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DISCUSSION

Proc. Paper 11469

INFORMATION RETRIEVAL

The key words, abstract, and reference "cards" for each article in this Journal represent part of the ASCE participation in the EJC information retrieval plan. The retrieval data are placed herein so that each can be cut out, placed on a 3 × 5 card and given an accession number for the user's file. The accession number is then entered on key word cards so that the user can subsequently match key words to choose the articles he wishes. Details of this program were given in an August, 1962 article in CIVIL ENGINEERING, reprints of which are available on request to ASCE headquarters.

[a]Discussion period closed for this paper. Any other discussion received during this discussion period will be published in subsequent Journals.

11488 PRESSUREMETER IN STRAIN-SOFTENING SOIL

KEY WORDS: **Elasticity; Finite elements; Geotechnical engineering; Plasticity;** Pressure measurement; **Soil mechanics;** Strain hardening; **Strains;** Strength; **Stresses**

ABSTRACT: Strain-softening behavior is defined as a gradual loss of shear resistance after a peak strength has been reached. The basic concepts of the theories of elasticity and plasticity are reviewed, and the classical formulation is extended to include analysis of strain softening. A general effective stress-strain-strength model is described, but attention herein is focused on undrained behavior. Closed-form mathematical solutions for stresses, strains, and pore-water pressures around a pressuremeter are worked out, and detailed comparisons are made between the results from strain-hardening and strain-softening behavior. The proposed theory makes it possible to back-figure basic soil stress-strain and strength properties from strain-controlled pressuremeter tests.

REFERENCE: Prevost, Jean-Herve, and Hoeg, Kaare, "Analysis of Pressuremeter in Strain-Softening Soil," *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 101, No. GT8, **Proc. Paper 11488**, August, 1975, pp. 717-732

11495 ELECTRO-OSMOSIS AND UNSTABLE EMBANKMENT

KEY WORDS: Clays; **Drydocks; Electrochemistry; Electroosmosis;** Embankments; **Geotechnical engineering; Soil stabilization;** Stabilization

ABSTRACT: In the course of construction of a large dry dock project in Singapore, an 8-m high cofferdam embankment was constructed by end tipping decomposed granite material into the sea. At the time of dewatering the cofferdam, large movements of the embankment occurred, and electro-osmosis was chosen as a rapid stabilization technique. The electrode layout, which was chosen after a field test, enabled stabilization to be achieved with a low power consumption of 0.5 kWhr m^3 of soil. The success of this operation has been attributed to the relatively high cationic concentration in the boundary layers of South East Asian clays.

REFERENCE: Chappell, Brian A., and Burton, Peter L., "Electro-Osmosis Applied to Unstable Embankment," *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 101, No. GT8, **Proc. Paper 11495**, August, 1975, pp. 733-740

11493 CONSOLIDATION OF FIBROUS PEAT

KEY WORDS: Compaction tests; **Geotechnical engineering; Peat; Permeability;** Pore pressure; **Primary consolidation; Secondary compression;** Soil mechanics; Testing

ABSTRACT: A series of single increment vertical consolidation tests have been conducted on undisturbed samples of fibrous peat in the 10-in. (250-mm) diam Rowe cell. The results have been assessed in the light of a recently developed theory by Berry and Poskitt. Close agreement is obtained between the observed and predicted rates of settlement and pore pressure dissipation. The decrease in vertical permeability during a consolidation process is of the order of 10^3. As a result, the coefficient of vertical consolidation decreases markedly during a consolidation increment.

REFERENCE: Berry, Peter L., and Vickers, Brian, "Consolidation of Fibrous Peat," *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 101, No. GT8, **Proc. Paper 11493**, August, 1975, pp. 741-753

$F(\bar{\epsilon}^p)$ = strain-hardening or strain-softening law;
$f(\,)$ = general yield function;
I_1 = first invariant of stress tensor = $\sigma_{ii} = \sigma_1 + \sigma_2 + \sigma_3$;
I_2 = second invariant of stress tensor = $(1/2)(\sigma_{ii}\sigma_{jj} - \sigma_{ij}\sigma_{ij}) = \sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1$;
I_3 = third invariant of stress tensor = $(1/3)\,\sigma_{ij}\sigma_{jk}\sigma_{ki} = \sigma_1\sigma_2\sigma_3$;
$J_1 = 0$ = first invariant of deviatoric stress tensor;
J_2 = second invariant of deviatoric stress tensor = $(1/2)\,S_{ij}S_{ij} = -(S_1S_2 + S_2S_3 + S_3S_1) = (1/6)\,[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]$;
J_3 = third invariant of deviatoric stress tensor = $(1/3)\,S_{ij}S_{jk}S_{ki} = S_1S_2S_3 = [(\sigma_1 - (1/3)\,I_1][\sigma_2 - (1/3)I_1][\sigma_3 - (1/3)I_1]$;
K_0 = lateral soil stress coefficient at rest;
$M, M_{cs}, M_1, N, N_1, \beta$ = experimental constants used in effective stress-strain-strength model;
$p = (1/3)\,I_1$ = octahedral stress;
p' = octahedral effective stress;
$q = \sqrt{3J_2}$ = generalized shear stress;
r, θ, z = polar coordinates;
S_i = principal deviatoric stress in ith direction, $i = 1, 2, 3$;
S_{ij} = deviatoric stress tensor component, $i = 1, 2, 3 = \sigma_{ij} - (1/3)\,\delta_{ij}(\sigma_{kk})$;
u = radial displacement;
Y = yield strength;
δ_{ij} = Kronecker symbol;
ϵ_i = principal strain in ith direction, $i = 1, 2, 3$;
ϵ_{ij} = strain tensor component, $i = 1, 2, 3$;
ϵ_v^p = $\int d\epsilon_v^p$ = plastic volumetric strain;
$\bar{\epsilon}^p$ = $\int d\bar{\epsilon}^p$ = plastic shear distortion;
ν = Poisson's ratio;
σ_i = principal stress in ith direction $i = 1, 2, 3$; and
σ_{ij} = stress tensor component, $i = 1, 2, 3$.

JOURNAL OF THE GEOTECHNICAL ENGINEERING DIVISION

Electro-Osmosis Applied to Unstable Embankment

By Brian A. Chappell[1] and Peter L. Burton[2]

Introduction

A new dry dock, designed to handle a 400,000-tonne dead weight vessel, is currently being constructed in Singapore for the Sembawang Shipyard (Pte.) Ltd. The dock is sited partly onshore and partly offshore, with the offshore section being constructed behind a large cellular cofferdam (Fig. 1). As part of the temporary works, the contractor elected to construct a 60-m long 8-m high, earth embankment in place of a planned cofferdam cell in the vicinity of the shore (Fig. 2). The seabed was prepared by removing a silt layer by dragline, and the embankment was constructed by end tipping a decomposed granite material (excavated from the dock site) into the water. The soil profile is shown in Fig. 3.

The embankment became noticeably unstable at the time of dewatering the cofferdam. Large longitudinal cracks appeared on the slopes above water level, and it was necessary to place material on the crest in daily lifts of 0.3 m-0.6 m to maintain the design level. This instability can be attributed to several factors, the most important being that the decomposed granite, a silty clay material, deflocculated on submersion in water, forming a low strength "slurry". The permeability of the material was low (approx 10^{-4}-10^{-5} cm/s), and thus no significant consolidation and consequent strength increase occurred in the 5 months between construction and cofferdam dewatering. In addition, the embankment was loaded immediately after completion by construction vehicle traffic, which also applied a vibrational loading, and by a 4-m tidal range which created a pumping action and applied a cyclic loading.

In an attempt to stabilize the embankment, a sheet pile wall was installed

Note.—Discussion open until January 1, 1976. To extend the closing date one month, a written request must be filed with the Editor of Technical Publications, ASCE. This paper is part of the copyrighted Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers, Vol. 101, No. GT8, August, 1975. Manuscript was submitted for review for possible publication on November 22, 1974.

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through the crest to reduce seepage, and a sheet pile wall with rockfill backing was installed at the toe to inhibit movement (Fig. 3). Neither of these measures, however, proved effective.

Under these conditions, it was felt that the embankment would not be able to resist the loads applied to it under the rapid drawdown conditions arising from cofferdam dewatering, and as it formed an integral part of the cofferdam

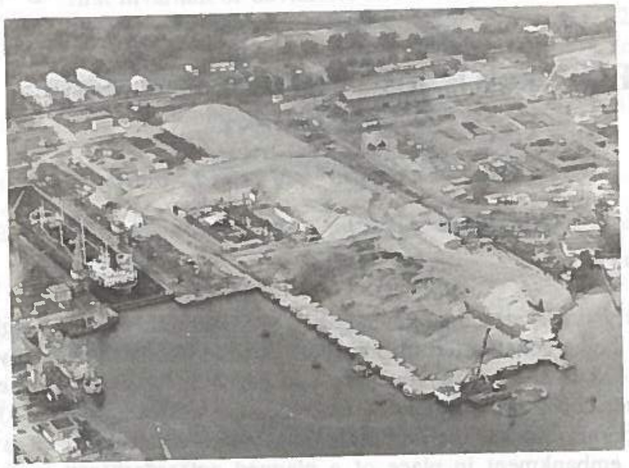

FIG. 1.—Sembawang Dry Dock Under Construction. (Western Embankment Is in Lower Right, where Two Sheet Pile Walls Are Visible)

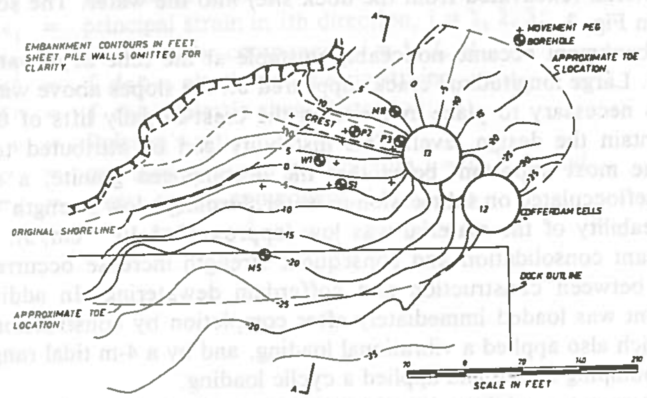

FIG. 2.—Plan of Western Embankment

system, its stability was of vital concern if dewatering was to proceed on schedule. Thus, with minimum time as the main objective in selecting a stabilization technique, electro-osmosis was chosen. To save further time, a quick field test was performed instead of laboratory testing to design an effective system.

A short description of the osmotic principle is given herein, together with a description of the field tests performed and the drainage system used.

Electro-Osmosis Method

Most soils which require improved drainage can be dewatered by one or a combination of the five methods: (1) Sumps and ditches; (2) sheeting and open pumping; (3) deep well sumps; (4) well point systems; and (5) vacuum dewatering systems.

However, there are many silts, clayey silts, and fine clayey silty sands which cannot be successfully drained by the previous methods, but which can be

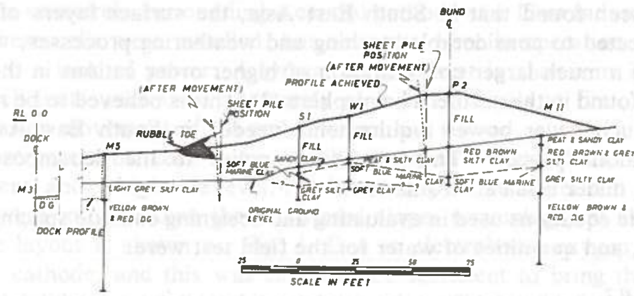

FIG. 3.—Inferred Soil Profile on Section AA

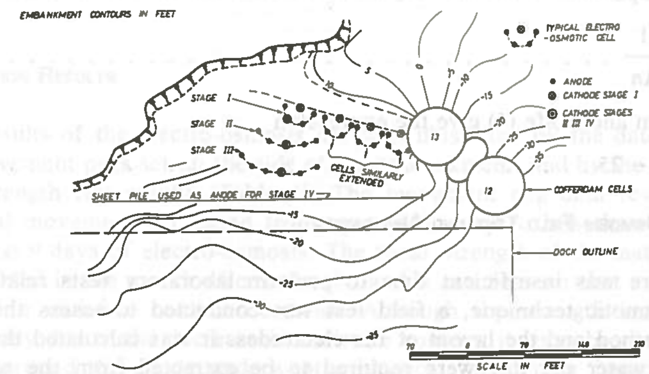

FIG. 4.—Electro-Osmotic Cell Layout

drained with the help of electrical flow through the soil. Water will migrate through the soil from the positive electrode (anode) to the negative electrode (cathode), where it collects and is usually removed by pumping. The migration mechanism is not completely understood, but it appears that several processes are in operation: (1) The removal of adsorbed water from the clay particles; (2) the flow of water associated with ion transfer through the pore fluid; and (3) the flow of water due to a hydraulic (pore pressure) gradient set up by the electrically induced flow (4).

Electro-osmosis is basically part of a wider process generally termed "electro-chemical stabilization." In addition to the stabilization effect of reducing pore pressures by induced drainage, and the strengthening effect of removing adsorbed and capillary water, ion exchange, ion migration, electrolysis, and chemical reactions occur leading to the formation of irreversible compounds. Chemicals such as calcium chloride and sodium silicate are sometimes added to ensure the formation of irreversible cementing accretions. Implementation of the complete electro-chemical process, however, requires considerable power (e.g., 60 $kWhr/m^3$ of soil). The first application of electro-osmotic control of ground water was in 1939 where a long railway cutting in Germany was stabilized (2), and several examples of the full process of electro-chemical stabilization are given by Zhinkin (7).

It has been found that in South East Asia, the surface layers of soil have been subjected to considerable leaching and weathering processes, which have resulted in a much larger concentration of higher order cations in the soil than is usually found in the northern hemisphere (3). This is believed to be responsible for the much lower power requirements needed in South East Asia for the electro-osmotic process. This reasoning applies to the decomposed granite weathered under a sea environment.

The basic equations used in evaluating and designing cathode spacings, electric potentials, and quantities of water for the field test were:

$$Q_e = k_e i_e a z \quad \text{(1)}$$

in which $k_e = \rho Dn/(4\pi\mu)$; k_e can also be determined experimentally from the relationship

$$k_e = \frac{Q_e l}{tVAn} \quad \text{(2)}$$

Maclean and Rolfe (6) give the expression

$$It = 4.1c - 25 \quad \text{(3)}$$

Electro-Osmosis Field Test and Application

As there was insufficient time to perform laboratory tests related to the electro-osmotic technique, a field test was conducted to assess the viability of the method and the layout of the electrodes. It was calculated that at least 140 l of water per day were required to be extracted from the soil with a 3-m separation between anode and cathode. This would be sufficient to dry out the soil and remove any water that might find its way into the embankment through cracks and seepage. (Rainfall occurred every day between 4 p.m. and 6 p.m. during the stabilization process). The depth of stabilization chosen was 5 m so as to include all of the embankment material and some of the foundation. The trial design was based on a depth of 5 m, an effective spacing of 3m, and assumed values of 90 v for the applied voltage and 0.5×10^{-4} cm/s per V/cm for k_e. This latter value was chosen to be of the order of Casagrande's observed value of 0.4×10^{-4} cm/s for a saturated soil (5). An approximate flow of 180 l per day was calculated from Eq. 1 which was therefore adequate for the purpose.

In the field test, a 10-cm diam hole was drilled to a depth of 5 m for the cathode, which consisted of a 2.5-cm diam reinforcing bar surrounded by filter sand. (This was later changed to a hole cased with a 10-cm diam plastic tube having slots cut at the base. The reinforcing bar was inserted in the tube with a little water at the bottom.) The anode consisted of a 2.5-cm diam reinforcing bar driven 5 m into the ground and at a distance of 3 m from the cathode. A portable welding generator was used as the power supply, giving a 40-v potential difference and a direct current of 25 amps-30 amps to the anode. The test was run for 24 hr, and a discharge of water of approx 550 l per day was measured. This was four times the amount required.

As a result of this test, it was decided to increase the anode-cathode spacing to enable a larger volume of soil to be drained, and a pattern of four to six anodes in a semicircle surrounding a central cathode at a 12-m radius was used. Four of these cells were installed, but only two were in operation at any one time due to a lack of power. A typical arrangement is shown in Fig. 4. The pairs of cell units were used alternately at 1-day intervals at first, then 3-day intervals when movement of the embankment had slowed.

The electro-osmotic cells were initially installed on the dock side of the embankment, above high tide level. As dewatering of the cofferdam proceeded, the cells were moved down the dewatered slope, remaining just above water level. The layout is shown on Fig. 4. Due to electrolysis, oxygen was given off at the cathode, and this was found to be sufficient to bring the water to the surface without a sand drain or plastic pipe. This enabled the anodes of disused cells to subsequently become the cathodes of new cell units, requiring only additional anodes to be driven downslope near the receding water level (Fig. 4).

Stabilization Results

The results of the electro-osmosis are well illustrated by the data obtained from movement pegs set on the side of the embankment, and by the laboratory shear strength test results (Table 1). The movement peg data revealed that horizontal movement decreased from up to 1 m/day to less than 1 cm/day in the first 9 days of electro-osmosis. The shear strength of the material more than doubled in the month after osmosis, and it can be seen that a significant decrease in moisture content occurred. Although the strength increase was undoubtedly due to the decrease in moisture content, it was observed that the material around the anode underwent a physical "hardening" process which from observations to date appears to be irreversible and thus is most probably due to an electro-chemical effect occurring as well as the drainage.

The difference between northern hemisphere experience and South East Asia is made clear when comparing power requirements and permeability characteristics. Typical power requirements for the operation in Singapore were approx 0.5 $kWhr/m^3$ of soil. This contrasts favorably with typical values of 10 $kWhr/m^3$-60 $kWhr/m^3$ in the Union of Soviet Socialist Republic (7) and 17 $kWhr/m^3$ in Norway (1) for electro-chemical stabilization. In regard to permeability, Zhinkin (17) states that in Europe, material with a hydraulic permeability greater than 10^{-6} cm/s cannot be satisfactorily stabilized by electro-osmotic techniques without the addition of chemical stabilizers. However, the permeability of the embankment in Singapore at the time of the stabilization was approx 10^{-4} cm/s-10^{-5} cm/s. A plot of the embankment grading characteristics (Fig. 5) against recommended grading limits put forward by Moretrench Corp., and

TABLE 1.—Laboratory Shear Strength Test Results

	Properties						
Material (1)	C' (2)	ϕ' (3)	C_u, in pounds per square foot (4)	ϕ_u, in degrees (5)	W, as a percentage (6)	γ saturated, in pounds per cubic foot (7)	Source (8)
Fill							
A	144	37°	332	19	40	112	S1
B	288	34°	1,000	14	36	115	W1
Soft blue clay							
A	–		100		72	103	S1
B	144	23.5	288	14	35	106	W1
Grey/white clay/dg							
A			600	3	39	116	M5
B			800	7	20	122	M11

Note: *A* = before stabilization; *B* = after stabilization.

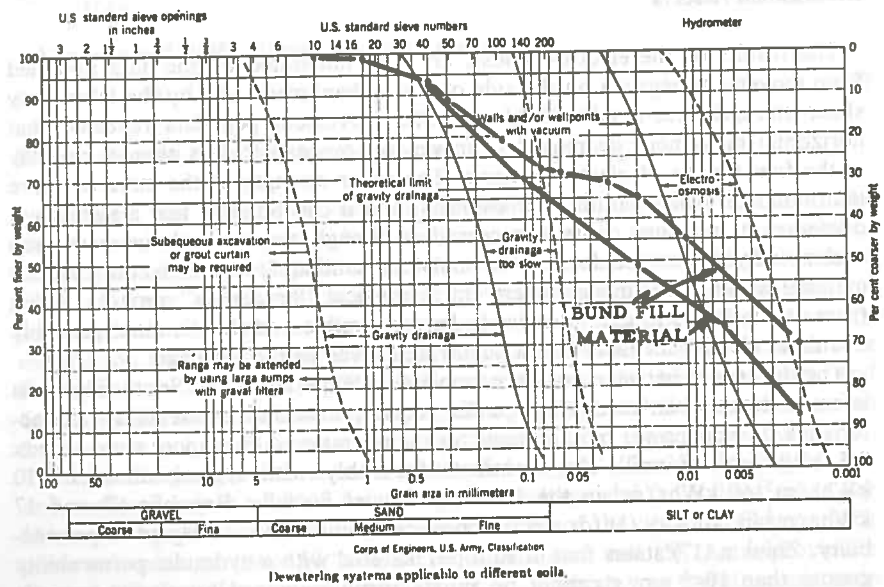

FIG. 5.—Typical Grading for Embankment Material Superimposed on Recommendations of Moretranch Corp.

reported by Leonards (5) shows that the material would be considered outside the grading limits for electro-osmosis in North America.

Conclusions

The need arose to stabilize an embankment within a short period of time and within a tight financial budget. Because of the low permeability of the embankment and foundation materials, gravity drainage was not possible in the short time available. Strengthening of the toe area by adequate sheet piling, rock placing, etc., was considered to be too expensive. Although electro-osmosis offered a possible solution, it appeared to be too costly based on northern hemisphere experience. Nevertheless, a field trial was undertaken, and this showed that excellent results could be obtained using power requirements very much less than expected.

It is thought that the reason for this success lies in the fact that the salt content and the corresponding cations in the boundary layer of silts and clays of the recent tertiary and quaternary periods (i.e., the last 25,000,000 yr) in South East Asia and Australasia are generally high, on the order of 3%-5% (cationic), whereas in the northern hemisphere material of equivalent age contains no more than 1% of salt.

From the observations made at the site it was clearly evident that chemical stabilization was occurring as well as that attributable to dewatering. Irreversible hardening was occurring at the anode (to a radius of about 1 m), and as a result of electrolysis, oxygen was given off at the cathode.

Acknowledgment

The work described in this paper was carried out by Maunsell Consultants Asia for the Sembawang Shipyard (Pte.) Ltd., Singapore.

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Appendix II.—Notation

The following symbols are used in this paper:

A = cross-sectional area of electro-osmotic cell;
a = effective spacing of electrodes;
c = percent by weight of soil finer than 0.002 mm;
D = dielectric constant;
I = current (amp) required per gram of water expelled;
i_e = potential gradient;
k_e = coefficient of electro-osmotic permeability;
l = distance between electrodes;
Q_e = discharge at the cathode;
t = current flow time;
V = potential difference;
Z = depth of soil being stabilized;
μ = viscosity of water; and
ρ = electrokinetic potential.

JOURNAL OF THE GEOTECHNICAL ENGINEERING DIVISION

Consolidation of Fibrous Peat

By Peter L. Berry[1] and Brian Vickers[2]

Introduction

Fibrous peat is a particularly complex engineering material, and one of the major problems is its high compressibility and associated creep effects. The deformation process, in fact, involves two separate but interlinked time effects associated with primary pore pressure dissipation and secondary viscous creep. A proper treatment of the consolidation process requires consideration of such factors as large strain behavior, with a moving drainage boundary and markedly decreasing values of permeability and compressibility. Because of the generation of gas the pore fluid may be compressible. The soil particles themselves may be compressible and there are important viscous creep effects.

A general one-dimensional consolidation theory which takes account of these main factors has been developed by the senior writer and Poskitt (3), and the object of this paper is to carry out a detailed experimental assessment of this theory. For this purpose a series of single increment vertical consolidation tests have been conducted on undisturbed samples of fibrous peat in the 10-in. (250-mm) diam Rowe cell (9).

The permeability of the samples has been determined from vertical flow constant head tests carried out at the initial effective bedding pressure and again at the end of the consolidation increment.

Vertical Consolidation of Fibrous Peat

The writers present first a brief resume of the Berry and Poskitt (3) theory for the one-dimensional consolidation of fibrous peat. The development of this theory incorporates the following assumptions: (1) The soil is homogeneous and saturated; (2) the strains and flow of water are one dimensional (i.e., vertical);

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