for both shear hardening and volumetric hardening. The realistic oedometric/triaxial moduli ratios are also recommended for the local design practice. Low cost and popular Oedometer tests then can be used to estimate the ratio of unloading/reloading to primary loading without the need to conduct the expensive and slow CID tests.

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