Tikrit Journal of Engineering Sciences 20(7) (2013) 63-74

TJES

ISSN: 1813-162X
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

Effect of Anisotropy on Compression, Strength and Permeability Properties of Clayey Soil

Suhail Idrees Abdulqader Khyatt, Mohammed Nawaf Jirjees Al-Zaidy
Civil Engineering Department, Mosul University, Nenawa Province, Republic of Iraq

ABSTRACT

Anisotropy on compression, strength and permeability of a clayey soil selected from Mosul city was studied in this paper. Laboratory standard tests were conducted on sets of duplicate disturbed and undisturbed specimens prepared in the vertical, 45° inclined and horizontal directions from block samples retrieved from the site. The one dimensional consolidation of the clayey soil was shown to be cross-anisotropic for the vertical and horizontal directions, the 45° inclined showed an intermediate results. Drainage occurred more rapidly in the horizontal direction comparing with 45° inclined and vertical directions, with horizontal to vertical permeability ratio (*rkh*) not less than (2.0) for disturbed and undisturbed specimens from both consolidation and permeability tests. Compression at higher effective stresses caused significant reductions in the coefficient of consolidation (c_v) and permeability (k) although the *rk* values remained independent of the stress level. Furthermore the clayey soil specimens were noticeably anicotropic in strength, where the relationship between stresses and strains for vertical, 45° inclined and horizontal directions exhibited consistently dissimilar peak values as well as deformations at various strain levels.

Key words: Anisotropy; Directional Variation; Oedometer Test; One-Dimensional Consolidation; Permeability; Strength Test.

تأثير خاصية التباين الاتجاهي على خصائص الانضغاط والمقاومة والنفاذية لتربة طينية

الخلاصة

تم في هذا البحث دراسة تأثير خاصية التباين الاتجاهي على خصائص الانضغاط والمقاومة والنفاذية لتربة طينية مختارة من مدينة الموصل/العراق. أجريت الفحوصات المختبرية القياسية على نماذج تربة مخلخلة وغير مخلخلة وباتجاهات مختلفة، تم أخذ نماذج عمودية ومائلة بزاوية 45° وأخرى أفقية من كتل كبيرة تم جلبها من الموقع. أظهرت نتائج فحص الانضمام أن التربة متباينة اتجاهياً وذلك من خلال مقارنة نتائج النماذج المأخوذة بالإتجاه العمودي والأفقي، بينما أظهرت النماذج المأخوذة بالاتجاه مائل نتائجاً وسطيةً. كذلك فإن التصريف يحدث أسرع في الإتجاه الأفقي مقارنةً مع الاتجاهات الأخرى (العمودي والمائل)، إذ لم تقل نسبة النفاذية بين الاتجاه الأفقي الى العمودي (*rkh*) عن (2.0) للنماذج المخلخلة وغير المخلخلة المستحصلة من تجربتي النفاذية والانضمام. إن الضغط المسلط عند قيمة إجهاد عالية يعمل على تقليل كل من معاملي الانضمام (c_v) والنفاذية (k) على الرغم من أن النسبة (*rk*) لا تتأثر بقيمة الإجهاد المسلط. كذلك فقد أظهرت نتائج النماذج المأخوذة بالاتجاهات الثلاثة تبايناً ملحوظاً في المقاومة، من خلال الحصول على قيم عظمى مختلفة من إجهاد القص والتشوه عند مستويات انفعال مختلفة.

الكلمات الدالة: التباين، التغاير الاتجاهي، فحص الانضمام باتجاه واحد، فحص الأودوميتر، النفاذية، فحص المقاومة.

INTRODUCTION

Soil deposits are often cross-anisotropic in their mechanical and drainage properties due to the preferred horizontal alignment of the solid particles during deposition and subsequent consolidation under the overburden weight [1],[2]&[3]. Hence, the rate of consolidation is often greater for horizontal than for vertical drainage conditions and the state of anisotropy can be assessed in terms of the horizontal to vertical permeability ratio (*rkh*). Table 1 lists typical *rkh* values reported for natural clayey deposits.

Accurate predictions of the amount and in particular the rate of settlement of the ground under an applied load are necessary since geotechnical design is largely driven by serviceability limit state conditions. The consolidation properties of the ground are often determined in practice using standard oedometer tests for vertical drainage conditions only. The measurement of the consolidation properties under horizontal drainage conditions receives less attention and an assessment of the state of anisotropy in terms of the permeability ratio is often made on the basis of the soil description and engineering judgment. Consequently, design predictions for the field consolidation rate are generally conservative [4]. It was in this context that the degree of compression, consolidation, strength and permeability anisotropy of a clayey soil were studied by comparing the responses of duplicate sets of disturbed and undisturbed specimens.

TEST PROGRAMME

Standard oedometer, permeability and direct shear tests were conducted on duplicate sets of disturbed and undisturbed specimens. The tested specimens were cut in different directions to indicate the influence of anisotropy on the mechanical properties. The sets were carved out and tested in the vertical, 45º inclined and horizontal directions. The oedometer tests with 63.5 mm in diameter and 19.0 mm in height specimens dimensions were comprised six maintained load stages, each stage of 24 h duration. The applied axial stress range was (25–800) kPa and a stress increment ratio of unity was used throughout. A 97 mm in diameter by 38.5 mm in height specimen was used in permeability test with hydraulic gradient not greater than (20) according to ASTM specifications, [5]. A 60×60×20 mm specimen dimensions was used in direct shear strength test with drained condition to determine the effective shear strength parameters (c' & Ø') with strain rate (0.0089) mm/min [6].

Investigated materials for this study

Table 2 lists the description, index and in situ properties of the tested soil obtained from a site in the eastern south of Mosul city at a depth of 2.0 m in different directions. Fig. 1 shows the grain size distribution, it can be seen that the soil is a mixture of silt and clay, light reddish in color with a small lumps of $CaCO_3$. The consistency of the tested soil can be described as stiff and it is over-consolidated. From the Atterberg limits values shown in table 2, the soil can be described from Casagrande's A-line chart as a clay with medium plasticity.

Sample Preparation

The undisturbed soil specimens were obtained from the site by trimming into stainless steel retaining rings in the three directions (vertical, 45º inclined and horizontal directions), the lower edge of the ring has a sharp bevel to facilitate the trimming process.

The Compacted soil specimens were prepared in the laboratory from disturbed soil obtained from the same site, The natural soil was cleaned first from unwanted materials (such as, brick chip, stone, grass etc.), broken into small pieces, air-dried, reduced into powder by grinding mechanically, subjected to pass through # 40 (425-µm) sieve ,and 60º oven dried for two days. Materials passed-through and oven dried were mixed with specific amount of water to obtain the same water content and unit weight of the undisturbed samples following the procedure suggested by [7]. The compacted specimens prepared in the laboratory using static compaction method with rate of (1.27 mm/min.), to achieve the desired unit weight of the undisturbed specimens. The compaction mold used is shown in Fig. 2, 4" in diameter by 4.6" in height to retrieve all compacted specimens except for permeability specimen, which was retrieved from 6" in diameter and 5" in height compaction mold. The specimen is compacted from the top to the half determinate distance, then it is reversed to complete the compaction process. This procedure is suggested to ensure obtaining homogeneous compacted specimens without any weakness planes between layers, (i.e., if the compaction process was consisting for several layers the density will not be homogeneous, where the soil in the lower part of the compacted specimen is probably denser than the soil in the upper part, since the lower part receives compactive energy from each overlying lift) [8]. After compacted process the specimens of consolidation, permeability and direct shear rings is retrieved in the mentioned three directions from the center.

RESULTS and DISCUSSION

Compression and yield behavior

Figure 3 shows the compressibility of the soil specimens for both disturbed and undisturbed for vertical, 45º inclined and horizontal directions in terms of void ratio versus effective stress (e–σ′) and logarithm effective stress (e–logσ′) plots. Table 3 lists the compression properties for the three directions in terms of the compression index for vertical direction (c_{cv}), inclined and horizontal to vertical compression indices (i:v & h:v ratios) respectively. The yield stress, in situ vertical effective stress (σ'_{vo}) and overconsolidation ratio (OCR_v) are also listed in Table 3. The yield stresses for the vertical (σ'_{vc}), inclined (σ'_{ic}) and horizontal (σ'_{hc}) directions were determined using the constructed compression curves after Casagrande (1936)[9]. The in situ vertical effective stress (σ'_{vo}) due to the overburden was calculated using the bulk unit weights (Table 2), and The OCR_v was calculated as the σ'_{vc} to σ'_{vo} ratio, a value of unity indicative of recent, normally consolidated deposits.

It is obvious from figure 3 and table 3 that the horizontal direction specimen is more compressible than any other directions under one dimensional loading. This could be explained as for horizontal direction the drainage occurred parallel to the soil particles which facilitate the water movement. Hence, the rate of consolidation is greater for horizontal than any other direction. The difference was more evident in undisturbed specimens than in disturbed specimens.

Coefficients of consolidation and permeability

Table 4 lists the coefficient of consolidation values for the vertical direction (c_{vv}), the ratios of the inclined and horizontal to vertical coefficients of consolidation. There are several procedures presently available to estimate the coefficient of consolidation (c_v), The Logarithm of Time curve fitting method (Casagrande and Fadum, 1940) was found to be more reliable in interpreting the data and was used instead of the Square Root Time curve fitting method (Taylor, 1942). [3,9]

Table 5 lists the coefficient of permeability values for vertical drainage conditions (*kv*), and the ratios of the inclined and horizontal to vertical coefficients of permeability (*rki* and *rkh*). The permeability values were calculated indirectly using the following equation corresponded to an ambient laboratory temperature of 21º C.

$kv = m_{vv}\, c_{vv}\, \gamma_w$

Where

m_{vv} = the coefficient of volume change for the vertical direction.

c_{vv} = the coefficient of consolidation for the vertical direction.

γ_w = the unit weight of water.

The coefficient of permeability was also calculated from the variable head test method according to the specification (ASTM-D5084-00),[5]. Table 6 lists the coefficient of permeability in vertical, 45º inclined and horizontal direction, furthermore the ratios of the inclined and horizontal to vertical coefficients of permeability (*rki* and *rkh*).

The data in Tables 4, 5 and 6 indicate that drainage occurred more rapidly in the horizontal direction than any other directions. The values of mean (*rki*) and (*rkh*) ratios in Table 5 were (1.6, 2.0) respectively for disturbed specimens, and (1.5, 2.9) respectively for undisturbed specimens. The (*rk*) ratio was for practical purposes independent of the applied stress, but its effect was significant in the coefficient of consolidation (c_v) and permeability (k), this is obvious from Figs. 4 and 5 which show an inverse log k, log c_v respectively plotted against log σ' relationship, after (Lambe and Whitman, 1979) which suggested an inverse log–log relationship [10]. The lines included in the figures are least-square best-fit regression lines. The significant reductions in the permeability at higher effective stresses can be explained by the closure of the fine root holes that had facilitated preferential drainage at lower effective stresses. It is obvious from table 5 and 6 that the coefficient of permeability calculated indirectly from consolidation test is less than this calculated from the standard permeability test, this is due to the sample size effect, and the effective applied stress on the specimens of consolidation which reduces the void ratio by closure of the soil particles to each other and finally reduces the coefficient of permeability.

The data in Tables 1 and 5 can be applied in practice to obtain more accurate predictions for the rate of consolidation settlement in the field. The permeability properties for drainage in the vertical direction can be scaled by an appropriate *rk* value to determine the corresponding properties for drainage in any other direction.

Shear strength behaviour and stress-strain relationship

Table 7 and Fig.6 show the effective shear strength parameters in the vertical, 45º inclined and horizontal direction for both disturbed and undisturbed specimens. The effective shear strength parameters for specimens retrieved in horizontal direction was greater than this retrieved for the other directions. The effective shear strength parameters for undisturbed specimens were greater than that for disturbed specimens. This may be due to the inter particles bond between soil particles which develops through deposition process in the undisturbed specimens [11]. Fig. 7 shows the effect of anisotropy on stress strain relationship for both disturbed and undisturbed specimens. Table 8 lists the statistical mean values of the peak shear strength in the three directions together with the standard deviation. Inclined and horizontal to vertical peak shear strength (τ_{mi}/τ_{mv} & τ_{mh}/τ_{mv}) respectively are also listed in table 8. Peak shear strength was measured from shear stress and shear strain relationship. The relationships between shear stresses and strains in the vertical, 45º inclined and horizontal directions specimens retrieved from a single mold were not similar. Rather they exhibited consistently dissimilar peak values as well as deformations at various strain levels. The maximum strength occurred in a horizontal specimens, The minimum occurred in the vertical specimens as shown in figure 8 which represents the relationship between the shear strength τ_m and θ (θ=0 in vertical direction). This is coincide with the search results of [7]. It is obvious from table 8 that the effect of applied stress level is not significant on the coefficient of anisotropy (τ_{mi}/τ_{mv} & τ_{mh}/τ_{mv}), or at least the significance was limited.

CONCLUSIONS

From the results of the tests described in this paper, a number of conclusions can be reached regarding the effects of certain testing conditions on the observed compression, strength and permeability properties.

1. The rate of consolidation is greater for the horizontal specimens than any other direction, because the horizontal specimens is more compressible.
2. The yield stress is greater for the vertical direction than any other direction, although the difference was slight.
3. Drainage occurred more rapidly in the horizontal direction than any other direction. Because water movement occurred parallel to the soil particles for this direction.
4. The coefficient of permeability (k) calculated indirectly from consolidation test is less than that calculated from the

standard permeability test. This due to the sample size effect and the effect of applied stress.

5. The effective shear strength parameters and peak shear strength are greater for the horizontal direction than any other direction.
6. The compression of these features at higher effective stresses caused significant reductions in the coefficient of consolidation (c_v) and permeability (k), although its effect on the coefficients of anisotropy is so slight. So the coefficients of anisotropy are remained independent of the stress level for practical purposes.
7. The compression properties, coefficients of consolidation and permeability and shear strength parameters were greater for undisturbed specimens than for disturbed specimens, furthermore the coefficients of anisotropy were more evident in undisturbed specimens.

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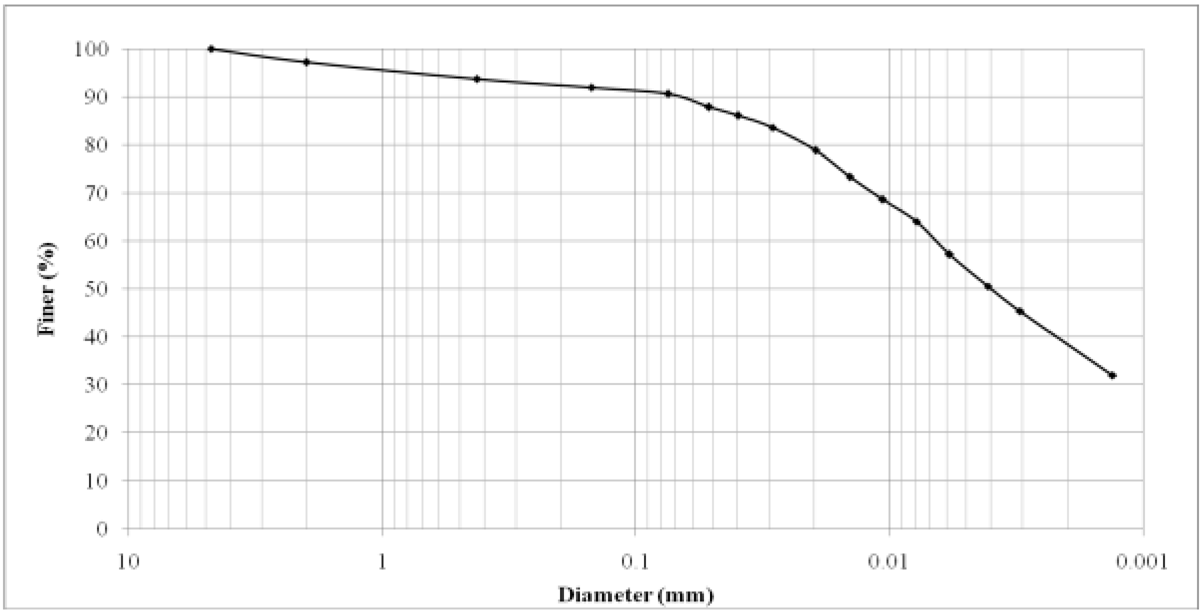


Fig. 1 Grain size distribution of the soil

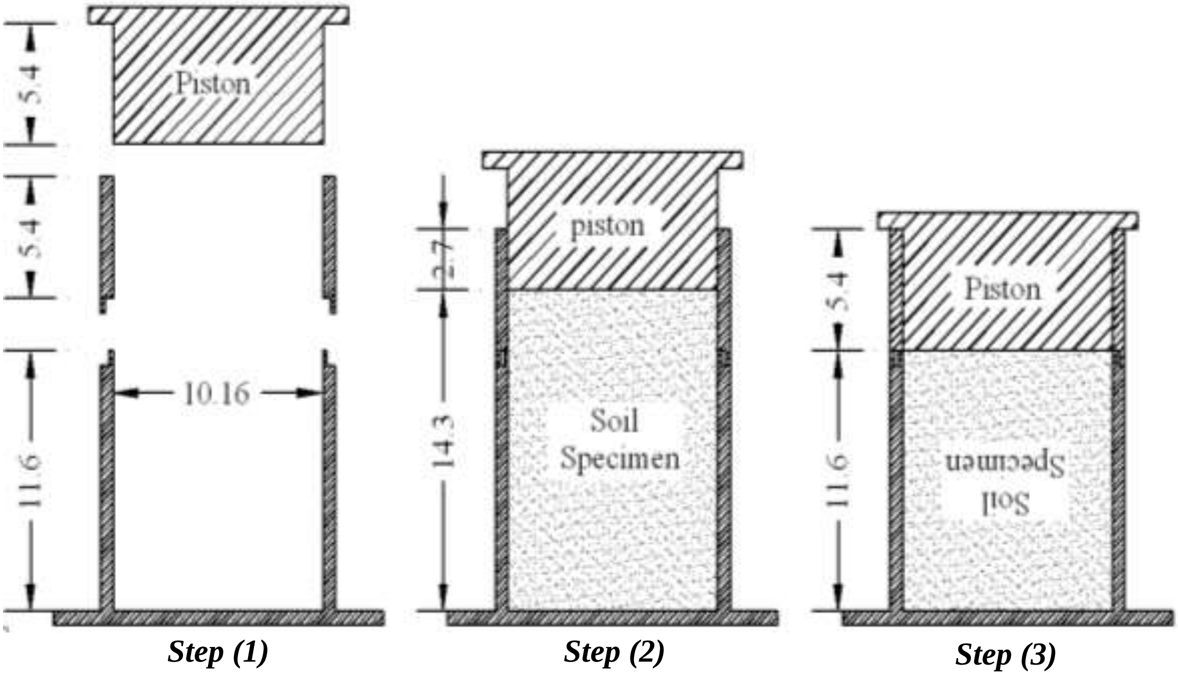
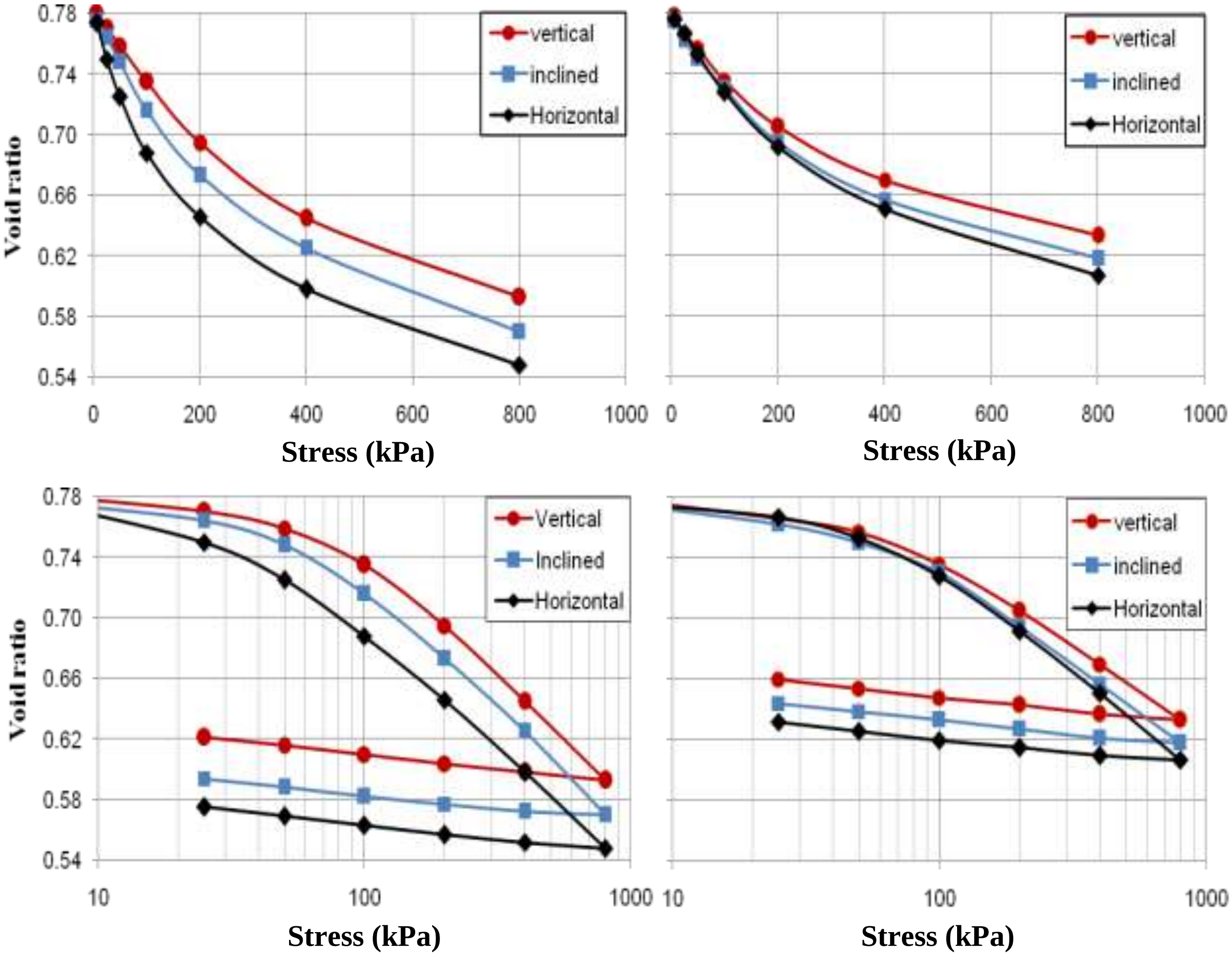
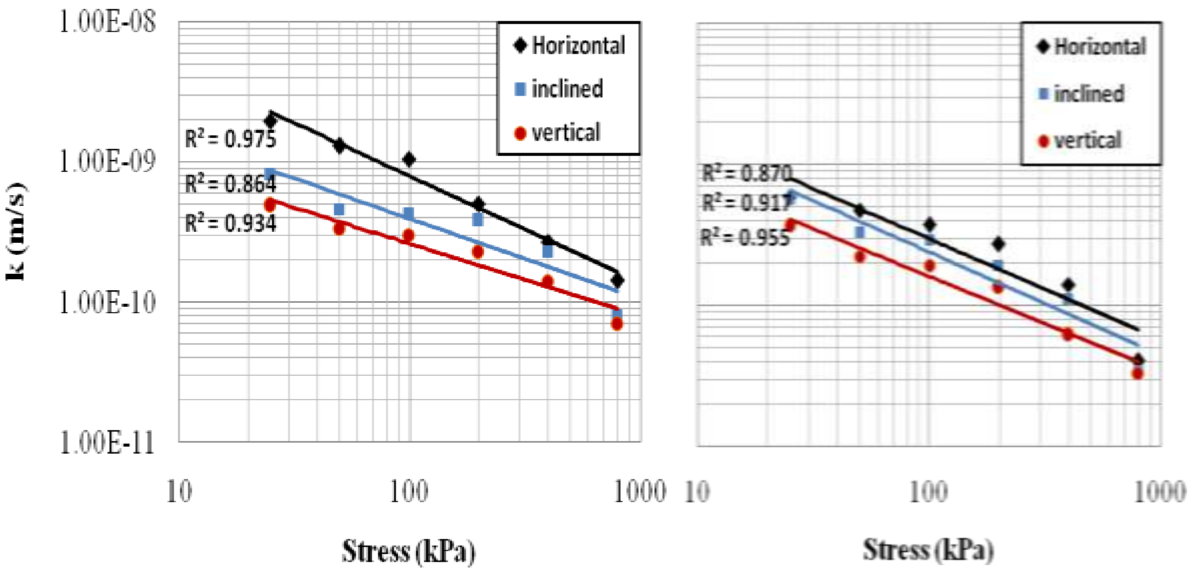


Fig. 2 Compaction mold (Dimensions in cm)



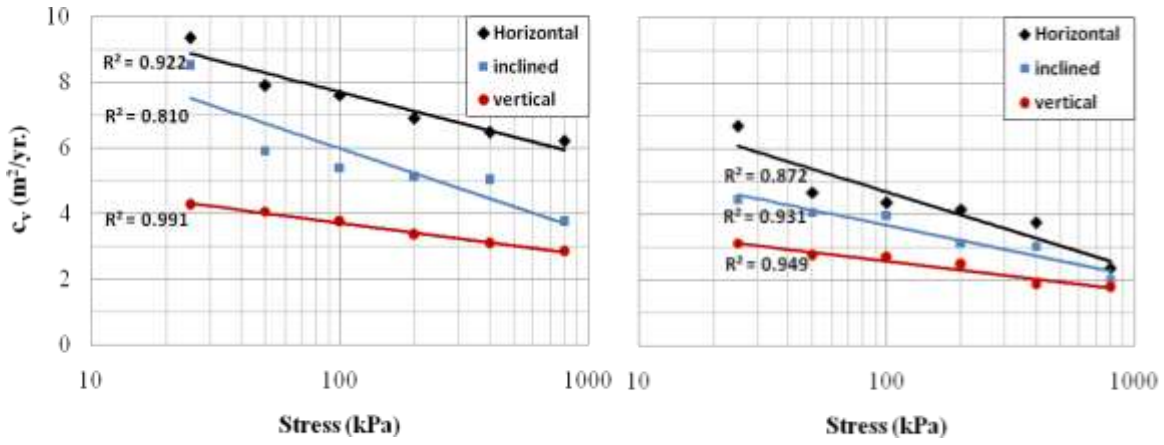
(a) ***(b)***

Fig. 3 Compression properties for the vertical, inclined and horizontal directions for a-undisturbed specimens, b-disturbed specimens



(a) ***(b)***

Fig. 4 Coefficient of permeability versus effective stress (Log-log scale) for a-undisturbed specimens, b-disturbed specimens



(a) ***(b)***

Fig. 5 Coefficient of consolidation versus effective stress (Log-log scale) for a-undisturbed specimens, b-disturbed specimens

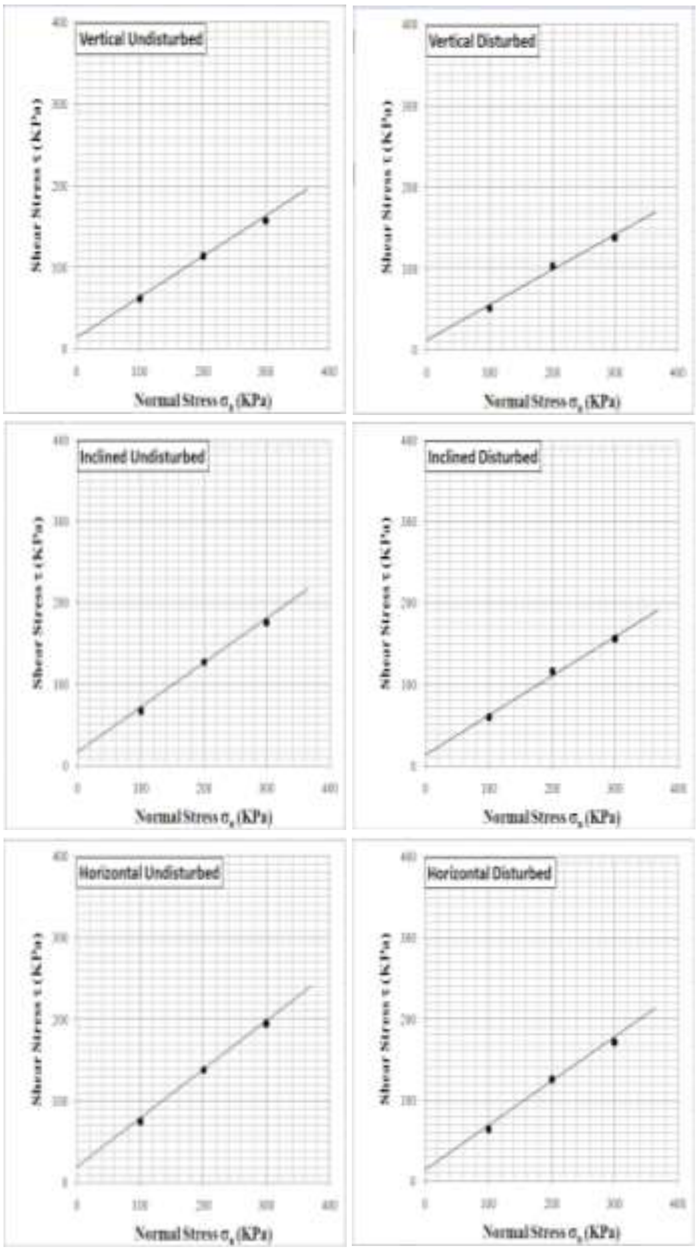


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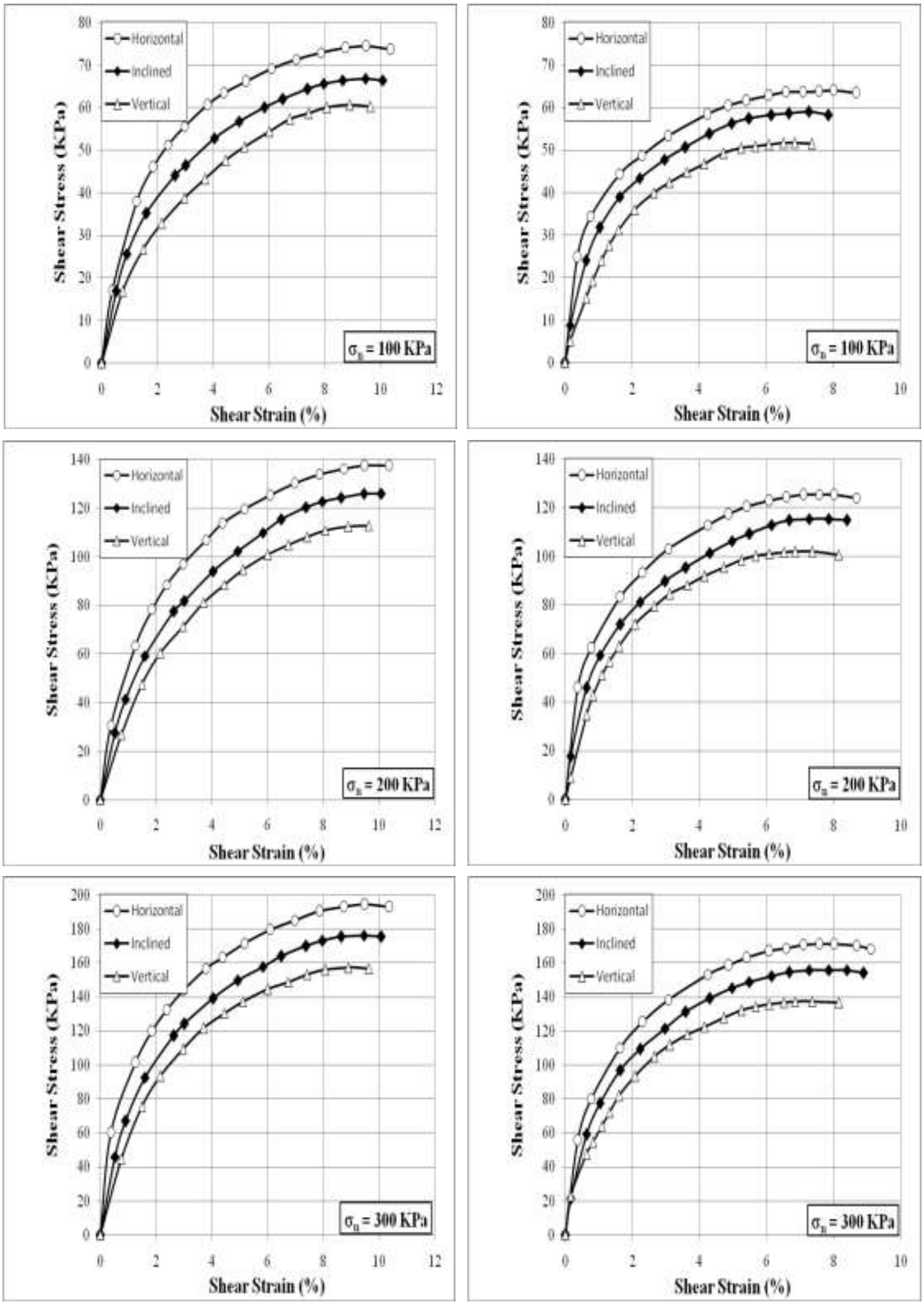
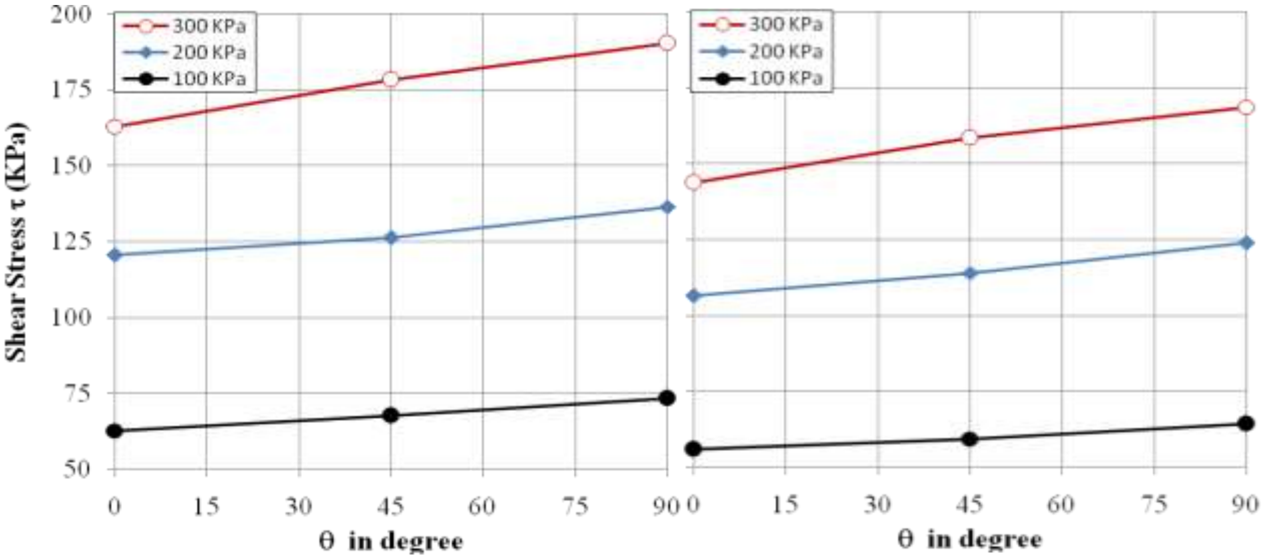
Fig. 6 Effective shear strength parameters for the three directions, a-undisturbed specimens, b-disturbed specimens



(a) ***(b)***

Fig. 7 Stress strain relationship for the three directions,
a-undisturbed specimens, b-disturbed specimens



(a) ***(b)***

Fig. 8 τ_m~θ relationship from direct shear test,
a-undisturbed specimens, b-disturbed specimens

Table1. Horizontal to vertical permeability ratios (rkh) [3]

Description	**r_{kh} Value**	**Reference**
Organic silt with peaty	1.2-1.7	Tsien (1955)
Soft clay	1.5	Basett and Brodie (1961)
Plastic marine clay	1.2	Lumb and Holt (1968)
Soft marine clay	1.05	Subbaraju (1973)
Louiseville soft marine clay	1.35	Leroueil et al. (1990)
Backebol soft marine clay	1.18–1.33	Leroueil et al. (1990)
Bothkennar soft silty clay	1.5–2.0	Leroueil et al. (1992)
Po soft clay	1.4–2.5	Cortellazzo and Simonini (2001)
Po soft silty clay	2.7–4.0	Cortellazzo and Simonini (2001)
Singapore marine clay	2.0–3.0	Chu et al. (2002)
Soft Bangkok clay	1.3–2.8	Seah and Koslanant (2003)

Table 2. Description and in situe properties of soil

Property		**Value**
Specific gravity		2.72
Gypsum content %		2.25
pH value		7.92
Grain size analysis	Gravel %	3
	Sand %	8
	Silt %	51
	Clay %	38
Atterberg limits	w_L %	46
	w_P %	24
	I_P %	22
In-situe properties	w_o %	16.6
	γ_d kN/m^3	14.6
Unified Soil Classification System		CL

Table 3. Compression properties for the vertical, inclined and horizontal directions

State of soil	Compression index			Preconsolidation pressures (kPa)			σ'_{vo} (kPa)	OCR$_v$
	(c_{cv})	i:v ratio	h:v ratio	σ'_{vc} (kPa)	σ'_{ic} (kPa)	σ'_{hc} (kPa)		
Disturbed specimens	0.12	1.1	1.2	80	80	75	34	2.4
Undisturbed specimens	0.17	1.0	1.1	100	95	80	34	2.9

Table 4. Vertical coefficient of consolidation (cvv), and state of anisotropy

State of soil	c_{vv} (m^2/yr)	i:v ratio	h:v ratio	c_{vv} (m^2/yr)	i:v ratio	h:v ratio	c_{vv} (m^2/yr)	i:v ratio	h:v ratio	c_{vv} (m^2/yr)	i:v ratio	h:v ratio	c_{vv} (m^2/yr)	i:v ratio	h:v ratio	c_{vv} (m^2/yr)	i:v ratio	h:v ratio	Mean i:v ratio	Mean h:v ratio
Disturbed specimens	3.12	1.43	2.14	2.74	1.45	1.70	2.67	1.52	1.59	2.46	1.27	1.73	1.87	1.67	2.00	1.76	1.13	1.33	1.41	1.75
Undisturbed specimens	4.25	2.00	2.20	4.06	1.35	1.77	3.74	1.47	2.27	3.11	1.66	2.06	3.32	1.63	2.04	2.83	1.32	2.19	1.57	2.09
Stress range	6.9-25 kPa			25-50 kPa			50-100 kPa			100-200 kPa			200-400 kPa			400-800 kPa				

Table 5. Vertical coefficient of permeability (kv), and state of anisotropy

State of soil	$k_v\times10^{-10}$ (m/s)	*rki* ratio	*rkh* ratio	$k_v\times10^{-10}$ (m/s)	*rki* ratio	*rkh* ratio	$k_v\times10^{-10}$ (m/s)	*rki* ratio	*rkh* ratio	$k_v\times10^{-10}$ (m/s)	*rki* ratio	*rkh* ratio	$k_v\times10^{-10}$ (m/s)	*rki* ratio	*rkh* ratio	$k_v\times10^{-10}$ (m/s)	*rki* ratio	*rkh* ratio	Mean *rki* ratio	Mean *rkh* ratio
Disturbed specimens	3.60	1.58	1.61	1.71	1.94	2.80	2.02	1.53	1.94	1.32	1.45	2.06	0.61	1.80	2.30	0.33	1.03	1.25	1.56	1.99
Undisturbed specimens	4.87	1.68	4.02	3.21	1.37	3.87	3.50	1.45	3.24	2.30	1.64	2.17	1.40	1.64	1.93	0.70	1.14	2.04	1.49	2.88
Stress range	6.9-25 kPa			25-50 kPa			50-100 kPa			100-200 kPa			200-400 kPa			400-800 kPa				

Table 6. Coefficient of permeability (k) from variable head test, and state of anisotropy

State of soil	**Coefficient of permeability (*k*), (m/s)**			***rki* ratio**	***rkh* ratio**
	(k_v)	**(k_i)**	**(k_h)**		
Disturbed specimens	2.5×10^{-9}	3.5×10^{-9}	5.3×10^{-9}	1.40	2.12
Undisturbed specimens	8.2×10^{-9}	1.3×10^{-8}	2.1×10^{-8}	1.59	2.56

Table 7. Effective shear strength parameters for the three directions

State of soil	**effective cohesion (*c*'), (kPa)**			**effective angle of internal friction (Ø'), (kPa)**		
	vertical	**inclined**	**horizontal**	**vertical**	**inclined**	**horizontal**
Disturbed specimens	11	13	15	23.6	25.8	28.4
Undisturbed specimens	13	18	20	26.3	28.4	30.5

Table 8. Peak shear strength for the three directions, and state of anisotropy

State of soil	**Normal stress (σ_n), (kPa)**	**Peak shear strength (kPa)**			**(τ_{mi}/τ_{mv})**	**(τ_{mh}/τ_{mv})**
		vertical	**inclined**	**horizontal**		
Disturbed specimens	100	52.8±2.9	58.1±1.6	63.0±2.1	1.10±0.032	1.19±0.027
	200	102.9±1.9	114.2±2.5	124.0±2.7	1.11±0.004	1.20±0.004
	300	138.9±2.6	154.7±2.3	170.1±2.9	1.11±0.004	1.22±0.007
Undisturbed specimens	100	60.2±2.9	67.4±3.1	75.2±2.7	1.12±0.003	1.25±0.016
	200	112.1±3.5	127.5±2.6	138.8±2.8	1.14±0.013	1.24±0.014
	300	156.7±2.4	176.8±3.2	195.1±2.6	1.13±0.003	1.25±0.003