Consolidation of a Bombay Marine Clay under Combined Surcharge and Electrical Gradient

by

P.N. Sundaram*

N. Balasubramaniam**

Introduction

IT is well-known that electrical energy can be utilised in the field of soil engineering, in the determination as well as alteration of certain properties of the soil (Esrig et al, 1967, Spangler and King, 1949). Electrical drainage is known to dewater and stabilize problem-soils that refuse to be dewatered by ordinary means (L. Casagrande, 1948, 1952, 1961). Besides, electrical stabilisation of fine silty and clayey soils result in decrease in void ratio and consequent increase in their shear strength (Bjerrum, et al, 1967 ; Fetzer, 1967).

When electricity is applied to a compressible soil mass, a certain amount of consolidation accompanies the other reactions (Preece, 1947 ; Vey, 1949 ; Casagrande, 1952). Investigations by Preece, Vey and others suggest that stresses are developed both in pore water and between soil particles themselves, as the basic effects of electro-osmosis. The mechanism of consolidation under an electrical gradient has been analysed by many investigators, until Esrig (1968) presented a systematic analysis, but not without certain simplified assumptions. He analysed development of pore pressures for both incompressible and compressible media under a constant electrical gradient. The tacit assumption in his analysis is that the flow of water due to an electrical gradient and that due to hydraulic gradient may be superimposed. The case of an incompressible, saturated medium is explained in Figure 1. It is obvious that except in case (a), there will not be any flow in the other two cases.

In case of compressible saturated medium, referring to Figure 1, the storage equation may be written for one-dimensional flow :

$$k_e \frac{\delta^2 V}{\delta x^2} + \frac{k}{\gamma_w} \frac{\delta^2 u}{\delta x^2} = m_v \frac{\delta u}{\delta t} \quad \ldots (1)$$

Where k_e and k are respectively electro-kinetic permeability (cm/sec/volt/cm) and hydraulic permeability (cm/sec) coefficients ; V is the voltage at a distance x, measured from cathode ; u is the excess hydrostatic pore pressure at x and m_v is the coefficient of volume compressibility.

* Lecturer in Civil Engg., Indian Institute of Technology, Powai, Bombay.

** Associate Lecturer, Thiagarajar College of Engineering, Madurai (S. India).

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Introduction of a variable

$$\theta = u + \frac{k_e}{k} V \gamma_w \qquad \ldots(1a)$$

reduces Equation (1) to

$$Cv \frac{\delta^2 \theta}{\delta x^2} = \frac{\delta \theta}{\delta t} \qquad \ldots(2)$$

where,

$$C_v = k \,/\, m_v \gamma_w$$

Equation (2) suggests that the rate of consolidation is governed only by the hydraulic permeability, independent of electro-kinetic permeability. The electrical field helps in imposing an 'additional surcharge' thereby increasing the total settlement.

Scope of the Present Study

The present study deals with the primary consolidation characteristics of a disturbed Bombay marine clay, for two initial void ratios, under combined surcharge and electrical loadings. The investigation is restricted to the study of overall engineering characteristics with respect to consolidation and the other side-effects such as a electro-phoresis, electro-chemical hardening are ignored.

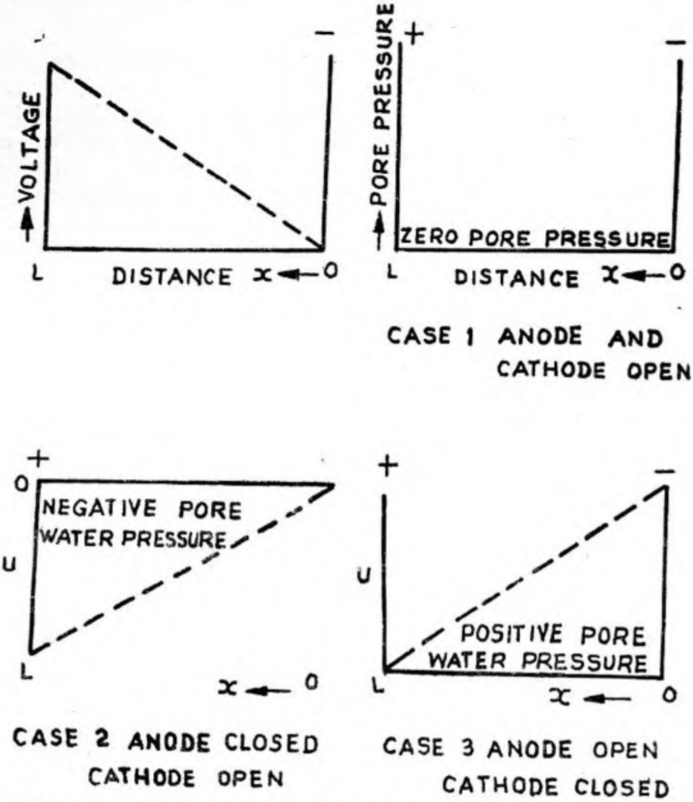

FIGURE 1 : **Effect of boundary conditions on development of pore water pressure in an incompressible porous medium under constant voltage gradient.**

Soil Under Study

The soil used was a marine clay from coastal Bombay, consisting mostly of illite mineral. The grain-size distribution indicates that the percentage of clay (2 μ) is nearly 67 percent. The relevant physical and engineering properties are presented in Table I. The soil *in situ* is very loose and almost flows out of sampler tube. Thus, for experiments, the soil was air-dried, removed of foreign matter, pounded and the material passing through 0.08 mm sieve was used for subsequent tests.

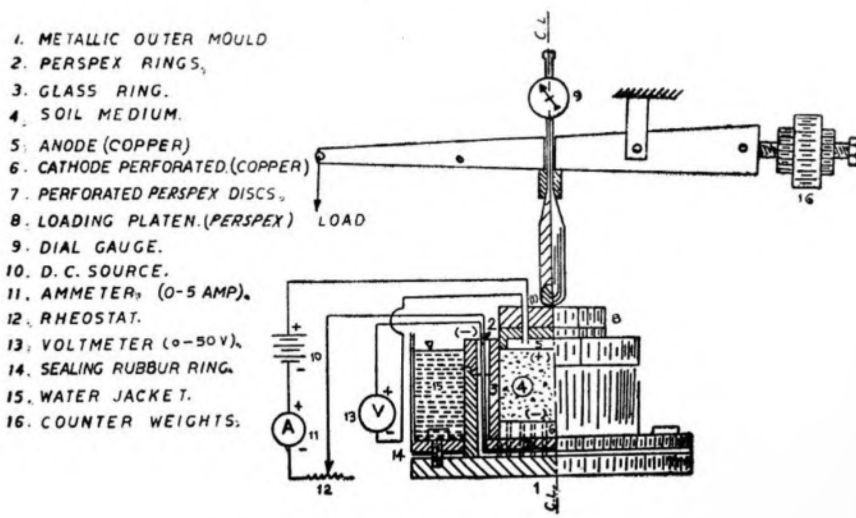

FIGURE 2 : Electro-osmotic consolidometer.

Modification of Testing Apparatus

The consolidometer, similar to the ordinary fixed ring type was modified to render it amenable to electro-osmotic consolidation, with and without surcharge and make the system electrically leak-proof, viz., the applied voltage should pass through the soil specimen only. Figure 2 shows the cross-section of the modified set-up. The ring is made up of ordinary transparent glass 0.35 cm thick, internal diameter 8.5 cm and of total height 5.2 cm. This ring is reinforced with three perspex rings of 1 cm thickness, to ensure against accidental breaking of the glass ring. The top platen is also a perspex disc 1.2 cm thick, and 8.5 cm in diameter, below which is introduced a copper electrode (anode). The soil sample initially 3.2 cm thick will be resting on another porous electrode (cathode). Polished copper electrodes were used, since they are good conductors and undergo little reaction with the soil.

The power was supplied from a 15 volts eliminator. For all the tests, an ammeter was placed in series and a voltmeter connected across the sample, thus giving continuous readings of current and voltage.

Test Programme

Three load increments were selected : (*a*) 0—0.5 kg/sq cm ; (*b*) 0.1—0.6 kg/sq cm ; (*c*) 0.1—1.1 kg/sq cm. The voltage gradients selected were 1 v/cm, 2 v/cm and 3 v/cm.

The above load increments are adequate from a practical point of view. However, the maximum voltage gradient applied was 3 v/cm, even though such high gradients are rarely applied in the field.

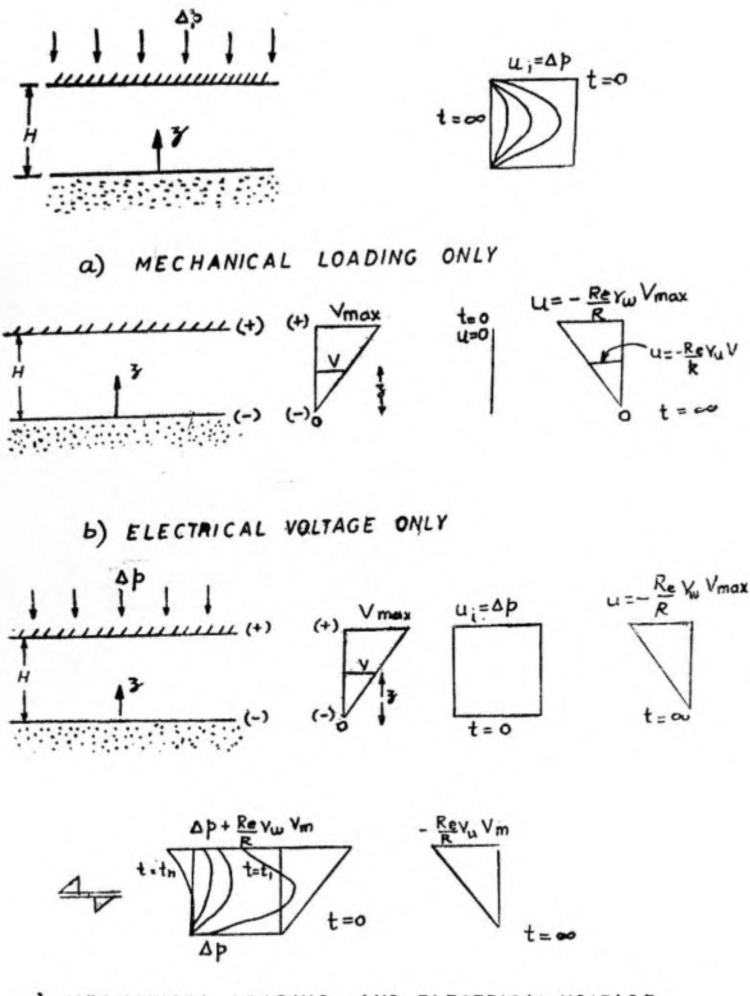

FIGURE 3 (a, b & c) : Key diagram for determination of average consolidation for combined loading.

For cases (*b*) and (*c*), an initial surcharge load of 0.1 kg/sq cm was applied and the soil was allowed to undergo complete consolidation ; then the increment of 0.5/1.0 kg/sq cm was applied, along with the required voltage gradient. No attempt was made to maintain the voltage gradient constant throughout the test. The range of moulding void ratios for the tests were between 1.90 and 2.20.

Corrosion effect was checked at anode, but the loss in material did not exceed for any test by more than 5 percent.

Ordinary consolidation tests were also conducted for the above surcharges, for purpose of comparison.

TABLE I

Properties of the Bombay Marine Clay Used

Specific gravity	...	...	2.70
Liquid limit	...	...	75%
Plastic limit	...	...	39%
Plasticity index	...	...	36
Shrinkage limit	...	..	13%
Average field moisture content	...	...	88%
Textural composition			
Gravel (2 mm)	...	...	0%
Sand (0.6—2 mm)	...	...	9%
Silt (2μ—0.06 mm)	...	...	25%
Clay (2μ)	...	...	66%
Classification			
Broad group		...	Marine clay
Textural classification		...	Clay
Chemical properties			
pH		...	7
Base exchange capacity meq/100 gm of soil		...	37
Probable clay mineral		...	Illite
Average coefficient of permeability (cm/sec)		...	2.8×10^{-6}

Analysis of Test Results

The dial-gauge readings versus log time in minutes were plotted for tests without electrical gradient and corrections applied for initial and secondary compressions. The following values were determined for all the three loadings :

(1) Primary settlement—δ_p
(2) 90 percent of primary settlement—δ_{90}
(3) Time for δ_{90}—t_{90}
(4) C_v

These values are given in Table V and Figure 5.

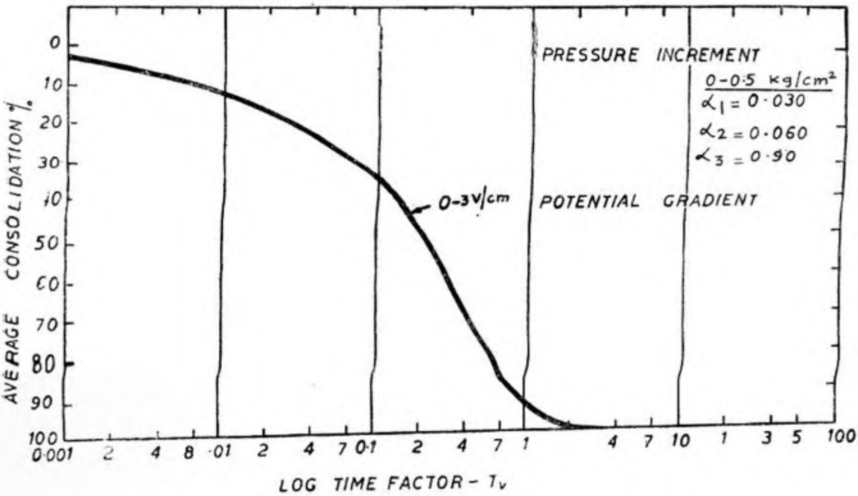

FIGURE 4 : $\bar{U}$—T_v relationship for typical combination of surcharge and voltage gradients.

CONSOLIDATION TESTS WITH ELECTRICAL GRADIENTS

After the completion of consolidation test, for a sample, it was observed that the copper anode was coated with a very thin layer of some white substance, most probably cuprous chloride. When the supply was switched off, it was observed that for high voltage gradients, there was a slight rebound.

Table II gives a typical set of vertical compression readings for 0—0.5 kg/sq cm surcharge.

DETERMINATION OF COEFFICIENT OF CONSOLIDATION

If Equation (2) is valid, it is obvious that the rate of excess pore pressure is governed only by C_v. A simplified approach for determining the average percentage consolidation-time factor relationship is herewith presented.

Figure 3 gives the essential steps involved. In particular, it may be noted that an initially zero pore water pressure is converted to a negative one at the end of consolidation, due to an electrical gradient V_{max}/H. The same effect can be achieved, by having an initially positive triangular pore pressure distribution which gets completely dissipated at the end of consolidation. This substitution is of decisive advantage, enabling superposition of surcharge loading and electrical gradient.

Referring to Figure 3 (*c*)

$$\bar{U}\left[\frac{1}{2}\left\{u_i+\left(u_i+\frac{k_e}{k}V_m\,\gamma_\omega\right)\right\}H\right]$$

$$=\bar{U}_{\square}(u_iH)+\bar{U}_{\triangle}\left(\tfrac{1}{2}\frac{k_e}{k}V_m\gamma_w\right)H \qquad \ldots(3)$$

where,

$\overline{U}$ = Average consolidation for combined case

$\overline{U}_{\square}$ = Average consolidation for surcharge loading

$\overline{U}_{\triangle}$ = Average consolidation for initial triangular distribution

V_m = Maximum voltage at anode

Rearranging

$$\overline{U} = \frac{\overline{U}_{\square} + \alpha \, \overline{U}_{\triangle}}{1 + \alpha} \qquad \ldots(4)$$

where,

$$\alpha = \frac{k_e}{2k} \quad \frac{V_m \, \gamma_w}{u_i} \qquad \ldots(5)$$

With the help of Equation (4), $\overline{U}$ for various values of T_v can be determined, since the value of α is known.

Figure 4 shows the extent of variation in percentage consolidation for different values of α. The variation, however, is negligible, for the range of values considered.

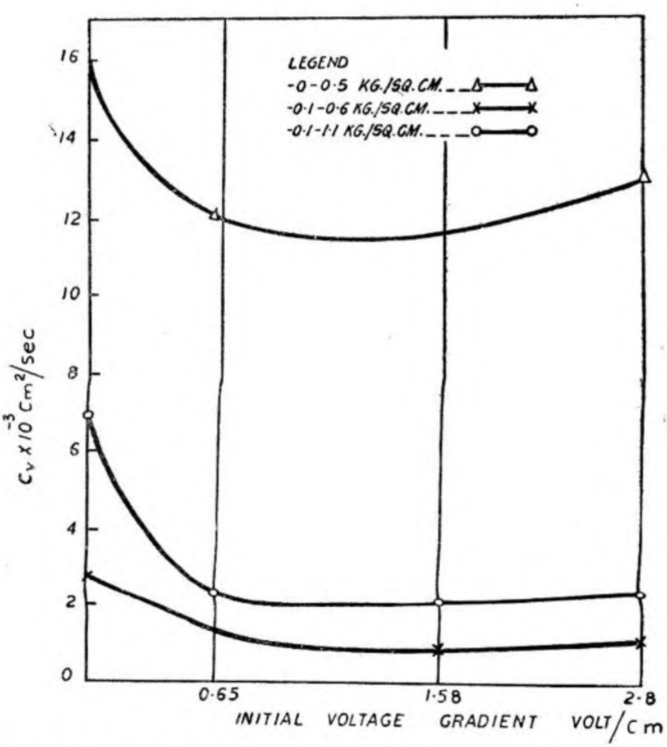

FIGURE 5 : **Coefficient of consolidation of marine clay versus voltage gradient relationship.**

TABLE II

Typical Consolidation Test Results with and without Electrical Gradient.

Load increment : 0 – 0.5 kg/sq cm

Maximum voltages applied : 3.2 volts (1 v/cm)
6.5 volts (2 v/cm)
9.6 volts (3 v/cm)

Current variation :
1 v/cm : 0.4 to 0.1 ampere
2 v/cm : 1.3 to 0.02 ampere
3 v/cm : 2.0 to 0.02 ampere

Sl. No.	Time in mts.	Vertical compression in mm			
		0 v/cm	1 v/cm	2 v/cm	3 v/cm
1.	0	0.0	0.0	0.0	0.0
2.	1	4.34	4.46	6.30	4.01
3.	2	5.04	5.11	6.85	4.68
4.	4	5.64	6.71	7.20	5.26
5.	9	6.07	7.12	7.60	5.73
6.	16	6.26	7.30	7.85	6.48
7.	25	6.38	7.41	8.00	6.83
8.	36	6.46	7.48	8.10	7.13
9.	49	6.52	7.52	8.20	7.33
10.	64	6.56	7.55	8.25	7.43
11.	81	6.60	7.58	8.35	7.55
12.	100	6.64	7.60+	8.40	7.62
13.	500	6.89	7.60	8.75+	–
14.	1000	–	–	8.75	7.98+
15.	1500	–	–	–	7.91

+ The time at which the electrical supply was switched off.

For the tests conducted, the values of C_v for different combinations of surcharge loading and electrical gradients were determined, utilising Equation (4). The values are presented in Figure 5. It is observed that the magnitude of C_v is not enhanced by the application of voltage gradient, but rather it has a tendency to decrease up to a limit and then increase. If electrical gradient were to affect the drainage rate, then the coefficient of consolidation should have been increased to at least k_e/k times that for ordinary consolidation. Values of k_e/k for different moulding void ratios are presented in Table III for Bombay marine clay (Balasubramaniam, 1969). Thus, the value of C_v should have increased at least fourfold. But, the laboratory test results do not support this view. Hence, the rate of consolidation seems to be unaffected by electrical gradient.

TABLE III

Ratio k_e/k for different Moulding Void Ratios.

Sl. No.	Void ratio	k_e/k
1.	1.00	160
2.	1.20	46
3.	1.30	29
4.	1.45	19
5.	2.00	7

TABLE IV

Time for δ_{90} of ordinary Consolidation for Combination of different Surcharge and Valtage Grodients :

δ_{90} of ordinary consolidation :

0–0.5 kg/sq cm = 2.33 mm

0.1—0.6 kg/sq cm = 2.45 mm

0.1—1.1 kg/sq cm = 3.35 mm

Sl. No.	Voltage grad. v/cm	Surcharge (kg/sq cm)		
		0–0.5	0.1–0.6	0.1–1.1
		Time in minutes		
1.	0	7.0	41	50
2.	1	4.8	30	21
3.	2	1.0	30	21
4.	3	1.5	31	17

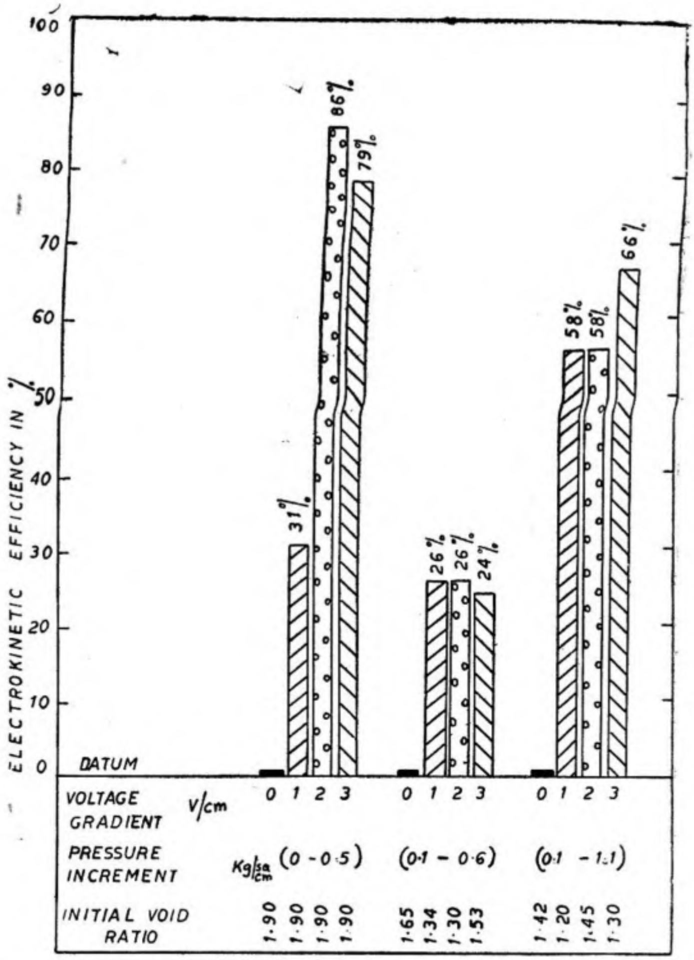

FIGURE 6 : Variation of electro-kinetic efficiency with voltage gradient, initial void ratio and pressure increment.

COMPARISON OF SETTLEMENT MAGNITUDES

1. Table IV gives the values of time for completion of δ_{90} for all the cases. The time for any particular settlement is found to generally decrease with increase in voltage gradient.

2. Another aspect of consolidation under combined surcharge and electrical gradient is that the total primary settlement increases with electrical gradient for the ranges tested. Table V gives the values of primary settlement for different cases. Thus, it seems the electrical gradient acts as a surcharge during consolidation.

This aspect is of decisive practical importance, since such an electrical 'surcharge' over and above the fill loading may not affect development of shear stresses and thus, bearing capacity failure, which, otherwise may occur for equivalent mechanical loading is eliminated, in case of combined application (Esrig, 1968).

3. *Electro-kinetic Efficiency* : In field applications of electro-osmosis, one is rather interested in decrease in time for a given magnitude of settlement to occur, which otherwise may be prolonged. For ordinary consolidation, the time for any percentage of consolidation is proportional to the square of the length of drainage path and the same rule can be extended for combined application. However, coefficient of consolidation may vary to the extent that the 'total' surcharge for the combined case may be more than that due to surcharge load only.

A term 'Electro-kinetic efficiency'—E is introduced which may serve as a gauging factor of the efficiency of electro-osmosis.

$$E = \frac{t_m - t_{me}}{t_m} \times 100 \qquad \ldots(6)$$

where,

t_m = time required for completion of a given magnitude of settlement under surcharge loading only.

t_{me} = time required for the same magnitude to occur under combined surcharge and electrical gradient.

For the marine clay tested, the values of E are presented in the form of bar graphs, in Figure 6, for 90 percent primary settlement for ordinary loading. However, the values of E may change for other settlement magnitudes.

4. *Effect of Initial Void Ratio* : The consolidation tests were conducted essentially for two initial void ratios—one representing a loose state and the other, a comparatively dense state. For the loading 0—0.5 kg/sq cm, the initial void ratio was of the order of 2.00. For the other two loadings, the void ratio at 0.1 kg/sq cm was in the range of 1.2 to 1.5.

TABLE V

Primary Settlement for the Combination of Surcharge and Voltage Gradients.

Sl. No.	Voltage gradient in v/cm	Primary settlement (mm)		
		0−0.5 kg/sq cm	0.1−0.6 kg/sq cm	0.1−1.1 kg/sq cm
1.	0	2.60	2.70	3.70
2.	1	3.90	2.85	4.60
3.	2	5.20	4.00	4.90
4.	3	5.40	3.80	5.35

The bar graphs in Figure 6 show that the efficiency is of a higher order, in the case of high initial void ratio, and for the other two cases, it is substantially lower. This may indicate that for soils with medium to low void ratios, electro-osmosis with nominal voltage gradients may not be very effective, in developing additional compression. However, additional tests are required to confirm this.

Again, since at low void ratios, the ratio k_e/k is higher (vide Table IV), the magnitude of negative pore pressure to develop also correspondingly increases. With coefficient of consolidation remaining practically same, the value of t_{me} increases and thus the efficiency is considerably decreased.

Thus, it is obvious that the effect of application of voltage gradient for a soft clay should materialise during the initial stages (when its void ratio is higher).

Conclusions

(1) The effect of application of an electrical gradient along with surcharge is generally found to decrease the time for a particular settlement, for the range of gradients studied.

(2) The electrical gradient does not improve the drainage rate for compressible soils.

(3) The total primary settlement for a surcharge increases with voltage gradient, suggesting that the gradient acts as a surcharge on the soil system.

(4) Bearing capacity failure for soft soils during reclamation may be eliminated by substituting electrical gradient for part of surcharge fill.

(5) Electro-kinetic efficiency—E is a function of voltage gradient and initial void ratio.

(6) By a simple approach based on Frohlich, it is possible to arrive at percentage consolidation-time factor relationship, for combined cases.

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References

BALASUBRAMANIAM, N. (1969) : "Electro-kinetics of a Bombay Marine Clay". M. Tech. Thesis (unpublished), Indian Institute of Tech., Bombay.

BJERRUM, L.; MOUM, J. & EIDE, O., (1967) : "Application of Electro-osmosis to a Foundation in Norwegian Quick Clay". *Geotechnique*, Vol. 17, No. 3, p. 214.

CASAGRANDE, L. (1948) : "Electro-osmosis". *Proc. 2nd Int. Conference of Soil Mech. & Foundation Engg.*, Rotterdam, Vol. I.

CASAGRANDE, L. (1952) : "Electro-osmotic Stabilisation of Soils". *Journal of Boston Society of Civil Engineers*, Vol. 39.

CASAGRANDE, L. (1952) : "Electrical Stabilisation in Earthwork and Foundation Engineering". *MIT Conference on Soil Stabilisation*, June 18-20, 1952.

CASAGRANDE, L.; LOUGHNEY, R.W. & MATICH, M.A.J. (1961) : "Electro-osmotic Stabilisation of a High Slope in Loose Saturated Silt". *Proc. 5th Int. Conf. of Soil Mech. and Foundation Engg.*, Vol. II.

ESRIG, I.M. (1968) : "Pore. Pressure, Consolidation and Electro-kinetics". *S.M. Proc. ASCE*, July 1968.

ESRIG, I.M., GEMINHARDT, J.P. (1967) : "Electro-kinetic Stabilisation of an illitic Clay". *Proc. ASCE, SM*, May 1967.

FETZER, A. (1967): "Electro-osmotic Stabilisation of West Branch Dam" *S.M. Proc. ASCE.*, July 1967.

JUMIKIS, R. (1962) : "*Soil Mechanics*". Affiliated East-West Press, New Delhi.

PREECE E.F. (1947) : "Geotechnics and Geotechnical Research". *Proc. Highway Research Board*, Vol. 27.

SPANGLER and KING (1949) : "Electrical Hardening of Clays Adjacent to Aluminium Friction Piles". *Proc. Highway Research Board*, Vol. 29.

TAYLOR, D.W. (1948) : "*Fundamentals of Soil Mechanics*". John Wiley & Sons, New York.

VEY, E. (1949) : "The Mechanics of Soil Consolidation by Electro-osmosis". *Proc. Highway Research Board*, Vol. 29.