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INTRINSIC COMPRESSIBILITY, STRENGTH PROPERTIES AND SOME STRENGTH MODELS FOR DHAKA CLAY

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ABSTRACT : In order to find out a basic frame of reference for evaluating the in-situ behavior of natural Dhaka clay from its intrinsic properties, the intrinsic stress-strain-strength characteristics and their interactions were investigated for the clay through a series of laboratory tests. Finally, strength models were developed for the natural clay for various stress history and stress conditions. The Intrinsic Compression Line (ICL) and the Intrinsic Swelling Line (ISL) for the clay were established as well. The clay was subjected to K_0 and isotropic consolidation adoptining a number of stress paths followed by different loading and unloading stress history at various overconsolidation ratios (OCR). Models were developed including those in terms of strength ratio, Su/σ_{vo} and other intrinsic parameters of the clay such as α and μ to predict the strength of natural Dhaka clay. The derived models can be used to predict the strength and deformation characteristics of Dhaka clay from simple measureements of in-situ void ratio (water content) and field overburden pressure only.

KEYWORDS : Intrinsic properties, strength model, intrinsic, strength ratio, ICL, SCL, ISL, void index.

INTRODUCTION

The properties of reconstituted clays are referred as 'Intrinsic' properties since they are basic or inherent to the clay and independent of the natural state. A reconstituted clay is one that has been thoroughly mixed at a water content equal to or greater than liquid limit (w_L)). The term "intrinsic" is used to describe properties of clays which have been reconstituted at a water content of between w_L and 1.5 w_L (preferably 1.25 w_L) without air drying or oven drying and then consolidated preferably under one dimensional conditions (Burland, 1990). The geotechnical characteristics of a natural clay differs from its intrinsic properties due to the influence of soil structure, its texture and bonding. Some important phenomena produce differences between natural soils from reconstituted soils. The influence of micro and macro structure which is the combination of 'fabric', i.e., arrangement of particles and interparticle 'bonding' produce these differences. Soil mechanics to a

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large extent has been developed from careful comprehensive studies of the properties of reconstituted natural soils since the intrinsic properties render a datum reference for assessment of the in-situ state of a natural clay. During the last several decades, some theories have been developed that correlate the relationship between reconstituted and natural soil behavior. With such theories, it is possible to find out the properties of natural clay. The undrained strength (S_u) of a natural clay is dependent on its existing effective overburden pressure (σ_{vo}), void ratio (e), past maximum pressure (σ_{vm}) and overconsolidation ratio (OCR = σ_{vm}/σ_{vo}) and their relationships are unique for a particular local clay (Ladd, 1971). Clays exhibit normalized behaviour between undrained shear strength, S_u, the in-situ overburden pressure, (σ_{vo}) and some index properties. The $S_u/(\sigma_v)$ values are related to plasticity index, liquidity index I_L and liquid limit. Once such unique relationships are established for a clay, its shear strength becomes predictable. Unfortunately, only results from the highest quality undisturbed samples can provide data for building such prediction models. It is thus imperative to initially study intrinsic properties of clays, the results of which may be used to build a model that may be calibrated from results on some quality field samples. This paper describes some shear strength and consolidation models of clays and show how these can be applied for Dhaka clay from its intrinsic properties.

LABORATORY INVESTIGATIONS

Samples of Dhaka clay was reconstituted to a water content 1.5 times the liquid limit to form a slurry. From slurry, normally consolidated and overconsolidated samples of various overconsolidation ratios were prepared with different stress systems under the following stress path conditions :

(a) Category I : K_o-consolidated normally loaded or K_oNC samples

(b) Category II : Isotopically consolidated normally loaded or KoINC samples

(c) Category III : Ko-consolidated unloaded or KoOC samples

(d) Category IV : Isotopically consolidated unloaded or KoIOC samples.

The details of the sample preparation, loading conditions and soil indices are given by Kamaluddin (1990). The Ko-consolidation was performed in a 210 mm dia and 245 mm height Rowe consolidation cell. Schematic effective stress path for preparation of four categories of samples and undrained strength test conditions are shown in Figure 1. In this figure, Ko indicates at rest pressure condition, k = 1 indicates isotropic stress condition and K_f indicates the failure condition.

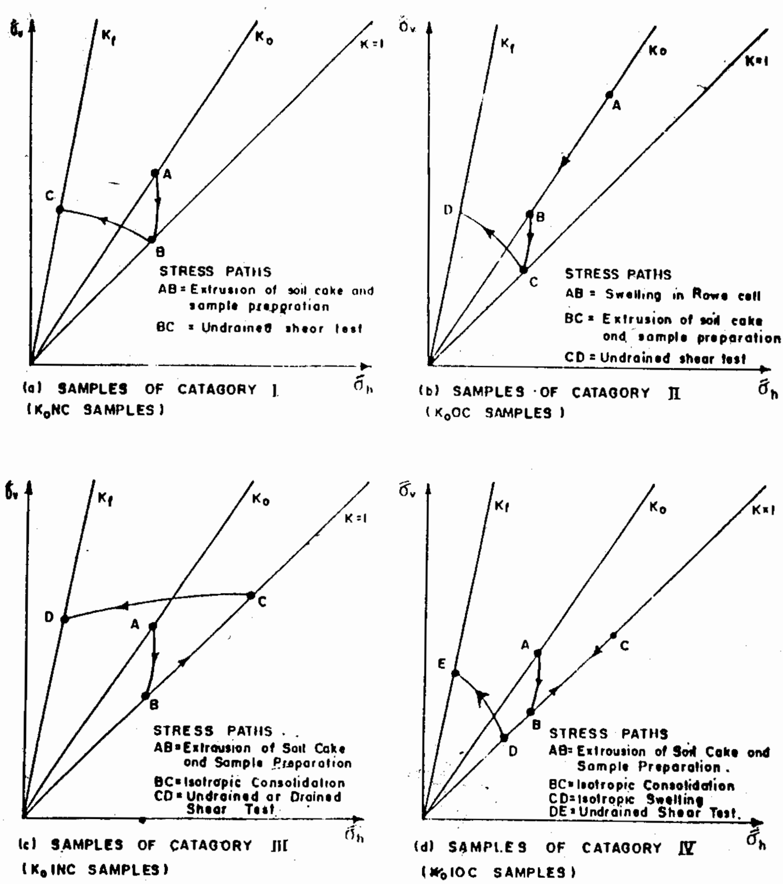


Fig 1. Qualitative Effective Stress Path for Loading and Unloading Sequence Followed in Four Categories of Samples

INTRINSIC PROPERTIES OF NORMALLY CONSOLIDATED DHAKA CLAY

For KoNC, KoINC and KoIOC, KoIOC samples, the semi-log plots of void ratio (e) or water content (w) versus consolidated pressure (σ_v), void ratio (e) or water content (w) versus undrained shear strength (S_u) show linearity. These relations demonstrate the uniqueness of water content or void ratio relations with consolidation pressure or undrained shear strength for saturated soils (Figure 2). Table 1 shows intrinsic behaviour of normally consolidated Dhaka clay under Ko-consolidation. It can be seen from the table that both the values of $E_{u(50)}/\sigma_v$ and Su/σ_v are nearly constant irrespective of the vertical consolidated pressure. Here $E_{u(50)}$ is the undrained secant modulus at 50% of undrained shear strength and σ_v is the vertical effective stress. The average values of $E_{u(50)}/\sigma_v$ and Su/σ_v were found to be 37.52 and 0.186, respectively. The later value compares very well with Skempton's (1957) equation, $Su/\sigma_v = 0.11 + 0.0037(PI)$. The average value of ψ [= $E_{u(50)}/S_u$] of these samples is 202.

Table 2 shows intrinsic behaviour of normally loaded Dhaka clay under isotropic consolidation. Again it is seen that both $E_{u(50)}/p$ and S_u/p values are constant irrespective of the consolidation pressure. The average value of the $E_{u(50)}/p$ and S_u/p of the remoulded Dhaka clay is found to be 50.90 and 0.295, respectively, which are higher than that for normally loaded K_0-consolidated samples. But average value of ψ is 172.

Table 1. Intrinsic Properties for KoNC Samples.

Maximum Vertical consolida-tion Pressure σ_v	Equilibrium Void Ratio e	Equilibrium Water Conten w	Un-drained shear Strength S_u	Undrained Secant Modulus at 5% of Ultimate Strength	$\frac{E_{u(50)}}{\sigma_v}$		Normalized undrained Secant Modulus $\psi = [E_{u(50)}/S_u]$		Undrained Shear Stregnth Ratio Su/σ_v	
(kpa)		(percent)	(kPa)	(kPa)		Ave.		Ave.		Ave.
100	0.775	31.32	18.60	3676	36.76		197		0.186	
200	0.705	27.83	37.60	7915	39.57		210		0.188	
300	0.658	25.84	55.20	11621	38.73	37.52	210	202	0.184	0.186
400	0.625	24.50	74.80	14247	35.61		190		0.187	
500	0.598	23.30	91.00	17773	35.54		195		0.182	
800	0.540	20.95	148.00	31157	38.94		210		0.185	

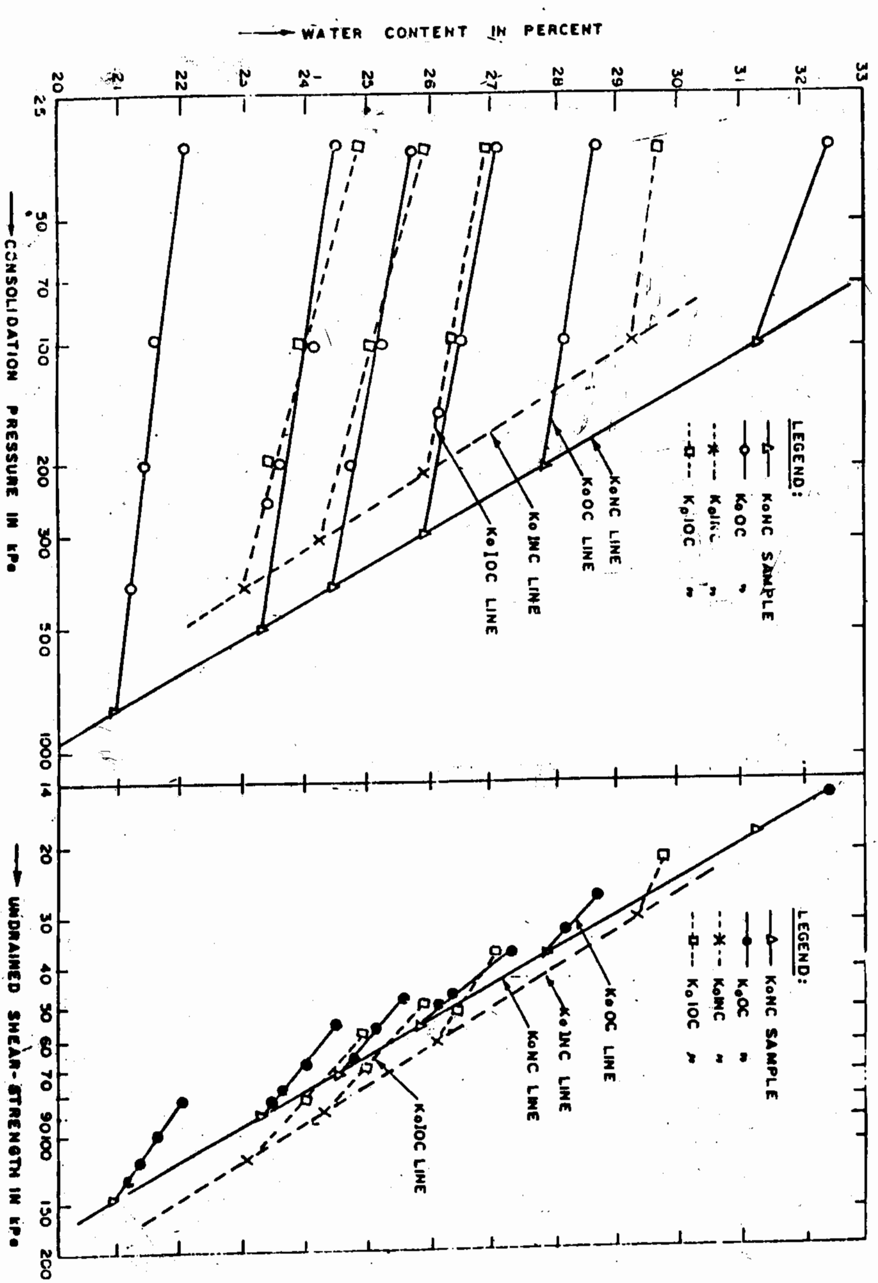


Fig 2. Water Content Versus Consolidation Pressure or Undrained Shear Strength for Dhaka Clays

The log-log plot in Fig. 3 shows the variation of undrained secant modulus $E_{u(50)}$ with consolidation pressure, σ for KoNC and KoOC samples. For both Ko an isotropic normally loaded samples, the relationship was found to be linear. Similar trend was found for KoINC and KoIOC samples. Because of the rebound characteristics of the clay, Hvorslev (1937) parameters were determined and the variation of shear strength at constant moisture content were studied (Figure 4). The values obtained for KoOC & KoIOC samples are $\beta' = -10.14°$, $\phi_e = 2.84°$ and $\beta' = -10.34° \phi_e, = 6.22°$ respectively. β' is the slope of the plot log c_e vs. w_f

Table 2. Intrinsic Properties for KoINC Samples.

Initial K_o consolid Pressure σ_v (IK_o)	Max. All-round Consolid. Pressure in Triaxial Cell $\bar{p}$	Equilibrium Void Ratio e	Equilibrium Water Conten w	Undrained shear Strength S_u	Undrained Secant Modulus at 5% of Ultimate Strength	$E_{u(50)}/\bar{p}$		Normalized undrained Secant Modulus ψ		Undrained Shear Stregnth Ratio $S_u/\bar{p}$	
(kpa)	(kpa)		(percent)	(kPa)	$E_{u(50)}$ (kPa)		Ave.		Ave.		Ave.
80	100	0.747	29.50	29.50	5306	53.06		179		0.295	
150	200	0.664	26.07	26.07	10365	51.82	50.90	174		0.298	0.295
250	300	0.615	24.34	24.34	14846	49.48		170	172	0.291	
350	400	0.585	23.06	23.06	19702	49.25		165		0.298	

INTRINSIC PROPERTIES OF OVERCONSOLIDATED DHAKA CLAY

Figure 5 shows the variation of undrained shear strength of the KoOC samples. It is clear that as the overburden pressure increases, the influence of OCR on undrained shear strength becomes pronounced. Normalized intrinsic Su/σ_{vo} versus OCR relationships for Dhaka clay are shown in Fig. 6 in semilog plot. When these data are plotted in log-log plot (Fig. 7), it yielded straight lines. In both the figures, published data for other well-known clays are also shown. In log-log scale, the intercept of the line (for KoIOC samples, which is undrained shear strength ratio (Su/p) at normally loaded state (OCR=1), has got value of 0.295. The slope of the line $\Lambda_o^{(Iso)}$ which is the critical state pore pressure parameter for isotropic stress condition, is equal to 0.734. For KoOC samples, $\Lambda_o = 0.821$ and $Su/\sigma_v = 0.186$ at OCR = 1. The results show that the intrinsic strength of Dhaka clay in Ko-condition is similar to Boston Blue clay within low OCR values.

A normalized Young's modulus, $E_{u(50)}/(\sigma_v$ or p versus OCR for remoulded Dhaka clay is shown in Figure 8. It can be seen that the Ko-consolidated sample (KoOC) lies above the isotopically consolidated sample (KoIOC) for the same OCR. The variation of ψ values, i.e., normalized undrained secant modulus, $E_{u(50)}/S_u$ with OCR for KoOC and KoIOC samples, are shown in Figure 9 with other clays.

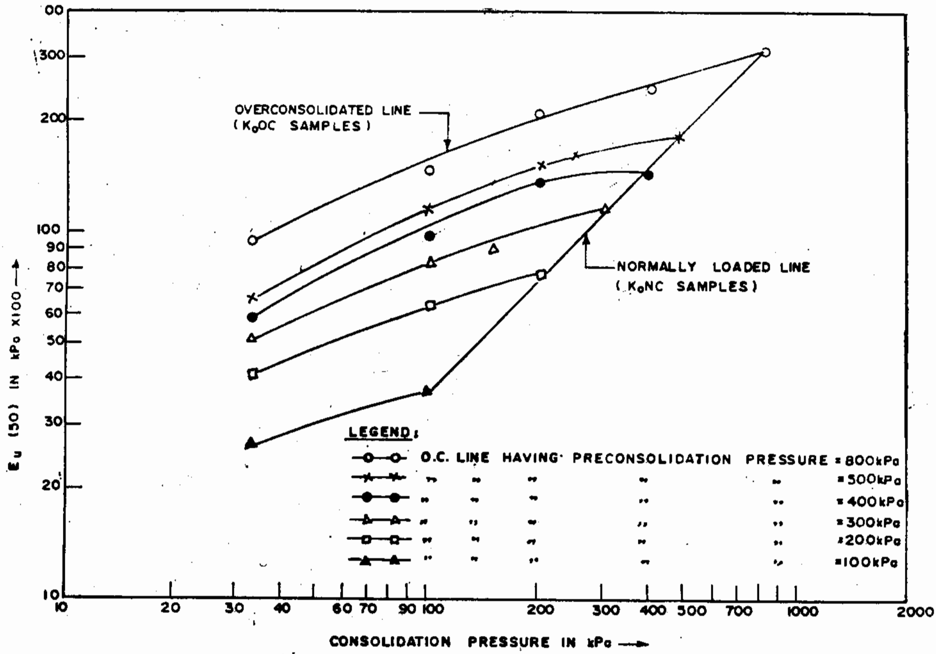


Fig 3.Variation of Undrained Secant-Modulus with Consolidation Pressure for KoNC and KoOC Samples of Dhaka Clay

UNDRAINED STRENGTH MODELS FOR RECONSTITUTED DHAKA CLAY

The results presented above can now be used to obtain parameters for intrinsic strength of Dhaka clay.

(a) Intrinsic Model for Normally Consolidated Dhaka Clay

Results show that it is possible to provide prediction models for clay soils in normally consolidated and fully saturated state in terms of strength ratio Su/σ_{vo} From the experimental results it has been shown earlier that for a saturated reconstituted normally consolidated Dhaka clay, the undrained shear strength ratios are 0.186 and 0.295 for K_o-consolidated and isotropic consolidated states, respectively.

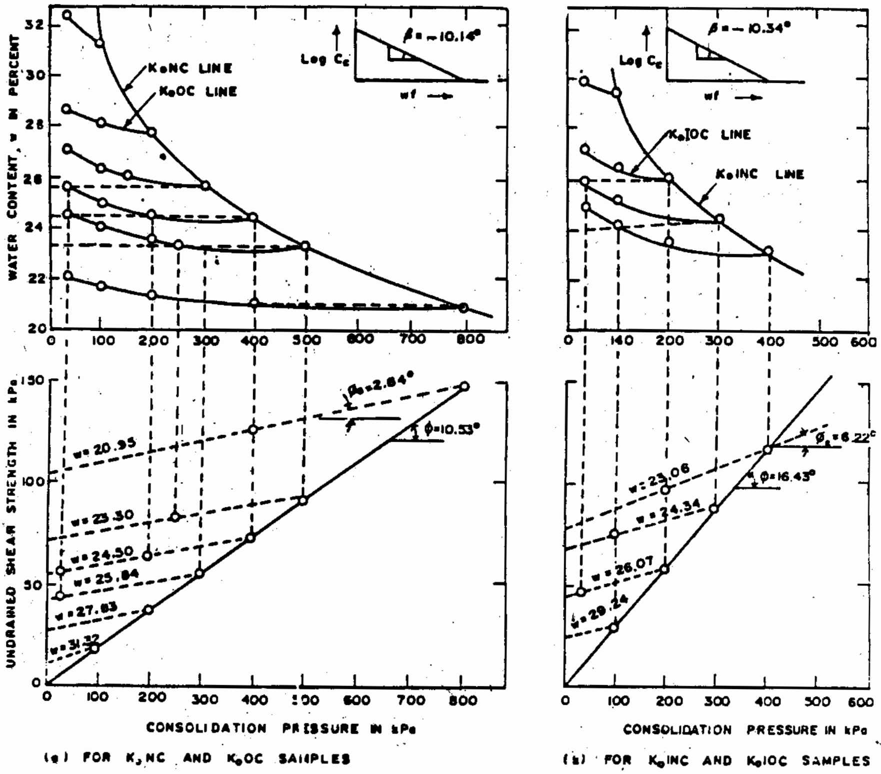


Fig 4. Determination of Cohesion Components at Constant Moisture Content

Thus,

$S_u^{(nc)} = 0.186\ \sigma_v$ for K_o stress condition (1)

$S_u^{(nc)} = 0.295\ p$ for isotopic stress condition (2)

$$\frac{S_u^{(nc)}}{\sigma_v} = \frac{3\mathrm{Sin}\phi}{3-\mathrm{Sin}\phi} = x\,\frac{1}{\exp(\Lambda_o)} \qquad (3)$$

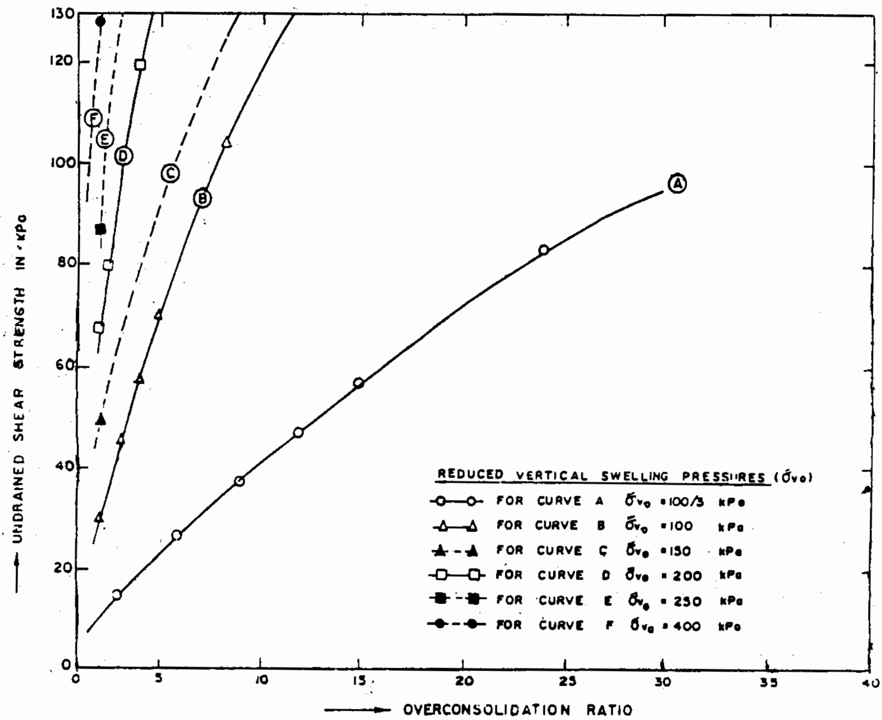


Fig 5.Relationship Between Undrained Shear Strength and Overconsolidation Ratio for KoOC Samples of Dhaka Clay

Equations 3 (Schofield and Wroth, 1967), based on Cam-clay model requires values of the critical state pore pressure parameter, Λ_0 and effective friction angle, ϕ for Dhaka clay. The value of Λ_0 is obtained from the relation $\Lambda_0 = 1 - [C_s^{(iso)}/C_c^{(iso)}]$, in which $C_s^{(iso)}$ is the swelling index and $C_c^{(iso)}$ is the compression index in isotropic consolidation. From a series of isotropic consolidation tests, value of $\Lambda_0^{(iso)}$ was found to be 0.863. The details of the tests are given by Kamaluddin (1990). The value of ϕ has been determined form drained tests on KoINC samples of remoulded Dhaka clay and found to be 23°. With above values of ϕ and Λ_0, Eq.3 gives the value Su/σ_v as 0.189 which is close to the laboratory value 0.186. Also Skempton's equation (1957), with plasticity index (PI) of 23 for Dhaka clay, the value of Su/σ_v becomes 0.195. In semilog plot of water content versus consolidation pressure (Figure 2), the linear relationships produce the following relationships by which strength can be estimated from water content only.

$$S_u(nc) = 10^{(3.99-0.086w)} \text{ for } K_0 \text{ stress condition} \quad (4)$$

$$S_u(nc) = 10^{(4.28-0.096w)} \text{ for isotropic stress condition} \quad (5)$$

(b) Intrinsic Model for Overconsolidated Dhaka Clay

Figures 6 and 7 can be used to predict intrinsic strength of overconsolidated Dhaka clay if σ_{vm} and σ_{vo} values are known. Using experimentally determined values, it is possible to estimate parameters for following equations of Atkinsos and Bransby (1978) and Mayne (1980),

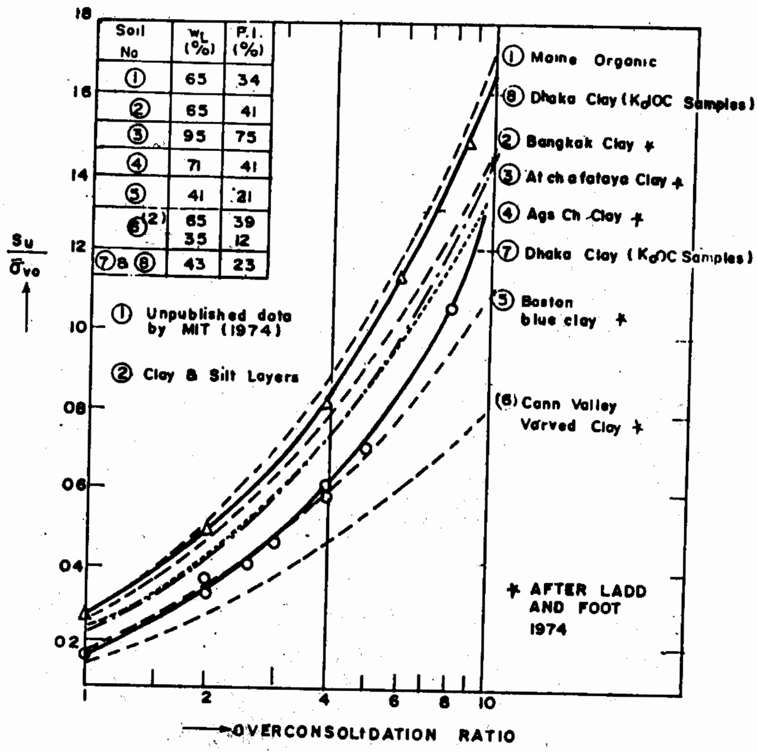


Fig 6. Undrained Strength Ratio Versus OCR for Dhaka Clay Compared to Other Six Clays

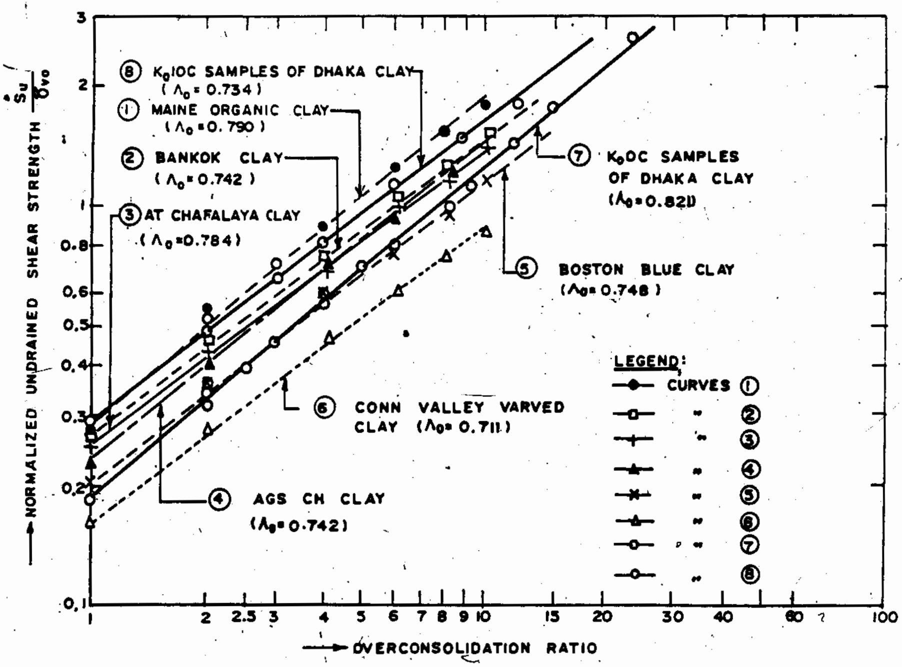


Fig 7. Normalized Undrained Shear Strength as a Function of Overconsolidation Ratio for Dhaka Clay Compared with Six Other Clays

$$\frac{S_u^{(oc)}}{\sigma_{vo}} = \frac{S_u^{(oc)}}{\sigma_v} \cdot (OCR)^{\Lambda o} \tag{6}$$

$$\frac{S_u^{(nc)}}{\sigma_{vo}} = \frac{3Sin\phi}{3-Sin\phi} X \frac{(OCR)^{\Lambda_0}}{{}^{o}exp(\Lambda_o)} \tag{7}$$

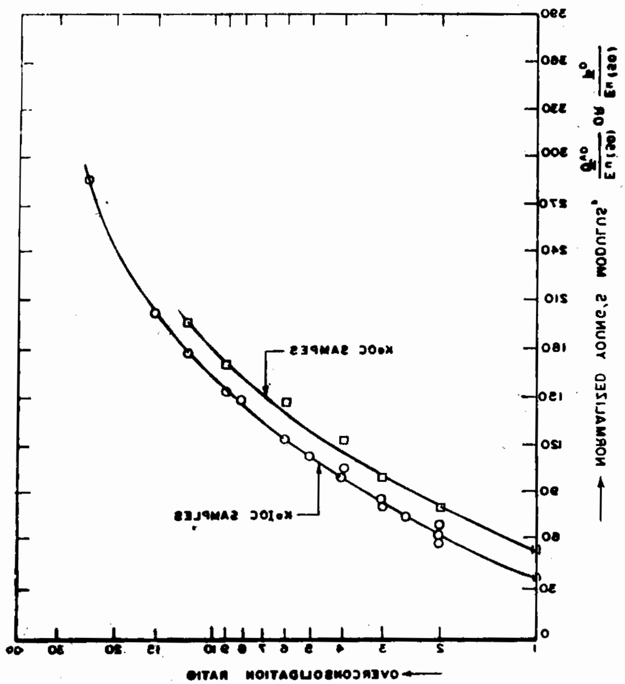


Fig 8. Normalized Young's Modulus Eu(50/σvo or Eu(50)po Versus Overconsolidation Ratio for Dhaka Clay

The curves α vs. OCR determined from experimental results of overconsolidated samples are shown in Figure 10.

Where, $\alpha = \dfrac{S_u^{(oc)}}{\sigma_{vo}} \Big/ \dfrac{S_u^{(nc)}}{\sigma_v}$

Therefore,

$S_u^{(oc)} = 0.186\ \alpha\ \sigma_{vo}$ for K_o-stress conditin (8)

$S_u^{(oc)} = 0.295\ \ \alpha\ p_o$ for isotropic condition (9)

since $S_u^{(nc)}/\sigma = 0.186$ for K_o-stress condition, and $S_u^{(nc)}/p = 0.295$ for isotropic stress condition respectively. For a particular value of OCR the value of α can be found out form Fig. 10 and undrained strength for overconsolidated soil can be predicted from equations (8) and (9). Similarly, undrained shear strength can be found out (from μ value) by using curves in Figure 11 where μ vs. OCR has been plotted from tes

CLAY	WL %	P.I. %	SYMBOL	SOURCE
BANGKOK CLAY	65	41	--□--	DATA FROM CKoU DSS TESTS (AFTER APPOLONIA POULOS AND LADD 1971)
MAINE ORGANIC CLAY	65 ± 10	33 ± 2	--△--	
BOSTON BLUE CLAY	41	22	--○--	
DHAKA CLAY (Ko CONSOL.)	41	22	--×--	DATA FROM UNDRAINED TRIAXIAL TEST (AFTER AMEEN, 1985)
" (ISO. CONSOL.)	"	"	--+--	
DHAKA CLAY (KoOC SAMPLES)	43	23	—⊗—	DATA FROM AUTHOR
DHAKA CLAY (KoIOC SAMPLES)	"	"	—⊠—	

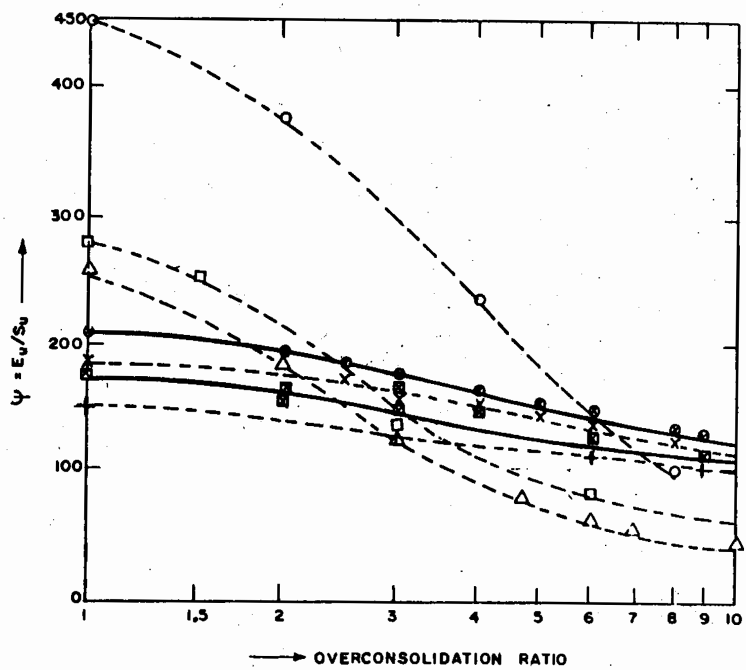


Fig 9. Comparison of Normalized undrained Secant Modulus for Dhaka Clay with That of Other Clays

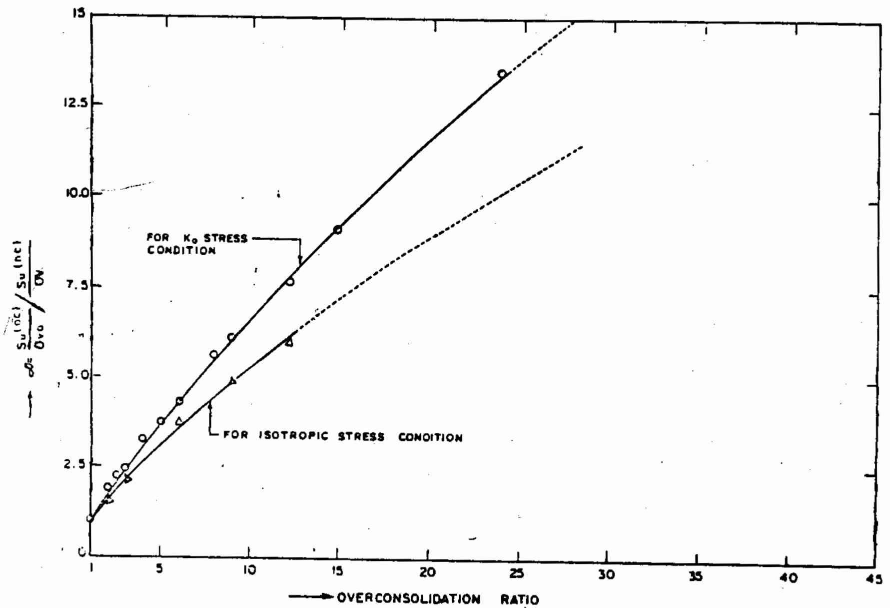


Fig 10. Prediction of Undrained Shear Strength of Overconsolidated Dhaka Clay from Plot of $\frac{S_u^{(oc)}}{\sigma_{vo}} / \frac{S_u^{(nc)}}{\sigma_v}$ *Versus Overconsolidation Ratio*

results for KoOC and KoIOC samples. The OCR of a soil under certain overburden pressure can be known if past maximum pressure is known. The maximum past pressure can be predicted from w log σv or p curves (Fig. 2) if water content and overburden pressure of in-situ soil are known.

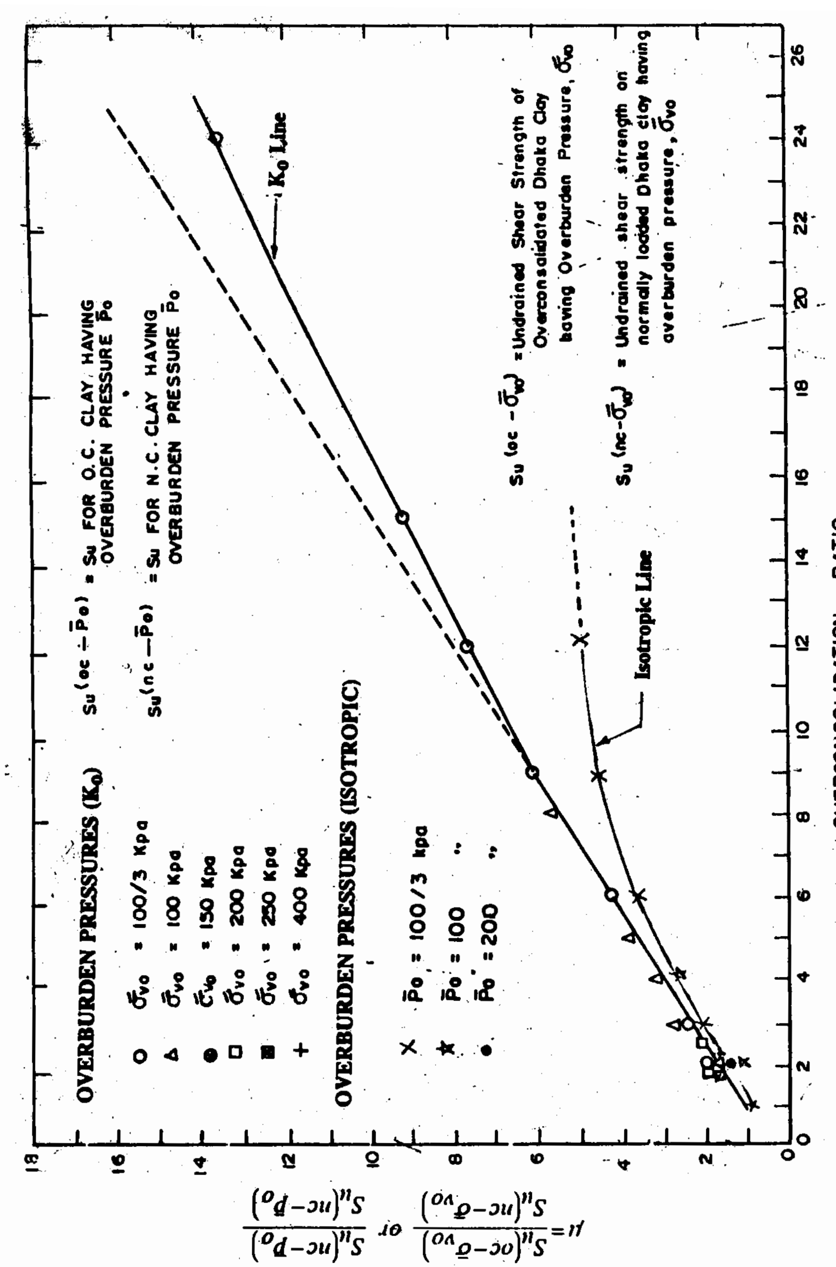


Fig 11. μ vs. OCR Plot for Prediction of Undrained Shear Strength of Overconsolidated Dhaka Clay Subjected to Ko and Istropic Stress Condition

From equation (6), the undrained shear strength ratio for Dhaka clay can be obtained once the parameters Λ_o and OCR are known. Replacing in Eq. (6), the values of $S_u^{(nc)}/\sigma_{vo}$ = 0.186 and Λ_o =0.821 obtained from test results (intercept and slope of line in Fig. 7), the following prediction models are obtained.

For K_o stress condition :

$$S_u^{(oc)} = 0.186\ (\sigma_v)^{0.821}(\sigma_{vo})^{0.179} \tag{10}$$

Similarly, for isotropic stress conditions

$$S_u^{(oc)} = 0.295\ (p)^{0.734}(p_o)^{0.266} \tag{11}$$

Using Eq. 7 and replacing values of ϕ = 23° and Λ_o (K0) =0.821 and Λ_o (iso) = 0.734 for K_o and isotropic conditions, respectively, the equation yields,

for K_o stress system

$$S_u^{(oc)} = 0.197\ (OCR)^{0.821}(\sigma_{vo}) \tag{12}$$

for isotropic stress system

$$S_u^{(oc)} = 0.216\ (OCR)^{0.734}(p_o) \tag{13}$$

The prediction models expressed by equation (11) and (12) have been shown in Fig. 12 where some tested values of undrained shear strength of some undisturbed samples of Dhaka clay have been plotted to compare with that predicted by the models.

VOID INDEX AND INTRINSIC COMPRESSION LINE (ICL) & INTRINSIC SWELLING LINE (ISL) FOR DHAKA CLAY

Figure 13 shows Intrinsic Compression Line (ICL) for Dhaka clay. The intrinsic void ratios e^*_{100} and e^*_{1000} for Dhaka clay has been found to be 0.775 and 0.525, respectively. So the intrinsic compression index C_c^* is 0.25. Thus the void index for Dhaka clay is

$$I_v = (e - e^*_{100})/C_c^* = (e-0.775)/0.25 \tag{14}$$

Using Eq. 14 ICL for Dhaka clay is plotted which coincides with ICL drawn by Burland (1990) for most soils. The Intrinsic Swelling Line (ISL) form data of reconstituted Dhaka clay is also drawn in Fig. 13. The value of C_s^* and C_s^*/C_c^* have been shown in the same figure. The values of C_s^*/C_c^* vary from 0.14 to 0.10.

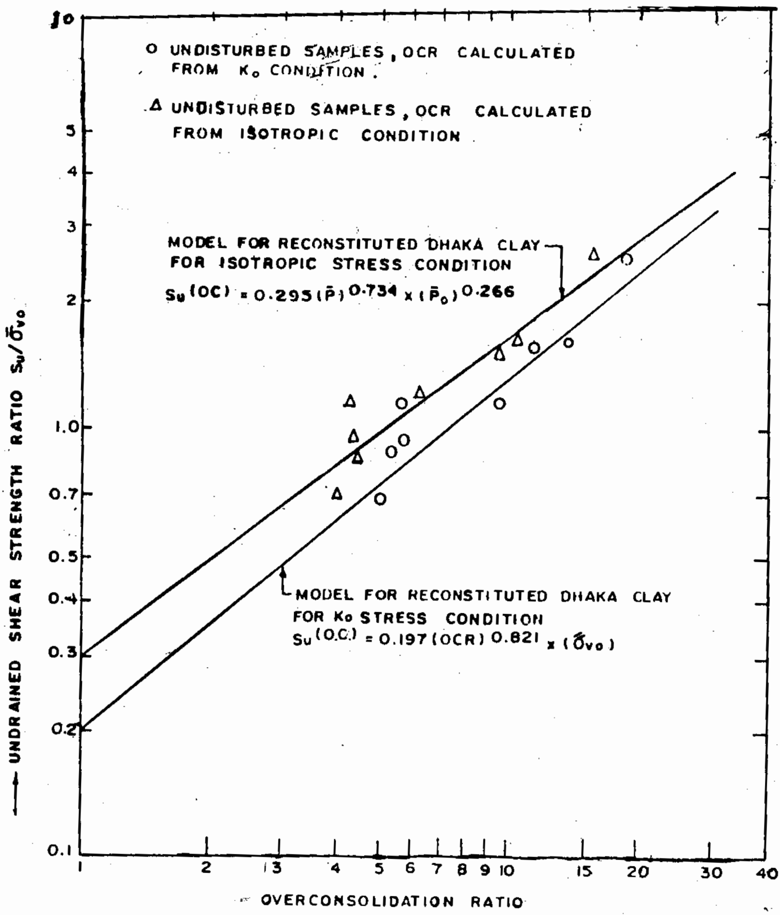
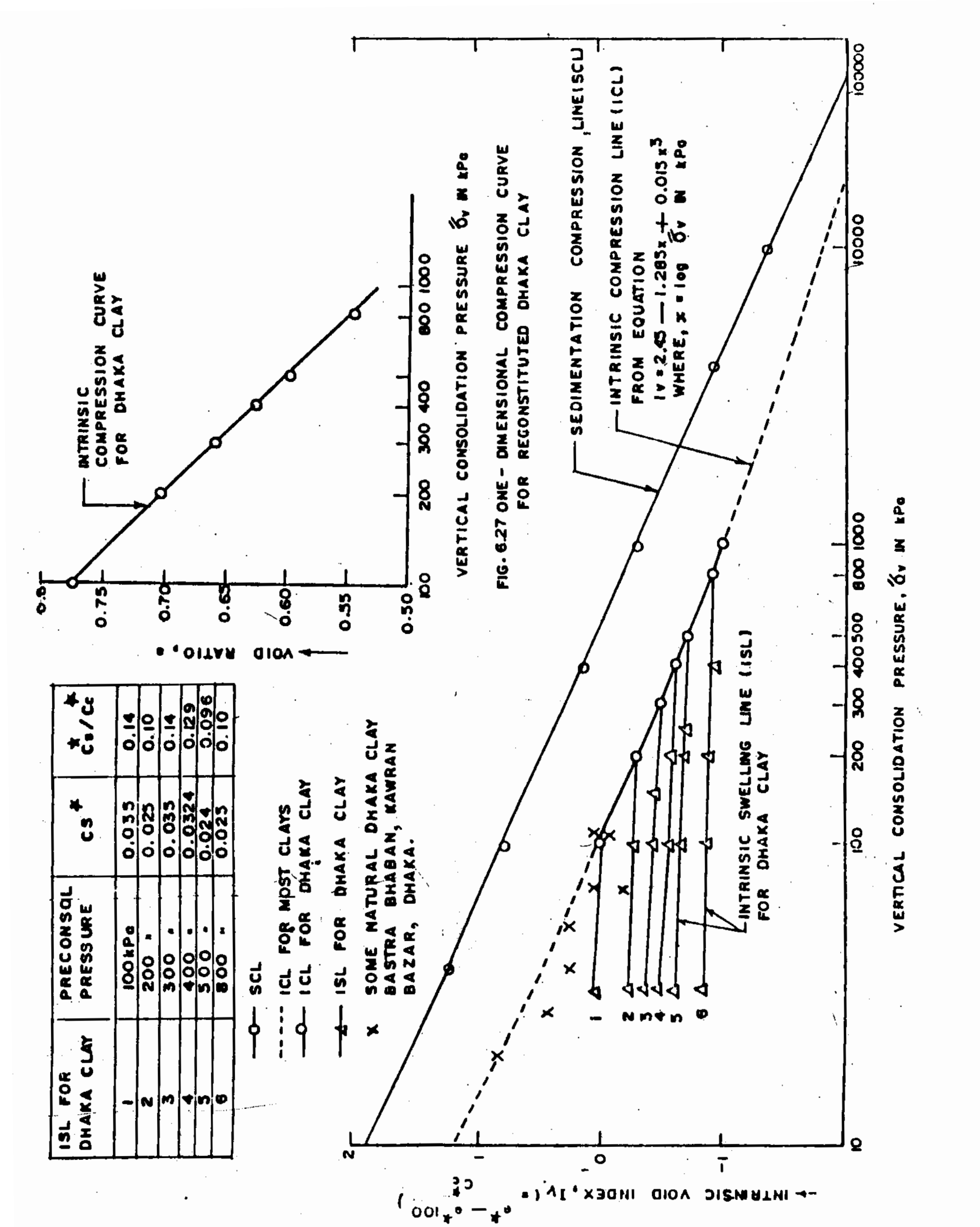


Fig 12. Comparison of Model Predicted Values and Tested Values of Undrained Shear Strength of Dhaka Clay

For comparison purpose also included in the figure is a sedimentation compression line (SCL) for most clays. It may be mentioned that void ratio corresponding to liquid limit (e_L) for Dhaka clay has been found to be 1.17. Some test results for undisturbed Dhaka clay are also plotted in Fig. 13 suggesting the soil to be overconsolidated as they fall parallel to the ISL.



ISL FOR DHAKA CLAY	PRECONSOL PRESSURE	Cs*	Cs*/Cc*
1	100kPa	0.035	0.14
2	200 "	0.025	0.10
3	300 "	0.035	0.14
4	400 "	0.0324	0.129
5	500 "	0.024	0.096
6	800 "	0.025	0.10

Fig 13. ICL And ISL for Dhaka Clay Shown with ICL and SCL for Most Clays

CONCLUSIONS

From experimental results of both normally and overconsolidated states, strength models for reconstituted Dhaka clay are obtained to predict intrinsic strength of the clay. In normally consolidated state, the strength ration (Su/σ_v) for reconstituted Dhaka clay are found to be 0.186 and 0.295 for K_o and isotropic consolidation conditions, respectively. Equations (1) through (5) can be used for normally loaded state. For overconsolidated state, equations (8) through (13) can be used to obtain intrinsic undrained strength (S_u) for Dhaka clay. The intrinsic strength represents a lower bound value for the soil since 'bond' between particles or structure of the soil is expected to increase these strength values. The concept of Intrinsic Compression Line (ICL), Sedimentation Compression Line (SCL) and Intrinsic Swelling Line (ISL) appears applicable to Dhaka clay and provide a better understanding of compressibility behavior of this clay. Available data on undisturbed samples of this clay indicate its overconsolidated nature. All foregoing features and phenomena demonstrate that strength and compressibility characteristics of Dhaka clay are predictable from simple measurement of in-situ void ratio (water content) and field overburden pressure only.

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NOTATIONS

Ce = True cohesion

$\bar{p}_o$ = In-situ overburden pressure or reduced all round swelling pressure under isotropic stress system for overconsolidated soil.

$S_u^{(nc)} = S_u$ in normally loaded state

$S_u^{(oc)} = S_u$ in overconsolidated state

$S_u^{(nc\text{-}\sigma vo \text{ or } po)} = S_u^{(nc)}$ with overburden pressure σvo or p_o

$S_u^{(oc\text{-}\sigma vo \text{ or } po)} = S_u^{(oc)}$ with overburden pressureee σvo or p_o

w_f = Water content at failure