

Electro-Osmotic Consolidation Studies on Peat and Clayey Silt Using Electric Vertical Drain

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Abstract Peat and soft soil deposits are abundant in Malaysia. Studies using electrokinetic geosynthetics (EKG) such as prefabricated electric vertical drains (EVD or ePVD) have shown the potential for the application of these materials in electrokinetic strengthening of soft clays and increasing solids content in mining tailings and sludges. There are no studies reported on the effectiveness of electro-osmosis using EVD in peat. Laboratory experiments were carried out to investigate the effectiveness of electro-osmotic stabilization of two peat samples and a slightly organic clayey silt sample, from the North Sarawak region. Commercially available EVD was used to induce electro-osmosis and drainage of pore water. The influence of voltage gradient, organic content, initial water content, anode–cathode configuration and presence of roots on electro-osmotic consolidation was investigated. Electro-osmotic consolidation using EVDs was effective in the improvement of peat, over a large range of initial water contents. An increase in the voltage gradient generally improved consolidation. The maximum voltage gradient for optimum results appeared to be in the region 120 V/m. The 2anodes-1cathode configuration performed better than the

1anode-1cathode configuration. The presence of roots reduced the electro-osmosis effect.

Keywords Clayey silt · Electrokinetic geosynthetics · Electro-osmosis · Peat · Vertical drain

Abbreviations

C_c	Compression index
C_α	Secondary compression index
d_c	Distance from cathode end mm
EOC	Electro-osmotic consolidation
EVD	Electric vertical drain
<i>MH</i>	Clayey silt
N	Organic content, %
<i>Pt</i>	Peat
Sc_i	Initial solids content, %
Sc_f	Final solids content, %
S_{uf}	Post-consolidation undrained strength kPa
S_{uf-av}	Average post-consolidation undrained strength kPa
S_{ui}	Initial undrained strength kPa
w_f	Post-consolidation water content, %
w_{f-av}	Average post-consolidation water content %
w_i	Initial water content, %
w_l	Liquid limit, %
ζ	Zeta potential, mV

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1 Introduction

There are different types of soft soil deposits in Malaysia. The soft clay deposits are generally of

marine origin and were formed about 15,000 years ago (Leroueil et al. 1990). The thickness of soft soil deposits range from 15 m to 30 m in coastal sites and from 2 m to 9 m in inland areas (Ting et al. 1988). In Sarawak, peat land is estimated to cover about 1.7 million ha or nearly 13% of the total land area of the State (Singh and Huat 2003). The government has development plans on large areas including peat land. The soft ground conditions, however, pose difficulties in the design, construction, and maintenance of infrastructure like roads, bridges and buildings.

Preloading using prefabricated vertical drains is commonly used in Sarawak for ground improvement. The problems faced in preloading are: (a) the need to import preload material to the site and cart it away after the treatment, (b) difficulties in construction of the preload embankment on very soft formations and (c) the long time required for ground treatment. Electro-osmosis is a well known means of improving soft fine grained soils. In the year 2007, the installed electricity generation capacity in Sarawak was 967 MW, but the consumption was only 810 MW (Suruhanjaya Tenaga 2008). The Sarawak Energy Berhad has a target to have an installed capacity of 6,000 MW by 2015 and 10,000 MW by 2020 (Sarawak Energy 2007). Therefore, electro-osmosis could become a viable technique of improving soft ground in Sarawak. A number of laboratory and field electro-osmotic consolidation studies have been reported on soft fine grained soils. However, there are no studies reported on the effectiveness of electro-osmosis and electric vertical drains (EVD) in peat and organic soils.

2 Objective

The objective of the study is to investigate the effectiveness of the electro-osmosis technique in the strengthening of peat of North Sarawak and the influence of selected parameters on the electro-osmosis phenomenon. A simple experimental set up was designed for the electro-osmosis tests. A commercially available EVD was used to induce electro-osmosis and drainage of pore water. A preliminary experiment was carried out to test and modify the apparatus, to identify test variables and to improve the experimental procedure. The influence of voltage gradient, initial water content, organic content, anode–cathode configuration and presence of roots

on electro-osmotic consolidation was investigated. Laboratory experiments were carried out on two peat samples of North Sarawak and a slightly organic clayey silt. The clayey silt was used as a reference material to compare the electro-osmosis behaviors in highly organic and slightly organic materials.

3 Soft Soils of Malaysia

The soft soil deposits of Malaysia can be categorized into two as: a) alluvial and marine clays and b) organic soils and peat. There is also local soft-soil-like condition created due to mining waste ponds (Kaniraj and Joseph 2006).

3.1 Alluvial and Marine Clays

Quaternary erosion, more due to climatic and sea level changes, has produced widespread and thick alluvial deposits in the coastal areas and major river valleys in Malaysia. Many coastal regions of Malaysia are covered with marine clays. They are generally very plastic, organic and normally consolidated. The thickness of these clays varies from 5 to 30 m. Soft and thick marine clay deposits have been found at several locations in the peninsular Malaysia. Deep soft marine clay is found in the Muar flat of the North–South highway (Huat and Ali 1992; Fauziah et al. 2003; MHA 1989). The clay in Klang area is an alluvial deposit and generally consists of very soft to firm clayey silt up to a depth of 25–30 m (Tan et al. 2004). Very soft marine clay up to 35 m thick has been reported near Klang city (Raju 1997). Soft clay varying in thickness from 1 to 4.5 m was encountered in one of the interchanges in the outer ring road from Dengkil to Putrajaya (Teau 2003). Much deeper soft marine clays, 20–30 m thick overlain by 1 m thick desiccated crusts, were encountered along the Federal Route 5 in Selangor (Kwong and Al Rifae 2003). The authors' university campus in Miri was built on reclaimed marsh land and the underlying soft clay extends to depths of 30 m.

3.2 Organic Soils and Peat

Peat is found over large areas in Sarawak. The peat in its natural state is waterlogged and very acidic. Al Raziqi et al. (2003a, b, c), Singh and Huat (2003),

Zainorabidin and Bakar (2003) and Duraisamy et al. (2007) studied the index properties, engineering properties and engineering behaviour of organic soils and peat in Malaysia and suggested several empirical correlations.

Peat is also abundant in the neighbouring Brunei Darussalam and Sumatra. Peat swamps cover 90,884 ha, about 15.6% of the total land area in Brunei Darussalam. In Belait district they form a contiguous block with the peat swamps of the Baram Basin in Sarawak (Davies 1999). In North Sumatra, peat has been found at highlands also. Nasution and Mansor (1999) reported that peat was found approximately over 2000 ha on the southern part of Toba Plateau at an altitude of 1,114 m above sea level. At some sites, the drying and drainage of peat created subsidence of as much as 4 m to 6 m within a period of 4 years.

4 Background

4.1 Electro-Osmotic Consolidation

Electro-osmosis is one of the several electrokinetic reactions that take place when a direct current voltage is applied across the electrodes inserted into a saturated porous medium. The ions in the pore water, which are attracted to the oppositely charged electrodes, drag the surrounding free water molecules along with them. The net water movement is towards the cathode. If there is drainage available at the cathode, then consolidation takes place. The rate of drainage of water in electro-osmotic consolidation, q_e , depends on the coefficient of electro-osmotic permeability, k_e , and is expressed as (Mitchell 1993).

$$q_e = k_e i_e A \quad (1)$$

In Eq. (1), $i_e = \Delta V / \Delta l$, is the electric field intensity or voltage gradient and ΔV is the voltage drop over a current flow path of Δl . For effective electro-osmotic treatment, the k_e required is about $10^{-9} \text{ m}^2/\text{sV}$ and the k_e of clay soils is often in this range. Asadi et al. (2010) have reported the k_e values of Malaysian peats in the range of 10^{-9} – $10^{-10} \text{ m}^2/\text{sV}$. In field applications, the voltage gradient typically ranges from 10 to $<100 \text{ V/m}$ (Shang 1998). Electro-osmosis is effective when the ratio k_e/k_h (k_h is the hydraulic coefficient of permeability) is high (Glendinning et al. 2007).

Electro-osmosis induces a negative excess pore water pressure, which in a uniform electric field when the anode is closed to supply of water and cathode is open to drainage is given by

$$u_e(x) = -\frac{k_e \gamma_w i_e x}{k_h} \quad (2)$$

In Eq. (2), $\gamma_w =$ unit weight of water and $x =$ distance from the cathode to the anode.

Electro-osmotic consolidation results in an increase in the shear strength of soft clays. Mohamedelhasan and Shang (2001) reported that current intermittence and polarity reversal had a significant effect on electro-osmotic consolidation. Several successful field applications of electro-osmotic stabilization are quoted in literature (e.g. Fetzer 1967; Chappell and Burton 1975; Wade 1976; Lo et al. 1991).

4.2 Electrokinetic Geosynthetics (EKG)

Electrically conductive geosynthetics called electrokinetic geosynthetics (EKG) have been developed recently (Hamir et al. 2001). In addition to the traditional filtration, drainage, separation, reinforcement and impervious membrane functions of geosynthetics, the EKG materials provide electrokinetic function also. Electrokinetic geosynthetics can be manufactured in the form of strips, sheets, blankets or three dimensional structures. Metallic electrodes tend to corrode due to electrokinetic reactions and this reduces the efficiency of electrokinetic treatment. In the EKG materials, the electrodes are less susceptible to corrosion due to protection from the geosynthetic cover. Prefabricated electric vertical drains (EVD or ePVD), for example, incorporate the metallic electrode within the fluted polymeric core. A commercially available prefabricated band-shaped EVD was used in the present study. It consists of a polyethylene core which encapsulates a 90 mm wide copper foil. The core is wrapped in a filter material. The manufacturer's specifications of the EVD are shown in Table 1.

It should be noted that other than encapsulated metallic core, ePVDs with exposed conductors which come into direct contact with the soil are also available. Corrosion of the exposed conductors can be controlled using oxide coatings. Studies using EVDs have shown the potential for the application of EKG materials in electrokinetic stabilization of soft

Table 1 Specifications of electric vertical drain

Drain composite	Filter	Core polymer
<i>Dimensions</i>	<i>Opening size</i>	Volumetric resistivity
Nominal width = 100 ± 3 mm	A.O.S < 150 µm	<1 × 10 ⁵ ohm-cm
Nominal thickness = 5.5 mm		
Roll length = 150 m		
<i>Discharge capacity (confining pressure)</i>	<i>Permittivity</i>	Surface resistivity
Straight (240 kPa) = 0.06 l/s	Water permittivity = 1.5 s ⁻¹	<1 × 10 ⁵ ohm-cm
Kinked (240 kPa) = 0.04 l/s	Coefficient of permeability = 15 × 10 ⁻⁴ m/s	
<i>Tensile properties (full width test)</i>	<i>Strength</i>	
Tensile strength = 2,300 N	Tensile strength (MD) = 9 kN/m	
Elongation at break >20%	Elongation at break (MD) = 40%	
Elongation at 1 KN <8%	Trapezoidal tear (MD) = 230 N	

A prefabricated band-shaped drain, consisting of a conductive polyethylene core profiled with rows of ribs along its length and wrapped in a filter material. The core encapsulates a copper foil of 90 mm width, perforated at intervals to secure bond

From EVD manufacturer's specification of Type: EVD-K9, effective January 2005

clays, mine tailings and sludges (Hamir et al. 2001; Fourie et al. 2007; Glendinning et al. 2007, 2008; Rittirong et al. 2008). Electro-osmotic consolidation studies using EKG materials as electrodes have been carried out on the soils of Southeast Asia also (Bergado et al. 2000, 2003; Chew et al. 2004; Lorenzo et al. 2004; Lee and Douglas 2007).

5 Peat and Clayey Silt Samples Used in the Experiments

5.1 Collection and Processing of Peat and Clayey Silt Samples

Two peat samples were collected. One peat sample was collected at a location along the Miri-Marudi road, about 35 km from Miri. The second peat sample was from Similajau, about 160 km from Miri. The peats were in very soft condition. The average moisture content of the Miri and Similajau peats were 552 and 643%, respectively. A clayey silt sample having low organic content was collected from the construction site at the Curtin University of Technology. This material was used as a reference material to compare the electro-osmosis behaviors in highly organic and slightly organic materials. The clayey silt was collected in stiff blocky form. It was evidently an uplifted marine deposit and transported from another location to the construction site as fill

material. This clayey silt was satisfactory for the objective of the study. Its low organic nature was the main reason for including it in the study to study the influence of organic content on electro-osmosis process. According to the Unified Soil Classification System, the peat samples were designated as *Pt* and the clayey silt sample as *MH*.

Sufficient quantity of representative samples of peat and clayey silt was transported in polymeric storage boxes to the laboratory. While conducting experiments, the samples were reprocessed according to the requirements. The organic matter in peat was highly humified. Large-size wood fibers and roots were removed from the peat to get similar peat specimens in the experiments. In the case of clayey silt, the soil blocks were manipulated to get soft specimens by first reducing the block to small pieces and then mixing with water to the required consistency.

5.2 Geotechnical Characterization of the Peat and Clayey Silt Samples

The geotechnical characterization experiments included determination of organic content, specific gravity, Atterberg limits and consolidation tests. Some salient results of these experiments are summarized in Table 2. It was difficult to determine specific gravity (*G*) by the density bottle method; the value was very low, as all organic matter floated up and remained at the surface of water. Therefore, the

Table 2 Geotechnical properties of peat and clayey silt

Properties	Peat		Clayey silt
	Miri-Marudi road	Similajau	
Natural water content, w_n (%)	552	643	–
Organic content, N (%)	97	96	11
Von post classification	H8	H8	–
Specific gravity, G	1.47	–	2.56
Liquid limit, w_l	413	323	62
Plastic limit, w_p	257	244	43
Plasticity index, PI	156	79	19
Average compression index, C_c	0.58	–	0.13
Average secondary compression index, C_α	0.065	–	0.003
Average C_α/C_c	0.11	–	0.03

G for peat was inferred from consolidation test data. The degree of saturation, S , for the consolidation test specimen can be expressed by Eq. (3).

$$S = \frac{w_f G W_d}{A \gamma_w H_f - W_d} \tag{3}$$

In Eq. (3), w_f = final water content; W_s = dry weight of the specimen; A = area of the specimen; and H_f = final height of the specimen. Assuming $S = 1$, G can be expressed by Eq. (4) and solved by substituting the measured quantities.

$$G = \frac{W_d}{A \gamma_w H_f - w_f W_d} \tag{4}$$

The average value of the ratio of secondary compression index (C_α) to compression index (C_c), $C_\alpha/C_c = 0.13$ for Miri-Marudi peat was higher than the range 0.05–0.07 reported in literature (Mesri and Ajlouni 2007). On the contrary, Duraisamy et al. (2007) have reported a low value of $C_\alpha/C_c = 0.027$, for peat in Peninsular Malaysia. In the e -log t plot from conventional one-dimensional consolidation test, it is difficult to distinguish the boundary between the primary and secondary consolidation phases, which could be a reason for the above differences.

Figures 1 and 2 show the scanning electron images of the Miri-Marudi Road peat and Similajau peat, respectively, at two different magnifications of 1,000× and 200×. The particles of the two peat samples have a highly porous structure. They

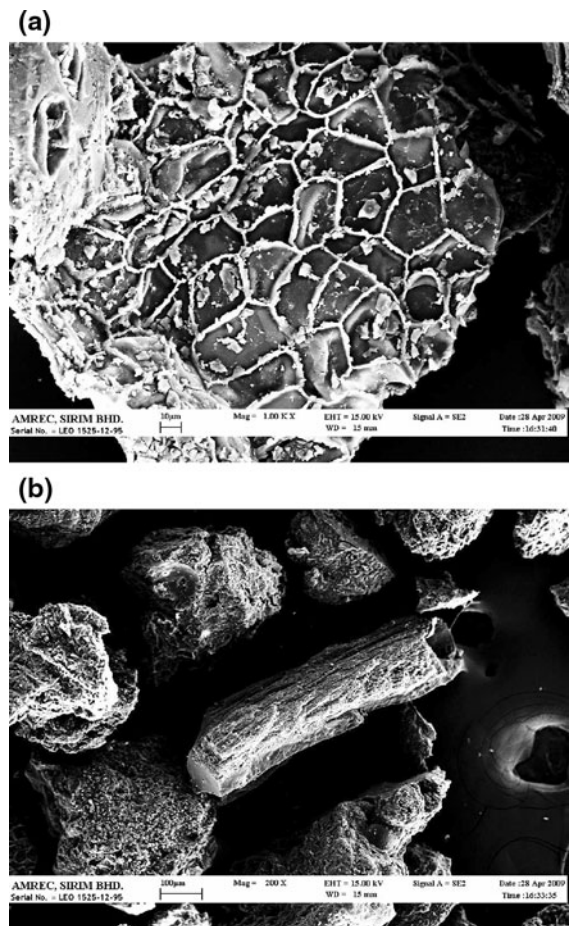


Fig. 1 Scanning electron micrograph of Miri-Marudi road peat. **a** Magnification = 1,000× and **b** Magnification = 200×

generally have large surface area and small thickness; the size of individual peat particles is of the order of 200–300 μm and thickness of the order of 40–50 μm.

6 Electro-osmosis Consolidation Experiments

6.1 Experimental Set-up

Electro-osmosis experiments were conducted in rectangular glass tanks of inner dimensions 250 × 110 × 250 mm. The set-up is similar to that used by Pączkowska (2005). Figure 3 shows the details of the test tanks. A hole in the two end walls, close to the floor of the test tank, facilitated the exit of drained water. To avoid evaporation losses, the top of the tank was kept closed with a polyethylene strip placed under a glass plate cover.

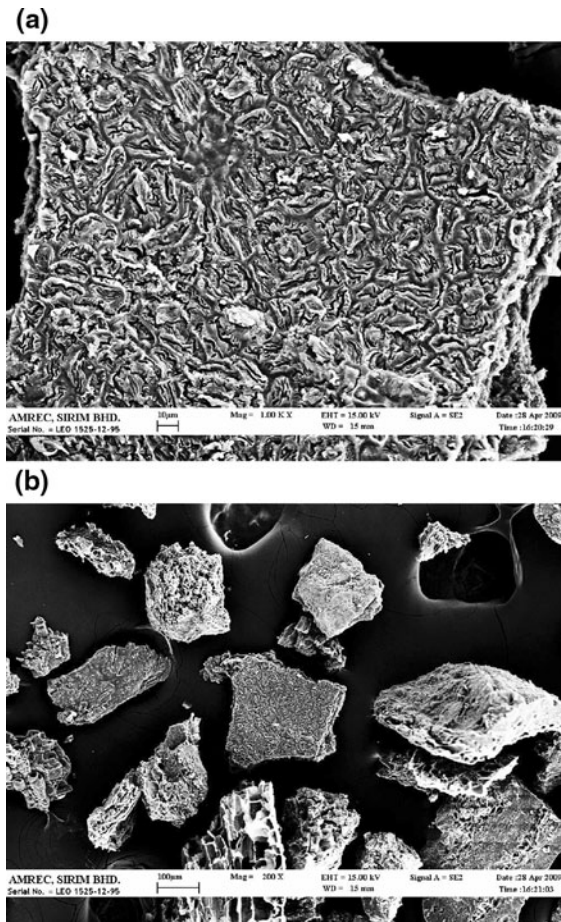


Fig. 2 Scanning electron micrograph of Similajau peat. **a** Magnification = 1,000 \times and **b** Magnification = 200 \times

6.2 Experimental Program

The experiments were organized in four series and their sub-series to investigate the effect of voltage gradient, initial water content, organic content, anode–cathode configuration and presence of roots on electro-osmotic consolidation. The details of the experimental program and test variables are summarized in Table 3. The preliminary test on peat from Miri-Marudi road is designated as Series I. Figure 4 shows the various anode–cathode configurations used in the experiments. In experiments of series I, IIa and III, the full width of the EVD was used (Fig. 4a). In these tests, the EVD nearly covered the full width of the test beds at the anode and cathode ends. Thus, the electro-osmosis effect was primarily a 2-dimensional effect in these experiments. The 3-dimensional electro-osmosis effect in the field was simulated in series

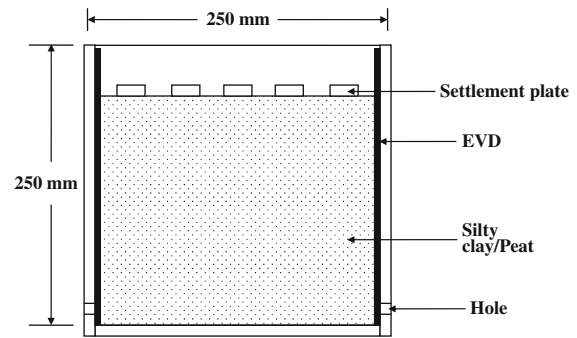


Fig. 3 Electro-osmosis experimental set-up

IIb, IIc and IV experiments by using 15 mm wide vertical EVD strips as electrodes. A single 15 mm wide EVD strip was used as cathode. Either two 15 mm wide EVD strips spaced 55 mm centre-to-centre apart (Fig. 4b, series IIc and IV) or one 15 mm wide EVD strip (Fig. 4c, series IIb) was used as anode.

The authors presented the preliminary test of series I in a previous paper (Kaniraj and Huong 2008). This paper explains all the 16 tests comprehensively.

6.3 General Experimental Procedure

The experimental procedure generally consisted of the following steps.

1. *Preparation of test material:* In series I, II and III tests, peat or clayey silt was kept in the bowl of a planetary mixer and water was added for the required consistency. Before placement, wood pieces and long roots were removed from the peat. The material was mixed for about 30 s and the slurry was then transferred to a container. The required quantity of slurry was collected and was mixed to make it uniform. The slurry was left standing for about 24 h to reach moisture equilibrium. In the process of mixing, significant amount of roots were removed from the peat by the planetary mixer. In the experiments of series IV, conducted to study the effect of presence of roots on electro-osmotic consolidation, the peat was not mixed in the planetary mixer. Long roots were removed while mixing the slurry by hand, leaving the other roots in the slurry.
2. *Preparation of EVD:* Pieces of EVD, each of length about 240 mm, were cut. At the bottom end, the outer geosynthetic cover was sealed with

Table 3 Electro-osmotic consolidation experimental program

Test series	Sample	EVD configuration	Voltage gradient, V/m	Presence of roots	Total number of tests	
I	–	Peat from Miri-Marudi road	Full width ^a	0 followed by 80	No roots	1 preliminary test
II	a		Full width	0 ^d , 80 and 180	No roots	3
	b		1–1 ^b	40 and 80	No roots	2
	c		2–1 ^c	40 and 80	No roots	2
III	–	Silty clay	Full width	0, 80 and 180	No roots	3
IV	a	Peat from Similajau	2–1	80	No roots	1
	b		2–1	80, 100, 120 and 140	Roots present	4

In field applications, the voltage gradient typically ranges from 10 to <100 V/m (Shang 1998). But, in many laboratory studies higher voltage gradients have been used, for example 60 and 120 V/m by Bergado et al. (2000, 2003), 100 and 150 V/m by Chew et al. (2004), 110 V/m by Fourie et al. (2007), 100 V/m by Glendinning et al. (2007), from ≈ 30 to ≈ 170 V/m by Hamir et al. (2001), 135 and 240 V/m by Rittirong et al. (2008), and from ≈ 35 to ≈ 250 V/m by Shang (1997a). Therefore, 80 V/m was chosen as the standard voltage gradient in the present study with respect to which the effect of other voltage gradient values was investigated

^a The EVD nearly covered the full width of the test bed at the anode and cathode ends

^b One 15 mm wide EVD strip was used at both anode and cathode ends

^c Two 15 mm wide EVD strips were used at the anode and one 15 mm wide EVD strip was used at the cathode

^d Voltage gradient = 0, is the self weight consolidation control test

silicone. A small portion of the polyethylene core was removed at the top end exposing the inner copper strip. The EVD strips were kept immersed in water to saturate the geosynthetic cover. In the experiments to investigate 3-dimensional effects, the EVD did not cover the full width of the tank. The EVD was cut to 15 mm wide and 240 mm long strips and encased in the geosynthetic cover.

3. *Preparation of test bed:* Drainage tubes were fitted to the holes at the ends of the test tank and kept closed. An EVD strip was placed at each end of the test tank. Small quantities of slurry were placed inside the tank and gently tapped with a wooden bar to remove air in the slurry. The slurry inside the tank was progressively built up to a thickness of about 200 mm. The initial moisture content of the slurry was determined. Vane shear tests were carried out at the top of the bed. Thin 25 mm square glass settlement plates were placed in position. The top of the tank was closed with a polyethylene strip placed under a glass plate cover. The test bed was left to stand overnight and no drainage of water was permitted during this time.
4. *Self weight consolidation tests:* To distinguish the effects due to electro-osmosis from consolidation due to self weight, tests were carried out on different identical test beds simultaneously. In

one of them, consolidation was allowed to take place only due to self weight. The drained water was collected in measuring cups at both ends of the test bed. The subsequent test procedure was the same as for the electro-osmotic consolidation tests.

5. *Electro-osmotic consolidation tests:* The exposed copper strips were connected to the direct current (DC) power supply and the required voltage was developed. The drainage tubes were opened immediately. After a lapse of about 24 h, the volume of water collected in the cups at the cathode end and anode end was measured, separately. If there was sufficient water available, its pH was determined. Readings for the depth of settlement plates from the top of the test tank were also recorded. These observations were repeated at every 24 h intervals for about a week. Then the self weight consolidation test and electro-osmosis consolidation tests were stopped simultaneously. Vane shear tests were carried out at the top of the consolidated beds at selected locations. Three Shelby tubes were pressed into the consolidated bed at 70, 125 and 180 mm from the cathode end. A vane shear test was performed on the specimen at the bottom of the Shelby tube. The specimen was extruded from the Shelby tube, sliced into a few segments and

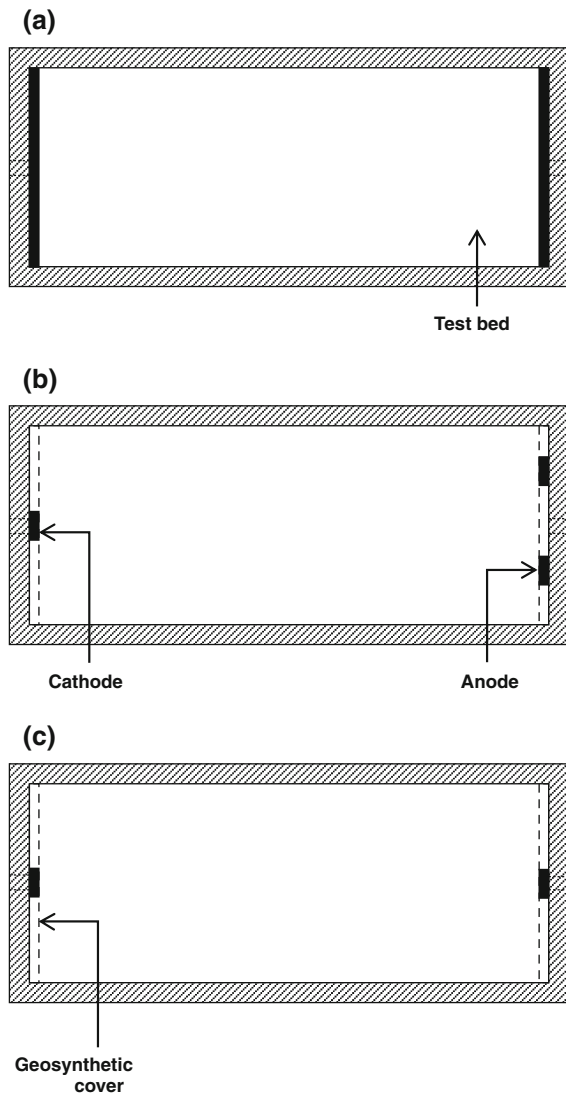


Fig. 4 Electrodes configurations in plan: **a** Full width electrode, **b** 2anodes-1cathode, **c** 1anode-1cathode

their moisture contents were determined to know the spatial variation in moisture content after consolidation.

6.3.1 Departures in the Procedure in the Preliminary Test, Series I

In the preliminary test, instead of discrete settlement plates, a continuous top plate was used. Consolidation showed uneven settlement across the tank, more at the middle than at the end. To some extent the lesser

settlement at the ends was caused by the adhesion of the consolidating material to the EVD strips. Because of the uneven settlement, discrete settlement plates were used in the subsequent experiments. Self weight consolidation was allowed to take place for 10 days first. Then, a voltage gradient of 80 V/m was applied for 1 day and then the current was stopped for 1 day. Then, the same voltage gradient was applied for 1 day with the polarity reversed. Finally, after 2 more days of consolidation without applying current, the experiment was stopped. This sequence of testing was used to determine the test variables as polarity reversal (Lo et al. 1991) had been reported to have a significant effect on electro-osmotic consolidation. However, polarity reversal did not show any effect on consolidation settlement. Therefore, polarity reversal was not used as a test variable in the other experiments. In their field study of a Norwegian quick clay deposit, Bjerrum et al. (1967) observed that when the polarity was reversed the settlement rate decreased indicating the unfavorable effect of polarity reversal. Also, Ou et al. (2009) in their field study at Taipei, Taiwan, found that polarity reversal did not produce favorable effects in terms of water discharged from the cathodes and improvement in undrained strength. The unfavorable effect of polarity reversal could be attributed to the drying of soil near the anode which needs to be saturated again to sustain the flow in the reverse direction. Further, the acidic conditions created at the anode also reduces the zeta potential (ζ) of the soil and thereby the potential for electro-osmotic flow. Asadi et al. (2009) have reported that the ζ of a peat sample from Selangor in Malaysia decreased from -39 mV at $\text{pH} = 11.5$ to nearly 0 at $\text{pH} = 3$. Shang (1997b) has reported k_e to be proportional to the ζ .

6.3.2 Departures in the Procedure in Series III Experiment at 180 V/m Gradient

In the series III test at 180 V/m gradient, the test bed could be prepared only to a thickness of about 100 mm due to shortage of the pre-prepared slurry. Vane shear test could not be performed at the top of the silty clay bed as the vane could not be lowered down to the top of the bed. The voltage gradient was applied only for 3 days, because due to reduced thickness of the test bed the rate of drainage of water decreased in a short time.

Table 4 Characteristics of drained water and changes in water content

Test no	Test designation	Voltage gradient, V/m	Test duration, days	w_i , %	w_{f-av} , %			Characteristics of drained water		
					$d_c = 70$ mm	$d_c = 125$ mm	$d_c = 180$ mm	Total volume, ml	Color	pH range
1	I	0 followed by 80	–	619	439 ^a	433 ^b	385 ^c	NA	NA	NA
2	IIa	0	8	305	276	277	271	93	NA	NA
3	IIa	80	6	303	238	210	201	1,293	NA	7–7.23
4	IIa	180	6	303	255	236	222	1,319	NA	7.23–7.5
5	III	0	6	81	64	67	64	619	NA	–
6	III	80	6	81	49	48	47	1,478	NA	–
7	III	180	3 ^d	83	44	44	42	834 ^d	NA	–
8	IIc	40	8	472	384	378	376	636	Dark brown	NA
9	IIc	80	8	472	301	301	298	1,423	Dark brown to clear	9.46–10.18
10	IIb	40	8	351	357	356	325	451	Dark brown to clear	NA
11	IIb	80	8	360	290	280	260	1,210	Dark brown to clear	9.57–10.10
12	IVa	80	8	623	437	395	351	1,674	Light brown to very clear	NA
13	IVb	80	8	554	482	447	416	1,160	Brown to very clear	8.76–10.26
14	IVb	100	8	555	428	396	368	1,340	Light brown to very clear	8.99–9.97
15	IVb	120	8	552	414	403	358	1,610	Light brown to very clear	9.13–10.28
16	IVb	140	8	554	443	422	392	1,466	Light brown to very clear	8.87–10.14

^a $d_c = 55$ mm

^b $d_c = 120$ mm

^c $d_c = 190$ mm

^d The thickness of the test bed was approximately only one half of that in the other experiments

7 Results and Discussions

The results of changes in average water content (w_{av}), total volume of drained water and its characteristics of color and pH are summarized in Table 4 for all the tests. Similarly, the changes in average undrained strength (S_{u-av}) are summarized in Table 5. Additional details are explained for different test series in the following sections.

7.1 Series I—Preliminary Test

7.1.1 Volume Change and Settlement Profile

During the 10 days of consolidation due to self weight, a total of 410 ml of water drained out from the two ends of the bed. However, during the next 24 h when there was a voltage gradient of 80 V/m nearly 405 ml of water drained out at the cathode end and no water drained out at the anode end. Only about

10 ml of water had drained out during the 24 h prior to the application of direct current. The effect of direct current on consolidation of peat is also evident from Fig. 5, which shows the variation in the surface profile and thickness of the peat bed with time. Comparison of surface profiles of $t = 9$ and $t = 10$ days (change during 24 h before electro-osmosis) with those of $t = 10$ days and $t = 11$ days (change during 24 h of electro-osmosis) shows that electro-osmosis not only accelerated but also induced additional volume reduction in peat.

7.1.2 Post-Consolidation Water Content, w_f

Generally, the water content increased from the cathode end to the anode end. This was more evident at the top of the peat bed. The non-uniform post-consolidation water content distribution was caused mainly by electro-osmosis as during electro-osmosis water moves from anode to cathode.

Table 5 Summary of vane shear test results

Test no	Test designation	Voltage gradient, V/m	S_{ui} , kPa	S_{uf-av} , kPa		
				$d_c = 70$ mm	$d_c = 125$ mm	$d_c = 180$ mm
1	I	0 followed by 80	NA	2.56 ^a	2.56 ^a	4.66 ^a
2	IIa	0	2.38	5.74	5.50	5.29
3	IIa	80	2.52	29.05	Stiff	Stiff
4	IIa	180	3.97	51.06	Stiff	Stiff
5	III	0	0.66	1.43	0.94	1.43
6	III	80	0.53	17.85	24.74	26.24
7	III	180	0.60 ^b	20.73	11.41	21.43
8	IIc	40	1.46	2.91	3.18	4.50
9	IIc	80	1.19	22.16	19.04	26.60
10	IIb	40	1.19	2.65	2.12	5.62
11	IIb	80	1.33	9.08	16.65	31.16
12	IVa	80	0.79	6.44	15.93	31.84
13	IVb	80	2.25	11.47	14.92	18.80
14	IVb	100	1.32	10.89	18.63	24.42
15	IVb	120	0.92	15.34	18.33	34.04
16	IVb	140	1.32	8.77	11.85	28.69

^a S_{ui} values at the top of bed

^b S_{ui} not determined, but assumed from similar initial conditions of Tests 5 and 6

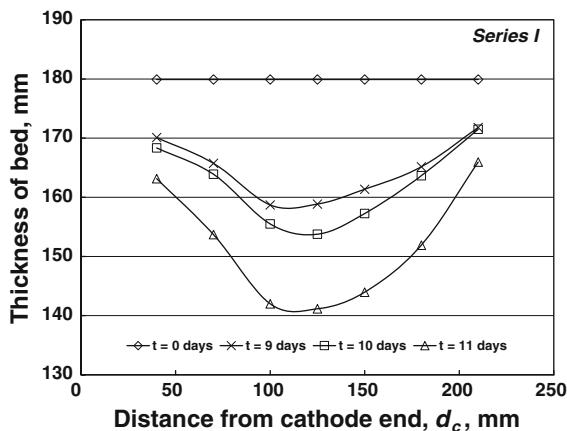


Fig. 5 Variation of surface profile and thickness of peat bed with time in series I preliminary test (Kaniraj and Huong 2008)

7.1.3 Post-Consolidation Shear Strength, S_{uf}

Because of the very high water content, the peat bed was presumed to have no shear strength initially, $S_{ui} \approx 0$. Consolidation increased the shear strength of the peat and the trend was consistent with the changes in water content. Shear strength increased from the wetter cathode end to the drier anode end. The shear strength near the cathode end was still very low as the post-consolidation water content was close to the liquid limit. The shear strength near the anode

end was somewhat higher as the post-consolidation water content was below the liquid limit.

7.2 Test Series IIa on Peat from Miri-Marudi Road

Figure 6 shows the variation of total volume of water drained from the test beds with time for series II and III tests. Generally, in self weight consolidation tests, water drained out at both ends. In electro-osmosis tests, water drained out mostly at the cathode end only.

7.2.1 Initial Water Content, w_i

The average initial water content of the peat beds in tests series IIa (303–305%) was significantly less than the initial water content in the preliminary test (619%) and less than the liquid limit. The test results showed that electro-osmosis was effective in peat at lower water content also.

7.2.2 Volume Change and Settlement Profile

Because of the low initial water content, there was no significant consolidation due to self weight. However, electro-osmosis caused significant volume reduction.

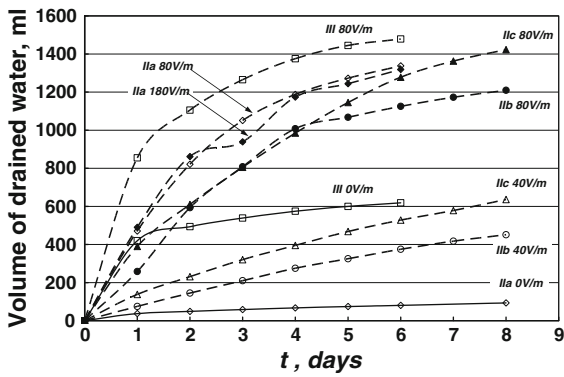


Fig. 6 Variation of total volume of water drained from test beds with time in series II and III tests

Compared to the 80 V/m voltage gradient, the higher voltage gradient of 180 V/m did not benefit the consolidation process significantly. This was evident from total volume of drained water and the variation in the surface profile and thickness of the peat beds with time for the two voltage gradients. In the 180 V/m test, during first 2 days, water collected at the deformed trough at the surface, some of which drained out through anode end also. In their studies of electrokinetic treatment of sewage sludge, Glendinning et al. (2007, 2008) also observed that some water collected around the top of the anodes and cathodes. Due to water recharging at the anode, a closed anode condition is not achieved. This reduces the efficiency of electro-osmotic consolidation as additional electrical energy is required to move the recharge water. Further, the development of negative pore water pressure is reduced. These are possible reasons why the 180 V/m gradient test did not improve the consolidation significantly over the 80 V/m gradient test. Figure 7 shows the surface profiles of the 80 V/m gradient test. Prolonged electro-osmosis continued to cause volume reduction, however, at a decreasing rate with time.

The pH values of the water collected at the cathode are reported in Table 4. In the test at 180 V/m gradient, the water which drained out at the anode end during the first 2 days was mildly acidic and its pH varied from 5.85 to 6.1. The pH values, particularly in the tests with full width EVD, are low compared with the values reported in the literature. As very little water drained out in the self weight consolidation test, the initial pH of the water in the

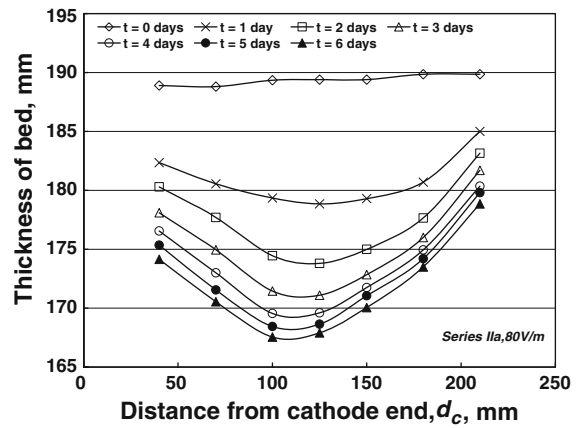


Fig. 7 Variation of surface profile and thickness of peat bed with time in series IIa test at 80 V/m gradient

peat could not be measured. The initial pH could have been low because of the acidic nature of the water. Also, due to the lateral shrinkage of the test bed some of the acidic pore water at the anode end could have drained from the sides and got mixed up with the alkaline pore water at the cathode.

7.2.3 Post-Consolidation Water Content, w_f

Figure 8 shows the comparison of the spatial variation of water content after consolidation in the test beds of self weight consolidation and 80 V/m

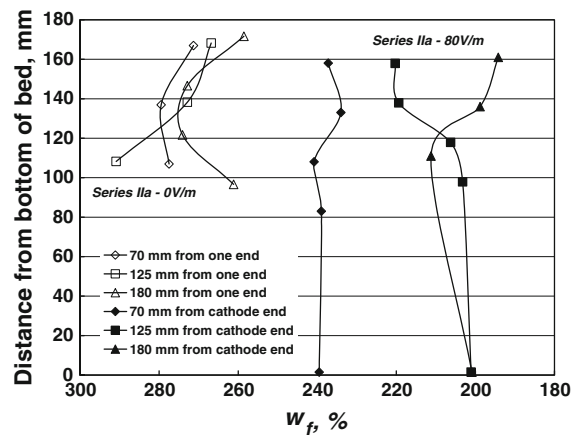


Fig. 8 Spatial variation of water content in peat bed after consolidation in test series IIa, due to self weight (0 V/m gradient) and at 80 V/m gradient

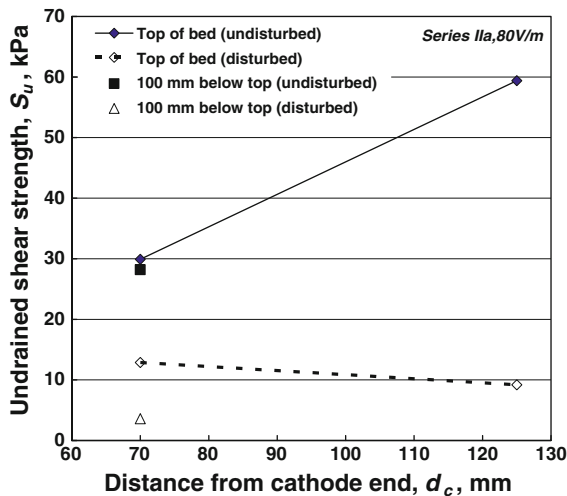


Fig. 9 Variation of S_u with d_c in peat bed after consolidation in test series IIa at 80 V/m gradient

gradient tests. The water content distribution did not vary much in the self weight consolidation test. The average reduction in water content in the peat bed due to self weight consolidation was about 31% and the final water content was slightly above the plastic limit. In the tests at 80 V/m and 180 V/m gradient, the water content generally increased from the cathode end to the anode end. All the water content values were below the plastic limit (w_p). On the average, the reduction in water content was 87% in the test at 80 V/m gradient and 71% in the test at 180 V/m gradient. Thus, electro-osmosis contributed to an additional 56 and 40% decrease in water content in the tests at 80 and 180 V/m gradient, respectively.

7.2.4 Post-Consolidation Shear Strength, S_{uf}

In the self weight consolidation test, the undrained strength increased from the initial value of 2.4 kPa and varied from 4.2 to 6.8 kPa. In the tests at 80 and 180 V/m gradient, the increase in shear strength was significant which was consistent with the post-consolidation water content of less than the plastic limit. Figure 9 shows the variation of S_{uf} in the peat bed in the test at 80 V/m gradient. Close to the anode, the shear strength was too high to perform the vane shear test. The results show that using electro-osmosis soft peat can be stabilized to very stiff consistency ($S_u > 50$ kPa).

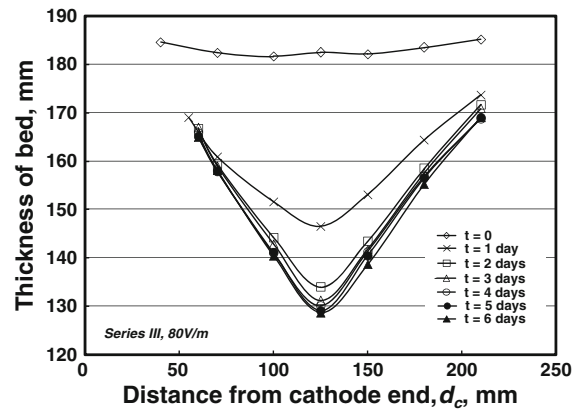


Fig. 10 Variation of surface profile and thickness of clayey silt bed with time in test series III at 80 V/m gradient

7.3 Test Series III on Clayey silt

7.3.1 Initial Water Content, w_i

The average initial water contents of the clayey silt test beds in this test series (81–83%) were significantly above the liquid limit of 62%.

7.3.2 Volume Change and Settlement Profile

Because of the high initial water content, there was significant consolidation in the self weight consolidation test. Electro-osmosis caused an additional 140% volume reduction in the 80 V/m gradient test. It is not possible to conclude on the effect of voltage gradient as the test beds in 80 and 180 V/m gradient tests were not similar. When the experiments were in progress, there was condensation of water inside the tank. The difference between the initial and final weights of the tank with the test bed was compared with the drained volume of water. It was concluded that evaporation of water and the conversion of water to oxygen and hydrogen gases during electrokinetic reaction caused additional removal of water, which was equal to about 10, 3 and 6% of the total loss of water in the self weight consolidation, 80 V/m gradient and 180 V/m gradient tests, respectively.

Figure 10 shows the variation in the surface profile and thickness of the clayey silt bed with time for the 80 V/m gradient test. Comparison of the surface profiles in Figs. 5, 7 and 10 shows that electro-osmosis caused much steeper surface profiles in the clayey silt bed than in the peat bed. The clayey silt moved away

from the EVD over large depth at both ends and the clayey silt bed was cracked nearly vertically in the middle from bottom upwards over a large length. The test bed undergoes contraction due to removal of water. There is also a tendency for the clayey silt to adhere to the EVDs at both ends. This restraint to volume contraction at the ends causes build up of tensile stresses near the middle of the shrinking mass. The vertical crack in the middle of the silty clay bed is probably due to its inability to withstand the tensile stresses. As there is no contact between the two portions adjoining the crack, the efficiency of electro-kinetic treatment would be reduced.

7.3.3 Post-Consolidation Water Content, w_f

The spatial variation of post-consolidation water content in the test beds was within a narrow range of about 5% in all the tests. The average reduction in water content in the self weight consolidation test was about 16% and the final water content was well above the plastic limit. In the 80 and 180 V/m gradient tests, as in the electro-osmosis consolidation tests of series I and II, generally the water content increased from the cathode end to the anode end. All the w_f values were close to the plastic limit of clayey silt. On the average, the reduction in water content was 34% in the 80 V/m gradient test and 39% in the 180 V/m gradient test. Thus, electro-osmosis contributed to additional 100% decrease in water content in these two tests.

7.3.4 Post-Consolidation Shear Strength, S_{uf}

As the post-consolidation water content of the clayey silt bed in the self weight consolidation test was well above the plastic limit, it was difficult to retain the soft clayey silt core in the Shelby tube. In the self weight consolidation test, the undisturbed S_u increased slightly from the initial value of 0.66 kPa and generally varied from 1.06 to 1.79 kPa. In the 80 V/m and 180 V/m gradient tests, the increase in shear strength was significant, which was consistent with the post-consolidation water content being close to the plastic limit. S_u increased significantly from the initial value of 0.53 kPa to as high as 29 kPa. In the comparable tests on the peat from Miri-Marudi Road in Series IIa, the increase in post-consolidation S_u was even higher. From initial values in the range of $S_u = 2\text{--}4$ kPa, the test bed reached a stiff consistency

($S_u > 50$ kPa). This showed that electro-osmosis was more effective in soft peat than in soft clayey silt.

7.4 Test Series IIb and IIc on Peat from Miri-Marudi Road

7.4.1 Initial Water Content, w_i

The average initial water contents were 472% in the 2anodes-1cathode configuration (series IIc) and 355% in the 1anode-1cathode configuration (series IIb) tests. These values lie between $w_i = 619\%$ in the preliminary test of series I and $w_i = 303\%$ in the tests of series IIa.

7.4.2 Volume Change, Post-Consolidation Water Content, w_f , and Post-Consolidation Shear Strength, S_{uf}

The volume of water drained out in the 2anodes-1cathode and 1anode-1cathode configurations were nearly the same. Both configurations produced substantial electro-osmosis effects under 80 V/m voltage gradient. However, under 40 V/m voltage gradient they were only about 40% as effective as under 80 V/m voltage gradient.

The anode–cathode configuration had a significant influence on the electro-osmosis process. The tests performed with the 2anodes-1cathode configuration had significantly higher initial water content ($w_{i-av} = 472\%$) than the 1anode-1cathode configuration tests ($w_{i-av} = 355\%$). Still, under 80 V/m voltage gradient, the post-test water content and undrained strength in the tests with 2anodes-1cathode configuration were comparable to the values in the tests with 1anode-1cathode configuration. The 2anodes-1cathode configuration induced electro-osmosis in a more uniform manner than the 1anode-1cathode configuration. In the test with 1anode-1cathode configuration, the peat bed settled more near the cathode than near the anode. However, in the test with 2anodes-1cathode configuration the surface profile after consolidation resembled the profiles in Figs. 5, 7 and 10 with nearly the same amount of settlement at the cathode and anode. The variations of w_f and S_{uf} with distance from cathode, d_c , for tests at 80 V/m gradient with 1anode-1cathode and 2anodes-1cathode configurations, are shown in Figs. 11 and 12, respectively. These figures demonstrate that the 2anodes-1cathode configuration

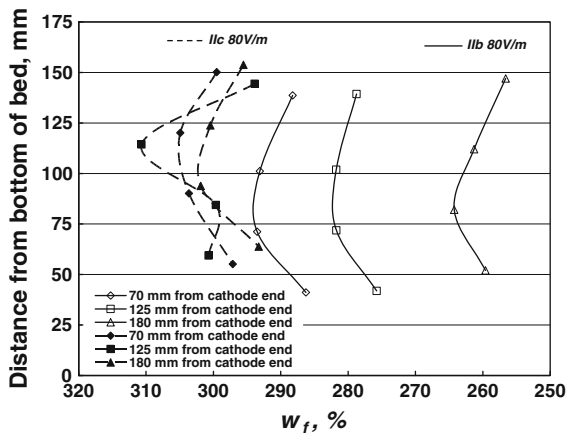


Fig. 11 Spatial variation of water content after consolidation in tests IIb and IIc at 80 V/m gradient

produced a more uniform reduction in water content and increase in shear strength across the peat bed than the 1anode-1cathode configuration. Therefore, for electrokinetic treatment in the field, an EVD installation pattern which simulates the 2anodes-1cathode configuration is the appropriate choice.

7.5 Test Series IV on Peat from Similajau

Experiments were conducted on Similajau peat to study the effect of presence of roots on electro-osmotic consolidation. Based on the results of series IIb and IIc tests, 2anodes-1cathode configuration was used in all series IV tests. The series IVa test was a control test with the peat bed containing no roots. The effects due to presence of roots and voltage gradient on electro-osmotic consolidation were investigated in the series IVb tests.

7.5.1 Initial Water Content, w_i

The average initial water content was 623% in the series IVa test and in the series IVb tests, it varied over a narrow range of 552–555%. The removal of roots decreased the solids content in the peat, which was the reason for the higher initial water content in the series IVa test than in the series IVb tests.

7.5.2 Volume Change and Post-Consolidation Shear Strength, S_{uf}

From the results for volume of water drained out at voltage gradient of 80 V/m in Table 4 and Fig. 13,

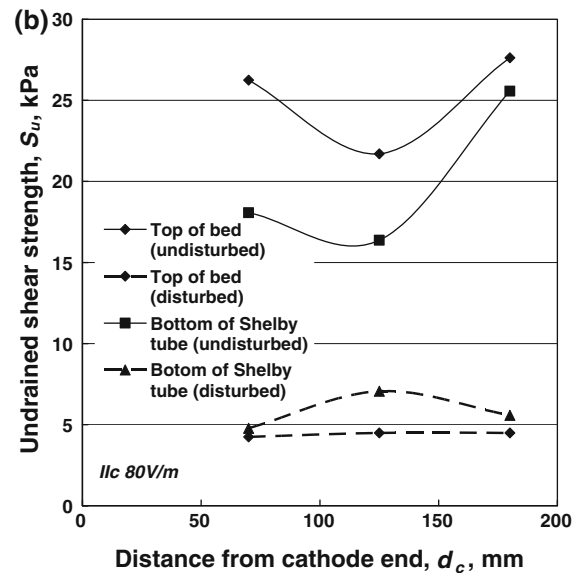
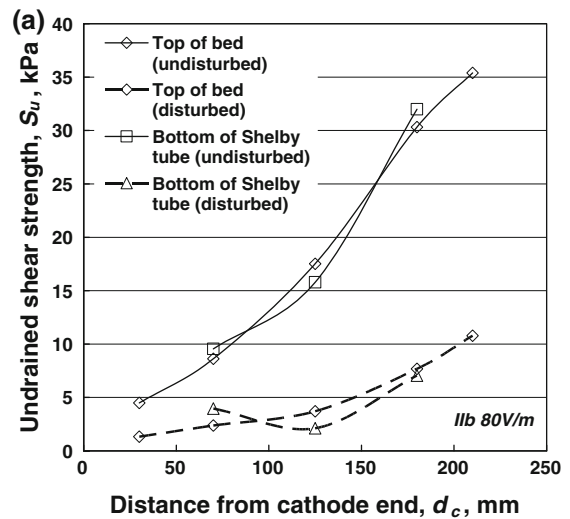


Fig. 12 Variation of S_u with d_c after consolidation at 80 V/m gradient. **a** Test IIb and **b** Test IIc

the presence of roots appears to reduce the total volume of drained water. This is consistent with the fact that the initial water content of the peat bed is reduced by the presence of roots. The voltage gradient had a significant effect as in the series IIb and IIc tests. Increase in voltage gradient increased the total volume of drained water, particularly in the first 2 days. There was a maximum voltage gradient for optimum results. Maximum volume of water drained out at 120 V/m voltage gradient.

Figure 14 shows the variation of the undrained strength along the top of the peat beds after

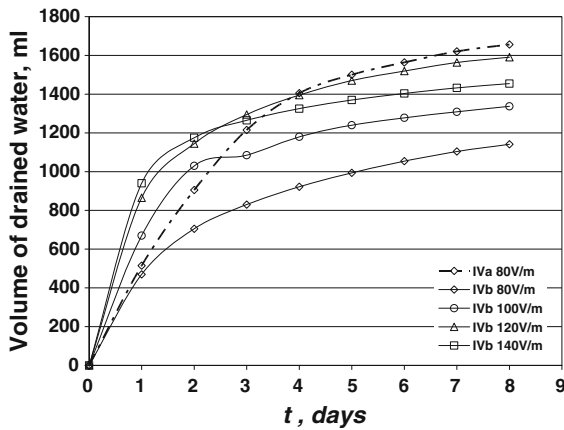


Fig. 13 Variation of volume of water drained from test beds with time in series IV tests

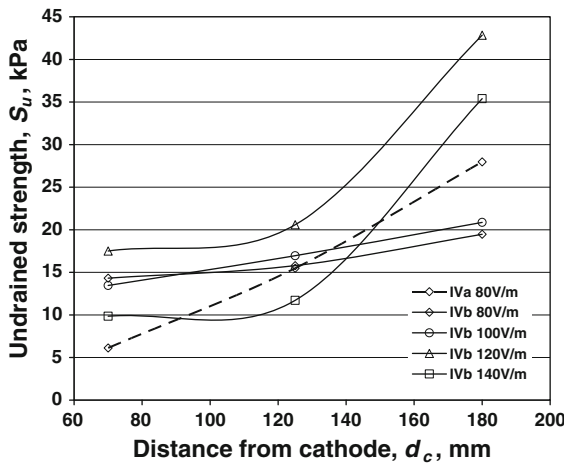


Fig. 14 Variation of S_u at top of bed with d_c in series IV tests after consolidation

consolidation. Comparison of the results of the two tests conducted at 80 V/m voltage gradient, shows that the electro-osmosis was more effective when there were no roots in the test bed. The test bed in test IVa without roots had a higher w_i and a lower S_{ui} than the test bed of test IVb with roots. Still the test bed without roots, generally had higher shear strength after consolidation. This may be attributed to the lower post-consolidation water content of test bed IVa than of test bed IVb, as a result of higher volume of water draining out from test bed IVa than test bed IVb. The effect of voltage gradient on undrained shear strength was in line with its effect on volume of water drained. Increase in voltage gradient increased

the undrained strength and the maximum increase in strength resulted at 120 V/m voltage gradient.

8 Comments on Energy Consumption

It is commonly considered that the cost of energy required for electrokinetic treatment of soft soils is high, which is a limitation to its application in the field. The amount of energy consumed is expressed in units of kWh per cubic meters of soil in ground improvement applications and in kWh per tonne of dry material in dewatering of tailings. Table 6 summarizes the energy consumption reported in some previous studies of electro-osmotic consolidation of soft grounds. Some other values of energy consumption reported are: 0.5 kWh/m³ for the stabilization of a shipyard embankment (Chappel and Burton 1975); 6.7 kWh/m³ for slope stabilization at Kootney River (Wade 1976); and 1 kWh/m³ for the improvement of a pile group’s performance (Milligan 1994). El Naggar and Routledge (2004), in their study of electro-osmotic treatment of piles, reported the energy consumption for different durations of treatment as 1.2, 4.3, 12, 24 and 72.3 Wh for 1.6, 6.4, 16.9, 35.4, and 107.8 h, respectively. The reported energy consumption thus varies over a large range, from a low value of 0.5 kWh/m³ to as high as 17 kWh/m³. But, even at the highest energy consumption rate of 17 kWh/m³, Bjerrum et al. (1967) reported the treatment as an economical solution. Further, based on the cost analysis of the various components of treatment, Burnotte et al. (2004) remarked, “Contrary to what is often perceived, the cost of electrical power was not a major item compared to the installation of the electrode system”. The cost of electricity was only 7% of the total cost in their study. The energy consumption will depend on a number of factors such as the magnitude of voltage gradient, polarity reversal, current intermittence, electrode type, initial ground conditions (w_i , S_{ui}), improvement targets (w_f , S_{uf}), particle size, composition, and zeta potential (ζ) of the treated material, and treatment duration. For example, smaller voltage gradient, higher ζ and smaller treatment duration will result in lower energy consumption.

Similar conclusions regarding energy consumption can be drawn in the case of electro-osmotic dewatering of tailings and sludges also. Table 7 shows a

Table 6 Energy consumption in studies of ground improvement by electro-osmotic consolidation

Study	Test details	Results	Energy consumption, kWh/m ³
Construction of sewage treatment plant in Norwegian quick clay (Bjerrum 1967)	$i_e = 20\text{--}30$ V/m Duration = 120 days Polarity reversal = 51–58 days	$S_{u\text{-initial}} < 9.81$ kPa $S_{u\text{-final-av}} = 39.2$ kPa $S_{u\text{-final-max}} = 107.9$ kPa	17.00 The treatment was reported to be an economical solution
Soft clay near Ottawa, Canada (Lo et al. 1991)	$i_e = 4, 8, 20$ and 40 V/m Duration = 32 days Polarity reversal = after 17 days	$S_{u\text{-initial}} = 18$ kPa Increase in $S_u = 40\text{--}60\%$	6.45
Soft clay at Tuas view reclamation phase IV, Western Singapore (Chew et al. 2004)	$i_e = 4\text{--}10$ V/m Duration = 13 days Polarity reversal = 7–10 h interval	S_u increased from 30 kPa to 42 kPa (40% increase)	1.80
Soft clay near Mont St Hilaire, Quebec, Canada (Burnotte et al. 2004)	$i_e = 31$ V/m Duration = 48 days	Midway between anodes and cathodes and close to cathodes, S_u almost doubled. Closer to anodes the S_u increased by at least six times	The cost of electrical power (7% of the total cost) was not a major item compared to the installation of the electrode system
Soft clayey silt at Kuching, Sarawak (Rittirong et al. 2008)	$i_e = 5\text{--}21$ V/m Duration = 5 days Polarity reversal = 20 h interval	$S_{u\text{-initial}} = 5\text{--}13$ kPa $S_{u\text{-final}} = 15\text{--}50$ kPa $S_{u\text{-final-avx}} = 22\text{--}39$ kPa	0.70

summary of the energy consumption values reported in the studies of electro-osmotic dewatering of tailings. The variation in energy consumption of 0.6–880 kWh/dry tonne is higher than that reported in the ground improvement studies. Reddy et al. (2006) studied the effect of polymer flocculants on electro-osmotic dewatering dredged sediments at $i_e = 100$ V/m. The duration of the tests ranged from 145 to 290 h. The polymers further improved the efficiency of electro-osmotic dewatering. Depending on the flocculant used and test duration, the energy consumption varied from 0.28 to 1.022 kWh/m³. The energy consumption values in a study of electro-osmotic treatment of sewage sludge (Glendinning et al. 2008) are shown in Table 8. The hexagonal array of electrodes reduced the time of treatment and also the energy consumption.

The voltage and current were not measured in the present study and therefore the energy consumption cannot be determined. In view of the trends reported in literature and the conclusions thereof, the absence of data on energy consumption is considered not to affect the contribution of the study significantly.

9 Conclusions

The following conclusions can be drawn from the experimental study of electro-osmotic consolidation tests.

1. Comparison of the results of self weight consolidation tests and electro-osmotic consolidation tests using electro vertical drains showed that electro-osmosis was effective in strengthening of soft peat and clayey silt samples. In terms of improvement in undrained strength, electro-osmosis was more effective in peat than in clayey silt.
2. Electro-osmotic consolidation was effective over a large range of water contents.
3. The pore water generally drained out from the cathode end only. After electro-osmotic consolidation, the water content was more at the cathode end than at the anode end. Correspondingly, the undrained strength was lower at the cathode end than at the anode end.
4. Voltage gradient had a significant effect on electro-osmotic consolidation. An increase in

Table 7 Energy consumption in studies of electro-osmotic dewatering of tailings (after Fourie et al. 2007)

Tailings	Results	Energy consumption kWh/dry tonne
Metal mine (Sprute and Kelsh 1975a)	NA	25–30
Metal mine (Sprute and Kelsh 1975b)	$Sc_i = 72\%$; $Sc_f = 83\%$	20
Molybdenum (Sprute and Kelsh 1980)	$Sc_i = 23\%$; $Sc_f = 44–65\%$	17–68
Coal (Sprute and Kelsh 1982)	$Sc_i = 17\%$; $Sc_f = 45\%$	64
Coal (Lockhart and Stickland 1984)	NA	14–36
Kimberlite (Wilmans and Van Deventer 1987)	$Sc_i = 8\%$	144–880
Coal washery (Lockhart 1992)	$Sc_i = 45\%$; $Sc_f = 75\%$	20
Sand mining (Lockhart 1992)	NA	1
Gold (Chen et al. 1996)	$Sc_i = 60–67\%$; $Sc_f = 69\%$	NA
Phosphate (Shang and Lo 1997)	$Sc_i = 13\%$; $Sc_f = 34\%$	96
Sand mining (Veal et al. 2000)	$Sc_i = 27\%$; $Sc_f = 44\%$	94
Illeminite, zircon (Veal et al. 2000)	$Sc_i = 27\%$; $Sc_f = 56\%$	33
Sand mine washery (Veal et al. 2000)	NA	0.6
Kimberlite (Johns 2004)	NA	130–615
Mineral sands (Fourie et al. 2007)	$w_i = 158\%$; $w_f = 75\%$	0.9

Sc_i initial solids content; Sc_f final solids content

Table 8 Energy consumption for electro-osmotic consolidation of sewage sludge (Glendinning et al. 2008)

Arrangement of electrodes	Results	Energy consumption kWh/m ³
Rectangular array	30% reduction in volume is 95 days	170.1
Hexagonal array	30% reduction in volume is 72 days	128.7
Rectangular array	40% reduction in volume is 126 days	193.7
Hexagonal array	40% reduction in volume is 96 days	160.7
Rectangular array	50% reduction in volume is 157 days	230.9
Hexagonal array	50% reduction in volume is 122 days	182.7

the voltage gradient generally improved consolidation and increased the volume of water drained and undrained strength. The maximum voltage gradient for optimum results appeared to be in the region 120 V/m.

- The anode–cathode configuration had a significant influence on the electro-osmosis process. The 2anodes-1cathode configuration performed better than the 1anode-1cathode configuration in terms of surface deformation and more uniform distribution of water content and undrained strength after consolidation.
- Electro-osmosis was more effective when the roots were not present. The drained volume of water was higher when roots were not present, resulting in lower post-consolidation water contents.

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