

TA7

C6

CER 57-20

COPY 2

**REPORT ON LABORATORY TESTING OF THE
SEDIMENT-SEALING METHOD**

Part Two

By

R. T. Shen

**SEALING EFFECTS OF DISPERSED BENTONITE SUSPENSIONS
AND DISPERSANT SOLUTION ON GREELEY FINE
SANDY LOAM AND LOVELAND LAKE SAND**



Department of Civil Engineering

ENGINEERING RESEARCH

SEP 10 '70

FOOTHILLS READING ROOM

COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

August 1957

CER No. 57RTS20

REPORT ON LABORATORY TESTING OF THE SEDIMENT-SEALING METHOD

Part Two

By

R. T. Shen

**SEALING EFFECTS OF DISPERSED BENTONITE SUSPENSIONS
AND DISPERSANT SOLUTION ON GREELEY FINE
SANDY LOAM AND LOVELAND LAKE SAND**



Department of Civil Engineering

COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

August 1957



U18401 0591037

CER No. 57RTS20

FOREWORD

This work together with Part One by E. C. Newman reports the laboratory research phase¹ of the Sediment Sealing Project at Colorado State University² during 1955-1957. Newman conducted experiments on a dune sand; the present program has been devoted to Greeley fine sandy loam and Loveland Lake sand. Identical equipment has been used in the two programs and the procedures adopted have been essentially the same.

Budgetary and time limitations made it necessary to exclude many variables and confine the tests to dead-ponding of de-aerated, homogeneously packed soil columns. Within this narrow scope, some phenomena in the basic sediment sealing process have been revealed that may prove helpful in field work. These findings are by no means conclusive because of insufficient data, but are ample to indicate some probable trends and the need for further research.

The author wishes to thank the following members of the Colorado State University staff: Mr. R. D. Dirmeyer, Jr., Leader of Sediment Sealing Project, for his guidance and encouragement, Dr. A. T. Corey, Research Engineer, for his technical advice, Mrs. Constance McDonough for her laboratory assistance and drafting, Mr. Phillip McOllough for his help during the early phase of the program, and Miss Ruth Sekora for her preparation of the manuscript for publication.

¹ Activities in the field development phase of the research project has been reported by R. D. Dirmeyer, Jr. in his latest annual report (3).

² The University had been Colorado A and M College prior to May 1, 1957.

Acknowledgements are also due to Messrs. F. S. Watanabe and V. C. Cole, Soil Scientists, U. S. Agricultural Research Service, and the Committee on Lower Cost Canal Lining, U. S. Bureau of Reclamation, for their technical advice and reviewing the manuscript.

This research program was made possible through the financial support of the U. S. Bureau of Reclamation and the Colorado State Experiment Station.

CONTENTS

<u>Chapter</u>	<u>Page</u>
FOREWORD	i
FIGURES	v
TABLES	vii
I INTRODUCTION	1
II TEST PROGRAM	7
Soil Tested	7
Bentonite and Dispersant	8
Procedure	10
Post-run Evaluation	13
III RESULTS	17
Series V	21
Series VI	21
Series VII	26
Series VIII	39
Clay-content Evaluation	39
IV DISCUSSION	47
Penetration and Retention	47
Total Surface Area	50
Other Factors	52
V SUMMARY	55
BIBLIOGRAPHY	57
APPENDIX	59

FIGURES

<u>Fig.</u>		<u>Page</u>
1	Conversion chart between intrinsic permeability and hydraulic conductivity	6
2	Size-distribution curves of the soils tested	9
3	Collection of data during run (Series VI)	12
4	Bentonite suspension by-passed the soil column at boundary (Series V Run B)	19
5	Discoloration at the soil surface section by dispersant solution (Series VI)	20
6	Time-history of intrinsic permeability for Series V Run A	22
7	Time-history of specific discharge for Series V Run A	23
8	Time-history of intrinsic permeability for Series V Run C	24
9	Time-history of specific discharge for Series V Run C	25
10	Time-history of intrinsic permeability for Series VI Run A	27
11	Time-history of specific discharge for Series VI Run A	28
12	Time-history of intrinsic permeability for Series VI Run B	29
13	Time-history of specific discharge for Series VI Run B	30
14	Time-history of intrinsic permeability for Series VI Run C	31
15	Time-history of specific discharge for Series VI Run C	32
16	Time-history of intrinsic permeability for Series VII Run A	33
17	Time-history of specific discharge for Series VII Run A	34

FIGURES --Continued

<u>Fig.</u>		<u>Page</u>
18	Time-history of intrinsic permeability for Series VII Run B	35
19	Time-history of specific discharge for Series VII Run B	36
20	Time-history of intrinsic permeability for Series VII Run C	37
21	Time-history of specific discharge for Series VII Run C	38
22	Time-history of intrinsic permeability for Series VIII Run A	40
23	Time-history of specific discharge for Series VIII Run A	41
24	Time-history of intrinsic permeability for Series VIII Run C	42
25	Time-history of specific discharge for Series VIII Run C	43
26	Removal of colloidal suspension by an aspirator siphon .	63
27	Preparation of a 6-per cent bentonite suspension by the use of a high-speed rotary beater	65
28	Wall-building evaluation apparatus in operation	66
29	Measuring the filter cake thickness in the wall- building evaluation of bentonite	67
30	Viscosity determination of bentonite suspension.	69

TABLES

<u>Table</u>		<u>Page</u>
1	TEST PROGRAM DURING 1956-57	7
2	SPECIFIC GRAVITY AND MOISTURE CONTENT OF SOILS TESTED .	8
3	EVALUATION RESULTS OF "ROYAL EARTH" BENTONITE	10
4	SUMMARY OF RESULTS	18
5	RESULTS OF ETHYLENE GLYCOL RETENTION DETERMINATION . .	45

I. INTRODUCTION

The work of Curry (2) demonstrated the difficulty of obtaining simultaneously penetration and retention of bentonite suspensions in chemically inert sand media. When the medium was not chemically inert, the chance for retention of the suspensions was increased. It is apparent from his results that, among other factors, sealing with bentonite suspensions is influenced by (a) the relation between pore size of the soil and the particle size of the sediment, (b) the hydraulic gradient during the sedimentation process, and (c) the chemical characteristics of the water, the sediment, and the soil.

The findings of Newman, as presented in Part One of this report (9), provided laboratory evidence relating to the sealing of a dune sand. This sealing effect prevailed even when the sedimentation treatment brought about an apparent over-all reduction of fines contained in the sand. In addition to establishing a range of hydraulic gradient within which sealing by sedimentation is feasible under certain restricted laboratory conditions of soil, water and sediment, Newman showed the possibility of sealing with the dispersant solution alone. This phenomenon offered promise of a new realm for investigation, which could throw some light on the problem of understanding the fundamental mechanics of the sealing process.

Since Newman experimented on a dune sand containing very little clay-sized particles, and made only one run with the dispersant solution alone, it was felt that a continuation and an expansion of his tests

would be of value. On this basis a program of testing was duly set up and carried out during 1956-57. These tests are described and their results presented in this part of the report. It is obviously impossible to design and conduct a laboratory program so extensive as to include the entire range of field conditions that may be encountered in sediment-lining work; therefore, in interpreting these findings, one should bear in mind the controlled laboratory conditions and the limited scope under which the experiments were conducted.

The symbols and terminology used herein are identical to those used in Part One. The few additional terms are explained wherever they first appear in context. The same equipment as used in Part One was used in this program so as to obtain results supplementary to those obtained by Newman¹. The experiment procedure was basically identical to that followed by Newman, although some modifications were introduced. Two types of soil were tested: a Greeley fine sandy loam and a sand from the Loveland Lake. For all practical purposes, the bentonite and dispersant used were the same as those previously used.

Not all the auxiliary tests described by Newman were carried out in this program. The less significant ones were omitted, while others were slightly modified. An ethylene glycol retention test² was adopted in place of the hygroscopic moisture ratio determination, both being proven processes for evaluating relative clay content on the basis of total exposed surface area.

¹ For description, see Chapter II, Part One.

² Described in the Appendix.

Observations and computations were made in the same manner as in Part One. However, since the soils tested contained more fines and organic matter than the previous Torrington sand, bacteria growth gradually developed despite the thymol solution present. Thus it was not possible to collect reliable data for periods as long as seemed desirable. Yet all runs were allowed ample time at least to establish definite trends, for which the data collected were considered free from bacteria influence.

In expressing the extent of sealing, Curry computed the hydraulic conductivity of the soil from his data. Newman, however, selected the intrinsic permeability in lieu of the hydraulic conductivity. The former may be a convenient term familiar to many engineers but the latter is unquestionably a term that expresses closest to the true status of the soil. In the present program, therefore, adoption of the intrinsic permeability has been continued. For the sake of clarity, the terms in question are reviewed here, and it can be seen that the dimensional incompatibility of the two terms makes it impracticable to apply any conversion factor that can be considered technically correct.

The basic measurements at each reading interval consist of (a) the volume of discharge per unit time for the cross-sectional area A of the soil column, (b) manometer readings indicating the hydraulic gradient i , and (c) temperatures from which the dynamic viscosity η and the density of water ρ can be found. The discharge Q is in cu cm/sec; the area A is in sq cm; the hydraulic gradient i is dimensionless; the viscosity η is in poises or gm/cm-sec, and the density ρ is in gm/cu cm.

The hydraulic conductivity is defined as

$$K = \frac{Q}{Ai} ,$$

therefore, it is in cm/sec, which may be converted into ft/year by multiplying a conversion factor of 1.0346×10^6 . The intrinsic permeability K' , on the other hand, is defined as

$$K' = \frac{Q\eta}{A \rho g i} ,$$

in which the gravitational acceleration g is taken as 980 cm/sec^2 for Fort Collins (4:2810). Hence, the intrinsic permeability is in sq cm, which may be converted into sq microns (μ^2) by multiplying a conversion factor of 10^8 . It may be seen that the fluctuations in viscosity due to temperature changes are not taken into account in the computation of the hydraulic conductivity. Since the volume of discharge varies in simple inverse proportion to the viscosity, which can increase almost 30 per cent for a temperature decrease from 35°C to 20°C , any term ignoring this factor must necessarily be misleading in the description of the extent of sealing in a soil. Consequently it cannot be over-emphasized that any comparison of results derived from converting the one term to the other is not justified unless the temperature at which the hydraulic conductivity is measured is known. For conversion in this manner, the reader is referred to Fig. 1.

Aside from intrinsic permeability, the values of specific discharge have been computed and presented in graphical form. The term specific discharge has been defined by Newman (9) as:

$$Q' = K'i ,$$

or

$$Q' = \frac{Q\eta}{A\rho g} ,$$

which is expressed in sq microns, and ignores the effect of hydraulic gradient. This term may be conveniently transformed into a familiar percolation rate to show the amount of seepage per unit area of bed in 24 hours, expressed as cu ft per sq ft per day at 20°C. Since

$$\frac{Q}{A} = \frac{Q'\rho g}{\eta} ,$$

and $\rho \approx 0.996$ at laboratory temperatures, $g = 980$ ft per sec per sec, and $\eta = 0.01005$ poise at 20°C,

$$\frac{Q}{A} = \frac{Q' \times 0.996 \times 980}{0.01005} .$$

This value may be converted, by a factor of $\frac{60 \times 60 \times 24}{2.54 \times 12}$, into the English units mentioned above. Thus one sq micron of Q' is equivalent to a percolation rate of 2.755 cu ft/sq ft/day at 20°C.

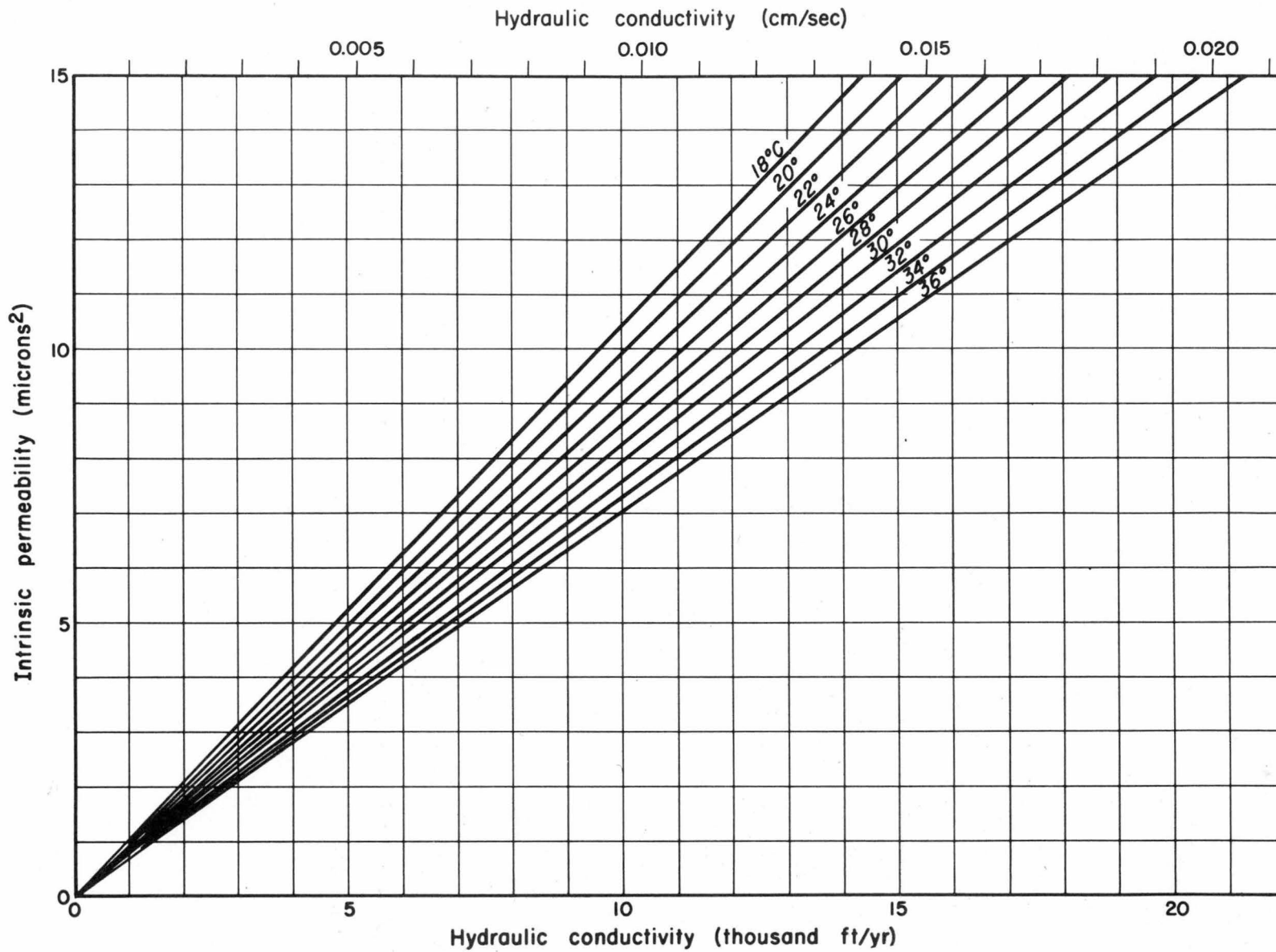


Fig. 1 Conversion chart between intrinsic permeability and hydraulic conductivity.

II. TEST PROGRAM

The test program consisted of four series; each of three runs under various hydraulic gradients. The complete list of runs is given in Table 1.

Table 1.--TEST PROGRAM DURING 1956-57

Series No.	Run No.	Soil Tested	Applied Hydraulic Gradient*			Material Used in Treatment
			Low	Medium	High	
V	A	Greeley	0.16			1% dispersed bentonite suspension for 24 hrs.
	B	Fine Sandy		0.59		
	C	Loam			0.96	
VI	A	Greeley	0.31			0.2% sodium tri-polyphosphate solution for 49.5 hrs.
	B	Fine Sandy		0.51		
	C	Loam			0.90	
VII	A	Loveland	0.13			1% dispersed bentonite suspension for 48 hrs.
	B	Lake		0.56		
	C	Sand			0.99	
VIII	A	Loveland	0.17			0.2% sodium tri-polyphosphate solution for 53 hrs.
	B	Lake		0.64		
	C	Sand			0.99	

* Over-all head per unit length of soil column at the time of sedimentation.

Soil Tested

The Torrington sand tested by Newman was practically free of clay-sized particles: only about four per cent passed through U. S. Standard Sieve No. 200¹. For the present program, two sandy soils containing relatively more fines were chosen. A Greeley fine sandy loam excavated from an open pit near Timnath, Colorado, was used for Series

¹ This size was defined as "fines" in Part One (p. 3).

V and VI; and a Loveland Lake sand was used for Series VII and VIII. These were used for testing in their air-dry state. The specific gravity and the moisture content of each soil were determined and the results are listed in Table 2.

Table 2.--SPECIFIC GRAVITY AND MOISTURE CONTENT OF SOILS TESTED

Soil	Specific Gravity			Moisture Content (per cent)		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Greeley Fine Sandy Loam	2.649	2.649	2.649	7.18	7.14	7.16
Loveland Lake Sand	2.699	2.701	2.700	3.47	3.66	3.57

For mechanical analysis of these soils, wet sieving was used to cover the size range of greater than 0.044 mm (U. S. Standard Sieve No. 325) and readings of bouyoucos hydrometer were taken to cover the smaller size range. The size distribution curves obtained are shown in Fig. 2.

Greeley fine sandy loam is a U. S. Department of Agriculture established series (4,11). Loveland Lake sand was collected from the washed beach of the Lake, and contains about 2% clay and considerable micaceous flakes. An appreciable amount of organic matter was present in both soils.

Bentonite and Dispersant

A commercial grade bentonite¹ in powder form was used. Evaluation results of the characteristics of this material are reported in Table 3.

¹ High-swell Wyoming bentonite, marketed by Royal Earth, Inc., Denver, Colorado.

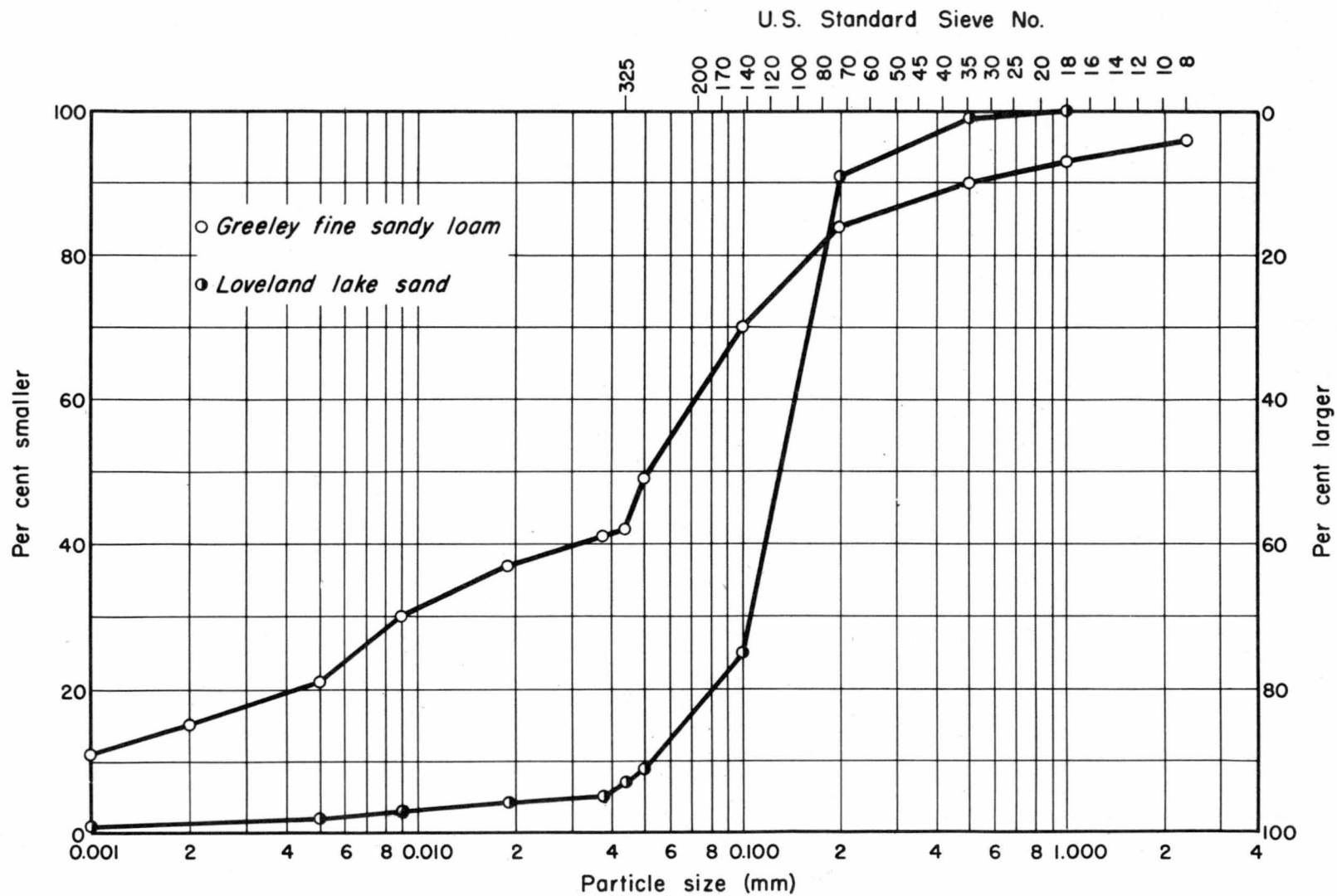


Fig. 2 Size-distribution curves of the soils tested.

Table 3.--EVALUATION RESULTS OF "ROYAL EARTH" BENTONITE¹

Sample No.	Grit Content %	Colloidal Yield %	Wall Filtrate (ml)	Building Thickness (in.)	Viscosity (centipoises)
1	2.96	--	12.5	1/32	13
2	3.24	84.71	11.5	1/32	14
3	3.11	84.73			
4	3.82	84.89			
Average	3.28	84.78	12.0	1/32	14

The dispersant used was identical to that used by Newman: sodium tripolyphosphate ($\text{Na}_5\text{P}_3\text{O}_{10}$) in granular form.

Procedure

In general, the procedure closely followed that described by Newman in Chapter IV, Part One. Some deviations were introduced in the light of Newman's experience and the difference in the soils tested. Where no mention is made, it is understood that Newman's technique was applied.

The soil column:- Both soils were used in their air-dry state. Newman's carbon dioxide displacement method was adopted for loading the permeameters with soil to be free of layering and entrapped air. The holes in the soil dispenser had to be enlarged slightly to accommodate the relatively more clayey soils tested. During the loading process occasionally some of the holes were plugged, especially when the soil was Greeley fine sandy loam because of either the high clay content or the slight moisture present. This was alleviated by tapping the dispenser and shaking the shutter release.

¹ See the Appendix for description of evaluation procedure.

The bentonite suspensions:- All suspensions contained approximately one per cent bentonite after standing for 24 hours together with 1.5 gm per liter of dispersant. The amount of air-dry bentonite (11 gm per liter) to be added was determined by empirical testing. The concentration of the suspension was checked at the beginning and the end of each treatment and found to be close to the desired one per cent. For runs treated with dispersant solution without bentonite, 2 gm per liter of sodium tripolyphosphate was used.

Collection of data:- Readings were taken for the most part at 12-hour and 24-hour intervals; longer intervals were occasionally used when it was apparent that no appreciable change had developed. Each reading consisted of recording (a) the volume of effluent collected during a 30-minute period¹, (b) the top and the bottom soil temperatures at the beginning and the end of the period, (c) the manometer readings at the beginning and the end of the period, (d) any change in length of the soil column, (e) any alteration of tailwater elevation, and (f) all other observed phenomena.

The run:- Each run comprised three phases:

- (a) Initial permeability determination - This phase extended over five to eight days depending on how rapidly the soil columns attained stable permeability. During this phase the tailwater elevation was usually placed at the same level for all runs in a series.

¹ Occasionally a longer or shorter period was used for practical reasons.



Fig. 3 Collection of data during run (Series VI). Note the different sized graduated cylinders needed for various hydraulic gradients.

Toward the end of this phase before the last readings were taken, it was changed to the desired level for each run where it remained throughout the next two phases.

- (b) Sedimentation treatment - The water above the soil column was then drained and a thin layer of soil was siphoned off the surface. The bentonite suspension or dispersant solution was introduced. The period of sedimentation was arbitrarily decided each time¹, one day for Series V and about two days for the other series. Effluent concentration measurements were omitted.
- (c) Final permeability determination - Clear water was introduced immediately after the sealing treatment but the surface cake, if present, was not removed until a few days later. It was the aim of this phase to establish the residual sealing effect that could be expected to last reasonably long. However, the danger of bacteria growth, despite the thymol present, dictated the length of each run, and as a result, no run extended beyond 20 days.

Post-run Evaluation

Aside from permeability measurements and visual observations, the movement of clay was of serious concern. The measurement of effluent

¹ See Table 1 for the specific length of sedimentation in each series.

concentration conducted by Newman was discontinued for the present program because its results had not been especially useful for interpreting the other data obtained. On the samples collected after the runs, Newman tried X-ray diffraction analysis as well as hygroscopic moisture ratio determination. The low clay content of the soils and its still lower fluctuation would be difficult for detection by X-ray diffraction. Besides, diffraction methods, as pointed out by Dyal and Hendricks (5) depend upon the degree of orientation of the layer minerals in the sample and therefore their quantitative accuracy is limited. Hygroscopic moisture ratio determination gives a measure of surface area, which may also be obtained by the ethylene glycol retention test outlined by the U. S. Salinity Laboratory (11).

Ethylene glycol retention test:- A twofold purpose can be achieved by the adoption of this test: (a) Physically, the total surface area may be measured and (b) chemically, the cation exchange capacity is indirectly determined.

The total surface area obtained by this method is a relative value, which can be converted into absolute units with a certain assumption (1, 12). However, for the detection of clay movement, a relative value is sufficient provided it is accurate enough to be within the range needed. Therefore, this method provides a good indication of the movement of clay for this program.

According to Reeve (10), an increase in exchangeable sodium is invariably accompanied by a decrease in water permeability for all soils. This was within expectation for all the tests in the program

because of the addition of sodium tripolyphosphate. Mortland (8) showed a very close relationship between cation exchange capacity and total surface area of soils, their correlation coefficient being as high as 0.985. He measured the total surface area and cation exchange capacity of various soils and found that

$$y = 0.176 x + 2 ,$$

where y is the cation exchange capacity in milliequivalents per 100 grams of soil, and x is the total specific surface in square meters per gram of soil.¹

Thus it was decided that ethylene glycol retention test be conducted on the samples collected after the tests in lieu of X-ray diffraction and chemical analyses as originally planned. The samples were taken from different locations in the soil columns and dried in a 110°C oven. A description of the procedure is given in the Appendix.

¹ Bower and Gschwend (1) also experimented on Wyoming bentonite.

III. RESULTS

In general, sealing effect was attained in all runs although the degree of success varied. Within each series, three runs were conducted: A, B and C, in ascending order of applied hydraulic gradient¹. Each run disclosed some significant information and helped to establish probable trends within each series. Some unexpected difficulties arose during a few runs, which could not be repeated because of the lack of time and the limited budget. Fortunately, however, these were either not sufficiently serious as to invalidate the data or dispensable without reducing the effective range of the series. No measurable settlement of the soil column was detected in any of the tests. Therefore, it is not likely that whatever sealing effect attained was due significantly to consolidation of the soil.

The intrinsic permeability of each soil column has been computed for two 10-in. sections: The upper section under a hydraulic gradient calculated from readings of manometer Nos. 5 and 6, and the lower section under a hydraulic gradient calculated from readings of manometer Nos. 6 and 7². A summary of the results is presented in Table 4. As different phenomena were observed in each series, the description of results is presented separately.

¹ See Table 1, Chapter II.

² For manometer tapping locations, see Table 2, Chapter II, Part One.

Table 4.--SUMMARY OF RESULTS

Run	Soil Type*	Applied Hydr. Gradient	Initial Bulk Density (lb/ft ³)	Sealing Treatment (hrs)	Specific Discharge			Intrinsic Permeability**			Remarks	
					Initial	Min. during Treatment	Final	Initial	Max. Final	Per cent Reduction		
					(Microns ²)			(Microns ²)			(%)	
VA	GFSL	Low (0.16)	78.4	1.1 % Bentonite	24	1.02	0.01	0.04	2.34	0.46	80.2	
VB	"	Medium (0.59)	79.2	"	"	0.82	--	--	1.11	--	--	By-passed soil column at wall
VC	"	High (0.96)	76.2	"	"	3.18	0.39	0.02	7.77	0.09	98.4	
									3.40	0.72	78.8	
VIA	"	Low (0.31)	80.0	0.2 % Na ₅ P ₃ O ₁₀	49.5	0.22	0.02	0.01	1.28	1.06	17.1	
VIB	"	Medium (0.51)	78.4	"	"	0.37	0.02	0.02	1.34	1.06	20.9	
VIC	"	High (0.90)	80.0	"	"	1.20	0.04	0.04	1.32	1.14	13.6	
									1.60	1.19	25.6	
									1.71	0.56	67.2	
									1.24	1.32	increased	
VIIIA	LLS	Low (0.13)	89.0	0.9 % Bentonite	48	1.68	0.02	0.86	14.00	5.95	57.5	Permeability
VIIB	"	Medium (0.56)	90.8	"	"	6.28	0.01	2.52	12.92	12.80	0.9	still falling
VIIC	"	High (0.99)	88.0	"	"	14.35	0.03	0.29	13.27	4.00	69.8	"
									11.06	8.95	19.0	
									18.02	0.82	95.4	
									16.20	2.44	84.9	
VIIIA	"	Low (0.17)	89.0	0.2 % Na ₅ P ₃ O ₁₀	53	1.95	0.02	0.01	14.98	0.03	99.8	Lower section
VIIIB	"	Medium (0.64)	90.0	"	"	8.40	0.33	--	15.30	9.98	34.7	not accurate
VIIIC	"	High (0.99)	86.8	"	"	14.96	0.10	0.06	13.72	--	--	Leaked at bottom
									13.51	--	--	
									15.81	0.07	99.6	
									18.35	0.03	99.8	

* GFSL denotes Greeley fine sandy loam, and LLS denotes Loveland Lake sand.

** The upper and lower figures relate to the upper and lower 10-in. sections respectively. For conversion into hydraulic conductivity in ft/yr under unit hydraulic gradient, see Fig. 1.



Fig. 4 Bentonite suspension by-passes the soil column at boundary (Series V Run B).

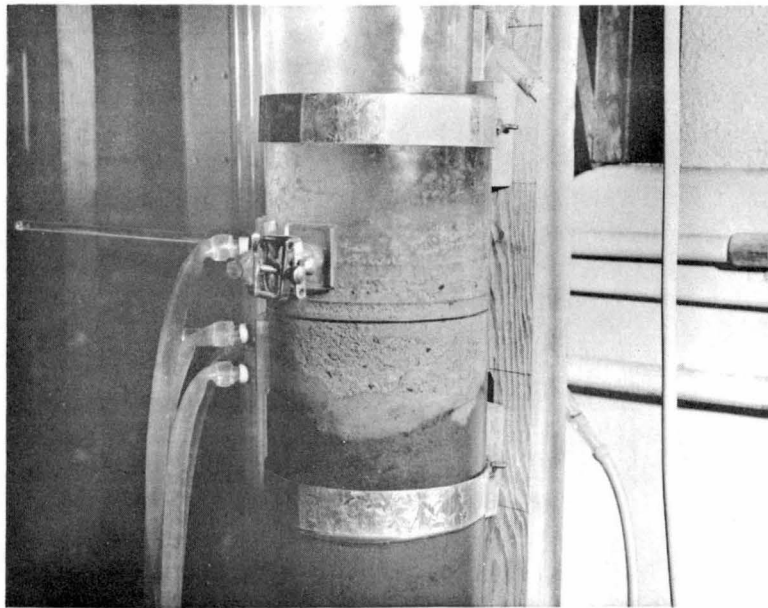


Fig. 5 Discoloration at the soil surface section by dispersant solution (Series VI).

Series V (Greeley fine sandy loam treated with bentonite suspension)

Some sealing was effected in all three runs. Run B, under medium applied hydraulic gradient, developed a leak along the cylinder wall some time during the sedimentation process. This was apparently rectified by a gentle tapping of the apparatus; nevertheless, the data for Run B are considered unreliable and have been discarded. Thus the tabulated results are from only Runs A and C, which covered the lower and upper limits of the intended range of applied hydraulic gradient. For a few days the manometers behaved abnormally, especially for Run A, because the bentonite tended to plug the tapings. This situation was remedied by lowering the tailwater level, which not only yielded better manometer readings but also produced more measurable quantities of effluent. Run C, under a higher applied hydraulic gradient, showed more sealing than Run A. In each case, the upper section sealed better than the lower section. The time histories of permeability and specific discharge are shown graphically in Figs. 6 to 9.

Series VI (Greeley fine sandy loam treated with dispersant solution)

On being treated with sodium tripolyphosphate solution, the soil surface showed a sharp discoloration, which may be ascribed to leaching action. This gradually traveled downward, its rate of travel being approximately proportional to the corresponding hydraulic gradient. An apparently almost complete sealing was obtained in all three runs but it was obvious from the manometer readings that practically the

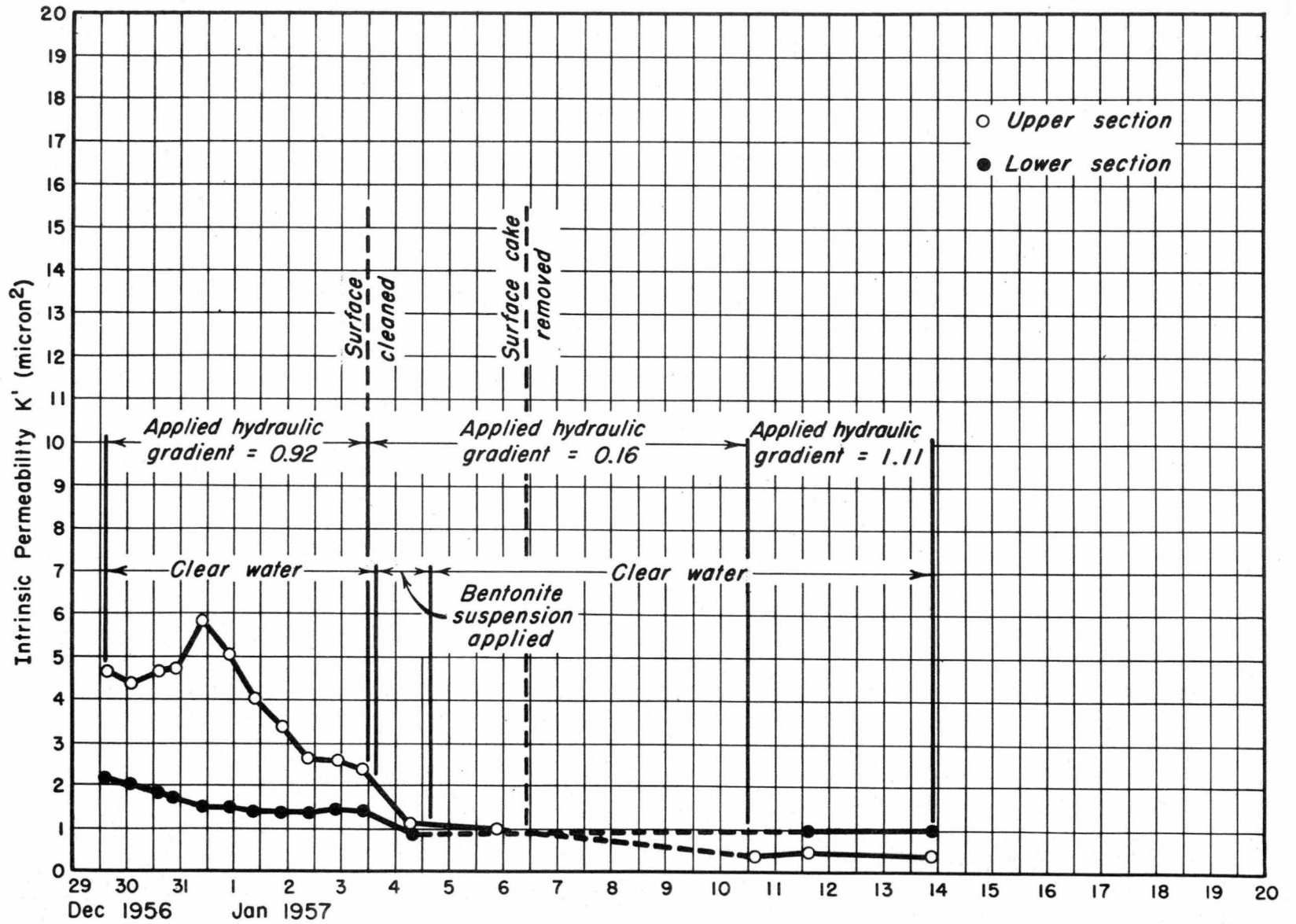


Fig. 6 Time-history of intrinsic permeability for Series V Run A.
(Greeley fine sandy loam treated with bentonite suspension under low hydraulic gradient.)

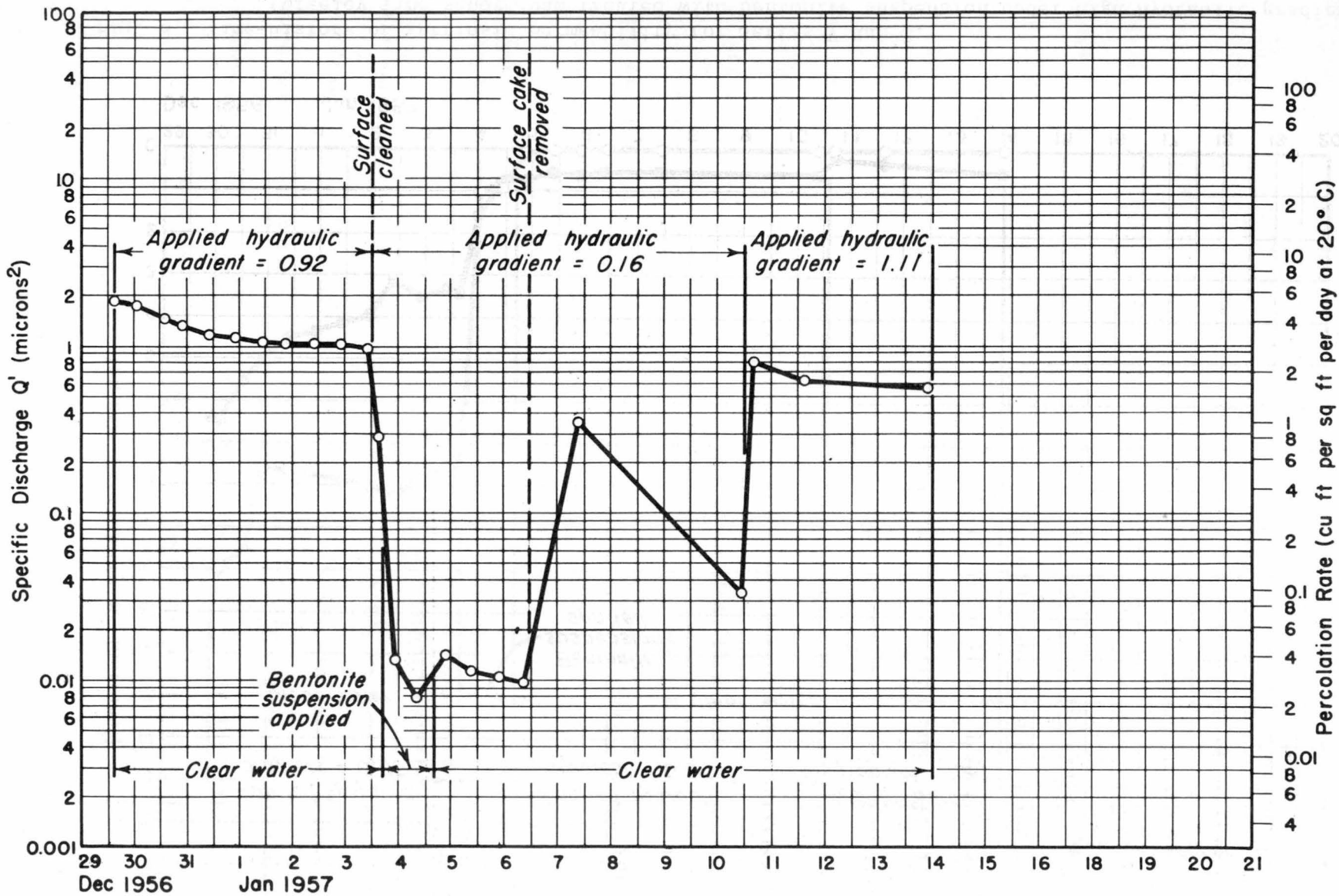


Fig. 7 Time-history of specific discharge for Series V Run A.
(Greeley fine sandy loam treated with bentonite suspension under low hydraulic gradient.)

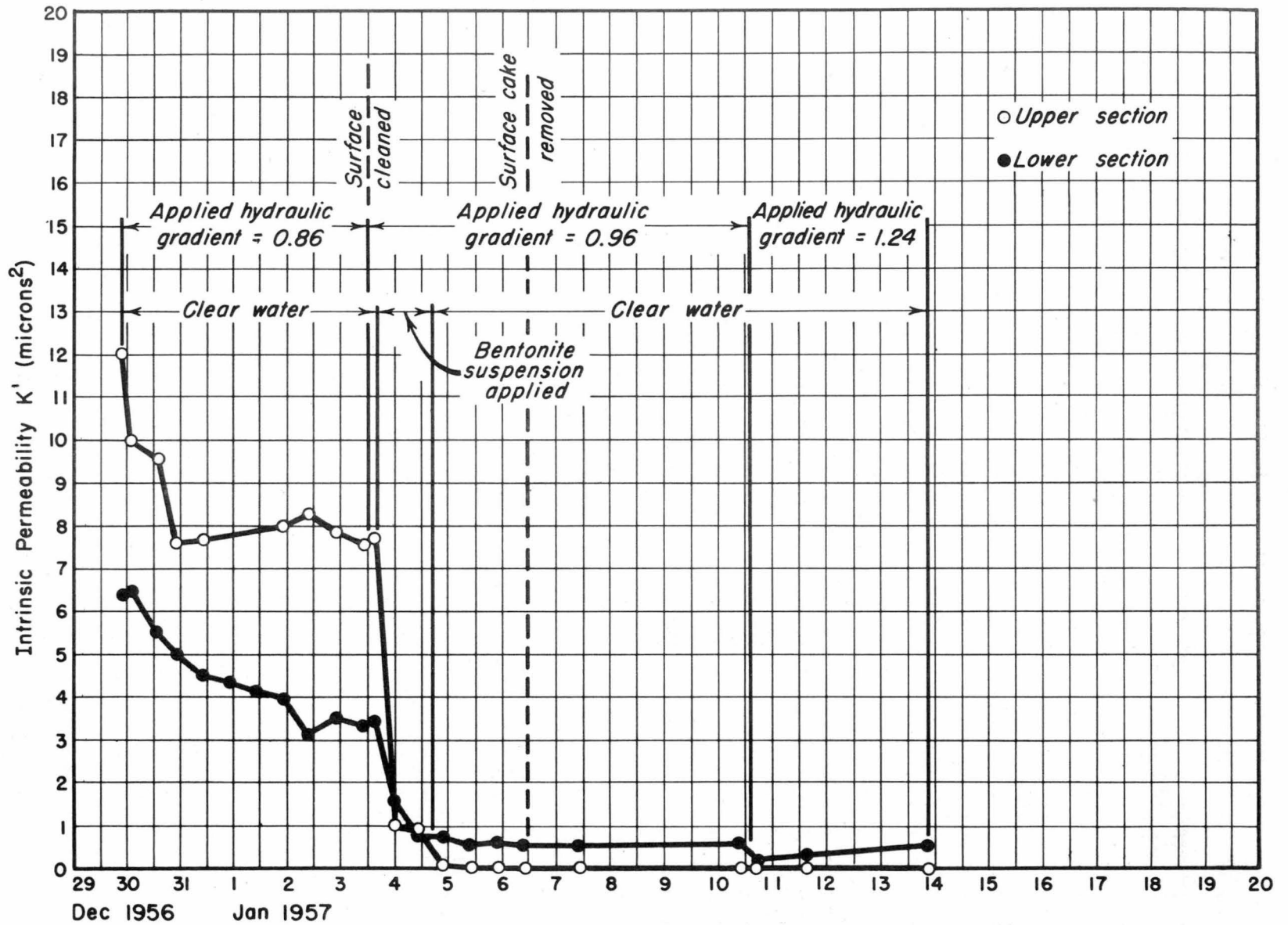


Fig. 8 Time-history of intrinsic permeability for Series V Run C.
(Greeley fine sandy loam treated with bentonite suspension under high hydraulic gradient.)

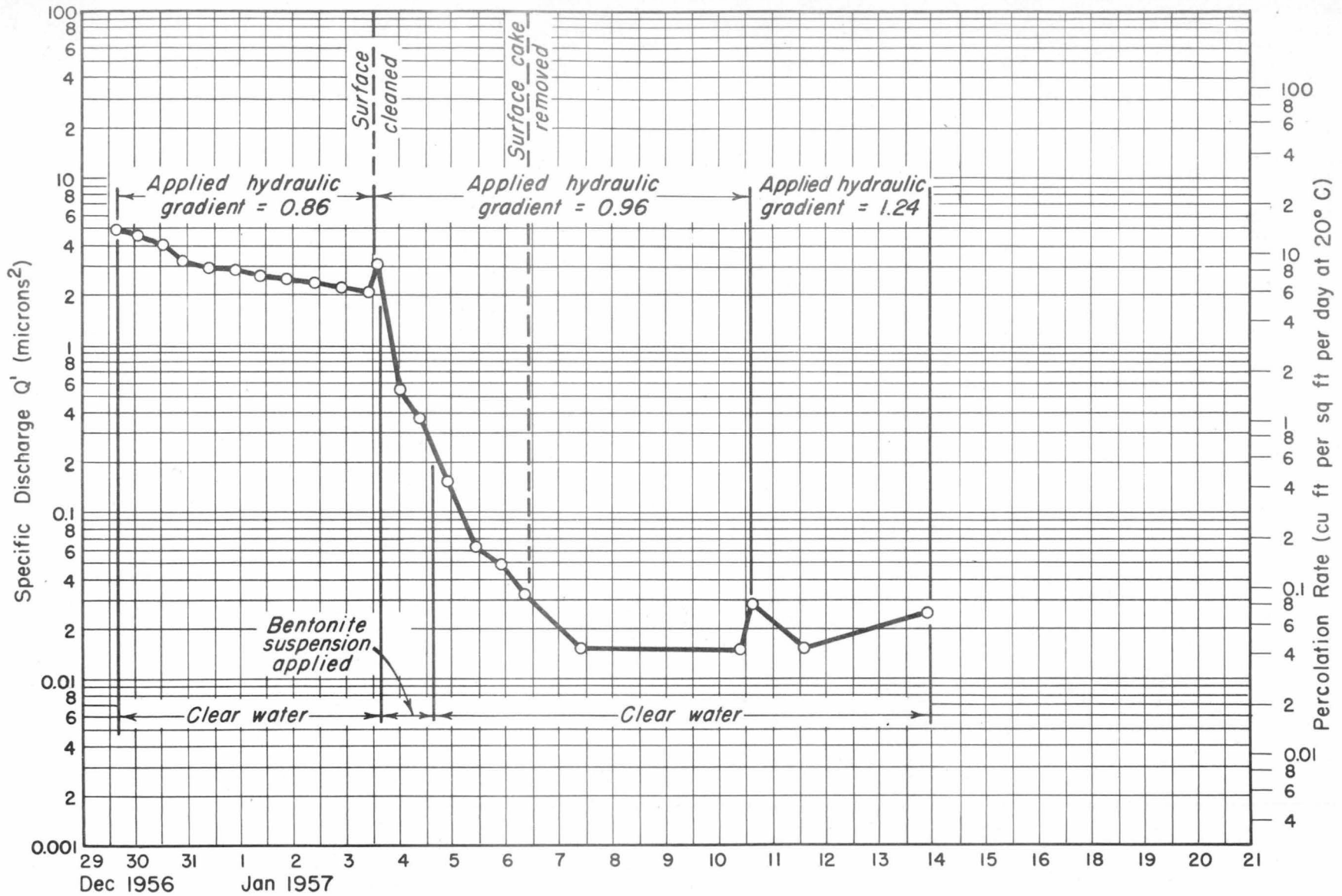


Fig. 9 Time-history of specific discharge for Series V Run C.
(Greeley fine sandy loam treated with bentonite suspension under high hydraulic gradient.)

entire sealing effect was confined to the uppermost section. The time histories of the permeability and specific discharge presented in Figs. 10 to 15 bear out this fact: only in Run C, under high applied hydraulic gradient, some sealing-in-depth can be witnessed. The sealing produced at the surface in Runs A and B made it difficult to collect enough effluent or to obtain appreciable differential in manometer readings for computation of permeability to any reliable degree of accuracy. Therefore the significance of their graphical representations must be qualified.

Since the three runs manifested a consistent trend, it was decided that Run B, under the medium applied hydraulic gradient, be further tested under hard water. A supply of synthetic hard water was thereupon fed to the soil column, but no significant recovery of percolation could be detected. Possibly a much harder water could have produced a contrary effect. However, this was beyond the scope of the present program.

Series VII (Loveland Lake sand
treated with bentonite suspension)

Sealing was effected in all three runs although it was far less complete in Run A, under low applied hydraulic gradient, than in Run C, under high hydraulic gradient. The permeability continued to fall even after clear water had been introduced. Removal of surface cake affected the permeability only momentarily and soon the permeability resumed its downward trend as can be seen in Figs. 16 to 21. In Runs A and B, it was still decreasing when the permeameters were dismantled. It is possible that, given adequate time, the sealing would have achieved the same effectiveness as in Run C.

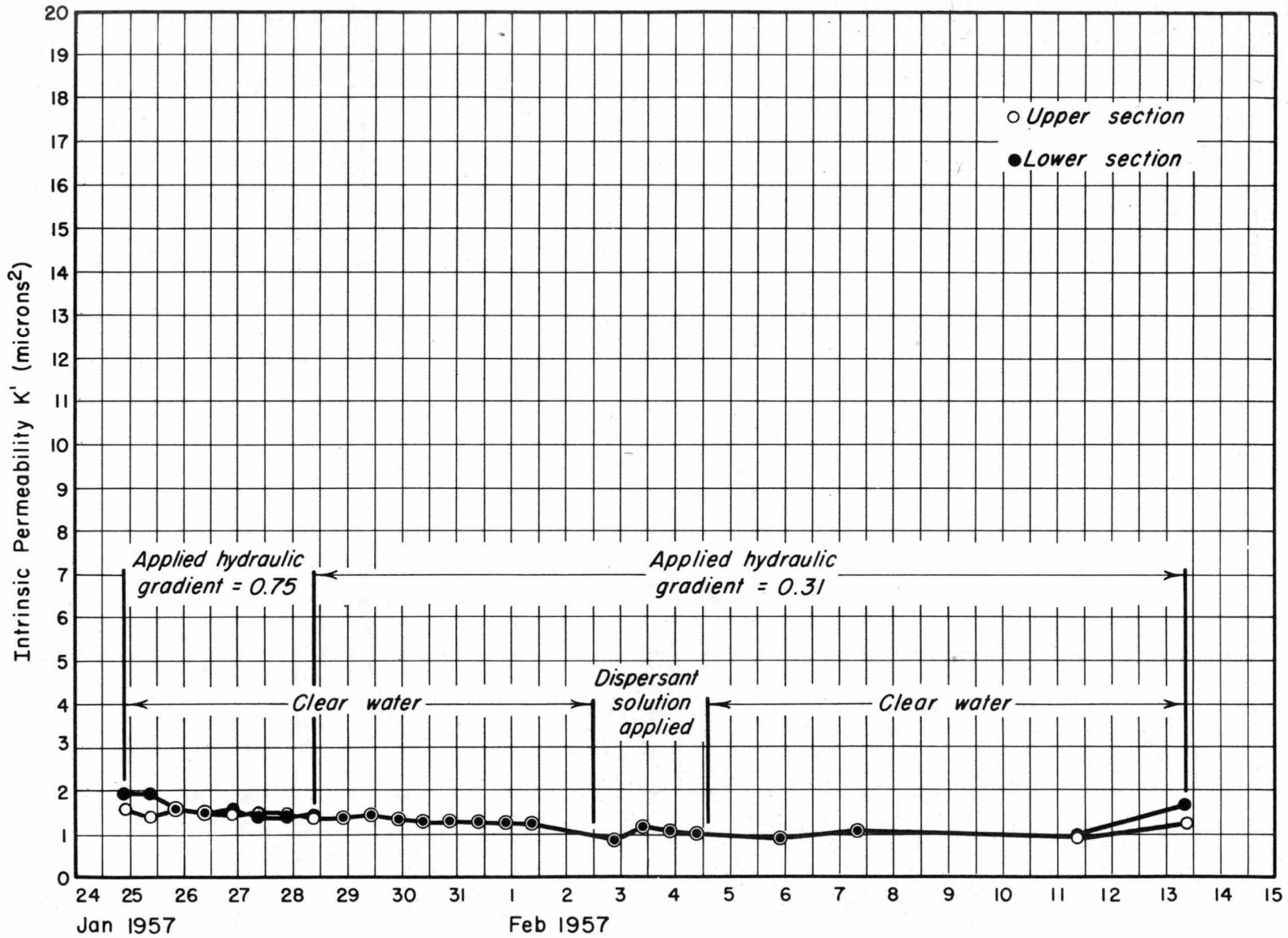


Fig. 10 Time-history of intrinsic permeability for Series VI Run A.
(Greeley fine sandy loam treated with bentonite suspension under low hydraulic gradient.)

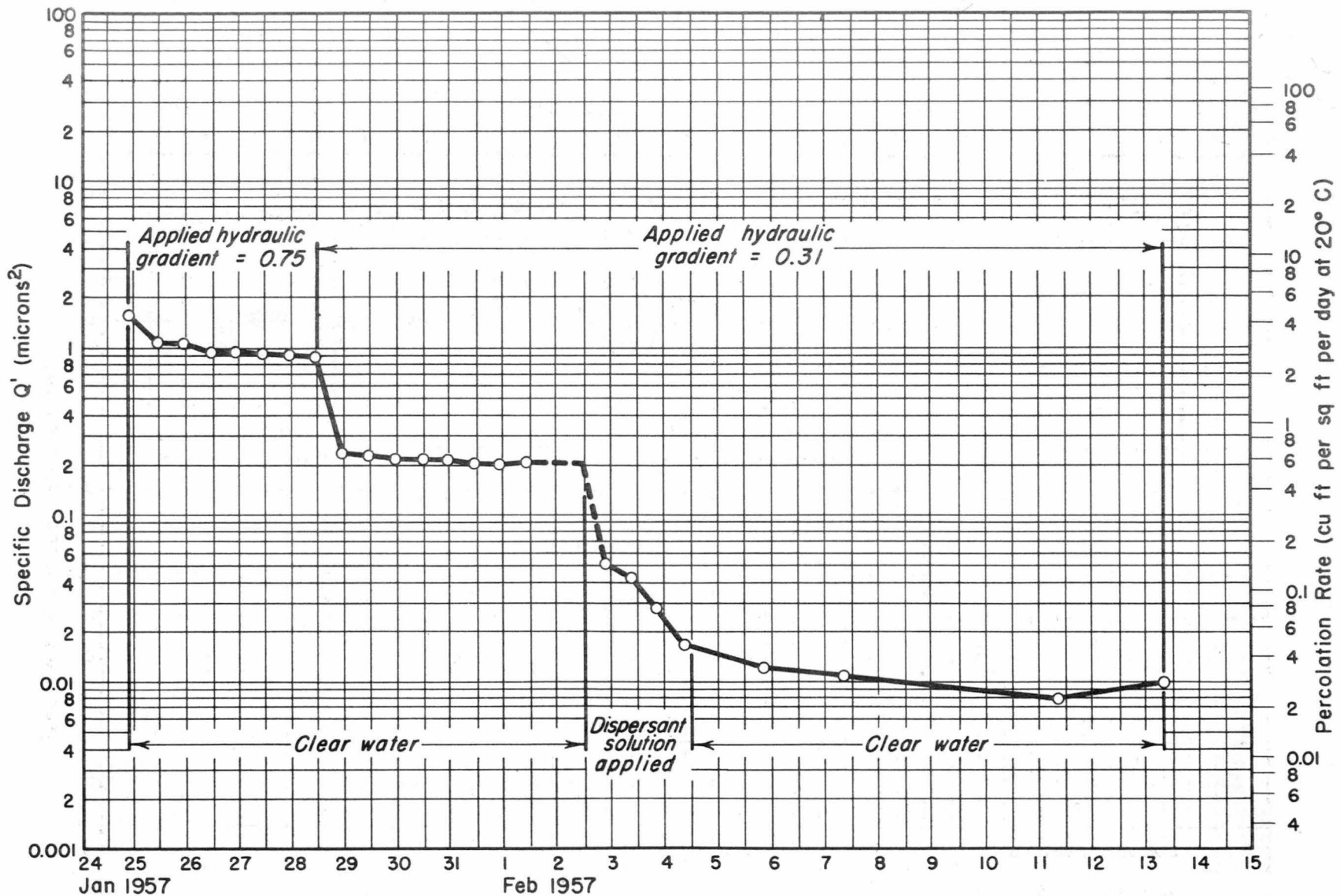


Fig. 11 Time-history of specific discharge for Series VI Run A.
(Greeley fine sandy loam treated with bentonite suspension under low hydraulic gradient.)

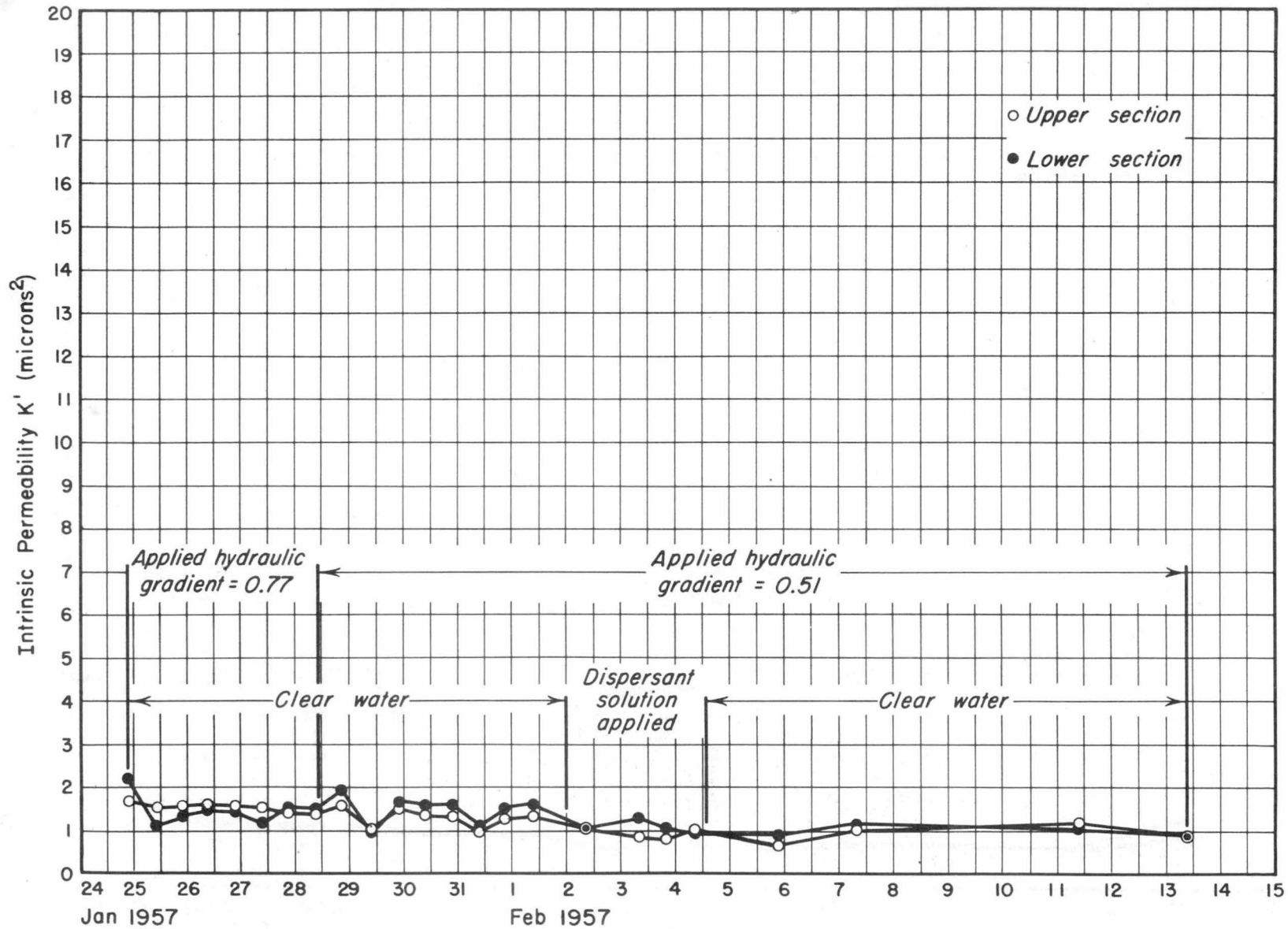


Fig. 12 Time-history of intrinsic permeability for Series VI Run B.
(Greeley fine sandy loam treated with bentonite suspension under medium hydraulic gradient.)

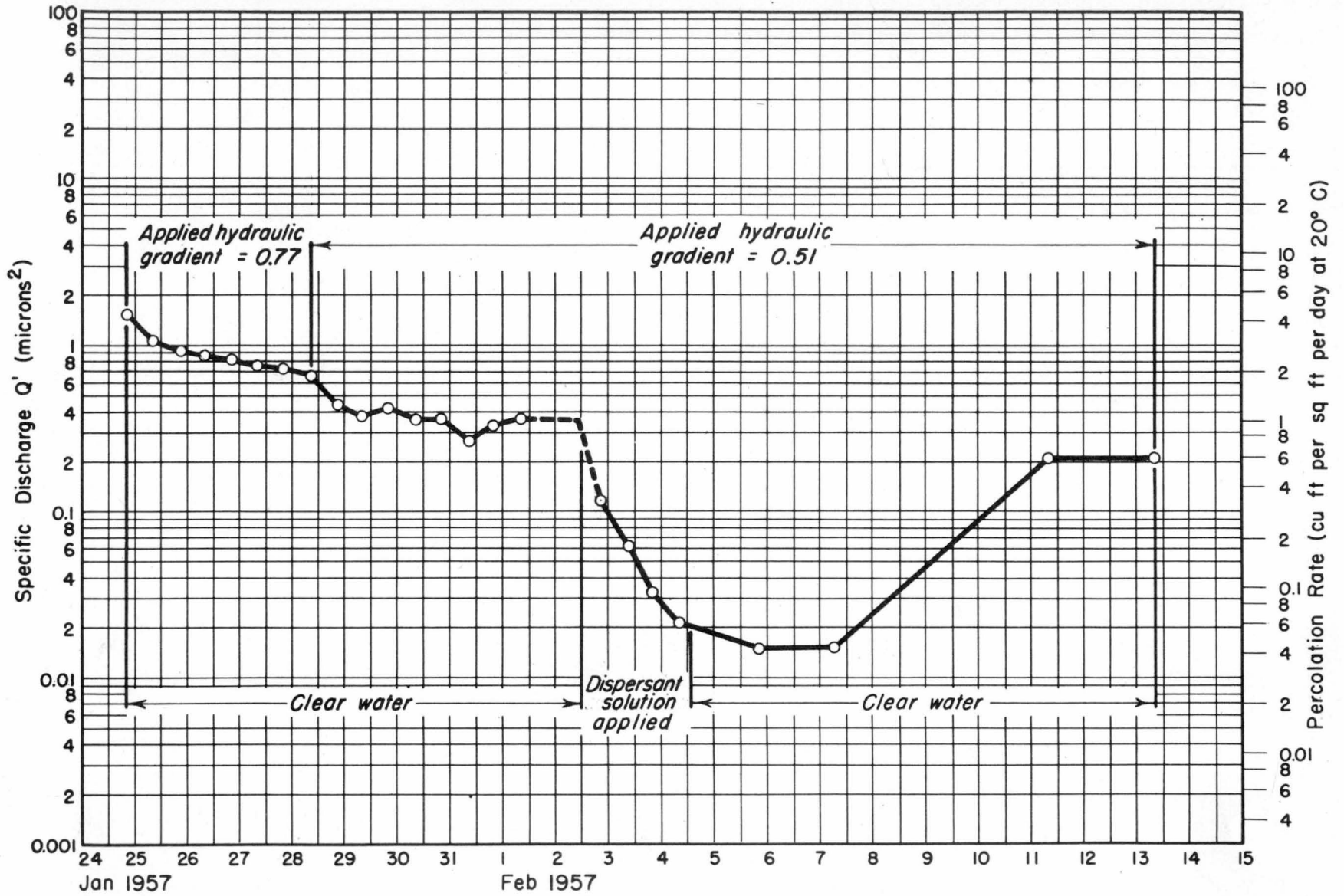


Fig. 13 Time-history of specific discharge for Series VI Run B.
(Greeley fine sandy loam treated with bentonite suspension under medium hydraulic gradient.)

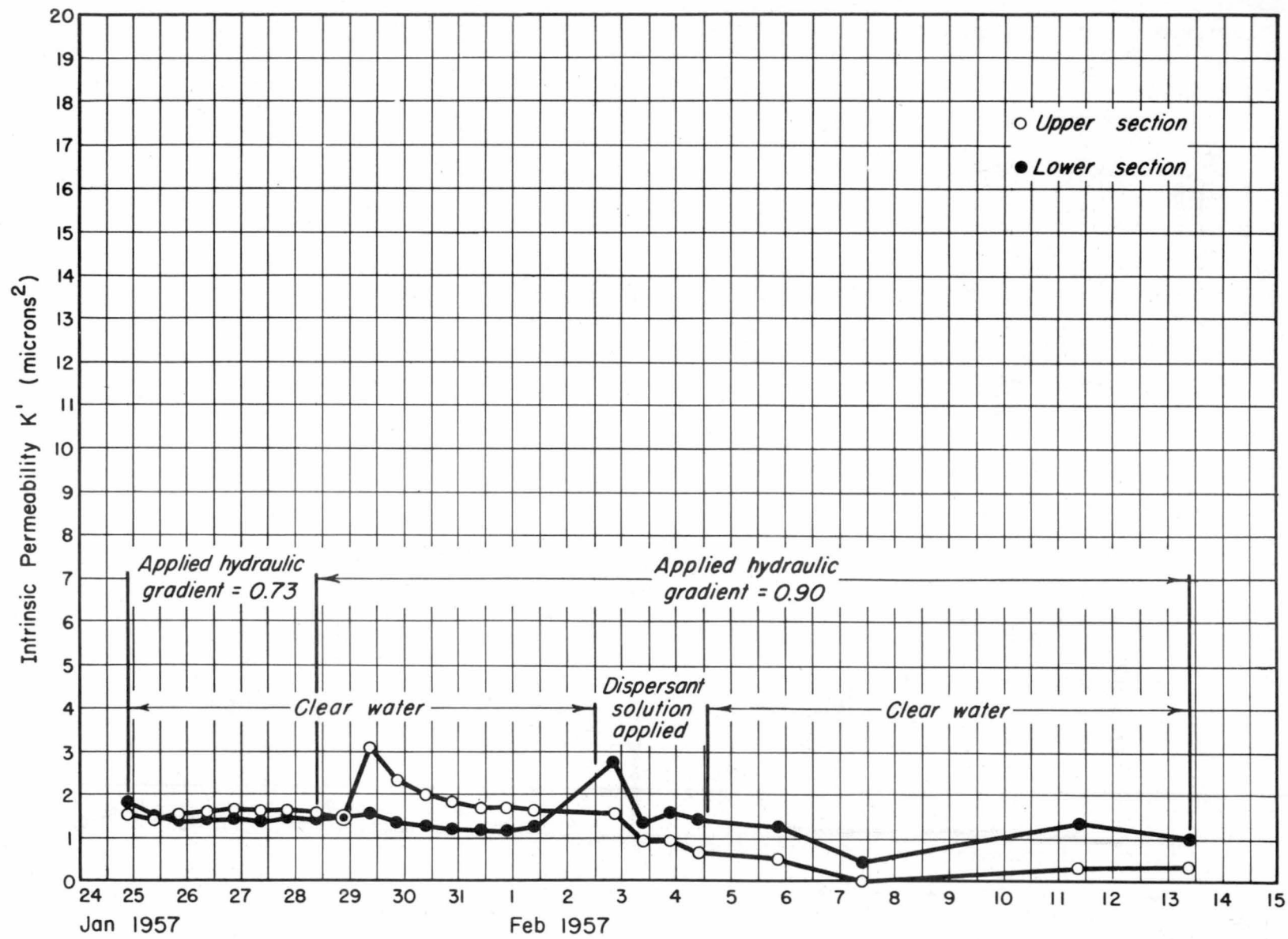


Fig. 14 Time-history of intrinsic permeability for Series VI Run C.
(Greeley fine sandy loam treated with bentonite suspension under high hydraulic gradient.)

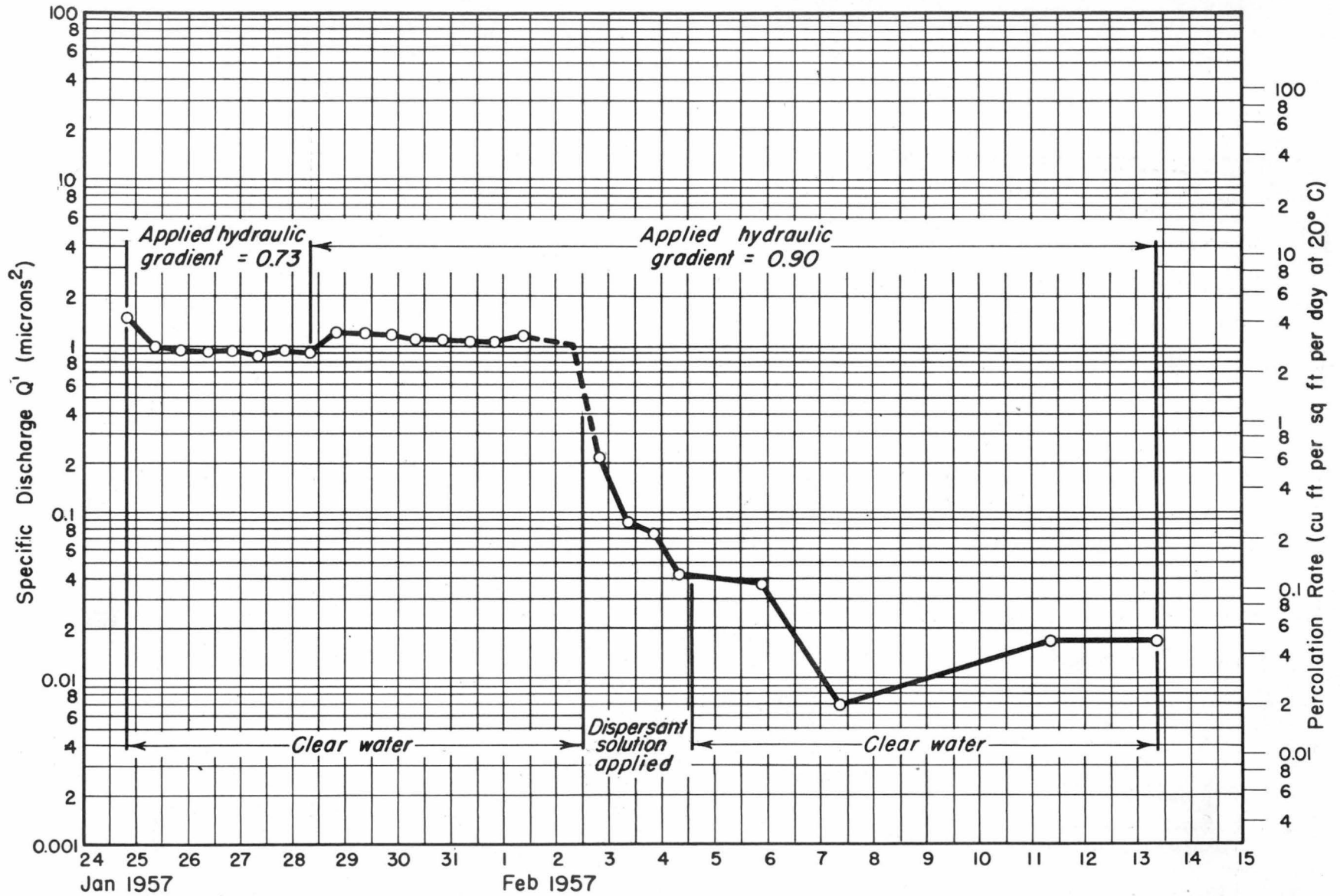


Fig. 15 Time-history of specific discharge for Series VI Run C.
(Greeley fine sandy loam treated with bentonite suspension under high hydraulic gradient.)

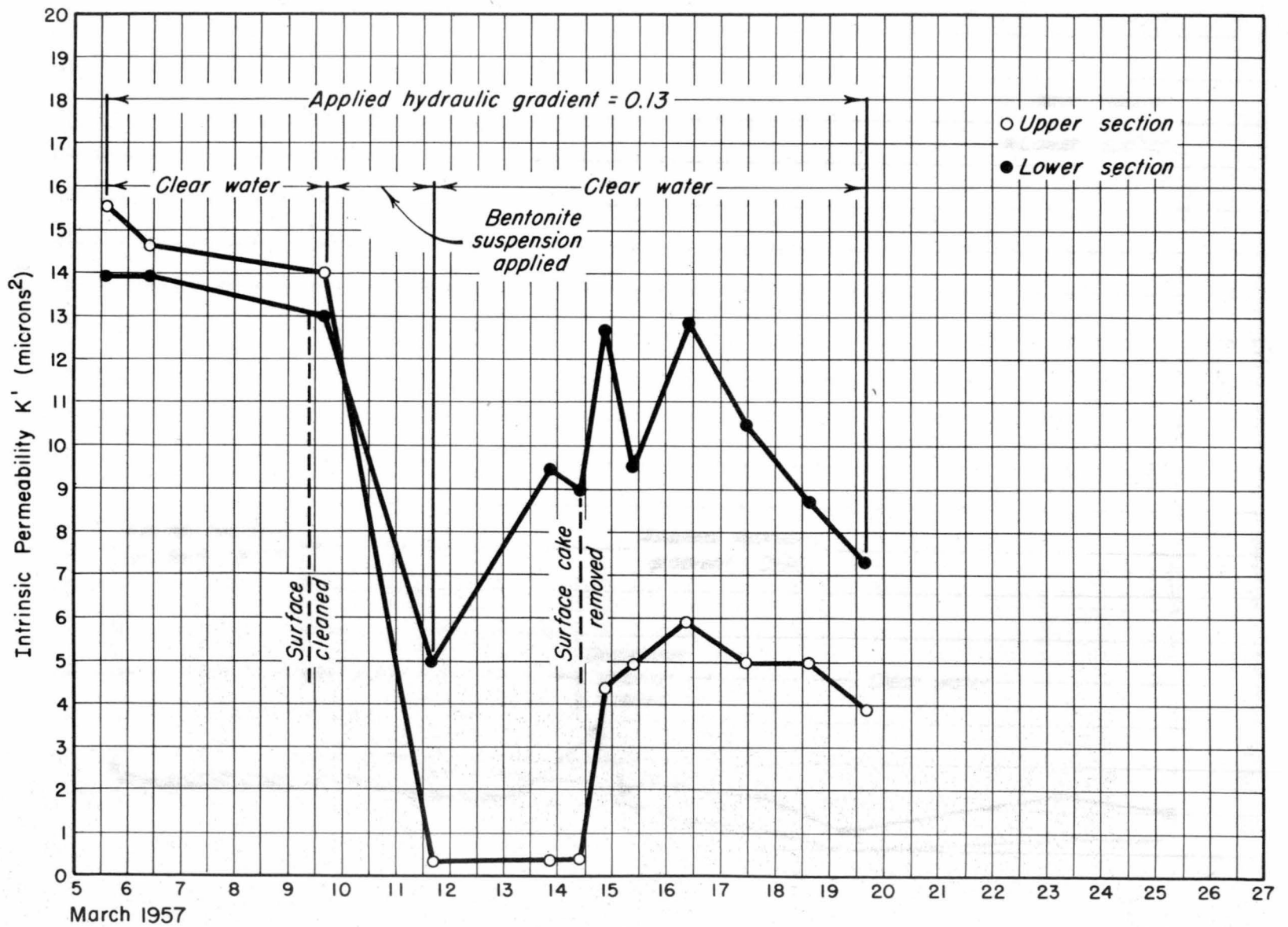


Fig. 16 Time-history of intrinsic permeability for Series VII Run A.
(Greeley fine sandy loam treated with bentonite suspension under low hydraulic gradient.)

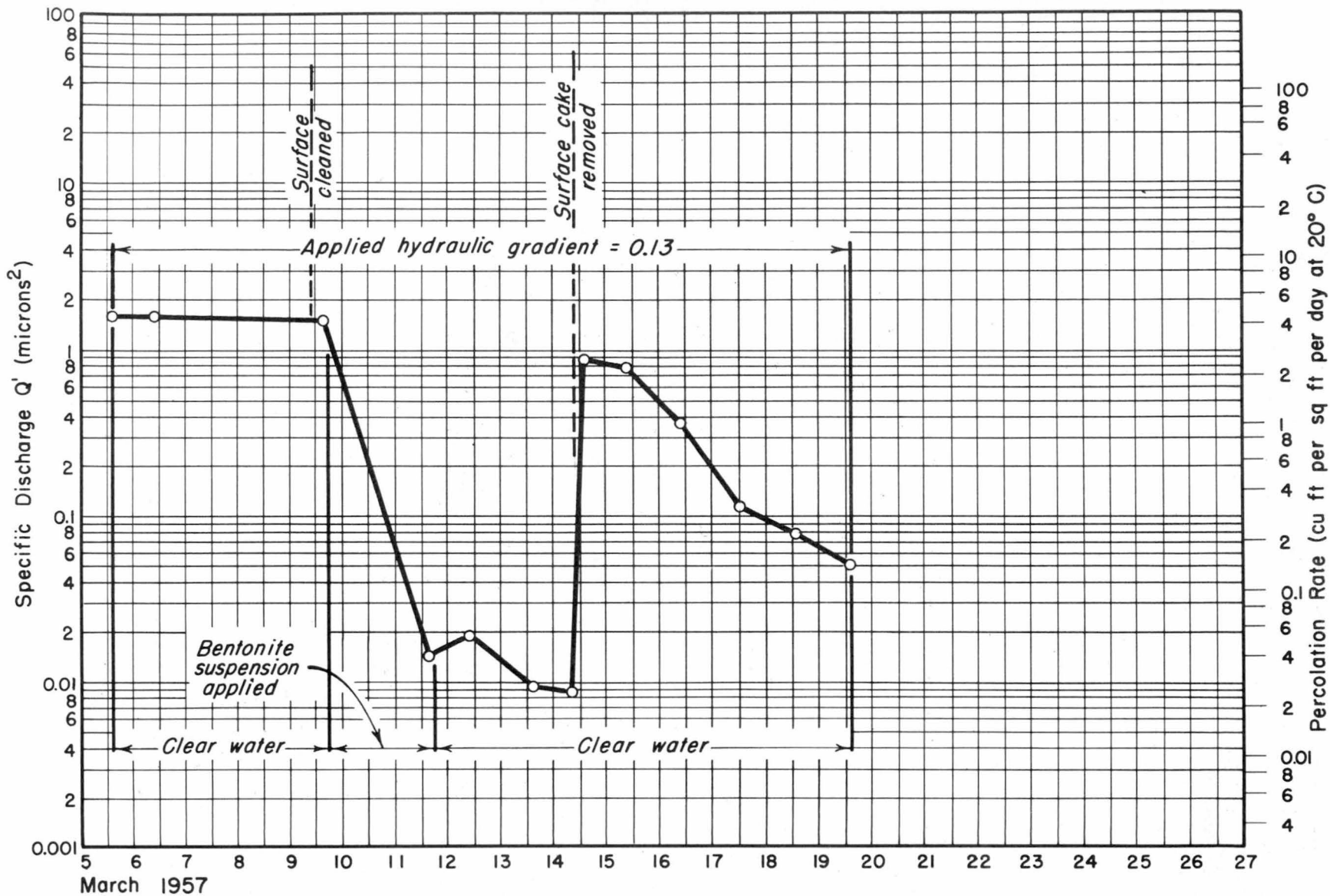


Fig. 17 Time-history of specific discharge for Series VII Run A.
 (Greeley fine sandy loam treated with bentonite suspension under low hydraulic gradient.)

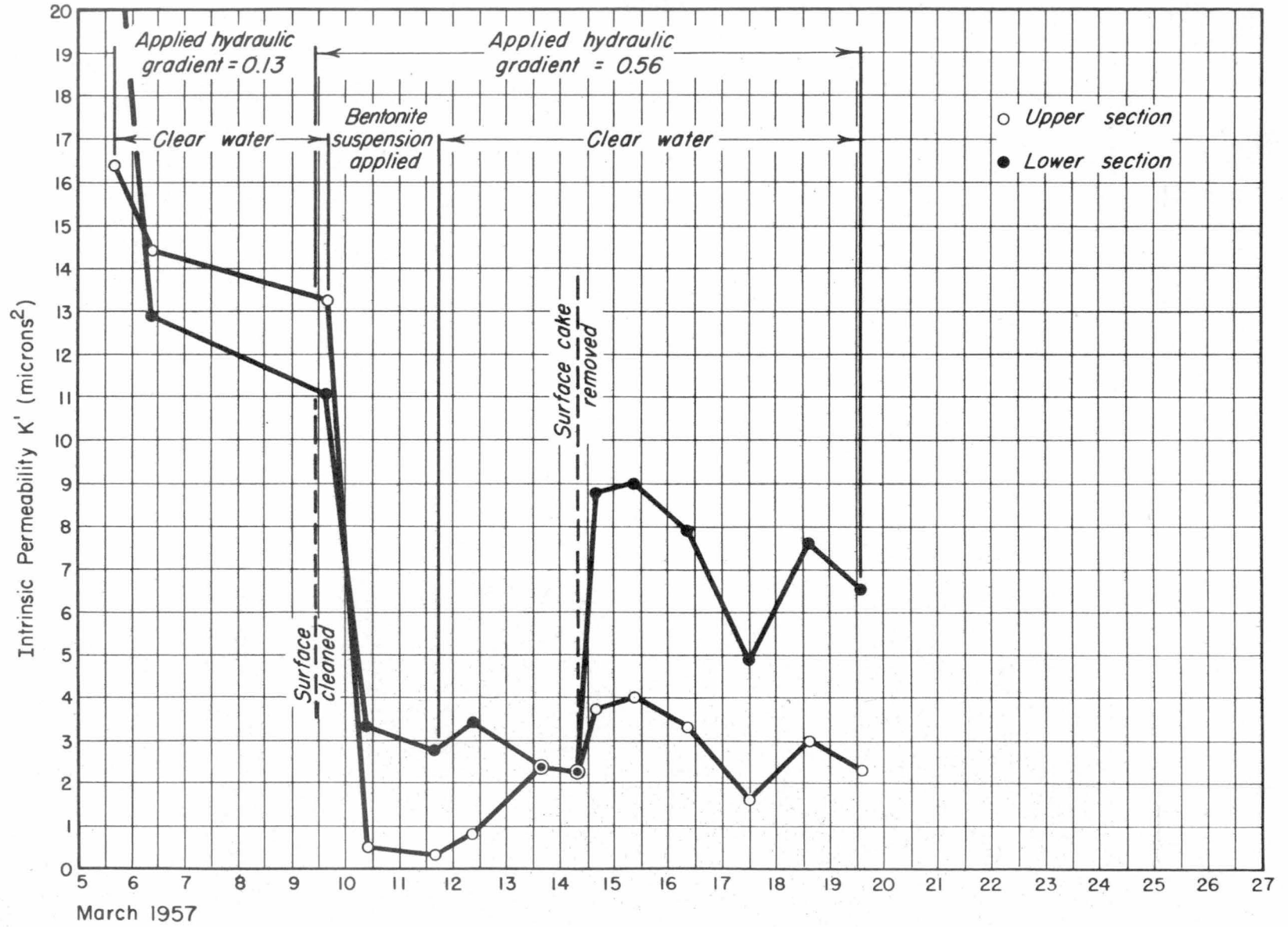


Fig. 18 Time-history of intrinsic permeability for Series VII Run B.
(Greeley fine sandy loam treated with bentonite suspension under medium hydraulic gradient.)

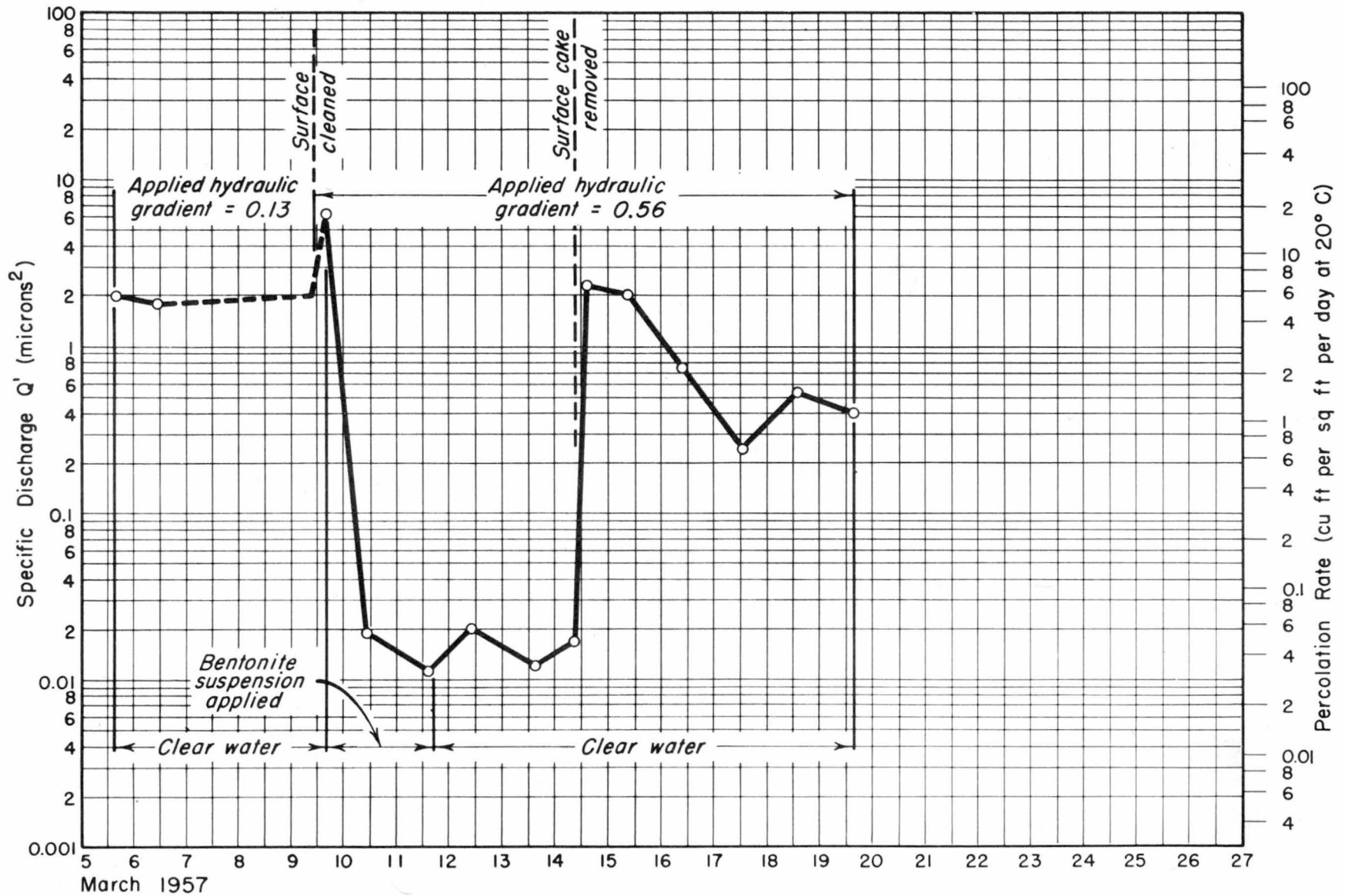


Fig. 19 Time-history of specific discharge for Series VII Run B.
(Greeley fine sandy loam treated with bentonite suspension under medium hydraulic gradient.)

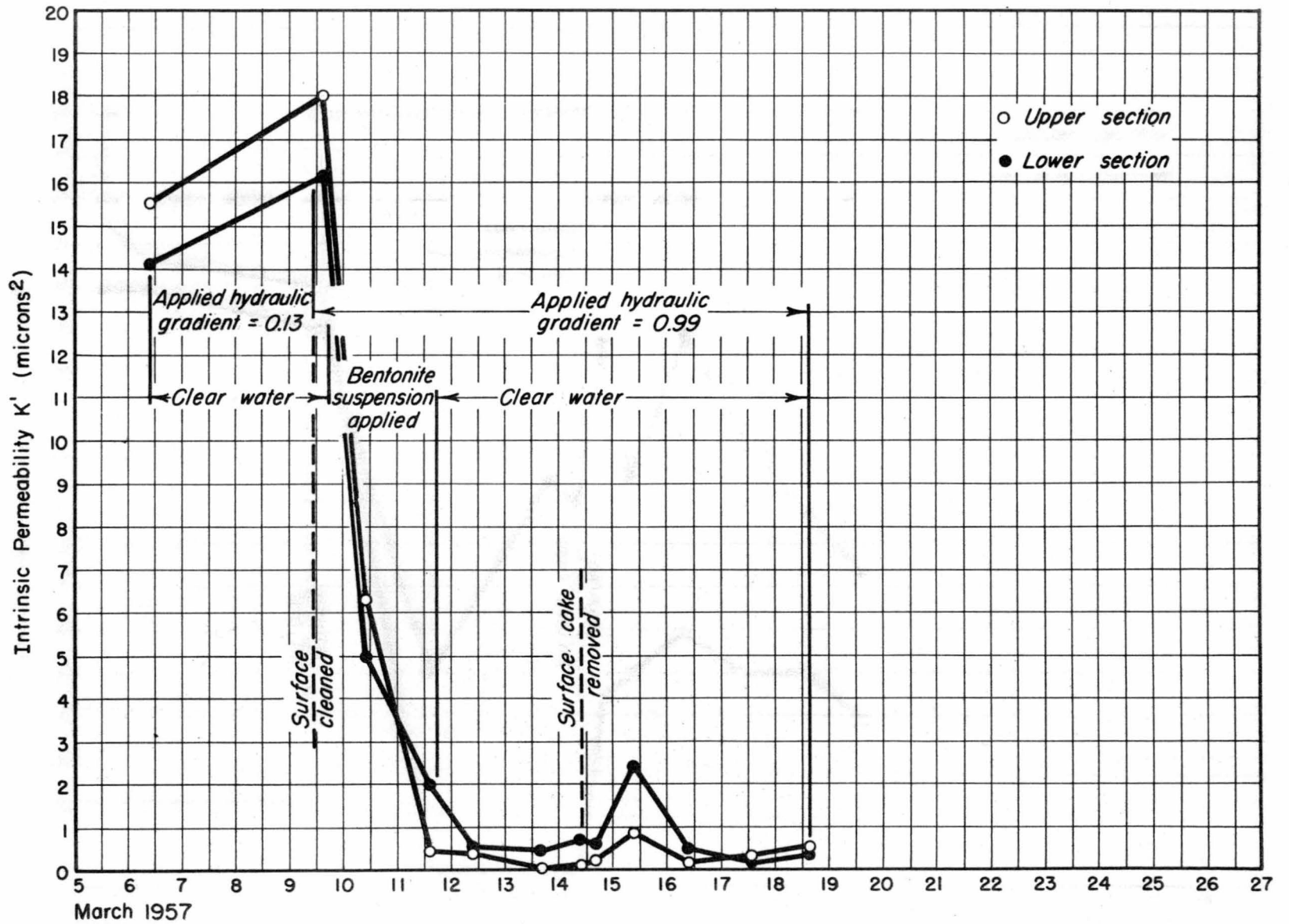


Fig. 20 Time-history of intrinsic permeability for Series VII Run C.
(Greeley fine sandy loam treated with bentonite suspension under high hydraulic gradient.)

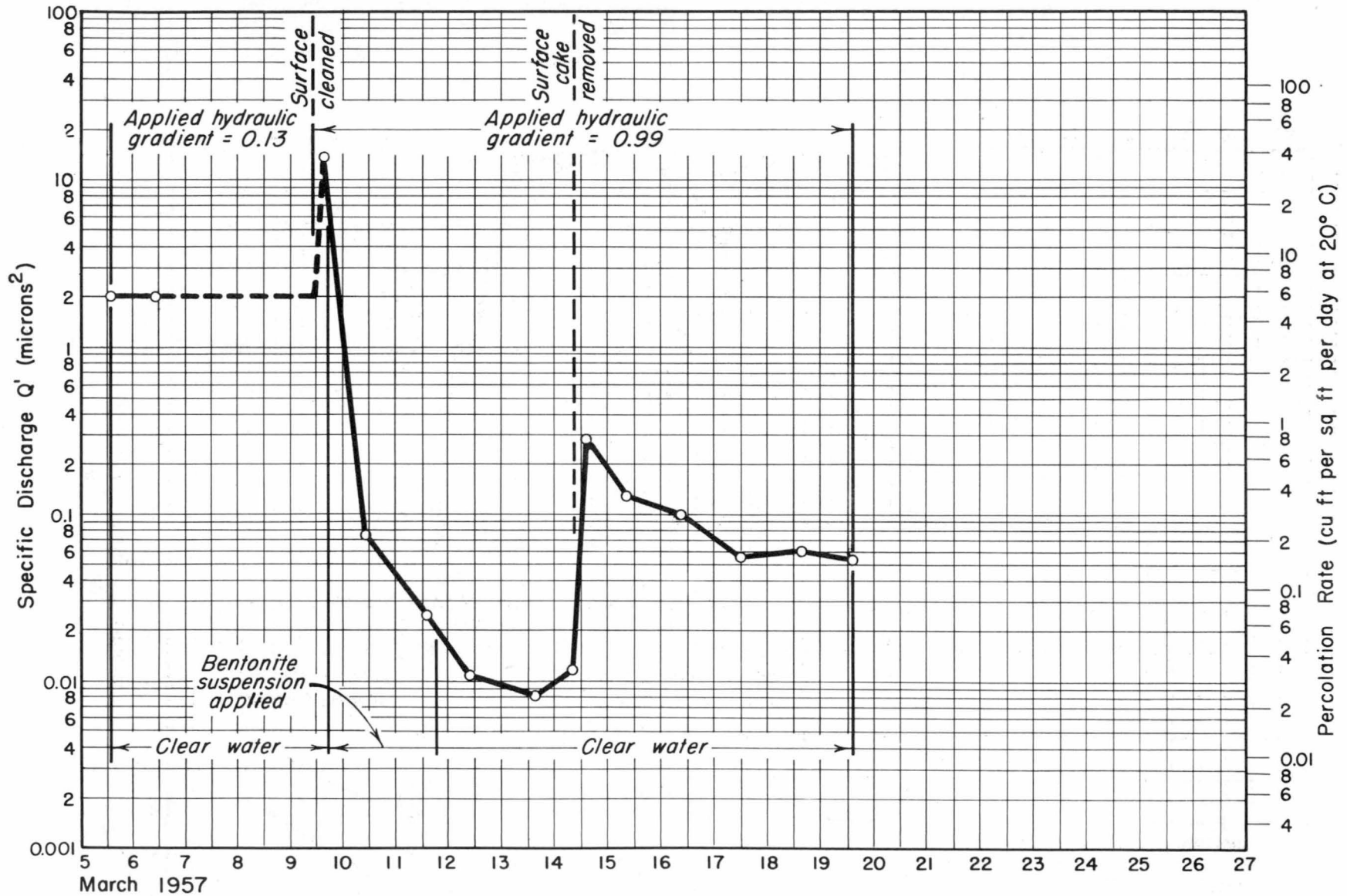


Fig. 21 Time-history of specific discharge for Series VII Run C.
(Greeley fine sandy loam treated with bentonite suspension under high hydraulic gradient.)

Series VIII (Loveland Lake sand treated with dispersant solution)

A discoloration phenomenon similar to that of Series VI was observed. The sealing effect, obtained in all three runs, was more penetrating however than in Series VI. Toward the end of the series the sealing could be considered complete for all practical purposes. In Run A, under low applied hydraulic gradient, the upper section was sealed so tightly that the differential manometer reading for the lower section was too minute to be accurate. Consequently the computed lower section permeability for the last two readings cannot be reliable. Some time during the application of dispersant solution, a leak developed in Run B at the bottom of the filter box. This leak became progressively worse until the tailwater surface fell far below its intended level and no effluent could overflow into the cylinder for volumetric measurement. This great increase in hydraulic gradient, however, did not destroy the sealing within the soil column. The time histories of the permeability and specific discharge are presented in Figs. 22 and 25.

Clay-content Evaluation

The ethylene glycol retention determination is a relative measurement of surface area and has served well to compare the clay-content of each sample of soil with that of the original untreated soil. All samples were run in duplicates or triplicates and the average values were taken. During the last run the vacuum pump was not in good working order and could not render the same low pressure obtained during the earlier runs. Consequently, the results for Series

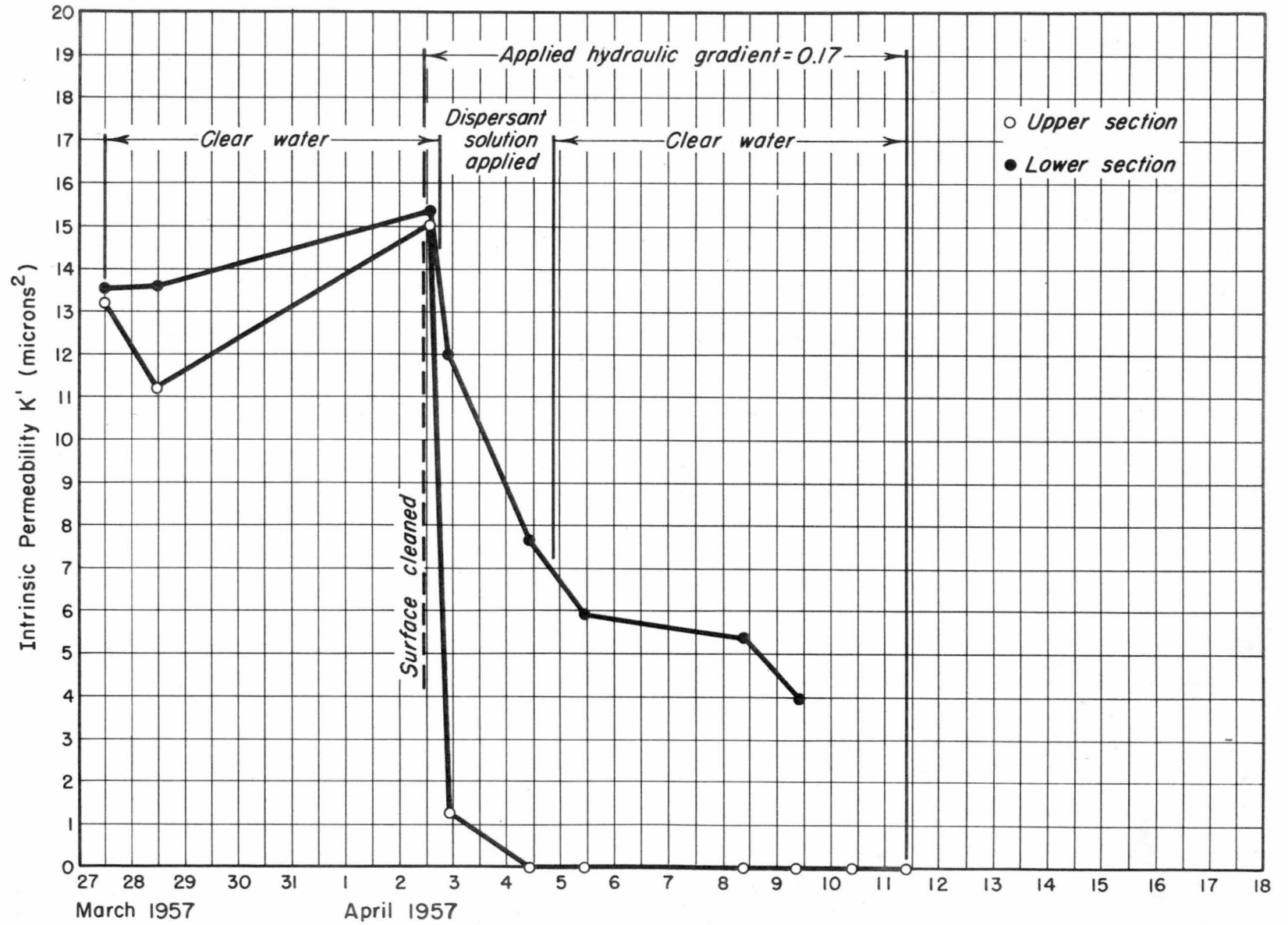


Fig. 22 Time-history of intrinsic permeability for Series VIII Run A.
(Greeley fine sandy loam treated with bentonite suspension under low hydraulic gradient.)

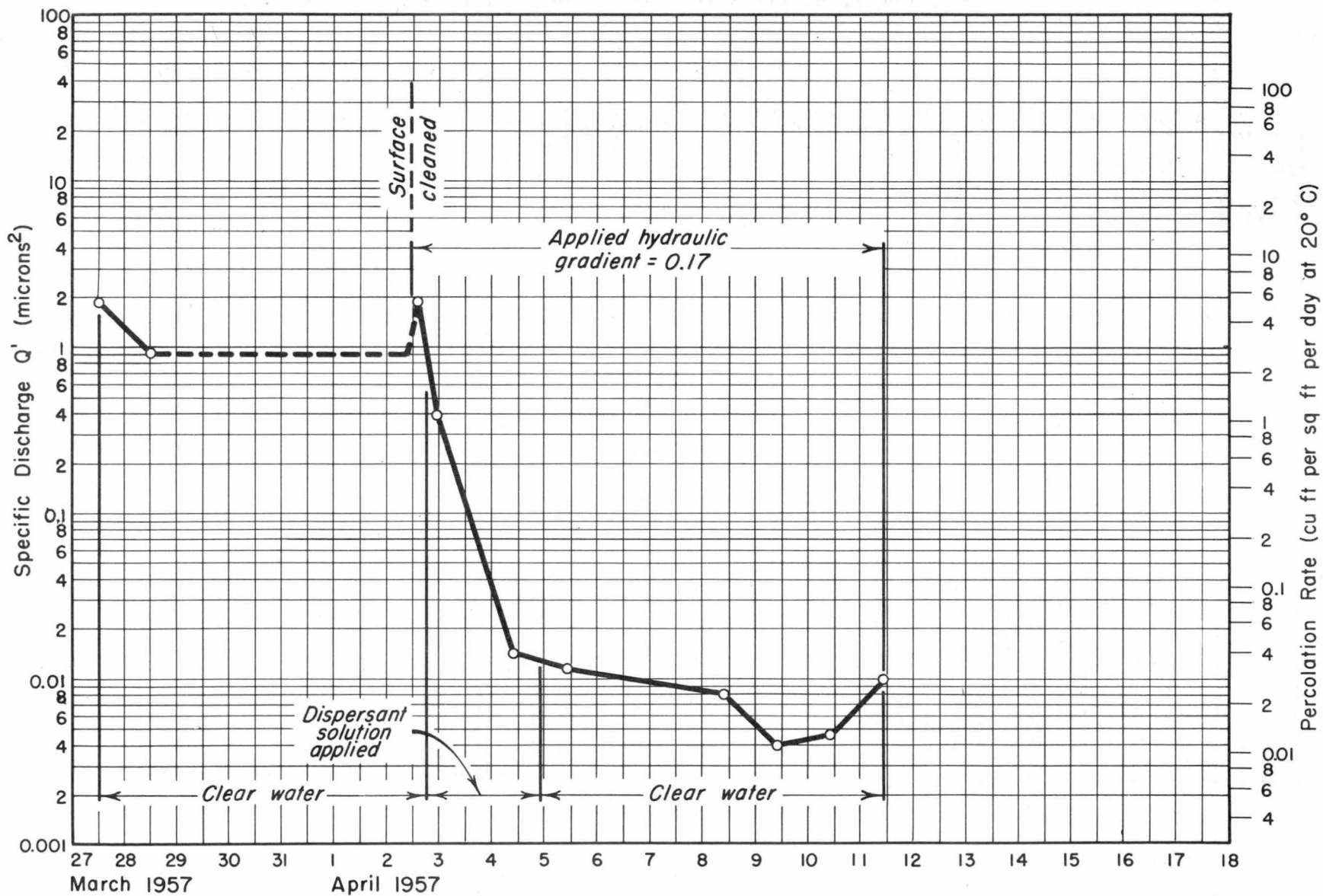


Fig. 23 Time-history of specific discharge for Series VIII Run A.
(Greeley fine sandy loam treated with bentonite suspension under low hydraulic gradient.)

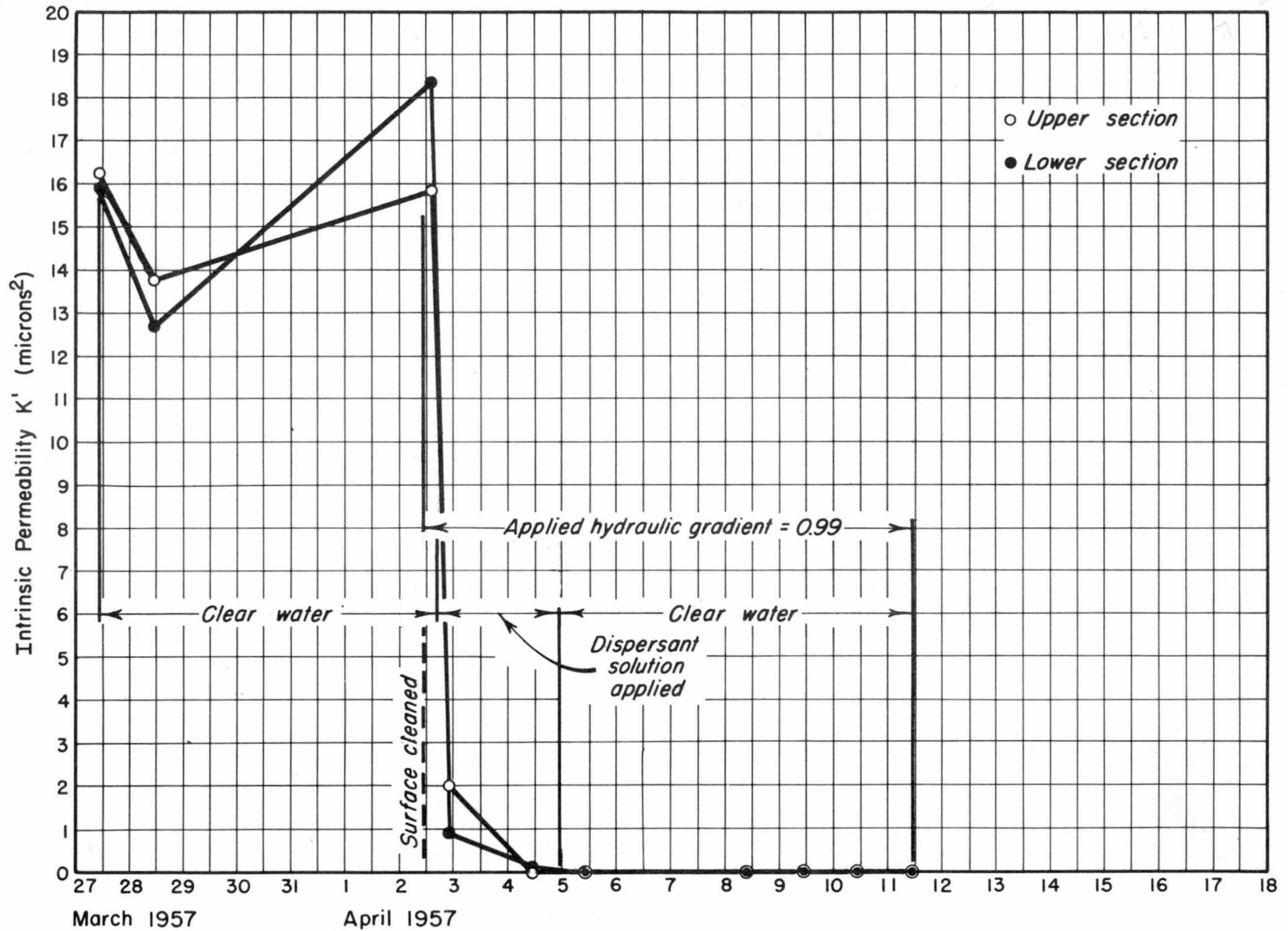


Fig. 24 Time-history of intrinsic permeability for Series VIII Run C.
(Greeley fine sandy loam treated with bentonite suspension under high hydraulic gradient)

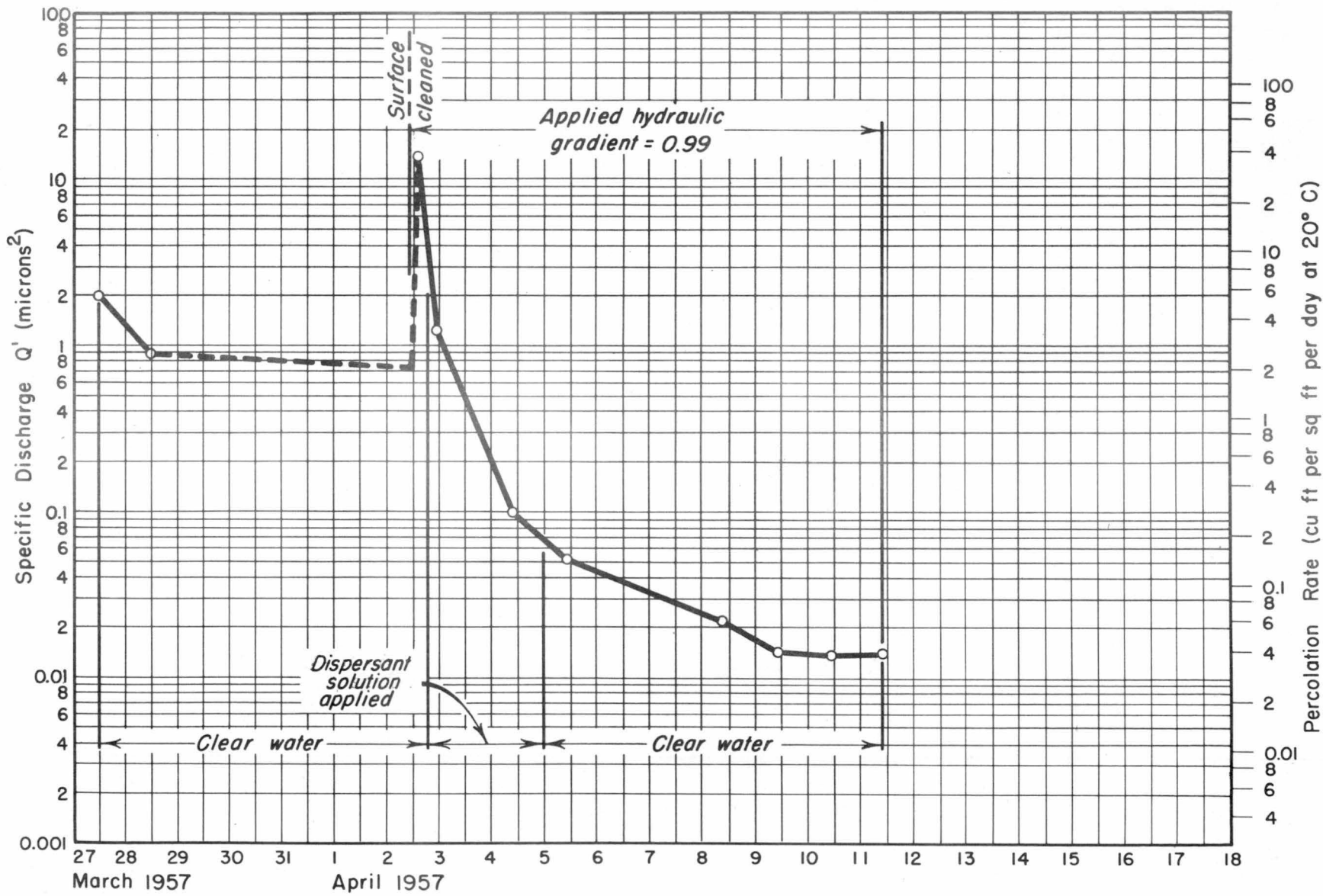


Fig. 25 Time-history of specific discharge for Series VIII Run C.
(Greeley fine sandy loam treated with bentonite suspension under high hydraulic gradient.)

VIII, Run A cannot be compared quantitatively with the other runs, although they are qualitatively valid.

The following table shows the differential of ethylene glycol retained per unit weight of each sample compared to that retained by unit weight of untreated soil¹. The average retained by the untreated Greeley fine sandy loam was 24.3 milligrams per gram of soil, and that by the untreated Loveland Lake sand was 3.0 milligrams per gram of soil (except in the case of Series VIII, Run A, which was 6.0 milligrams for the reason mentioned above). Standard deviation of these averages is less than 1.4 milligrams in all cases, therefore any increase or decrease of 1.5 or more is significant.

¹ The amount of ethylene glycol retained at the point when the rapid loss of weight of the sample was retarded to a very slow steady rate.

Table 5.--RESULTS OF ETHYLENE GLYCOL RETENTION DETERMINATION

Series V (Greeley Fine Sandy Loam Treated with Bentonite)				Series VI (Greeley Fine Sandy Loam Treated with Dispersant)			
Applied Hydr. Gradient	Run			Applied Hydr. Gradient	Run		
	A Low	B Medium	C High		A Low	B Medium	C High
Distance from Top (in.)				Distance from Top (in.)			
0	+0.5	*	+4.5	0	-1.5	-2.5***	+0.5
8	-1.5		+3.5	12	-2.5		0.0
16	-3.0		+3.5	24	-3.5		-2.0
24	-2.7		+1.0				
Series VII (Loveland Lake Sand Treated with Bentonite)				Series VIII (Loveland Lake Sand Treated with Dispersant)			
Applied Hydr. Gradient	Run			Applied Hydr. Gradient	Run		
	A Low	B Medium	C High		A Low	B High	C*** Very High
Distance from Top (in.)				Distance from Top (in.)			
0	+4.0	+4.0	+12.0	0	+0.5	+3.5	+1.5
				2	0.0	+3.0	+1.5
				4	+1.8	+3.5	+2.5
				6	+0.5	+3.5	+2.8
8	+4.5	+5.3	+7.3	10	+1.0	+3.0	+2.8
16	+3.8	+4.0	+6.5	17	+1.0	+3.0	+3.3
24	0.0	+4.3	+4.0	24	+1.5	+2.5	+3.0

* Leaked at boundary. ** Discolored section at the top. *** Disproportionately high gradient caused by a leak in the tailwater tube.

Note: Numbers represent difference between sample and untreated soil in milligrams of ethylene glycol retained per gram of soil. Positive and negative signs indicate increase and decrease respectively.

IV. DISCUSSION

The four series of tests described here, despite their restricted laboratory conditions, furnish further support to the conclusions arrived at by Newman¹. They also disclose additional information regarding the sealing effect obtained by treatment with the dispersant solution alone. The results establish that, under favorable environment and with good installation techniques, the sediment sealing method can significantly reduce canal seepage losses. Furthermore, they indicate the need for more understanding of the mechanics of the sealing phenomenon, especially under field conditions, hence more elaborate procedure and wider range of experimentation.

Penetration and Retention

It may be safely assumed that any added presence of bentonite in the soil column will contribute to the reduction of intrinsic permeability. The questions arise as to how penetration of the bentonite suspension below the soil surface can be effected and how, after penetration, the bentonite can be retained. Judging from the test results, three factors may be considered dominant in governing the penetration and retention, viz., bentonite particle size and applied hydraulic gradient.

Curry (2) achieved penetration in Ottawa sand, Loup River sand, Loveland Lake sand, and synthetic zeolite. The USGS achieved penetration in Ottawa sand, Salt Lake sand, Loveland Lake sand, and

¹ See Chapter VI, Part One.

glass beads larger than 28-micron size. Both used 1% suspension of Volclay Bentonite² after standing for 24 hours. However, the former applied a hydraulic gradient of four while the latter applied that of less than one. Besides, Curry closed the outlet valve for 24 hours in some cases thereby altering the hydraulic gradient. Their results cannot therefore be compared directly, nor can their conclusions be considered complete. On the one hand, information on the hydraulic gradients generally found in the field is incomplete but in many instances they appear to be much lower than Curry's, so that it is entirely possible that successful penetration into the soils he tested is much more difficult under field conditions. On the other hand, it may be feasible to penetrate into soils finer than 28-micron size with a bentonite suspension of either lower concentration or finer-sized particles than used by USGS or with a longer sedimenting period than 24 hours. Curry's failure to retain the bentonite in the soils may also be attributed to the high hydraulic gradient and therefore may be of little practical significance.

The work by Curry and USGS indicated that an appreciable sealing effect can be achieved with only a trace of bentonite retained. In fact, in almost every case some sealing was detected even without retention at all. This creates a suspicion in the adequacy of the sensitivity of the benzidine-stain test and also arouses further postulation on the actual mechanics of the sealing phenomenon. Newman improved the clay detection method by using the hygroscopic moisture ratio determination,

² Commercial high-swelling Wyoming bentonite marketed by American Colloid Company.

and introduced a treatment with dispersant solution alone as a first step toward understanding the fundamentals of the sealing process.

Newman experimented on only one soil material, a dune sand with very little clay placed at one nearly uniform bulk density. He obtained penetration for runs having hydraulic gradients of 0.1 or greater. In the present program the hydraulic gradient ranged between 0.1 and 1.0, which is a range reasonably expected to occur in nature. Penetration was obtained in all runs on Loveland Lake sand and all runs except at the lower limit of hydraulic gradient on Greeley fine sandy loam. Hence, it may be concluded that penetration is directly proportional to the hydraulic gradient and that it is dependent on particle size of the soil. It is evident that the smaller the particle size the more difficult the penetration, although how the uniformity and the gradation of particle size affect penetration remains to be tested. In this regard, future studies may be directed toward evaluation of the influence of soil structure, pore size, and secondary void openings on penetration.

It is logical to suspect that the ease of penetration may depend also on the particle size of the bentonite. The data available so far cannot furnish sufficient information for a conclusion. Curry let the suspension stand for 24 hours and claimed that it then contained particles of 2-micron size or smaller; Newman followed the same procedure to obtain the so-called maximum one-micron sized suspension. The validity of such claims is questionable. The fall velocity of particles stipulated by Stokes' Law cannot prevail for bentonite particles because

of their colloidal size, not to mention their platey shape in contrast to spheres. Moreover, the chemical environment affecting zeta potential and adherence of ions may well be the major governing factor of the penetration process insofar as the bentonite suspension is concerned. Consequently, it seems appropriate at this time to draw no conclusion but recommend further studies of this aspect of the penetration phenomenon.

Total Surface Area

Both hygroscopic moisture ratio determination, used by Newman, and ethylene glycol retention test, used in the present program, furnish results to indicate the relative total soil surface. This is proven to be a valid test of clay-content (5). Newman found a decrease in surface area in all cases except those treated with bentonite suspensions of maximum one-micron size under a hydraulic gradient of 0.10. Nevertheless he achieved some sealing in all cases treated with dispersed bentonite suspension. In the present program, mostly increase in surface area has been disclosed. Since both tests are relative and depend greatly on environment control, it is futile to compare these results directly, especially when the soils tested were not identical.

In the light of the results from ethylene glycol retention test, the following general statements may be justified:

- (a) When Greeley fine sandy loam is subjected to permeating water some fines are washed out.

- (b) Dispersed bentonite suspension under an applied hydraulic head of 0.16 cannot penetrate and replace the washed-out fines; yet some sealing can be effected (Series V, Run A).
- (c) Dispersed bentonite suspension under an applied hydraulic head of 0.96 can penetrate the soil and more than replace the washed-out fines, hence almost complete sealing can be effected (Series V, Run C).
- (d) When Loveland Lake sand is treated with dispersed bentonite suspension, penetration and sealing take place (Series VII).
- (e) When Greeley fine sandy loam is treated with dispersant solution some fines are washed out, sealing occurs only at the surface (Series VI).
- (f) When Loveland Lake sand is treated with dispersant solution an increase in total surface is noted and almost complete sealing can be effected (Series VIII).

Several explanations can be offered for the sealing effect accompanied by a reduction of total surface area, such as re-arrangement of the remaining fines into a tighter packing and replacement of in-place clay by the more impermeable bentonite particles. The apparent increase in total surface area of Loveland Lake sand treated with dispersant solution may be attributed to the dispersion of clay particles originally adhered to the sand grains. These are only speculations, however, which cannot be verified without additional data.

Other Factors

Aside from hydraulic gradient, the element of time may have considerable influence on the sealing phenomenon. For instance, penetration may be attained with prolonged treatment even if the soil surface is not very porous; enough bentonite to effect a complete seal may be accumulated with prolonged treatment even if the concentration of the suspension is low; retained bentonite may be washed out in time even if the sealing is apparently complete.

The experiments hitherto conducted have been on homogeneous soil samples. The packing has been artificially rendered exceedingly loose. In the field, one is apt to be confronted with much different bulk densities; and it stands to reason that any appreciable change in density will materially alter the requirements for penetration and retention. It must therefore be recognized that the ease of penetration in the laboratory may not be obtained under all field conditions. Thus further studies may be aimed at reducing the necessary concentration of bentonite suspensions to facilitate penetration. It should be noted that the reduction of the amount of bentonite required for mixing will also reduce cost as well as operational inconveniences.

The presence of stratified or otherwise heterogeneous structures, including macropores, will present both new problems and new advantages. Animals, marine life, plants, and microbes may all contribute toward non-uniformity in packing; yet the related macropore development may assist sediment penetration and sealing in depth. Actually heterogeneity in soil structure and secondary void space development are rather the rule than the exception. The results of laboratory testing should be viewed with this important consideration in mind.

The water used in the laboratory was very soft and artificially rendered air-free. Also a steady-flow condition exists in the permeameter with no turbulence. In the field allowance must be made for a harder water. As for the effects of dissolved air and turbulence, such as the extent to which air bubbles will disrupt or increase the building of impermeable strata, further studies are necessary.

Another important factor, which undoubtedly influences the permanence of any achieved sealing, is climatic changes. The water temperature in the laboratory varied from 19° to 37°C, which is a very limited range compared to the field conditions. Alternative drying and wetting, freezing and thawing present another phase for future investigation.

Finally, a vast number of soil types remain to be tested to cover the range of bed materials encountered in leaky channels. Also a great many materials may be tried besides bentonite. Sodium tripolyphosphate solution alone is indubitably effective in certain soils under certain conditions as demonstrated in the present program. Thus it may be stated conclusively that the sedimenting method of sealing canals is fundamentally feasible but extensive research and practical development work are required to perfect its technique.

V. SUMMARY

This research program was a continuation and expansion of the work done by Newman as presented in Part One of this report. It was aimed at further studies of the penetration and sealing effects of the sediment-sealing method.

Two types of soil, Greeley fine sandy loam and a sand from the shore of Loveland Lake, were tested in the laboratory. They were uniformly packed by being dropped into carbon dioxide in plastic columns, 5 in. in diameter and about 24 in. in length. Clear tap water was run through these columns until the permeability became stable. Then the sedimenting treatment was introduced, consisting of either a one-percent dispersed Wyoming bentonite or a 0.2-percent solution of sodium tripolyphosphate (the dispersing agent alone). The period of treatment ranged from 24 to 53 hours; and the applied hydraulic gradient ranged from 0.1 to 1.0 approximately.

After treatment, clear water was again introduced in order to detect any change in permeability. Throughout the runs, manometer readings at various levels along the columns were taken, and the effluent per unit time was recorded at regular intervals. Temperatures immediately above and below the columns were also registered. Thus the intrinsic permeability of the soil columns could be computed and time-history curves could be drawn. Samples from the treated columns were taken and compared with untreated soil for clay content by ethylene glycol retention determination.

Different degrees of sealing in depth were attained although all were sealed at the surface. Sealing was found to be more complete under a higher hydraulic gradient, and also better penetration was obtained with increased hydraulic gradient. An increase in total surface area was noted in the sand column under treatment of dispersant solution alone. This increase, and hence an increase in cation exchange capacity, was accompanied by a considerable lowering of the intrinsic permeability. No complete sealing was noted because the sensitivity of the system of measurement was inadequate for the region of near complete sealing.

BIBLIOGRAPHY

1. Bower, C. A. and Gschwend, F. B. Ethylene glycol retention by soils as a measure of surface area and interlayer swelling. Soil Science Society of America, Proc. 16: 342-5, 1952.
2. Curry, R. B. Penetration and retention of bentonite suspensions in porous media. Fort Collins, Colorado, Colorado A and M College, 1955. 45 p. (CER No. 55RBC9).
3. Dirmeyer, R. D. Jr. Report of sediment lining investigations, fiscal year 1956. Fort Collins, Colorado, Colorado A and M College, 1956. 34 p. (CER No. 56RDD17).
4. Division of Soil Survey. Soil series description. United States Dept. of Agriculture. (Rev. JT 5-2-1946).
5. Dyal, R. S., and Hendricks, S. B. Total surface of clays in polar liquids as a characteristic index. Soil Science 69:421-32, 1950.
6. Fisk, H. G. Bentonite, with test method and results of tests of Wyoming bentonites. Wyoming University, Natural Resources Research Institute Bul. 2-1-39, 1946.
7. Hodgman, C. D. Handbook of chemistry and physics, 33rd ed. Cleveland, Ohio, Chemical Rubber Publishing Co., 1951. 2894 p.
8. Mortland, M. M. Specific surface and its relationships to some physical and chemical properties of soil. Soil Science 78:5, 1954.
9. Newman, B. C. The penetration and sealing effects of dispersed and flocculated bentonite suspensions in a dune sand. Unpublished Master of Science thesis. Colorado A and M College, Fort Collins, 1956.
10. Reeve, R. C., et al. A comparison of the effects of exchangeable sodium and potassium upon the physical condition of soils. Soil Science Society of America, Proc. 18:130-2, 1954.
11. Sweet, A. T., et al. Soil Survey of the Greeley Area, Colorado. United States Dept. of Agriculture, Bureau of Chemistry of Soils, Series No. 5, p. 18, 1929.
12. United States Salinity Laboratory. Diagnosis and improvement of saline and alkaline soils. United States Dept. of Agriculture. Handbook 60:106, 1954.

A P P E N D I X

A. DETERMINATION OF TOTAL SURFACE AREA BY
ETHYLENE GLYCOL RETENTION TEST

From each oven-dry (110°C) sample 2.30 gm is weighed into an aluminum moisture box of known tare weight. This includes samples taken from the soil columns after a run and a sample of the original untreated soil, the Greeley fine sandy loam having been passed through U. S. Standard Sieve No. 50 (0.295 mm). They are placed in a desiccator over phosphorous pentoxide, P_2O_5 , under a vacuum of about 4 mm of mercury, for at least 10 hours. Then they are weighed to the nearest 0.001 gm. About 35 drops of distilled ethylene glycol, $C_2H_4(OH)_2$, are distributed dropwise over the soil surface in each box, and allowed to soak overnight in a desiccator over oven-dry bentonite. Then the same vacuum is applied for about six to nine hours until the soil color begins to lighten. The boxes are all weighed to the same precision and put under vacuum over the bentonite again. Thereafter the weighing is done at hourly intervals until the box ceases to lose weight.

The amount of ethylene glycol retained per unit weight of dry soil for each sample is computed and compared with that for the untreated soil. The difference indicates an increase or decrease as the case may be in total surface area, hence the clay content fluctuation.

B. COLLOIDAL YIELD EVALUATION OF BENTONITE

From an air-dry sample, 10 gm of bentonite is weighed into a soil testing cylinder of 1000 ml capacity. This is soaked in 500 ml of distilled water and mixed thoroughly with an air mixer (see Fig. 13, Part One) for at least 30 minutes. Another 500 ml of distilled water is mixed in so that the level of the suspension comes up to the 1000 ml mark. The suspension is then allowed to stand under cover for 24 hours. At the end of the standing period a siphon is used to remove all the colloidal suspension slowly so that the sediment at the bottom is not disturbed (Fig. 26). The sediment is then washed into an aluminum dish of known tare weight and oven-dried (110°C). The weight of the colloidal portion is obtained by subtracting the dry weight of the sediment from 10 gm. The colloidal yield is expressed in per cent of total weight.

1916-17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100

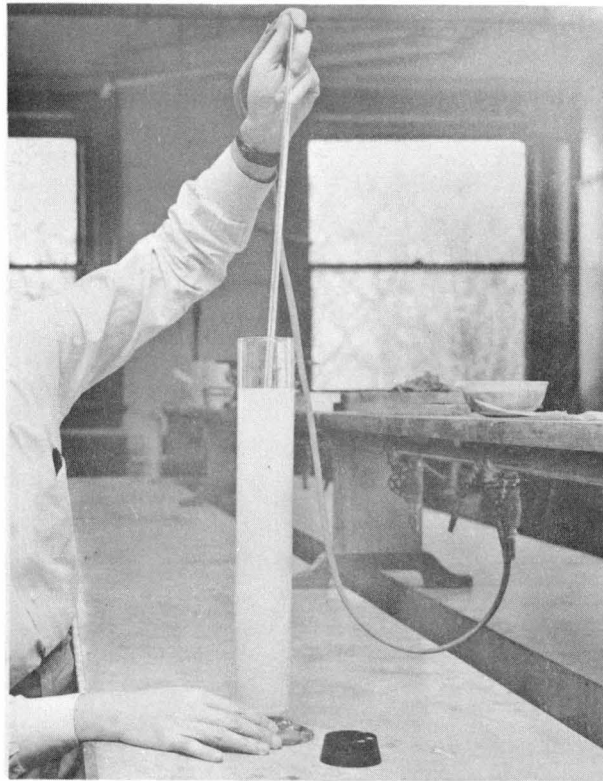


Fig. 26 Removal of colloidal suspension by an aspirator siphon. Note presence of sediment at the bottom of the cylinder.

C. WALL-BUILDING EVALUATION OF BENTONITE (5)

A 6-per cent suspension of bentonite in distilled water, say 24 gm in 400 ml, is made by adding bentonite very gradually into water while a high speed rotary mixer is in operation (Fig. 27). The mixture should be very homogeneous and smooth. This is placed in a special apparatus (Fig. 28) over a piece of filter paper under a pressure of 100 lb/in.². The area of the filter paper exposed to the bentonite slurry is 3 in. in diameter. The filtrate for the first 30 minutes is collected and recorded. At the end of the 30-minute interval the pressure is released, the filter paper is rinsed very gently and measurement of the thickness of the filter cake is taken (Fig. 29).

For a desirable grade of bentonite, the filtrate should be little and the filter cake should be thin.



Fig. 27 Preparation of a 6-per cent bentonite suspension by the use of a high-speed rotary beater.

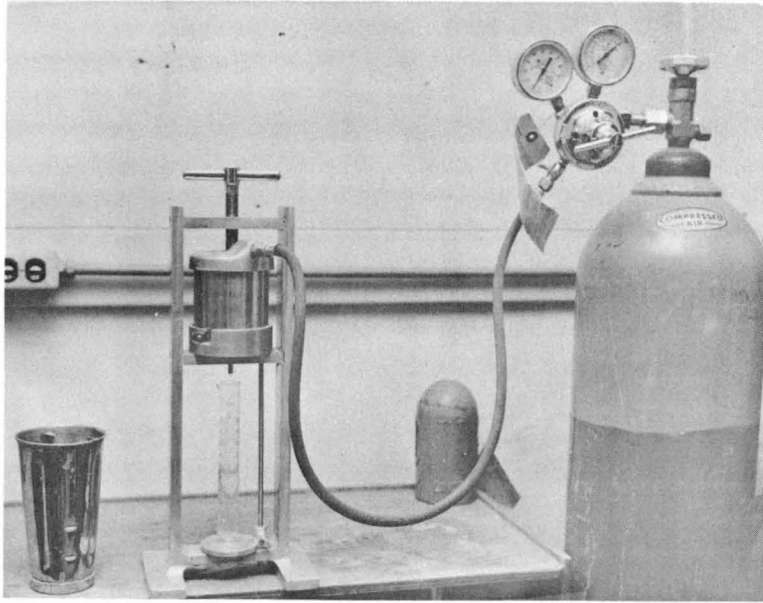


Fig. 28 Wall-building evaluation apparatus in operation. The pressure gage for the compressed air is regulated to read 100 lb/in.². Filtrate is collected into the graduated cylinder.



Fig. 29 Measuring the filter cake thickness in the wall-building evaluation of bentonite.

D. VISCOSITY EVALUATION OF BENTONITE (5)

A "Baroid Viscosimeter" is used for this purpose (Fig. 30).

A small amount of the 6-per cent suspension obtained in the wall-building test (described in C) is needed. This is poured into the test bucket, which in turn is immersed in a water bath to maintain a temperature of 20°C. By trial and error with a stop watch, the weight required to turn the center spindle through six revolutions in exactly six seconds is found. This is then referred to a calibration chart, which furnishes directly the dynamic viscosity of the specimen.



Fig. 30 Viscosity determination of bentonite suspension.