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FG.

DREDGED MATERIAL RESEARCH PROGRAM

MISCELLANEOUS PAPER D-77-2

FIELD STUDY TO DETERMINE THE FEASIBILITY OF ELECTRO-OSMOTIC DEWATERING OF DREDGED MATERIAL

by

Charles E. O'Bannon
Tempe, Arizona 85282
and
U. S. Army Engineer District, Mobile
Mobile Alabama 36628

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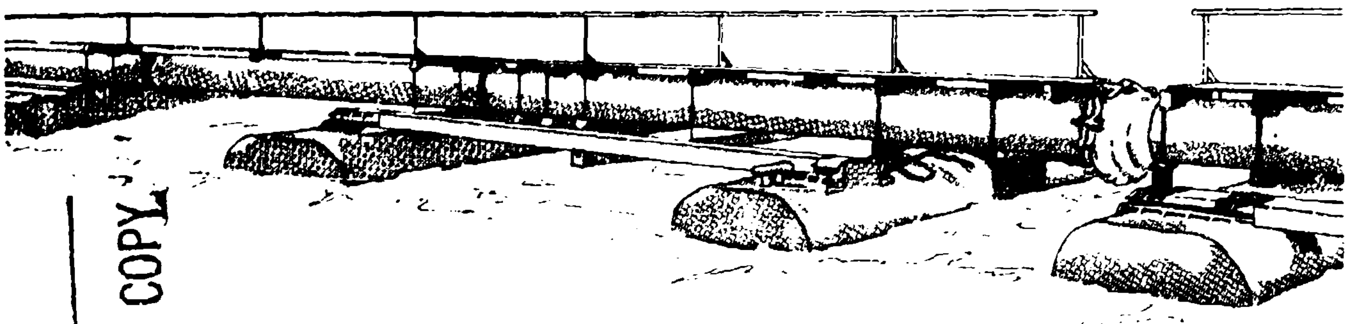

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P. O. Box 631, Vicksburg, Miss. 39180

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

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TO: All Report Recipients

1. The report transmitted herewith represents the results of a study of dredged material dewatering concepts evaluated as part of Task 5A (Dredged Material Densification) of the Corps of Engineers' Dredged Material Research Program (DMRP). This task is a part of the Disposal Operations Project of the DMRP and is concerned with developing and/or testing promising techniques for dewatering or densifying (i.e., reducing the volume of) dredged material using mechanical, biological, and/or chemical techniques prior to, during, and after placement in the containment area.

2. Rapidly escalating requirements for land for the confinement of dredged material, often in the midst of urbanized areas where land values are high, have dictated that significant priority within the DMRP be given to research aimed at extending the life expectancy of existing or proposed containment facilities. While increased life expectancy can be achieved to some extent by improving site design and operation and to a greater extent by removing dredged material for use elsewhere, the attractive approach considered under Task 5A is densification of the in-place dredged material. Densification will not only increase site capacity but also will result in an area more attractive for various subsequent uses because of improved engineering properties of the material.

3. Electro-osmotic dewatering has been used successfully for years primarily for stabilizing embankments composed of fine-grained soil. For this purpose, relatively high voltage gradients (in the order of 1 volt per centimetre) are used over a very short period of time (days to weeks). In planning seminars for Task 5A, various experts in the field of dewatering recommended that electro-osmosis at low voltage gradients (available at most disposal sites) for long periods of time may be an economical method for dewatering existing deep deposits of dredged material. If the technique was indeed feasible, it would provide the only economical densification technique for rejuvenating existing deep dredged material containment areas.

4. A laboratory study was conducted, and the results indicated that electro-osmosis did dewater fine-grained dredged material at relatively low voltage gradients of 0.1 volt per centimetre or less. Therefore, a field test was planned and implemented by personnel from the U. S. Army Engineer District, Mobile, with the assistance of Dr. Charles E. O'Bannon, Consulting Engineer, Tempe, Arizona.

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5. The field tests were initiated in August 1976 at the Upper Polecat Bay Disposal Area in the Mobile District. This is the site for other field tests being conducted as part of Task 5A. The electro-osmosis test area was divided into four sections, each containing a single cathode discharge well and 2 anodes. Coke-breeze with electrode inserts was used for anodes and cathodes in two of the sections; slotted steel casings containing steel rods, pipes, or railroad rails were used successively in the other two sections because of anode corrosion. Electrode spacing was 6.1 and 12.2 metres.

6. The field installation was accomplished routinely. From September 1976 to January 1977, a series of problems caused by anode corrosion, surface water, and equipment servicing caused the system to be inoperative most of the time. From 29 January through 14 March 1977, the system was in continuous operation.

7. Although water was removed from the dredged material by the system, the water content of the dredged material was not changed. It appeared that surface infiltration at the anodes and desiccation cracks replaced water removed by the electro-osmosis system. Based on the water-removal rates, the installation of railroad rails and slotted steel pipe electrodes on the 6.1-metre spacing was the most efficient. However, the cost per cubic metre of water removed for this test section was $21.20.

8. Many of the problems encountered during this test were operational problems that it is felt can be overcome now that they are recognized. Presence of sodium chloride in the dredged material pore water caused high current demands and thus high power cost. It is believed that the current demand would be considerably reduced for nonsaline conditions or under conditions where the sodium chloride was removed during the operation of the electro-osmosis system.

9. This study was one of several field studies conducted at the Upper Polecat Bay Disposal Area. The results of all of the studies will be presented in a site report. Final guidelines and recommendations on dewatering techniques will be contained in the synthesis report on Task 5A.

John L. Cannon

JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

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Removing water from in-place dredged material would increase the capacity of disposal sites for deposition of additional material and a variety of other purposes. To accomplish dewatering of in-place dredged material economically and within a reasonable period of time, research was conducted to determine the feasibility of using electro-osmosis. The process of electro-osmosis is used in soil stabilization work and entails passing low-level electrical energy through soil. Water associ[illegible]ed with positive ions in a solution migrates to a negative electrode and is th[illegible]e removed from the soil mass. (Continued)

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20. ABSTRACT (Continued).

The theory of electro-osmosis states that the rate of flow through soil is proportional to the voltage gradient and the cross-sectional area. The constant of proportionality is not dependent upon soil porosity, but does vary with interstitial water salinity. The relationship is similar to Darcy's law for flow through a porous medium under the influence of a hydraulic gradient.

A preceding laboratory study showed that electro-osmosis does dewater dredged material at relatively low-voltage gradients. Dewatering proceeded rapidly during the first several weeks of laboratory testing, but then declined. The decrease in the rate of dewatering with time was not related to moisture content, but rather to drying at anodes and concentration polarization at electrodes. Water was removed more rapidly at high-voltage gradients in these tests than at low-voltage gradients. However, the cost per gallon of water removed from dredged material was found to be proportional to applied voltage.

In August 1976, the field installation was accomplished routinely; however, from September 1976 to January 1977, a series of problems caused by anode corrosion, surface water, and equipment servicing caused the system to be inoperative for a majority of the time. From 29 January through 14 March 1977, the system was in continuous operation. However, it appears that surface water infiltration at the anodes and desiccation cracks replaced water removed by the electro-osmosis system and resulted in no reduction in the moisture content of the dredged material.

The test site was divided into four sections, each containing a single cathode discharge well and two anodes. Coke-breeze with electrode inserts was used for anodes and cathodes in two of the sections and slotted steel casings with steel rods, pipes, or rails were used in the other two sections. Electrode spacing was 6.1 and 12.2 m. The section consisting of railroad rail and slotted steel pipe electrodes on the 6.1-m spacing was the most efficient. However, the cost per cubic meter of water removed for this best section was $21.20. Coke-breeze anodes and chlorine resistant electrodes and slotted steel pipe cathodes are recommended for future implementation.

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PREFACE

This report presents the results of a field investigation of confined dredged material dewatering by electro-osmosis. The work described herein, DMRP Work Unit 5A17, was a field study accomplished under agreement between the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, and the U. S. Army Engineer District, Mobile. The research was sponsored by the Environmental Effects Laboratory (EEL), WES, under the Dredged Material Research Program (DMRP), Task 5A, "Dredged Material Densification," Work Unit 5A17, "Field Demonstration of Electro-Osmotic Dewatering of Fine-Grained Dredged Material Slurry."

The study was conducted during the period July 1976 to June 1977 under the supervision of Mr. Patrick Douglas, Mobile District, Principal Investigator for the study. This report was written by Dr. Charles E. O'Bannon, Consulting Engineer, Tempe, Arizona.

The work was conducted as part of the DMRP Disposal Operations Project, Mr. Charles C. Calhoun, Jr., Manager. The contract was managed by Dr. T. Allan Haliburton, DMRP Geotechnical Engineering Consultant. The Chief of EEL was Dr. John Harrison.

Contracting Officer was COL J. L. Cannon, Director, WES. Technical Director was Mr. F. R. Brown.

CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

FIELD STUDY TO DETERMINE THE FEASIBILITY OF ELECTRO-OSMOTIC DEWATERING OF DREDGED MATERIAL

PART I: INTRODUCTION

Purpose of the Study

1. This field implementation study follows a laboratory study conducted by the investigators that indicated the feasibility of dewatering dredged material by electro-osmosis. The principal purpose of this field study was to determine if electro-osmosis is a viable dewatering method at low-voltage gradients at an actual dredged material disposal site. The study was also made to determine the efficiency and cost of dewatering, as well as the practicality of field installation and operation by Corps of Engineers personnel. Implied in the primary objective is the development of a workable dewatering system, optimizing electrode spacing, removal of water, and determining electrode materials.

Scope of the Study

2. A field study of electro-osmotic dewatering feasibility was conducted for the DMRP by the Mobile District, Corps of Engineers, at the Polecat Bay dredged material disposal site, located on the upper reaches of Mobile Bay.

3. A diagram of the test site is shown in Figure 1. This diagram shows the configuration of the disposal site and the location of the electro-osmosis site in relation to other dewatering techniques investigated during the same period. Figure 2 is an aerial photograph

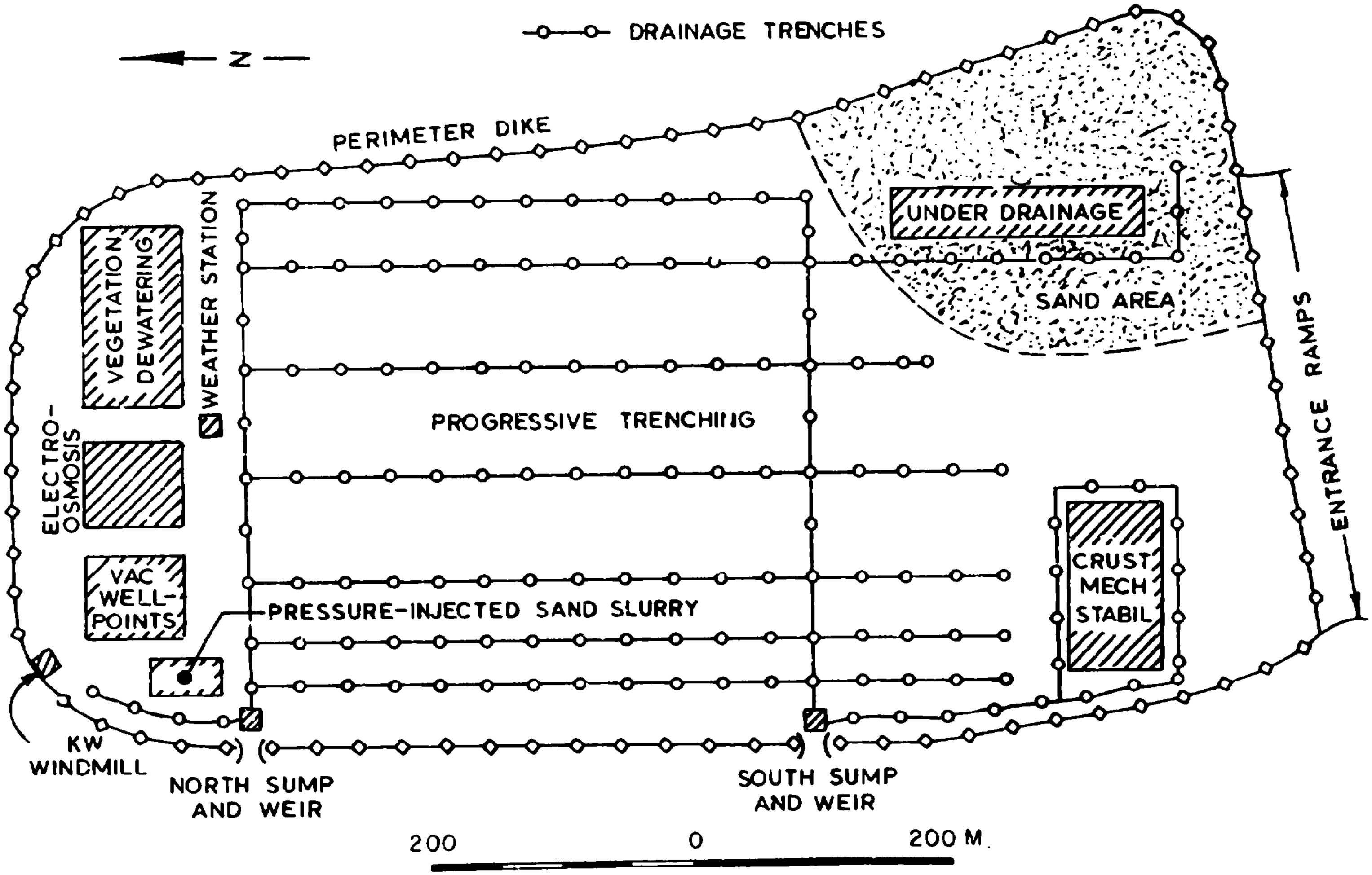

Figure 1. Dredged material dewatering field demonstrations
Upper Polecat Bay Disposal Area, USAE District, Mobile

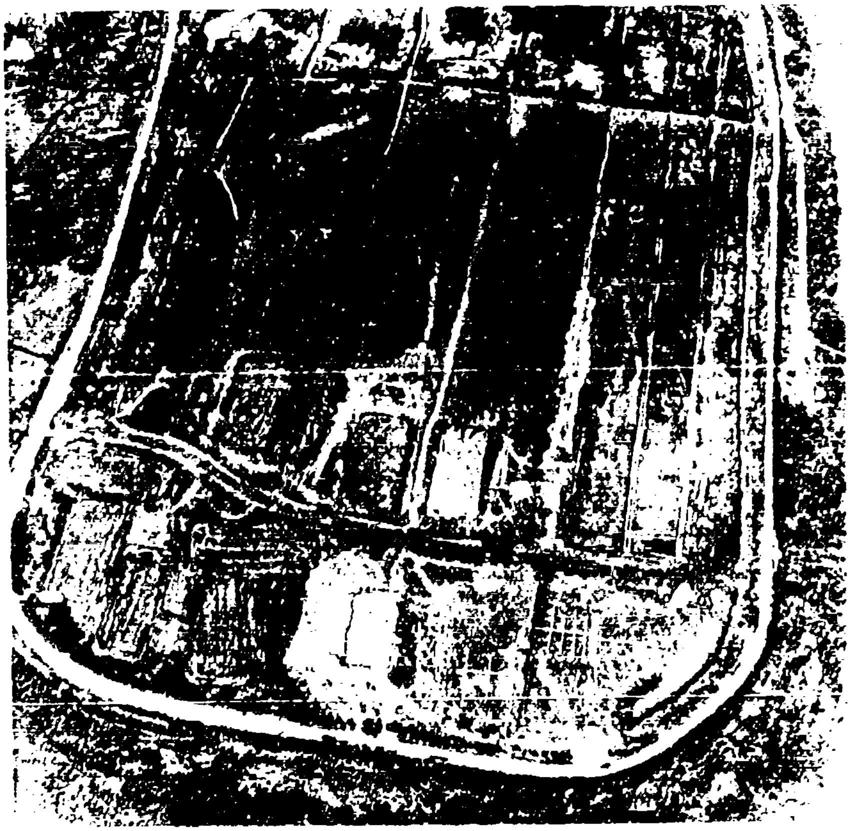

Figure 2. Aerial photograph of test site

of the test site.

4. Field installation and testing were accomplished during an eight-month period from August 1976 to mid-March 1977.

Theory of Electro-Osmotic Dewatering

5. The initial work on electro-osmotic dewatering was conducted in 1807 by Reuss. He demonstrated the movement of water by placing some powdered quartz in the bottom part of a U-tube, partially filling the tube with water, and placing a battery lead in each side. When the current was switched on, the water level rose on the negative side of the tube. This movement of the water through a porous medium from anode to cathode, due to an electrical potential of direct current, is the phenomenon called electro-osmosis.[1]

6. In 1879, Von Helmholtz proposed the double-layer theory for an idealized saturated clay soil.[2]

7. Using this double-layer concept, he mathematically described electro-osmotic flow through a single, straight, rigid capillary tube with the equation:

$$q_e = \frac{ED\, r^2\, \zeta}{4\eta L} \tag{1}$$

where q_e = rate of flow

E = electrical potential

D = dielectric constant of the liquid

r = radius of the capillary tube

ζ = zeta potential

η = viscosity of the liquid

L = length of the capillary tube

8. Tests have shown that the electro-osmotic coefficient of permeability (k_e) does not depend on the size of the capillary tubes. This has been confirmed experimentally by tests on soils with widely differing grain-size distributions, and, for all practical purposes, a value of $k_e = 5 \times 10^{-4}$ mm/sec can be assumed for most soils.[3]

9. Obviously, when a soil has a hydraulic coefficient of permeability greater than 5×10^{-4} mm/sec, dewatering can be accomplished more efficiently with standard gravity pumping methods. For highly impermeable soils, however, the advantage of electro-osmosis is quite spectacular.[3]

10. Dewatering of soils by electro-osmosis is a technique proven by various investigators.[4,5] The literature indicates that electro-osmosis can remove water from wet soils and, thereby, effect a strength improvement.

11. Electro-osmosis depends on the ion exchange capacity of a soil, water content, and the electrolyte concentration of pore water. A direct relationship exists between water content and the rate of water transport; higher water contents result in more rapid water removal. At very low water contents, electro-osmotic permeability is very small.[5]

12. Gray and Mitchell conducted studies using electrolyte solutions to aid in water transport.[5] Addition of electrolyte to the electro-osmosis process has been attempted by investigators, but this technique is not necessary for dewatering. Studies of electro-osmotic dewatering of dredged material are not cited in available literature.

13. Actual tests have been conducted by several organizations for the purpose of dewatering and densification of mine wastes and tailings. Sprute and Kelsh performed five tests on 13.76 m^3 of mill tailing samples.[6] Results indicated changes in dry densities from 892.2 to 1762.0 kg/m^3 and from 825.0 to 1512.1 kg/m^3 at power consumptions of 35.8 to 36.4 kwh/m^3. The cost of dewatering and densification was approximately 14.4 $cents/m^3$ of the original volume.

14. Sprute and Kelsh recommended intermittent power application to reduce resistivity buildup in the vicinity of the cathode.[7] The time periods recommended are 15 min on and 15 min off. Dewatering proceeds faster with this technique, but at the expense of increased power consumption. The intermittent technique can be effectively used if separate grids are used in the field, one on while the other is off.

15. Casagrande's report cites numerous cases in which electro-osmosis has effectively reduced water content and increased soil strength.[4] This report reviews past and current work and many tests covering various types of problems. Slope stability problems involving water contents above the liquid limits are quite common and are reported to be effectively solved or controlled by electro-osmosis.

Weak soil foundation problems are also well documented as being effectively controlled by electro-osmosis. Economics of water removal was reported at 1ℓ for every 1.06 kwh to 1.85 kwh.[4,8] Casagrande also showed that the intermittent application of power is more efficient than constant application.

16. Other problems, such as gas formation and the resulting interference with electrical conductivity, are discussed in Casagrande's[4] report, but are shown to be design problems that are easily overcome, as are soil intrusion problems at the cathode (water collection points).

PART II: LABORATORY STUDY OF ELECTRO-OSMOTIC DEWATERING FEASIBILITY

Laboratory Tests

17. A laboratory study was conducted prior to this field study to determine the feasibility of electro-osmotic dewatering of dredged material at low-voltage gradients.[9] The results of this laboratory study were used to determine appropriate voltage gradients and other design parameters incorporated into the field implementation project. The laboratory study also presented estimates of power utilization and anticipated dewatering costs for various voltage gradients. The material tested was obtained from the proposed field site. The material was a highly plastic clay (CH) with a liquid limit of 110 and a PI of 72. The laboratory work directly bears upon this field study and is summarized here as a preamble to the field implementation design.

Tube Tests

18. The initial study consisted of placing soil samples into 69.85-mm-diam plexiglass tubes. The tubes were filled with soil to a depth of 127.0 mm; steel electrodes were placed on the top and bottom of each sample; and the electrodes were connected to a constant d-c power source. Steel electrodes were selected because they are inexpensive and readily available for field installation.

19. Top- and bottom-drain testing was conducted to determine if flow direction had a significant influence upon electro-osmotic dewatering. A typical apparatus is shown in Figure 3. Water was removed from half of the samples through bottom drains. In these,

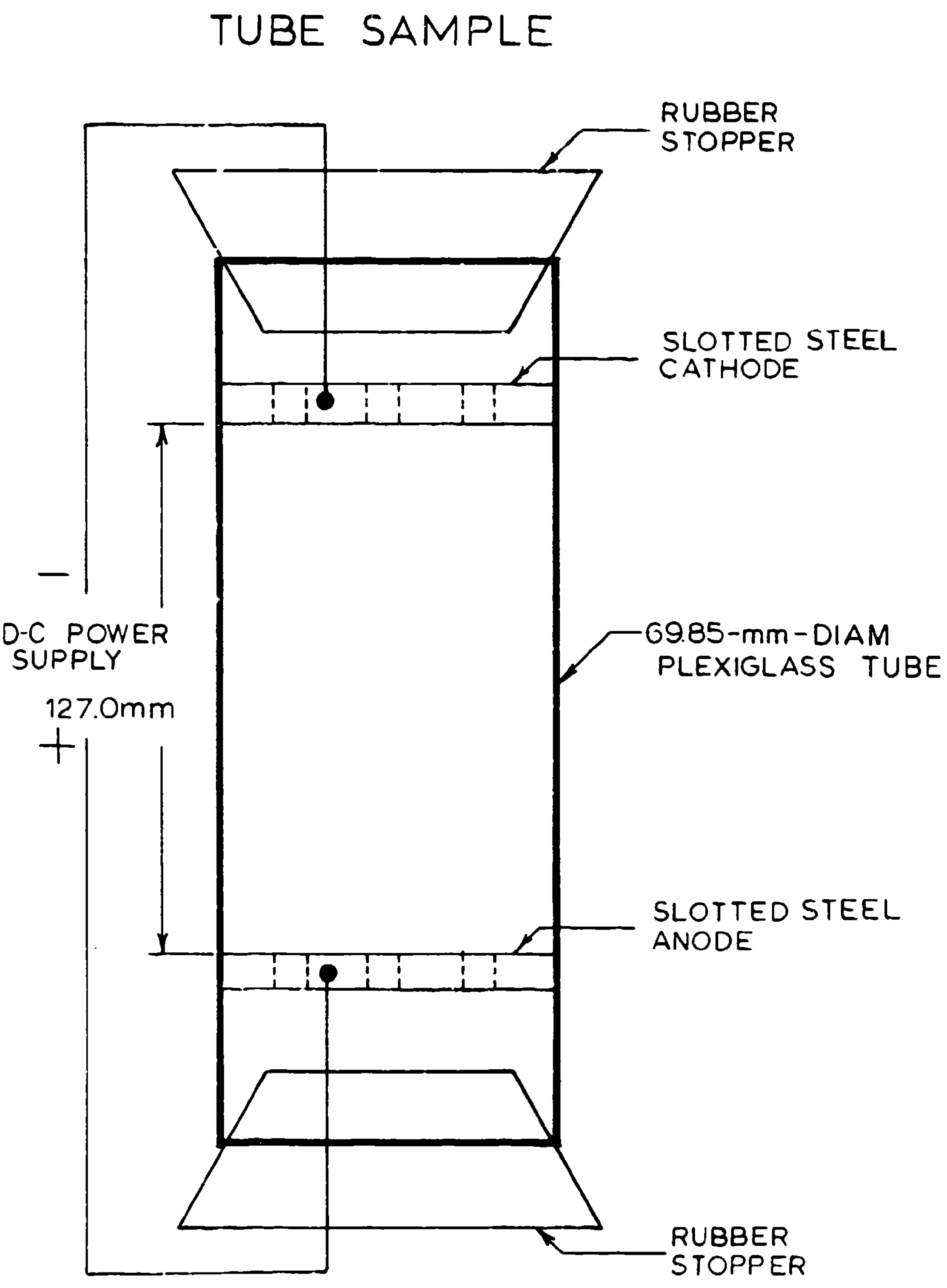

Figure 3. Typical tube testing apparatus

an anode was placed on top of the sample and a cathode on the bottom. Water migrated to the cathode and, from there, water flowed by gravity through a glass tube into a collection flask. The cathode and anode were reversed in the remaining tubes, and water flowed upward and collected on top of the tube samples. This water was removed by pipet. A summary of the test results is shown in Table 1.

Table 1

Summary Tube Tests

Sample No.	Initial Water Content %	Voltage Gradient V/mm	Drainage Condition Top or Bottom	Length of Tests Days
8-10-22	166.2	0.001	T	128
8-11-25	166.2	0.001	B	128
8-2-6	163.7	0.01	T	143
8-7-8	163.7	0.01	T	20
8-5-18	163.7	0.01	B	143
8-16-52	170.5	0.04	T	128
8-17-65	170.5	0.04	B	128
8-1-5	163.7	0.10	T	14
8-6-7	163.7	0.10	T	2
8-8-9	163.7	0.10	T	7
8-9-19	163.7	0.10	T	14
8-4-17	163.7	0.10	B	14
8-3-16	163.7	0.00	B	143

20. Changes in sample weights and the amounts of current used to dewater samples were monitored twice per day during the initial two weeks of sample dewatering, once each day during the next four weeks, and then once each week until the test was terminated.

21. The results of tube tests conducted on top-draining samples are shown in Figure 4. Figure 4 shows weekly average moisture contents as a function of time and applied voltage gradient. The curves show that moisture content generally declines exponentially at all voltage gradients, i.e., the rate of dewatering decreases with time. Voltage gradient has a marked effect upon the rate of dewatering and may or may not affect final moisture content. During the first two weeks of dewatering, the moisture contents decreased from 164 to 132% at a gradient of 0.01 V/mm, to 105% at 0.04 V/mm, and to 99% at 0.10 V/mm. The 0.001-V/mm sample did not lose a significant quantity of water, moisture content decreased rom 172 to 160% during the first 2 weeks and to 150% after 14 weeks. The final moisture content achieved in the samples was approximately the same (100%) for gradients between 0.01 and 0.10 V/mm. At 0.10 V/mm, the result was achieved after 2 weeks. It took 3 weeks at 0.04 V/mm and about 15 weeks at 0.01 V/mm.

22. Figure 4 also shows changes in moisture content as a function of time and applied voltage gradient for bottom-draining samples. The results shown for bottom-draining samples are similar to results obtained with the top-draining samples. A series of samples was allowed to drain without the application of a current to illustrate the

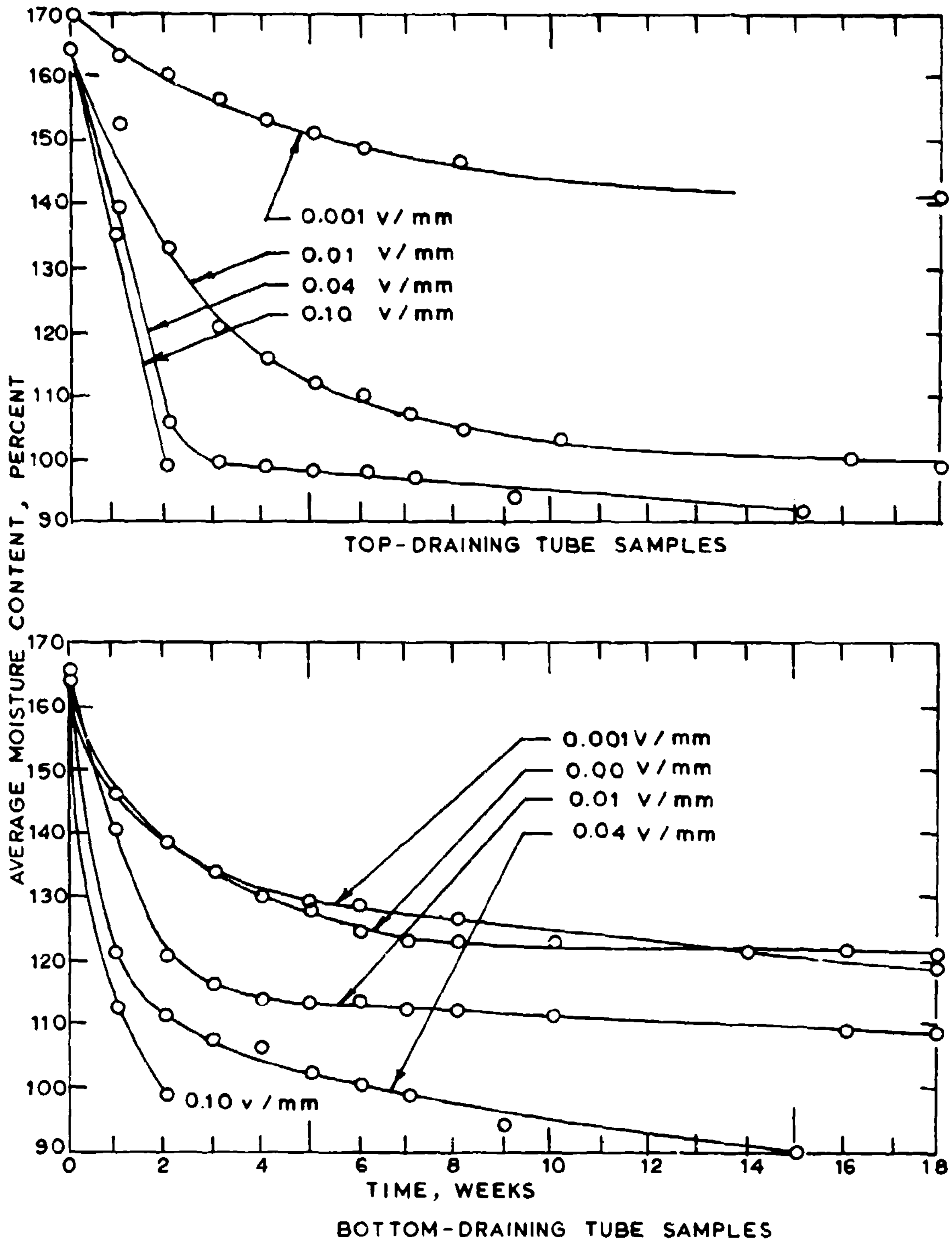

Figure 4. Average moisture vs. time for top- and bottom-draining tube samples

influence of gravity on the bottom-draining samples. A comparison of these controls, 0.00-V/mm and the 0.001-V/mm data, indicates essentially no difference in results. Figure 4 shows that the rate of dewatering increases with increasing voltage and final moisture content tends to decrease somewhat with increasing voltage.

23. When the tube tests were completed, tubes were disassembled, and it was observed that samples had well-defined wet and dry sides. Approximately half of each sample adjacent to a cathode was uniformly wet. The remaining sample fraction adjacent to an anode was nearly uniformly dry. Data plotted in Figure 4 are average moisture content values. The dry side and wet side values are, respectively, lower and higher than the average values shown. The dry and wet values could not be measured except at the conclusion of the tests when samples were removed from the cylinders. Dry side moisture contents were considerably lower than the average values and it is anticipated that dry side values could be achieved in the field by moving electrodes as the drying progressed. The volume and moisture content of each side of the dewatered test cylinders were determined and the percent volume reduction calculated for each sample. These data are shown in Table 2.

24. An analysis of data in Table 2 indicates that at a voltage gradient of 0.001 V/mm, there was an average volume reduction of 12.1%; for the 0.01-V/mm gradient, the reduction was 27.9%; for the 0.04-V/mm gradient, the reduction was 28.1%; and for 0.10 V/mm, the reduction was 26%.

Table 2

Constant-Voltage Tube Samples, Percent Volume Reduction

Sample No.	Voltage Gradient V/mm	Initial Water Content %	Dry Side Water Content %	Wet Side Water Content %	Init. Vol. x 10^3 mm^3	Final Vol. x 10^3 mm^3	% Volume Reduction
8-10-22	0.001	166.2	113.9	117.0	486.7	454.8	6.5*
8-11-25	0.001	166.2	100.9	121.9	486.7	400.5	17.7
8-2-6	0.01	163.7	85.8	98.0	486.7	336.2	30.9
8-5-18	0.01	163.7	76.2	122.7	486.7	365.4	24.9
8-16-52	0.04	170.5	56.2	115.4	486.7	331.1	31.5
8-17-65	0.04	170.5	45.0	144.6	486.7	366.4	24.7
8-9-19	0.10	163.7	62.2	146.3	486.7	365.0	24.9
8-4-17	0.10	163.7	57.9	154.2	486.7	355.2	27.0
8-3-16	0.00	163.7	115.0	115.0	486.7	455.2	6.5

* Probable error in measurement.

Box Model Tests

25. To model field conditions of horizontal flow to a vertical well casing, a series of box model tests were performed. The study consisted of placing soil samples of various moisture contents into 228.6 x 228.6 x 228.6 mm boxes (see Figure 5). Since the sample was well above the liquid limit, the material was literally poured into the boxes. The average initial dry density was 541.4 kg/m^3 and the average initial void ratio was 3.93. The boxes were completely filled with soil and one vertical slotted steel pipe cathode was placed in

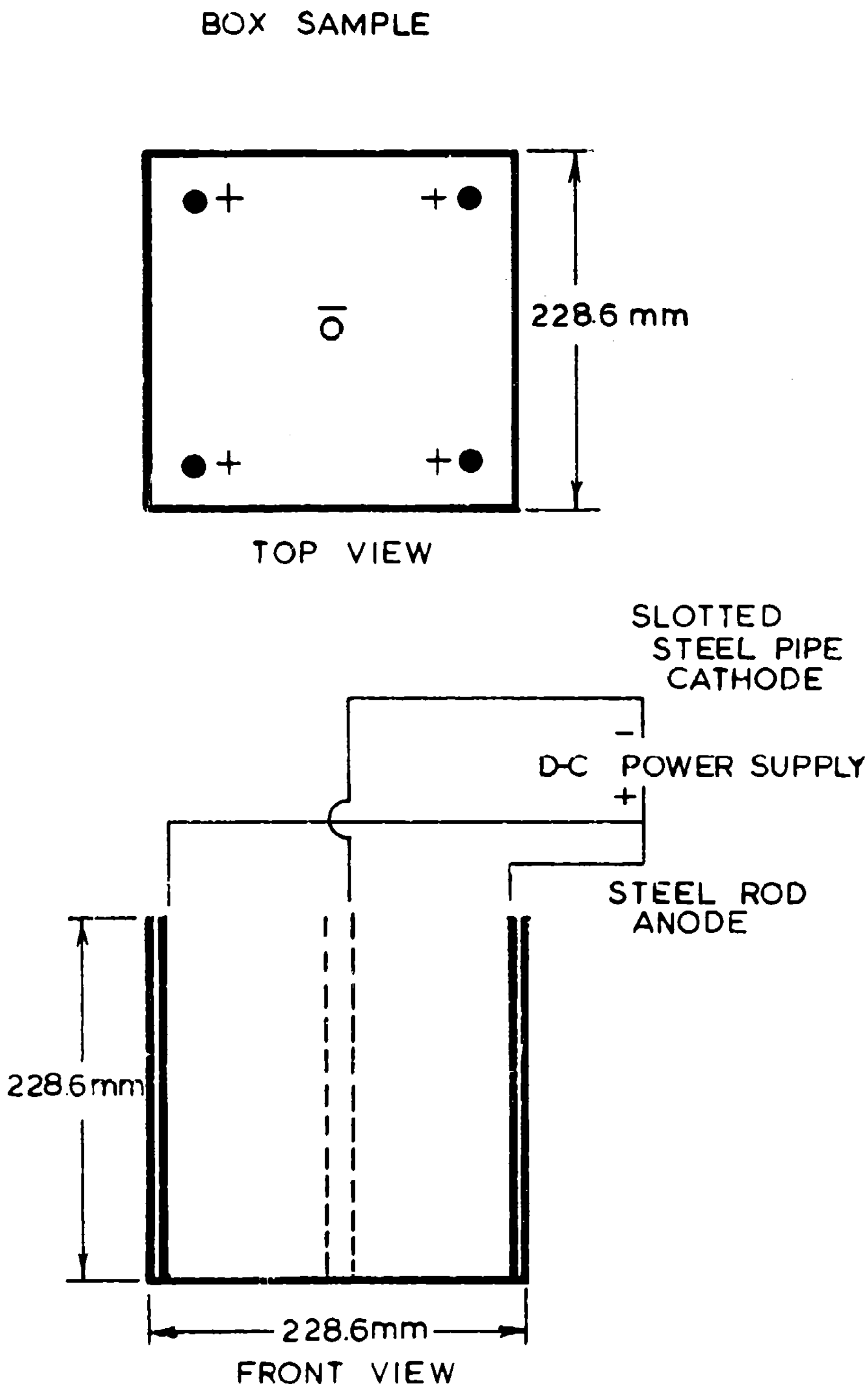

Figure 5. Box model testing apparatus

the center of the box, extending from the bottom to the top of the soil. Steel electrodes placed in each corner of the mold served as anodes.

26. A series of box model tests were conducted; the tests involved the application of various constant-voltage gradients for extended periods of time. With the establishment of a voltage gradient in the samples, water flowed into the slotted pipe and was removed by pipet.

27. Changes in sample weights and the amounts of current used to dewater each box were monitored twice daily during the first two weeks, once a day for the next four weeks, and then once each week until the tests were terminated.

28. The results of the tests are shown in Figure 6. Figure 6 shows weekly average moisture contents as a function of time and applied voltage gradients. The curves are very similar in shape to those obtained in the tube tests. Voltage gradient was once again found to have a marked effect upon the rate of dewatering. During the first two weeks of electro-osmotic dewatering, the moisture content decreased from 162 to 114% at a gradient of 0.04 V/mm to 143% at 0.01 V/mm, and 148% at 0.001 V/mm. After 13 weeks, the sample at 0.04 V/mm had decreased to 70%. After 13 weeks, the moisture content in the sample at 0.01 V/mm was reduced to 118%, and in the sample at 0.001 V/mm the final moisture content was 125%.

29. When the box model tests were completed, the models were

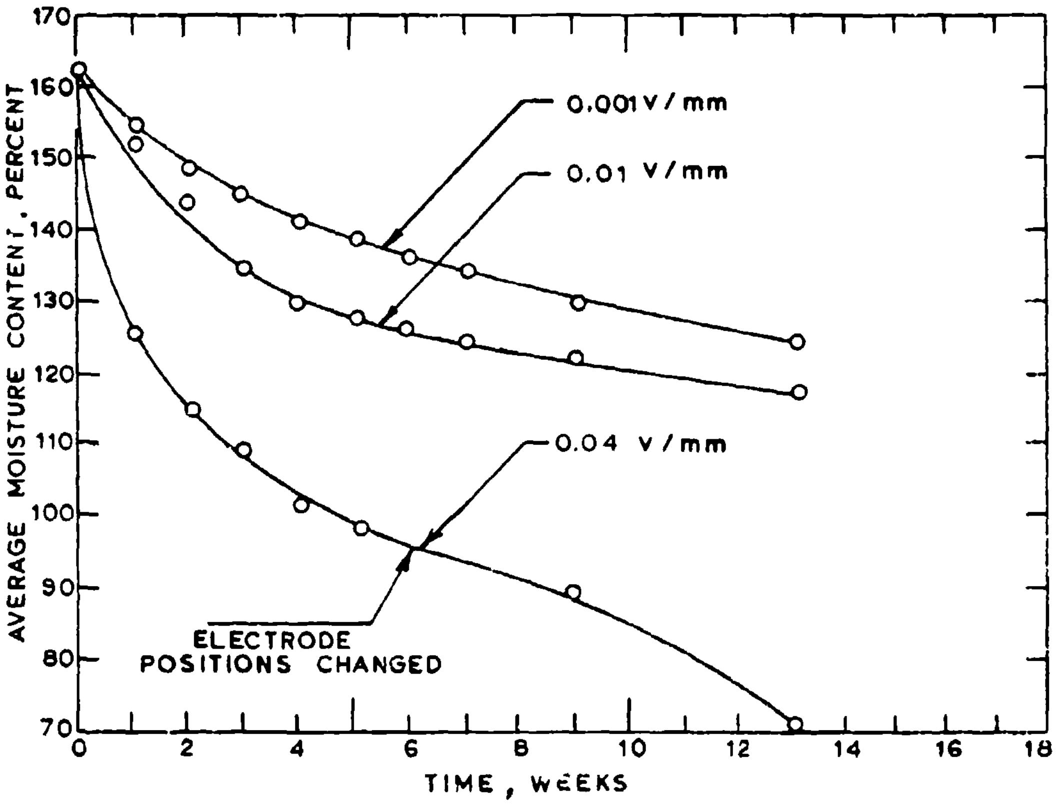

Figure 6. Average moisture content vs. time for box models

disassembled and the final water contents of both the dry and wet side of each sample were determined. Total volume was recorded and these data are shown in Table 3.

30. The data shown in Table 3 indicate the following: for the voltage test at a gradient of 0.001 V/mm, the average volume reduction was 22.2%; at 0.01 V/mm, the reduction was 22.9%; and at 0.04 V/mm, the reduction was 16.0 and 50.2% for the two samples tested. The 16.0% volume reduction for the 0.04-V/mm model is based upon height reduction in the original sample. It does not include the reduction of volume caused by shrinkage away from the sides of the model or the volume in the numerous cracks that formed in the model. If these had been measured as they were in other models, the total volume reduction would have been much higher. The 50.2% volume reduction for the 0.04-V/mm sample is very encouraging. This volume reduction was obtained by moving the anodes when the current and water removed reduced significantly. When the anodes were moved, the rate of water removal again increased. It is interesting to note that in this model there was no difference in final moisture content between the wet and dry side. Both had approximately 62% final moisture content. At this moisture content, the material could easily be removed or reworked.

Energy Requirements

31. An estimate of energy consumption was made by averaging all Mobile data for two ranges of moisture contents tested - low and intermediate to wet. The intermediate and wet data were combined into

Table 3

Constant-Voltage Box Models Volume Reduction

Sample No.	Initial Moisture Content %	Voltage Gradient V/mm	Time of Treatment Days	Final Moisture Content Dry Side %	Final Moisture Content Wet Side %	Final Volume Calculated ℓ	Final Volume Measured ℓ	Percent Volume Reduction
6-2-2B	141.1	0.001	100	100.4	102.0	9.55	8.52	22.7
6-1-1B	141.1	0.01	100	64.4	112.9	9.87	8.52	22.7
6-3-6-B	144.3	0.04	100	54.8	84.7	9.26	----	16.0
9-3-4B	162.1	0.001	100	102.5	107.2	9.65	8.61	21.8
9-2-3B	161.7	0.01	100	79.5	119.9	9.75	8.47	23.1
8-1-5B	165.9	0.04	100	62.0	62.3	8.55	5.48	50.2
5-1-7B	139.8	0	82	124.3	125.9	10.05	9.40	14.7

Note: Initial volume of model = 11.95ℓ

Volume of Cathode and Anodes = 0.91ℓ

Volume of Soil in Model = 11.04ℓ

a single range since a distinct difference between these data was not discernable. The results of these analyses are shown in Table 4.

32. At the voltage gradient of 0.001 V/mm, the average kwh per ℓ was 0.0063. At 0.01 and 0.04 V/mm, average power requirements were 0.1480 and 0.9778 kwh/ℓ, respectively. These estimates represent the average results of tube and box model tests conducted at constant power application. Variation in individual test results is shown in Table 4. These data indicate that an increase in voltage results in approximately a proportional increase in the cost of dewatering.

Table 4

Energy Consumption for Tube and Box Models

Sample Type	Voltage Gradient V/mm	Range of Moisture Content %	Energy Consumption Average kwh/ℓ	Energy Consumption Range kwh/ℓ
Tube	0.001	60-80	0.0121	0.0034 - 0.0202
Tube	0.001	100-170	0.0048	0.00003 - 0.0177
Tube	0.01	50-80	0.1189	0.0185 - 0.3092
Tube	0.01	90-170	0.1374	0.0132 - 0.3885
Tube	0.04	30-60	1.0571	0.3436 - 2.6427
Tube	0.04	80-170	1.2156	0.2114 - 3.3034
Box	0.01	100-160	0.1691	0.0476 - 0.5682
Box	0.04	70-150	0.6342	0.1057 - 1.1099

Cost Analysis

33. The primary concern of this laboratory study was: (1) Does electro-osmosis dewater dredged material at low gradients and (2) Is the process economical? In answer to the first question, electro-osmosis did dewater dredged material from 165 to 115 percent moisture content at a voltage gradient of 0.001 V/mm. At 0.04 V/mm, the reduction was from 165 to 70 percent. However, the cost per liter of dewatering at each voltage gradient is quite different. At 0.01 V/mm, the average power use was approximately 0.159 kwh/ℓ removed; at 0.04 V/mm, the average power use was 0.634 kwh/ℓ removed. At the lowest gradient used in the study, 0.001 V/mm, the moisture content was reduced from 172 to 150 percent, only a 12.8 percent decrease in eight weeks. The average power use at 0.001 V/mm was 0.005 kwh/ℓ removed.

34. It appears that even though the 0.001-V/mm gradient yielded the lowest cost per liter, little water was removed, and the most efficient gradient is about 0.01 V/mm if a significant quantity of water is to be removed.

PART III: DESIGN OF THE FIELD INSTALLATION

Field Implementation

35. The design of the electro-osmosis field installation was based on the results of laboratory experimentation with vertical and horizontal flow models, utilizing dredged material obtained from the Polecat Bay disposal area. The resulting design was implemented by the U. S. Army Engineer District, Mobile.

36. The test site design consisted of four experimental test sections. These sections, labeled Sections 1 through 4, are shown in Figure 7. Each test section was set sufficiently apart from the others to eliminate interference and interaction, as tests on all sections were conducted during the same time periods. Various factors were considered in the design phase of the study. These were voltage gradient, time, electrode spacing, electrode configuration, type of electrode, and methods of removing water from the cathode wells.

37. The limiting factor in the design was the power available, using the diesel powered 62.5-kw direct current generator loaned to the U. S. Army Engineers for this test by the Arizona Department of Transportation. This generator was capable of producing a maximum of 125 V and 500 A. Based on previous laboratory work, a voltage gradient of 0.01 V/mm maintained for a period of 84 days had reduced the moisture content from 162 down to 118 percent. It was planned to move the anode periodically during the course of the test, in an attempt to reduce the

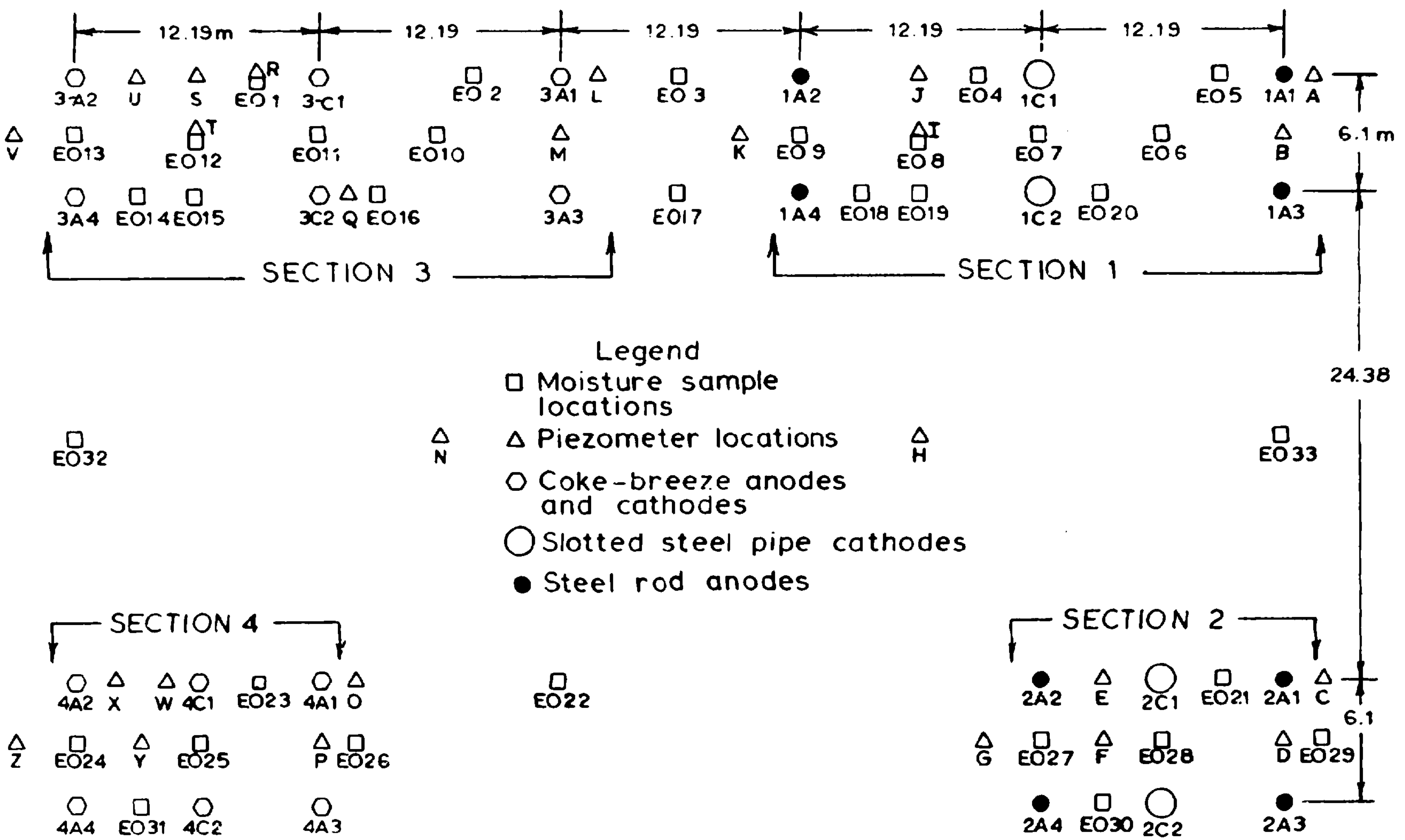

Figure 7. Plan view of test site showing electrode spacing and piezometer and moisture content sample locations

moisture content even further.

38. Casagrande's work on this material showed that below a gradient of 0.003 V/mm, no water would be removed.[10] Therefore, it was decided to use 0.005 V/mm as a minimum gradient. Not wanting to run the generator at maximum power for 84 days, the voltage was established whereby the generator would only have to put out 61 V to maintain the desired gradients. Once the volts and voltage gradient had been established, the spacing of electrodes was calculated to be 12.192 m for a gradient of 0.005 V/mm and 6.096 for a gradient of 0.01 V/mm.

39. It was felt that by laying out the electrodes in a rectangular pattern, the influence of side effects on the center of the test section would be minimal.

40. Figure 7 shows anode and cathode spacing, as well as the location of piezometer tubes and soil moisture sampling locations. Two cathodes (discharge wells) and four anodes were placed in each test section. Anodes in Sections 1 and 3 were placed 12.192 m from each cathode on opposite sides; in Sections 2 and 4, anodes were placed in a similar manner, but at a distance of 6.096 m from the cathodes.

41. The standard material used in past electro-osmotic dewatering projects has been slotted steel pipe cathodes and solid steel bar anodes. It was proposed to use these electrodes for the field test. In addition, a commercially available electrical conductive material, which is a by-product of steel manufacturing, called coke-

breeze, was also incorporated into the design. The coke-breeze used was well graded and ranged in size from 12.2 mm to 0.10 mm. One of the advantages of coke-breeze electrodes is that electrical potential reversal would be possible. In the standard pipe electrodes, this is not possible.

42. The field installation of the various electrodes was routine and was accomplished in seven working days with a crew of three men during the first two weeks in August. It took two days for two electricians to lay out and make the necessary electrical connections during this same time period.

43. In Sections 1 and 2, for the cathodes, the crust was removed and the 152.4-mm slotted casing was shoved manually into the dredged material to a depth of 2.44 m. The solid steel anodes were also shoved manually to the same depth. In the coke-breeze sections (3 and 4), electrodes were placed in the following manner:

- a. The crust was removed.
- b. A 152.4-mm casing was shoved manually to a depth of 2.44 m.
- c. The casing was water jetted clean.
- d. Coke-breeze was then placed to a depth of 304 mm and casing pulled to top of coke-breeze.
- e. The process of filling and pulling the casing was continued until the coke-breeze reached the surface of the dredged material.

44. Details of the anodes and cathodes are shown in Figures 8 and 9. The details on the sumps for each section are also shown in Figures 8 and 9. Cathodes used for Sections 1 and 2, shown in Figure

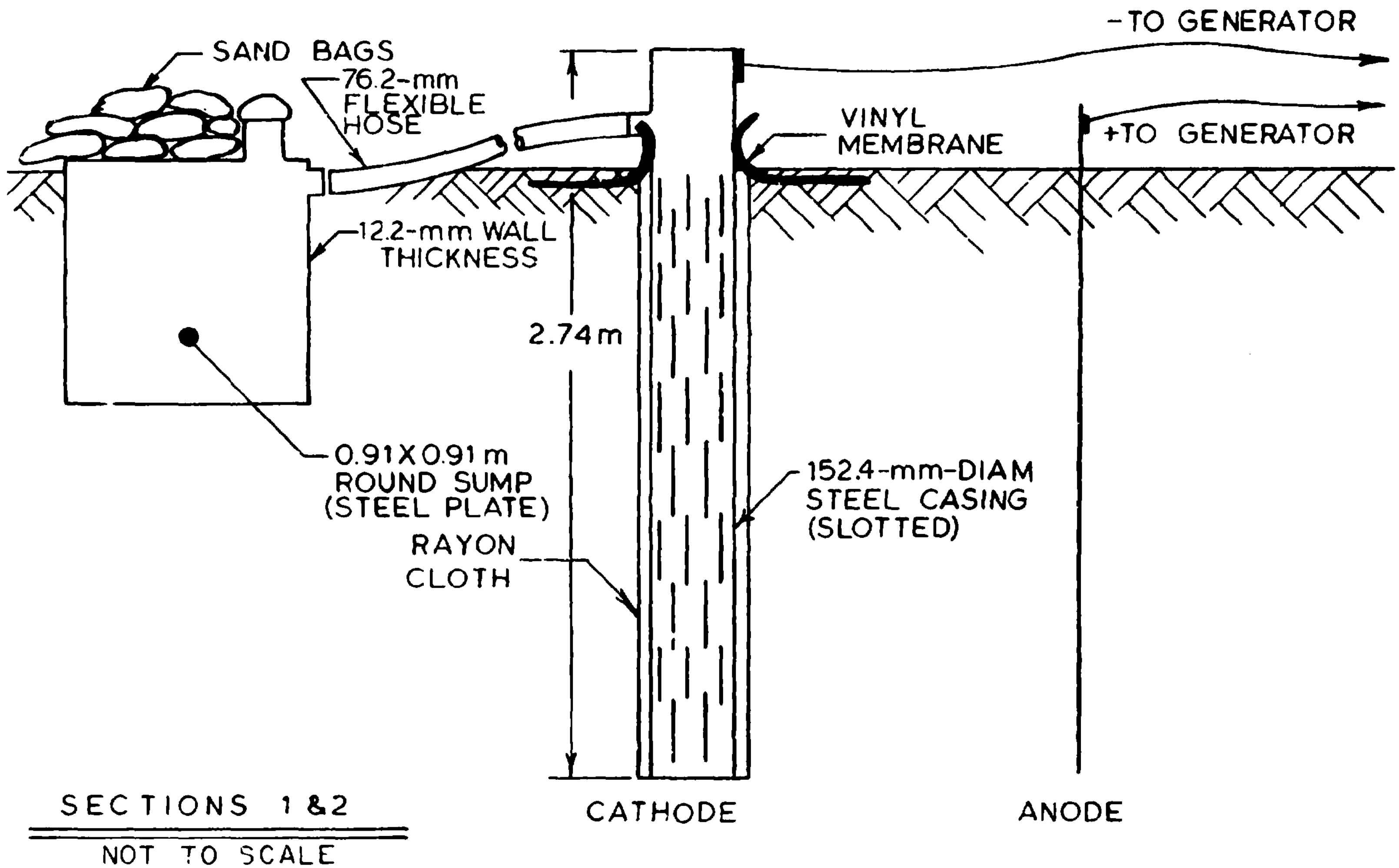

Figure 8. Details of electrodes and sump, sections 1 and 2

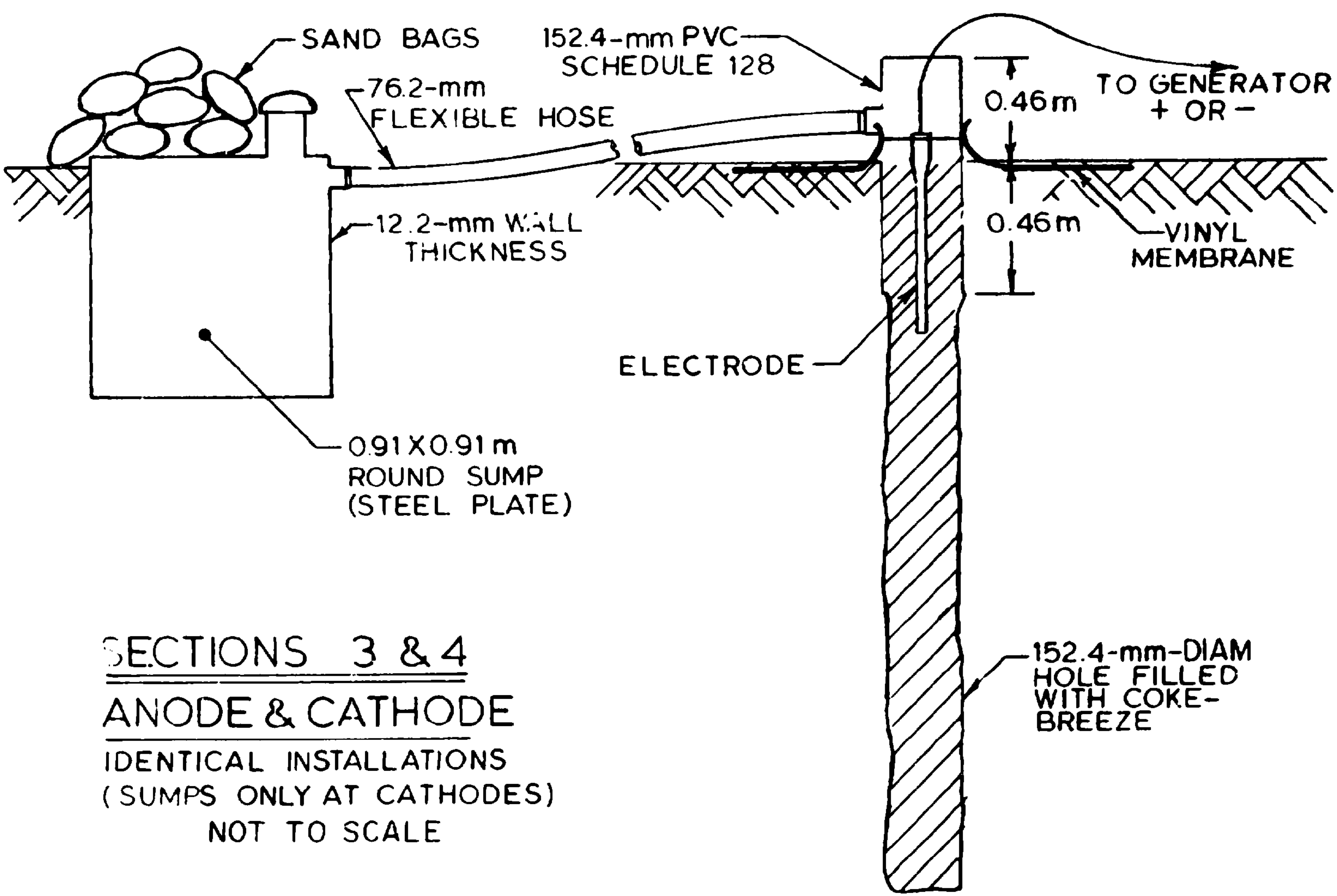

Figure 9. Details of electrodes and sump, sections 3 and 4

8, were 152.4-mm-diam slotted steel casings, approximately 2.74 m in length. Figure 9 shows the 152.4-mm-diam coke-breeze wells used as cathodes and anodes in Sections 3 and 4. A new 10.9-kg Duriron electrode and one that had lost approximately one half its weight after 25 days at a voltage gradient of 0.01 V/mm, are shown in Figure 10.

45. Anodes used in Sections 1 and 2 were initially 50.8-mm-diam hollow steel pipes with 6.3-mm wall thickness, but, during the course of experimentation, these pipes were replaced by 50.8-mm solid steel rods and later by 50.8-mm-diam carbon rods, and finally by railroad rail. Anodes with increasing mass were used during the course of testing because corrosion causes a significant reduction of the anodes and a severing of electrical connection in relatively short periods of time. The steel pipes, both hollow and solid, lasted only 5 to 6 days, the carbon rods 20 days, and the railorad rail 26 days.

46. A series of piezometer tubes were located throughout the four test sections. The placement of these is shown in Figure 7. The piezometers were to be used to measure the decline in water surface as dewatering progressed. A grid system of bench marks was provided to enable monitoring surface subsidence if it occurred.

47. At each cathode, a 76.2-mm flexible rubber drain pipe was provided several inches above the ground surface, connecting the cathode casings with 208-ℓ metal drums. The drums did not prove satisfactory; they corroded and were subsequently replaced by 0.91-m-diam, 0.91-m-deep, 12.7-mm-thick steel sumps, as shown in

Figure 10. New 10.0-kg Duriron electrode and one that has lost one half its weight after use for 25 days at a voltage gradient of 0.01 V/mm

Figures 8 and 9. Water flowing from cathodes to the sumps was removed periodically by pumping.

48. Based on previous work, it was estimated that each section would pull 125 A at the given voltage gradients.[11] Each section was designed to carry 125 A with a maximum of 200 A in any section before the fuse for that section would blow and shut off that particular section. When the power was turned on for the first time, each section carried between 160 and 200 A. The power limitation of the generator necessitated reducing the number of test wells utilized during the course of the study. Only one cathodic discharge well and two anodes were used in each of the four test sections.

49. The limits on voltage gradient were determined by the basic formula:

$$I = \frac{E}{R} \qquad (2)$$

where

I = current

E = voltage

R = resistivity of the soil

50. The resistivity of the soil would change due to changes in ion concentration in the pore water, temperature, and/or moisture content. Therefore, the angstrom drawn by the system was the controlling factor. The voltage was set daily so as not to exceed the 500-A maximum for the system or 200-A maximum in any given section. The range of voltage was from 48 to 54 V with an average of 51 V during

most of the time the test was in operation. At 51 V, the resulting voltage gradient over the 12.192-m distance between anodes and cathodes in Sections 1 and 3 was 0.004 V/mm and a gradient of 0.008 V/mm over the 6.096-m spacings used for Sections 2 and 4. Amperage varied from about 195 A to zero when electrical circuits were severed as a result, primarily, of anode corrosion.

51. Apparatus and spacing within each test section are summarized in Table 5.

Table 5

Electrode Spacing and Voltage Gradients

	Section Number			
	1	2	3	4
Spacing, m	12.192	6.096	12.192	6.096
Cathode Material	Slotted Steel		Coke-Breeze	
Voltage Gradient, V/mm	0.004	0.008	0.004	0.008

Test Procedure

52. The test was designed for application of a single constant-voltage gradient within each test section. Amperage was monitored in two ways: first, a single channel strip chart recorder was connected to each section and a continuous chart, moving at the rate of 0.45 m/hr, was maintained during the operation of the generator; second, the generator had its own panel, whereby each section could be read directly.

53. The two systems agreed with each other; since there was very

little change in amperage in a given 24-hr time period, it was faster and simpler to monitor twice daily the ammeters on the generator by visually reading the ammeters and recording the values.

54. Process disruption, caused by anode corrosion, poor drainage, equipment malfunction, and procedural changes, resulted in an actual application of current for a total period of between 70 and 78 days over the entire eight-month study period.

55. Based upon anticipated horizontal flow of water from anodes to cathodes, piezometers would not, in any event, register a vertical drop in water surface; had this occurred, they would have indicated drying in a section. Piezometer measurements were made daily for a period of the first week in September, about two weeks in November, nine days in January, and every day from 29 January through 14 March 1977.

56. Five series of moisture samples were taken to determine soil moisture content changes with progressive dewatering. Samples were taken at locations shown on Figure 7. Samples were taken at depths of 0.6096 - 0.9144 m, 1.2192 - 1.5240 m, and 2.1336 - 2.4384 m. These data did show variation of moisture content with depth throughout the containment area.

57. Water was pumped from sumps in all four sections during a 45-day period from 29 January through 14 March, and water depths were recorded daily. This was the only period during the test in which the sumps were routinely pumped; up to this time, the system was so infrequently in operation that it was not necessary to pump the sumps.

PART IV: RESULTS OF THE FIELD STUDY

Test Period

58. Table 6 shows the number of days that current was applied continuously and totally for each month during the test period. These data include only days in which applied current was greater than 25 A. Laboratory studies indicated that, for the field installation, effective dewatering would not occur at an induced current below 25 A at the 0.008 and 0.004 V/mm used in this test. During the first five months of the study, from August through December, testing averaged about one week per month. During this period, operational difficulties were encountered and experimental procedures and equipment were modified. In effect, the process was being refined during this period.

59. The field installation was started and completed in the first two weeks of August; however, it was decided to start the test in the first week of September. During this period, from completion of field installation to test initiation, the support personnel of the Mobile District were instructed on the procedure for starting and maintaining the generator and the manner in which data were to be collected. The generator was operated for approximately a total of three days at various times.

60. The test began on 7 September 1976, but ran for only two days in Section 1 and three days in Sections 2, 3, and 4 before the

amperage dropped to zero. The support personnel had been instructed to expect a reduction in the amperage with time and thought that this was a normal reaction. It was not until the end of September that it was determined that the electrodes in all sections had corroded to such an extent that the electrical current was not complete. During the first week in October, the hollow steel pipe electrodes in Sections 1 and 2 were replaced with 50.8-mm solid steel pipes. In Sections 3 and 4, the 2.27-kg Duriron electrodes were replaced by 10.9-kg Duriron electrodes. The system was restarted on 6 October but, once again, the electrodes in Sections 1 and 2 were corroded away by 12 October. Sections 3 and 4, during this period, were in constant operation with no indication of electrode deterioration. In Sections 1 and 2, the solid steel pipe was replaced by 50.8-mm solid carbon rods and these sections continued to function until the system was shut down on 14 October. At this time, it was determined by on-site inspection that not all of the water moving towards the cathode was entering the slotted steel casing in Sections 1 and 2, or the plastic sleeve in Sections 3 and 4; instead, some water was seeping up around the slotted pipe and coke-breeze cathodes and collecting on the surface. From 14 to 21 October, the system was shut off and a ditching system was installed. This system consisted of shallow trenches from each cathode, extending to a central location in the site from which the water could be removed. This system did not prove to be successful because the trenches filled up in a matter of days with the highly plastic dredged material. From the period of 27 October to 12 November, a 3.05

square m vinyl membrane was installed around each cathode. The installation consisted of placing the membrane around the cathode, in each section, and covering it with a 101.6- to 152.4-mm layer of sand. A typical vinyl membrane, shown in Figure 11, was successful in preventing migration of water to the surface around the cathodes. Before the system was restarted on 12 November, the carbon rods in Sections 1 and 2 were wrapped with plastic tape 228.6 mm above and below where the crust and the underlying material were in contact. From 12 November through 14 December, Sections 3 and 4 ran continuously; however, Sections 1 and 2 were not in operation from 20 through 30 November due to a blown fuse in each section. The fuses were replaced, and from 1 December through 6 December, both sections continued to run. The carbon rods lost electrical connection on 6 December and were replaced with railroad rail in Section 2; this section continued to function until 14 December when the system was shut off in order to replace the 208-ℓ metal drum sumps. This was necessary because the thin metal drum had badly corroded and would no longer hold water. In the period from 14 December through 22 December, heavy duty sumps (see Figures 8 and 9) were installed in each section. These sumps proved to be effective and were operational when the test was stopped in March 1977. From 22 December through 1 January 1977, the total system was off for most of the time due to blown fuses, holidays, and generator servicing. On 17 January, the carbon rod anode in Section 1 was replaced with a railroad rail. From 1 January through 31 January, all sections were

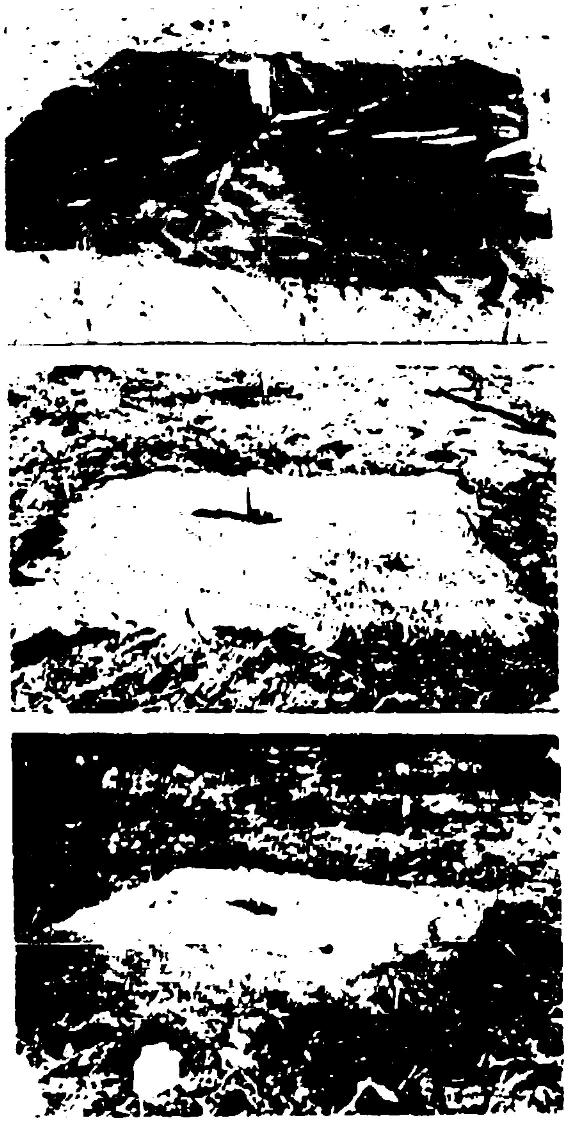

Figure 11. A typical vinyl membrane installed at cathode in all sections

on and off for various lengths of time due to blown fuses, generator servicing, and burnt out clamps. During this time, two weeks of testing were accomplished, but the longest continuous test period was less than a week. Testing was continually operational from the last of January through 14 March for a continuous period of about 45 days.

61. The long refining period was due to a number of factors. Problems associated with anode corrosion and water removal from the site were not fully anticipated by the consultant in the field installation design. Heavy work loads on District personnel precluded continuous on-site supervision by engineers and resulted in frequent change of technical support personnel with a corresponding loss of continuity in the project.

Table 6

Number of Days Current Was Applied to Test Sections During the Eight-Month Test Period, Max. No. Continuous Days/Total No. Days

Month	Section 1	Section 2	Section 3	Section 4
August	0	0	0	0
September	1/1	3/3	1/2	1/1
October	5/9	5/8	4/7	4/8
November	2/3	2/2	3/5	5/9
December	5/7	4/8	7/12	8/11
January	4/12	6/15	6/15	6/11
February	24/27	11/22	23/26	24/27
March	12/12	12/12	12/12	5/9
Totals for Test Period	53/71	43/70	56/79	53/76

Test Results

62. Soil moisture content data were collected during the months of August, November, December, February, and March at the locations shown in Figure 7. The August data were used to determine the pretest in situ moisture content at the various locations. Soil moisture content data collected during the months of November and December are of little value as a measure of electro-osmotic dewatering, since there were few days during the period in which there was an established continuous voltage gradient. Moisture content data collected in February and March also showed no appreciable reduction and, in some cases, even an increase over the moisture content, as determined in August 1976. A typical plot of moisture content vs. depth for each electro-osmotic section and two control sections where there was no electro-osmosis is shown in Figure 12; all moisture content data are shown in Table 7. Although between 3.78 and 151.4 ℓ of water were removed daily from the sumps during February and March, moisture contents did not change to any great extent.

63. During January 1977, it rained for a total of 14 days in Mobile; accumulated rainfall was 140.7 mm. In February, 47.24 mm fell in a period of 6 days, and, during the first 2 weeks of March, 73.21 mm fell in a total of 7 days. This rain caused the anodes and cathodes to often be submerged in water; this is shown in Figures 13 and 14.

64. Piezometer measurements were made daily for a period of the first week in September, two weeks in November, nine days in January,

Table 7

MOISTURE CONTENT DATA

Location	Depth m	Aug. 12, 1976	Nov. 3, 1976	Dec. 29, 1976	Feb. 20, 1977	Mar. 17, 1977
EO-1	0.61-0.91	99.6	102.4	128.8	154.7	-
	1.22-1.52	118.3	89.3	112.5	104.2	-
	2.13-2.44	85.6	75.6	85.8	94.3	-
EO-2	0.61-0.91	110.5	112.2	131.6	139.7	-
	1.22-1.52	103.5	86.6	127.7	110.0	-
	2.13-2.44	89.9	75.7	94.0	87.5	-
EO-3	0.61-0.91	114.3	106.4	124.6	118.4	-
	1.22-1.52	101.5	81.8	118.3	95.1	-
	2.13-2.44	80.0	83.4	87.0	86.8	-
EO-4	0.61-0.91	122.9	107.8	124.4	120.0	-
	1.22-1.52	111.7	95.3	108.9	107.1	-
	2.13-2.44	88.4	83.7	88.3	100.7	-
EO-5	0.61-0.91	107.7	104.7	130.3	131.5	-
	1.22-1.52	109.7	94.2	118.5	111.4	-
	2.13-2.44	77.3	83.8	91.4	105.8	-
EO-6	0.61-0.31	117.8	130.6	132.2	134.9	-
	1.22-1.52	110.0	99.2	125.1	110.5	-
	2.13-2.44	88.8	78.7	86.2	103.8	-
EO-7	0.61-0.91	100.8	113.9	141.1	138.8	-
	1.22-1.52	104.2	94.4	122.0	111.6	-
	2.13-2.44	83.7	81.8	87.9	87.8	-
EO-8	0.61-0.91	126.2	127.4	141.0	126.6	-
	1.22-1.52	109.3	113.9	115.1	97.7	-
	2.13-2.44	89.1	84.8	85.7	88.8	-
EO-9	0.61-9.91	150.1	117.4	138.5	131.6	133.7
	1.22-1.52	94.6	95.8	127.5	93.1	97.6
	2.13-2.44	81.3	83.7	86.9	90.6	82.0
EO-10	0.61-0.91	122.6	133.9	160.1	135.4	-
	1.22-1.52	119.0	107.9	129.3	112.5	-
	2.13-2.44	91.9	86.1	92.5	101.3	-
EO-11	0.61-0.91	124.8	120.0	134.1	117.3	-
	1.22-1.52	113.4	112.7	120.7	117.5	-
	2.13-2.44	100.3	73.8	91.5	102.9	-
EO-12	0.61-0.91	113.4	124.6	133.2	117.0	-
	1.22-1.52	117.5	113.9	118.5	103.3	-
	2.13-2.44	106.2	76.5	103.4	94.1	-
EO-13	0.61-0.91	121.7	111.9	125.6	124.6	-
	1.22-1.52	126.7	120.8	123.4	122.5	-
	2.13-2.44	101.0	83.9	98.7	106.6	-
EO-14	0.61-0.91	133.6	124.4	133.3	132.4	141.2
	1.22-1.52	108.3	97.1	103.1	98.4	113.4
	2.13-2.44	104.1	86.5	99.5	107.1	81.4
EO-15	0.61-0.91	121.6	112.6	140.7	131.8	120.0
	1.22-1.52	98.9	102.7	130.1	99.0	97.9
	2.13-2.44	97.2	79.4	91.4	101.0	100.6
EO-16	0.61-0.91	117.9	113.1	121.3	119.7	141.5
	1.22-1.52	102.4	110.6	128.1	115.9	113.6
	2.13-2.44	81.1	82.1	85.8	92.9	91.9
EO-17	0.61-0.91	114.2	112.7	141.0	128.9	-
	1.22-1.52	86.7	86.5	98.7	89.4	-
	2.13-2.44	80.7	83.6	87.5	81.4	-
EO-18	0.61-0.91	120.8	122.8	136.9	123.9	122.7
	1.22-1.52	103.1	96.9	112.2	83.4	131.1
	2.13-2.44	79.8	88.1	86.4	73.9	87.1
EO-19	0.61-0.91	118.1	119.6	126.2	127.1	-
	1.22-1.52	130.3	96.4	127.0	92.9	-
	2.13-2.44	81.7	80.2	88.4	82.8	-
EO-20	0.61-0.91	109.2	127.9	128.3	132.6	-
	1.22-1.52	114.0	105.5	128.5	114.4	-
	2.13-2.44	84.8	76.4	84.6	87.8	-
EO-21	0.61-0.91	87.3	100.5	137.9	130.4	-
	1.22-1.52	112.8	105.9	114.1	105.5	-
	2.13-2.44	98.1	77.2	91.3	89.7	-
EO-22	0.61-0.91	105.8	112.9	136.8	140.1	-
	1.22-1.52	108.0	112.1	136.7	120.2	-
	2.13-2.44	99.9	73.8	98.1	88.8	-
EO-23	0.61-0.91	122.9	124.9	126.4	122.6	-
	1.22-1.52	105.5	109.5	124.2	114.6	-
	2.13-2.44	86.0	92.9	93.7	104.0	-
EO-24	0.61-0.91	93.2	111.3	119.7	137.2	129.5
	1.22-1.52	105.7	114.9	134.3	116.1	116.6
	2.13-2.44	100.6	94.4	106.4	103.0	110.6
EO-25	0.61-0.91	112.4	126.5	143.7	129.2	-
	1.22-1.52	107.1	105.6	102.2	112.1	-
	2.13-2.44	91.0	94.5	97.8	107.4	-
EO-26	0.61-0.91	119.1	132.7	148.0	140.3	-
	1.22-1.52	94.0	94.0	103.4	105.7	-
	2.13-2.44	96.7	79.1	85.3	96.6	-
EO-27	0.61-0.91	135.1	123.6	135.1	128.7	160.8
	1.22-1.52	117.2	115.7	124.5	115.5	98.8
	2.13-2.44	85.3	80.5	82.3	87.2	84.2
EO-28	0.61-0.91	137.2	135.7	141.6	123.9	-
	1.22-1.52	110.6	107.7	111.2	119.0	-
	2.13-2.44	84.3	74.6	90.5	112.7	-
EO-29	0.61-0.91	117.4	131.7	133.1	131.2	-
	1.22-1.52	111.9	100.8	104.6	117.8	-
	2.13-2.44	78.5	76.2	78.5	85.1	-
EO-30	0.61-0.91	98.0	118.0	124.3	117.3	150.8
	1.22-1.52	133.9	114.3	109.8	99.1	115.7
	2.13-2.44	103.3	92.3	77.8	93.1	82.9
EO-31	0.61-0.91	124.7	124.6	129.4	120.9	127.4
	1.22-1.52	128.1	116.6	114.9	123.6	122.6
	2.13-2.44	80.8	104.8	106.0	115.[illegible]	110.8
EO-32	0.61-0.91	106.5	132.8	117.6	135.1	-
	1.22-1.52	112.3	107.1	130.7	123.3	-
	2.13-2.44	95.9	92.2	80.4	99.2	-
EO-33	0.61-0.91	127.2	116.0	136.9	129.2	-
	1.22-1.52	94.9	118.0	126.4	120.3	-
	2.13-2.44	82.4	80.4	86.6	102.8	-

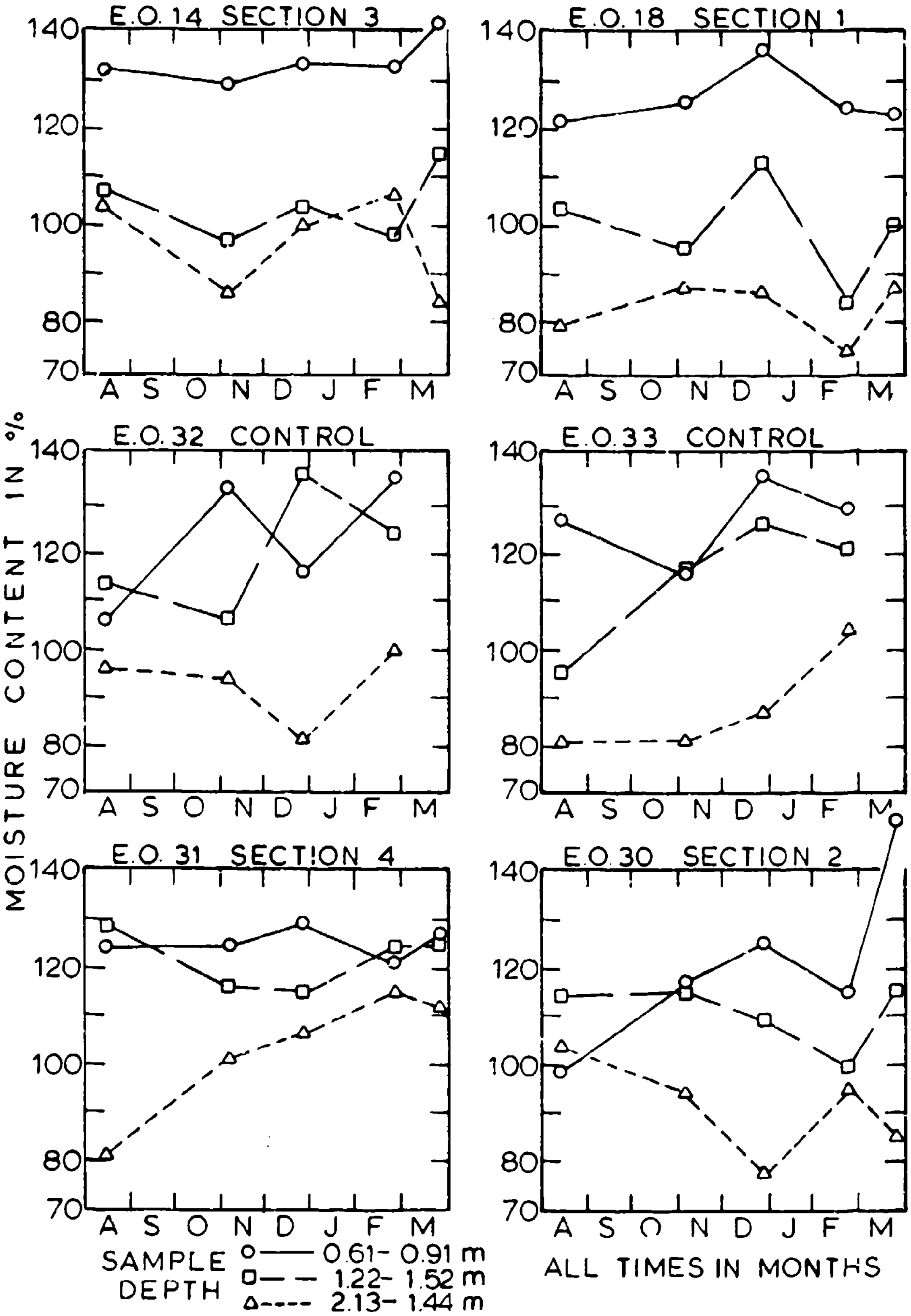

Figure 12. Typical moisture content vs. time at various depths, all sections and two control locations

Figure 13. Standing water at anode, Section 2

Figure 14. Standing water at cathode, Section 1

and every day from 29 January through 14 March 1977. These data did not show any drying front in any of the sections and, in fact, had very little variation during the entire eight-month period. A typical plot of the data for each section is shown in Figure 15.

65. Individual water samples were collected on 6 January 1977 from the sumps in all sections. pH tests were performed and the results are shown in Table 8.

Table 8

Water-Quality Tests

Section No.	pH
1	11.6
2	12.2
3	12.0
4	12.0

66. These values indicate that the water in the sumps had the characteristics of household ammonia and were consistent with the results obtained in the laboratory phase of the study.

67. In mid-January, daily measurements of water depths in the sumps were begun. A continuous record of flow to the sumps is available for a 45-day period from 29 January through 14 March. A summary of these data is shown in Table 9.

'e 9

Summary of W ... antities Removed by Electro-Osmosis and Energy Consumption

Test Section	1	2	3	4
Spacing of Electrodes, m	12.192	6.096	12.192	6.096
Type of Cathode	Slotted Steel Casing	Slotted Steel Casing	Coke-Breeze	Coke-Breeze
Average Voltage Gradient, V/mm	0.004	0.008	0.004	0.008
Total Water Removed, ℓ	1790	3986	742	1204
Average Amperage	95.0	78.7	78.7	83.8
Average Voltage	51	51	51	51
Time Period, Days	45	44	45	45
Power Consumption, kwh	10,740	4,240	4,330	4,620
Power Consumption/Unit Volume of Water Removed kwh/ℓ	6.00	1.06	5.84	3.84

68. Based on these data, it can be seen that for the 12.2-m electrode spacing, the kilowatt hour/ℓ removed is approximately the same, regardless of the type of electrodes used. For the 6.1-m spacing, the slotted steel cathodes are 3.62 times more efficient than coke-breeze and 5.5 times more effective than coke-breeze or slotted steel at an electrode spacing of 12.1 m.

69. Based on the theory of electro-osmotic flow, Section 2 should have twice as much flow as Section 1, since the gradient in

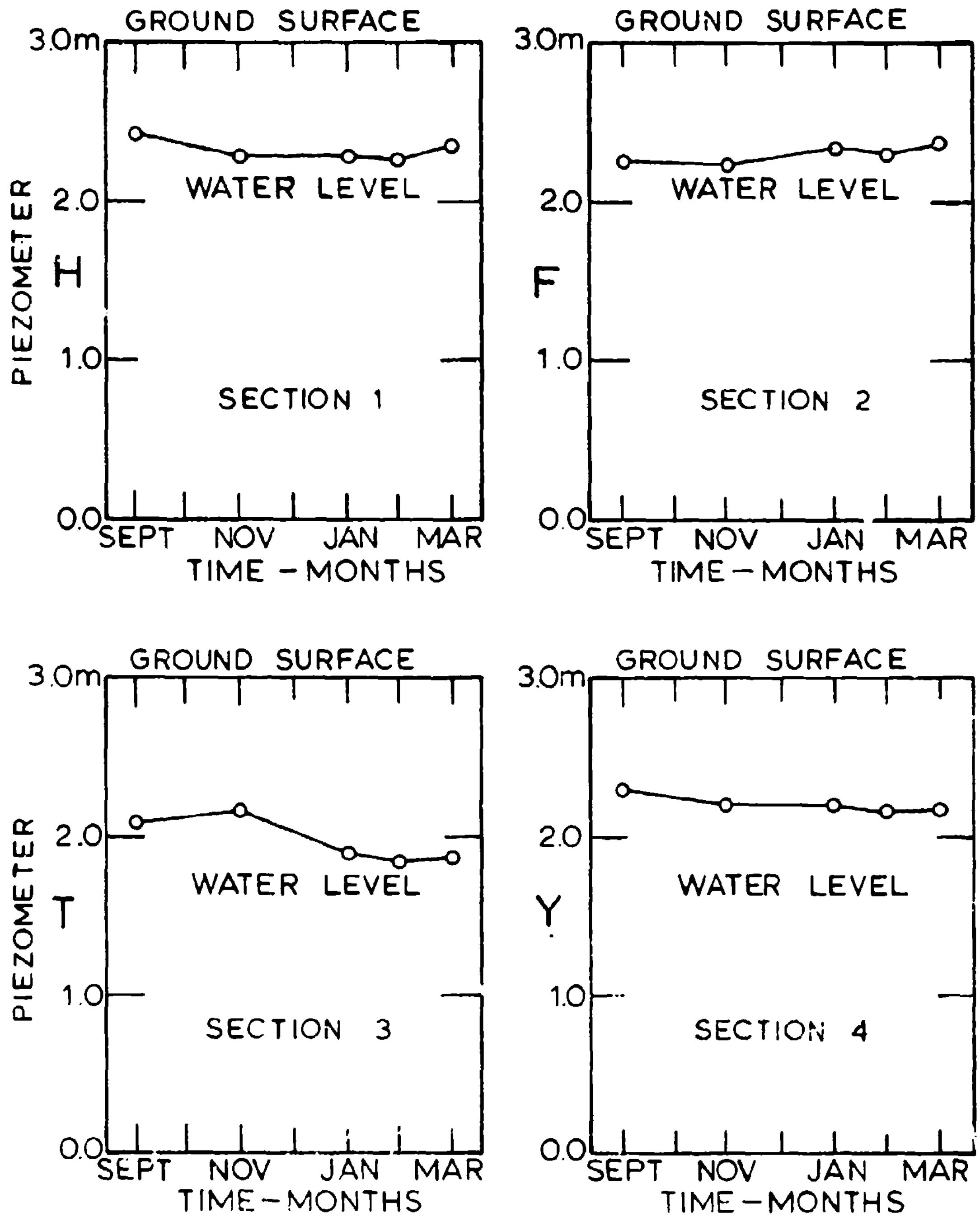

Figure 15. Typical plot of piezometer data vs. time (all sections)

Section 2 was twice as large as in Section 1. This is confirmed when one looks at the total quantity of water removed in Section 2, which was 3986 ℓ, compared to 1790 ℓ in Section 1. The same is true for Sections 3 and 4. Since both Sections 2 and 4 were run at the same gradient (different electrodes), one would expect the same quantity of flow. However, Section 2 (steel electrodes) had 3.3 times as much flow as Section 4. This discrepancy may be explained in the following observation. During the period 29 January through 14 March 1977, field personnel reported on numerous occasions that the electrodes in Section 4 were much hotter than the electrodes in Section 2. This could indicate that some of the power was being wasted in heating up the soil instead of moving water from the anode to the cathode.

70. The 1.06 kwh/ℓ, determined by the field test in Section 2, can be compared to the range of 0.05 to 0.57 kwh/ℓ as found in the laboratory test at the same voltage gradient, but on a much smaller sample. Based on the 1.06 kwh/ℓ and a power cost of \$0.02/kwh, it would cost \$21.20/m^3 of water removed. The cost of a cubic meter of volume created by this method cannot be completely calculated, as it is a function of initial void ratio and the consolidation characteristics of the material; however, it would more than likely be equal to or higher than the \$21.20 figure.

71. In Section 1, 1790 ℓ of water were removed from the sumps between 29 January and 14 March. Measured power consumption was 6.0 kwh/ℓ of water removed from the sump. Data for Section 1 show

two distinct periods, an initial period of 20 days of low water production and a final period of 25 days in which 1393 ℓ were removed from the sump and power consumption was 4.4 kwh/ℓ. A review of daily values for Section 2 shows water-quantity measurements and power consumption relatively consistent throughout the 45-day test period. The 1.06 kwh/ℓ obtained from Section 2 data is consistent with published values.[4,8]

Anode Corrosion

72. Chemical oxidation at anodes includes the production of chlorine gas from chloride ion and dissolution of the steel anode. The two primary oxidation reactions are:

$$2\ Cl^- \longrightarrow Cl_2\ (gas) + 2e^-$$

and

$$Fe^o(s) \longrightarrow Fe^{+++} + 3e^-$$

In addition to the electrochemical dissolution of iron, the generation of chlorine, which remains in intimate contact with an anode since Fe is positive and Cl is negative, creates a highly corrosive localized environment. The reaction of chlorine with the steel anode caused characteristic pitting, crevice corrosion, and general corrosion.

73. Steel corrosion occurred very rapidly at the Polecat Bay site. The 50.8-mm hollow steel pipe, used initially, failed by corroding to such a degree that the electrical circuit was broken in about five days. The steel pipe failures are shown in Figures 16 and

17. The 50.8-mm solid steel anode, shown in Figure 18, failed in a little over 6 days. This figure shows fairly uniform corrosion over most of the bars 2.74-m length, with excessive corrosion at the tip of the bar and localized corrosion just below the ground surface. Carbon bars, shown in Figure 19, failed in 20 days and were very difficult to install. The railroad rail, shown in Figure 20, failed in about 26 days. These rails could not be pulled out for inspection; however, failure generally occurred near the ground surface.

74. In Sections 3 and 4, the 10.9-kg Duriron electrodes failed by loss of electrical connection in about 53 days. Since it would have taken 3 weeks to obtain new ones from the manufacturer, a hardened aluminum bronze bar, approximately 50.8 mm diam, 1 m long, was used for the electrical connection. These bars lasted only 16 days, but were locally available, thereby allowing the test to continue. Figures 21 and 22 show deterioration of the Duriron and hardened aluminum bronze metal use as connectors in the coke-breeze sections.

75. It was initially intended to reverse the polarity in the coke-breeze sections when sufficient drying had occurred at the anode. Since the drying did not materialize, it was felt that current reversal would be of little value.

76. In Sections 1 and 2, it was proposed to move the anodes at 1-m intervals toward the cathodes, as the drying around the anode became sufficient to cause a reduction in flow. Once again, this did not

materialize, and, therefore, the anodes were not moved to any extent. Some minor location change, up to 0.5 m, was necessary when the railroad rails were replaced.

Figure 16. 50.8-mm hollow steel pipe anode in Section 2 failed in 5 days at a voltage gradient of 0.008 V/mm

Figure 17. Closeup view of 50.8-mm hollow steel pipe anode in Section 2 that failed in 5 days at a voltage gradient of 0.008 V/mm

Figure 18. 50.8-mm solid steel rod anode in Section 2 failed in 6 days at a voltage gradient 0.008 V/mm

Figure 19. 50.8-mm solid carbon bar anode in Section 2 failed in 20 days at a voltage gradient of 0.008 V/mm

Figure 20. Railroad rail anode in Section 2 failed in 26 days at a voltage gradient of 0.008 V/mm

Figure 21. 10.9-kg Duriron electrode anode in Section 4 failed in 53 days at a voltage gradient of 0.008 V/mm

Figure 22. 50.8-mm hardened aluminum bronze anode in Section 4 failed in 16 days at a voltage gradient of 0.008 V/mm

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

77. The initial purpose of this study was to determine the on-site feasibility of electro-osmotic dewatering of dredged material. Data from the test at the Polecat Bay test site confirmed that water was moved electro-osmotically to the discharge wells at both the 0.004- and 0.008-V/mm gradients.

78. The installation of the hardware for the test was routine. However, there was difficulty in the initial operation of the system, caused primarily by anode corrosion and standing water at electrodes. The anodes corroded faster in all sections than had originally been estimated and the subsequent loss of electrical connection caused several extended periods of time when the system was inoperative.

79. Various electrodes were used as anodes; of these, the Duriron electrode was the most efficient. It lasted 53 days at a voltage gradient of 0.008 V/mm, compared to only 5 to 6 days for steel pipe, 16 days for hardened aluminum bronze bars, 20 days for carbon bars, and 26 days for railroad rail.

80. An obvious conclusion of the study is the necessity of effectively removing surface water from areas undergoing dewatering. Cutting shallow draining channels into the dredged material proved infeasible. The depressions closed within a short period of time.

Surface water infiltration, at anodes and through surface cracks over the entire site, replaced water removed electro-osmotically and prevented utilization of moisture content data for appraisal of the process.

81. The data from the four test sections presented in Table 9 show that Section 2, railroad rail anodes and slotted steel pipe cathodes, spaced 6.096 m apart, were 3.62 times more efficient than the next best section. In Section 2, 3986 ℓ of water were removed from 29 January to 14 March 1977. The power consumption was 1.06 kwh/ℓ of water removed. At this power consumption, it would cost $21.20 to remove a cubic meter of water. Based on this figure, it would be reasonable to conclude that this cost is prohibitive.

Recommendations

82. Based on the results of this study, the following recommendations are presented:

- a. Tests should be conducted with the daily on-site presence of an experienced engineer who will recognize operational difficulties, analyze data as experiments proceed, and make appropriate changes.
- b. To minimize anode corrosion and to maximize water removal from the site, slotted steel cathodic discharge wells and coke-breeze anodes with chlorine resistant electrodes are recommended.
- c. Based on data obtained [illegible] the test, it is suggested that a voltage gradient of 0.008 V/mm be used with an electrode spacing of 6.096 m.
- d. Wells should discharge to pipes or channels depressed into the dredged material surface. These conduits can also be used to carry away surface water. Thin vinyl plastic sheets or a surface drainage system should be used.

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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

O'Bannon, Charles Edward.

Field study to determine the feasibility of electro-osmotic dewatering of dredged material / by Charles E. O'Bannon, Tempe, Arizona, and U. S. Army Engineer District, Mobile, Mobile, Alabama. Vicksburg, Miss. . U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1977.

59 p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; D-77-2)

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