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RATE OF ADVANCE AND INFILTRATION ON FURROW IRRIGATED BLENCOE SOILS IN SOUTHEASTERN SOUTH DAKOTA

BY

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A thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science, Department of
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and Mechanic Arts

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RATE OF ADVANCE AND INFILTRATION ON FURROW IRRIGATED BLENCOE SOILS IN SOUTHEASTERN SOUTH DAKOTA

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser — 3/31/64 Date

Head of Major Department — 3/31/64 Date

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INTRODUCTION

History

The irrigation of the earth has been practiced since the earliest history of man. Irrigation is an age-old art. Historically, civilization has followed the development of irrigation.

The antiquity of irrigation is well documented throughout the written history of mankind. There are some indications from history that the Egyptians used irrigation as far back as 4000 B. C. There are records from China that indicate that the Chinese have practiced irrigation for over 4000 years.

The Bible talks of irrigation in the book of Genesis where the Laws of Hammurabi indicate to the people that they had to depend on irrigation for existence. The letters of Hammurabi about 2000 B. C. indicate that the government was doing much to promote irrigation. Irrigation is also mentioned in II Kings 3:16-17:

> And he said, Thus saith the Lord, Make this valley full of ditches. For thus saith the Lord, Ye shall not see wind, neither shall ye see rain; yet that valley shall be filled with water, that ye may drink, both ye, and your cattle, and your beasts.

Irrigation canals supposed to have been built before 2000 B. C. are still delivering water in the valleys of the Nile. Basin irrigation introduced on the Nile about 3300 B. C. still is very important to Egyptian agriculture.

The success of early kings in China was measured by their wisdom and progress in water-control activities. The famous Tu-Kiang Dam, still a successful dam today, was built in 200 B. C. and still provides irrigation water for about one-half million acres of rice fields.

There are reservoirs in Ceylon more than 2000 years old. Writings from that period indicate that the whole country was under irrigation and was very prosperous.

Irrigation ideas and practices were brought to the United States by the early Spanish missionaries. No effort was made to develop an agricultural economy based on irrigation until 1847 when the Mormans entered the Salt Lake Valley.

The pressure of survival and the need for additional food supplies are necessitating a rapid expansion of irrigation throughout the world. The importance of irrigation in the world today was well stated by N. D. Gulhali of India: "Irrigation in many countries is an old art--as old as civilization--but for the whole world it is a modern science--the science of survival." (7)

Definition

Irrigation can generally be defined as the application of water to the soil for the purpose of supplying the moisture essential for plant growth.

Irrigation may be accomplished in four different ways:

1. flooding
2. furrows
3. sub-irrigation
4. sprinkling.

PURPOSE AND OBJECTIVES

The increase of irrigation interest in southeastern South Dakota has brought about a need for some definite criteria for management. Irrigation management practices have not been fully developed for this area. Climate, topography, and soil conditions are not similar to those of other areas where irrigation management studies have been conducted.

The need for good management practices is very evident in southeastern South Dakota where specialty crops are becoming an important cash crop. If irrigation can be expanded, the growing of sugar beets and other agricultural crops can bring about a great change in the economics of southeastern South Dakota agriculture. The desire of farmers for information on planning and managing an irrigation layout is ever increasing. In order to best recommend an economical system or layout, information must be known about the soils, topography, climate, and crops of the area.

Much of the area under study has relatively flat slopes. With slight land grading and leveling, an economical gravity irrigation system could be developed.

The infiltration rate and furrow length are interrelated factors which determine the efficiency of water use in furrow irrigation. With the infiltration rate known, the period of irrigation time needed to replace given amounts of soil moisture may be computed. In furrow irrigation, the computed period of irrigation time begins after the entire length of furrow is wetted. Therefore, excess water is applied to the upper end of the furrow for a time interval equal to the time it takes water to travel the length of the furrow. Consequently, it is essential to know the influences of soil types and rate of water introduction into the furrow on the infiltration rate and the rate water travels down the furrow.

The objectives of this investigation:

1. To obtain relationships for the rate of advance of the wetting front for the particular soil investigated.

2. To obtain relationships for the infiltration rate of water for the particular soil investigated.

3. To investigate these relations in application to the design of an efficient furrow irrigation system.

REVIEW OF LITERATURE

The use of furrows for irrigating is almost as old as irrigation itself. Continued use and expansion of furrow irrigation has brought the need for more intensive research. Many surface irrigation systems are poorly adapted to the soils and topography. Many investigators have put much effort forward to find information that would be helpful, but the introduction of irrigation to less desirable land has brought a need for additional recommendations. Intake rates and water-holding capacities of the soils often are not known before a field is laid out for irrigation. The length of irrigation run needed for proper distribution of moisture in the root zone seldom is determined before the system is put into operation. Improper operation of a well designed irrigation system can also waste water, damage land, reduce production, and cut down net income.

The Soil Conservation Service (23) has developed a method for evaluating furrow irrigation systems. Lewis (8) has also done similar work. The method consists of measuring flows at points along a furrow to determine the amount of water that infiltrates between those points. The infiltration-time curve has the form:

$$I = KT^n \qquad \text{(Eq. 1)}$$

where:

I = the intake rate per unit length of furrow

T = the time after infiltration begins

K = the intake rate at unit time

n = the slope of the curve when plotted on logarithmic paper.

The exponent n is negative since the intake rate characteristically becomes smaller as the time increases. While this equation is empirical, it adequately represents most field data.

Intake data which does not fit the equation $I = KT^n$ may be represented by a slight modification:

$$I = C + KT^n \qquad \text{(Eq. 2)}$$

where C is the infiltration when T equals infinity.

The area under this curve is the depth of water (D) absorbed during the time (T). This area is, by integration:

$$60\ D = \left[\frac{K}{n+1}\right] T^{\,n+1} \qquad \text{(Eq. 3)}$$

or:

$$T = \left[\frac{60\ D\ (n+1)}{K}\right]^{\frac{1}{n+1}} \qquad \text{(Eq. 4)}$$

The factor 60 is inserted to allow time to be measured in minutes and the infiltration in inches per hour.

If the curve $I = KT^n$ is plotted on logarithmic paper for a furrow, K and n may be determined so that the time may be estimated for any depth of irrigation (D).

Shockley (18) stated that the time required for irrigation is dependent on the amount of water needed to replenish the root zone, the intake rate of the soil, and the furrow spacing. The time of irrigation must include the time for the water to advance to the lower end of the furrow, since the lower end is the location that receives the least amount of water. Shockley indicated that it is desirable to have the water travel the length of the furrow in approximately 25 per cent of the total irrigating time. The largest possible non-erosive stream should be used to advance the water to the lower end of the furrow as rapidly as possible. The furrow inflow should then be cut down to prevent inefficient use of water. The Soil Conservation Service (23) suggested that the "opportunity time" for the soil to absorb water is 25 per cent greater at the upper end than at the lower end. But the intake rate of the soil decreases with time, frequently inversely proportional to the square root of the elapsed time.

D. G. Shockley (19) used unit-streams to analyze an irrigation system. Shockley used a unit area of 100 square feet or an area one foot wide and 100 feet long. The unit-streams developed are the unit-streams required for application at 100 per cent efficiency. The unit-streams must be empirically adjusted for the expected level of field application efficiency. The general formula for the computation of unit-streams for any given soil is:

$$q = \frac{1}{E} \left[\frac{T}{T - T_L} \right] \frac{F}{7.2\ T} \qquad \text{(Eq. 5)}$$

where:

q = unit-stream in c. f. s.

E = efficiency expressed as a decimal

F = desired depth of water application in inches

T = time, in minutes, required for the infiltration of F inches of water

T_L = recession time lag in minutes (from the time the stream is cut off until recession begins).

Shockley (19) also presented an expression for the time required for an irrigation:

$$T = \frac{d}{432\ E\ q} \qquad \text{(Eq. 6)}$$

where:

d = required net depth of application in inches

E = expected efficiency level

q = design unit-stream in c. f. s.

T = time required for irrigation (hours)

Phelan (12), in his analysis, indicated that the maximum non-erosive stream could be expressed empirically as:

$$Q_e = \frac{10}{S} \qquad \text{(Eq. 7)}$$

where:

Q_e = maximum non-erosive furrow stream

S = slope in per cent.

This relationship, though very simple, does closely approximate a constant velocity in a parabolic furrow as computed by Manning's formula:

$$V = \frac{1.49}{n} R^{2/3} S^{1/2} \qquad \text{(Eq. 7a)}$$

where:

V = mean velocity in feet per second

R = hydraulic radius in feet

S = slope of energy line

n = coefficient of roughness (Manning's n).

Since it is a limit only, it appears to be satisfactory for design purposes.

The intake characteristics of furrows are different from those prevailing under flooding methods of irrigation. Some of the factors that may affect average intake in furrows directly or indirectly are:

1. soil type
2. size of stream
3. slope of furrow
4. roughness coefficient
5. furrow cross-section
6. furrow spacing
7. total depth of application.

Some attempts have been made to derive expressions for rate of advance, particularly for irrigation borders. Lewis and Milne (9) derived a rather complex equation for rate of advance in borders. They assumed an estimated depth of water and a predetermined functional relationship for infiltration. The effects of slope and surface roughness are not easy to distinguish but are reflected in the estimate of the depth of the flowing water.

In the design of furrow irrigation systems it is necessary to determine experimentally, or to compute by an analytical expression, the curve for the rate of advance of the wetted front down the furrow. In determining the curves experimentally, it is necessary to introduce furrow inputs of varying amounts into separate furrows and then time the advance of the wetted front as it passes the control points. This procedure can be repeated for different soil types and furrow slopes. The furrows can then be plotted with time (T) as the ordinate and the distance down the furrow (X) as the abscissa. The coordinates of each plotted point indicate the elapsed time that it takes the wetted front to advance to a point down furrow with respect to the head of the furrow. Figure I illustrates a typical set of rate-of-advance curves.

Criddle (3) has outlined a procedure for determining the proper design furrow length using a set of rate-of-advance curves. With the infiltration rate known, the total irrigation time to replace a given amount of soil moisture can be computed. Criddle has shown that for efficient irrigation the wetted front should advance to the lower end of the furrow in 1/4 of the total irrigation time. Therefore, 1/4 of the total irrigation time is computed and the straight-horizontal line is plotted on the same set of axes as the rate-of-advance curves. The value of $\underline{D}'$ at the intersection of the straight-line curve with the rate-of-advance curve becomes the design furrow length. An example is shown in Figure I.

Irrigation research personnel in Japan and Australia have proposed mathematical expressions for the equation of the rate of advance of a wetted front as a function of the furrow input, furrow slope, distance down the furrow, time, and variable coefficients depending on the soil type and furrow geometry. Shibata (17) obtained the following expression for water travel through a furrow on soils of Japan:

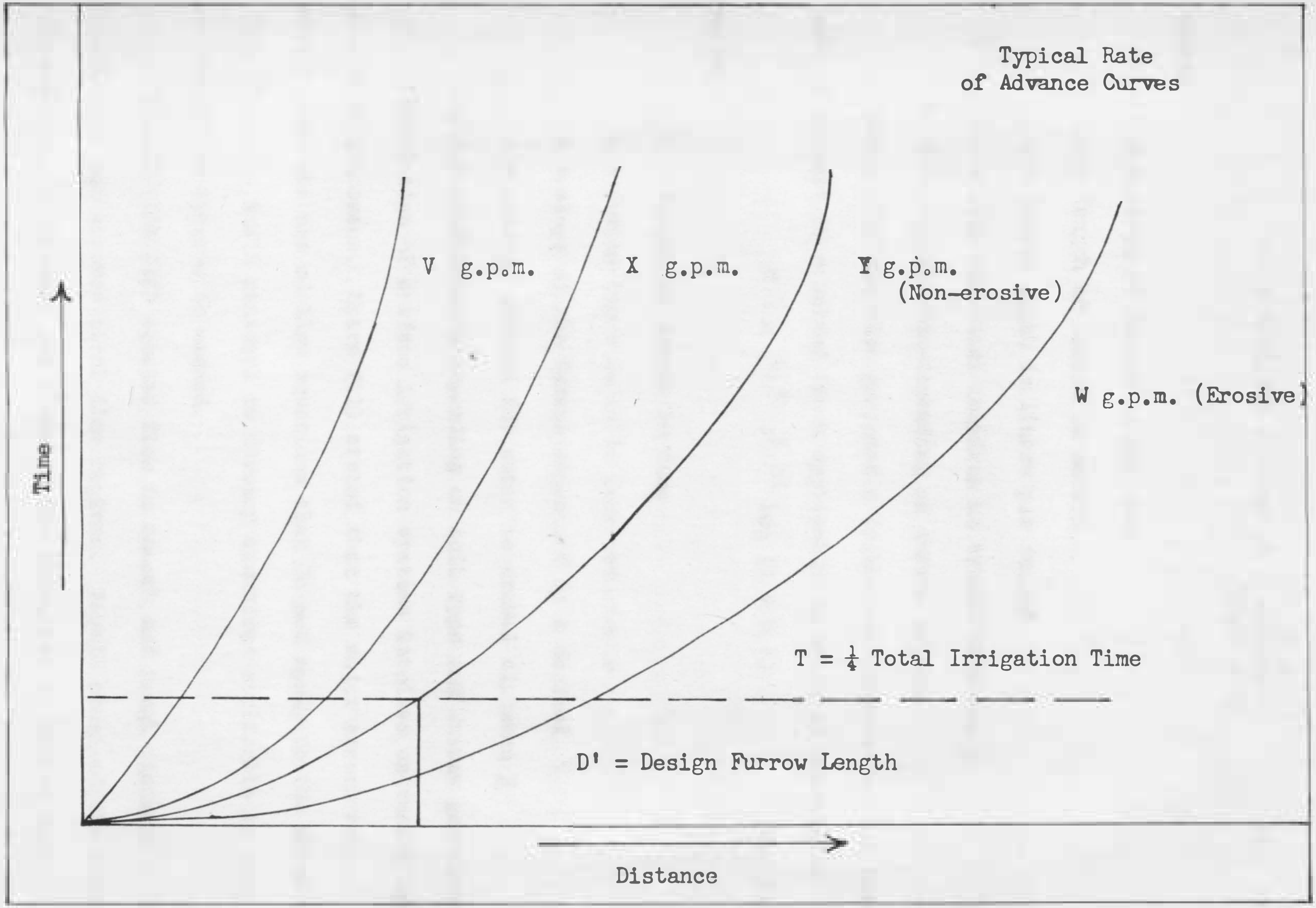


Figure I. Typical Rate of Advance Curves

$$\text{Log } t = (1.608 - 0.106\, q) + \frac{S\, x}{(K\, S - C)} \qquad \text{(Eq. 8)}$$

where:

S = slope of furrow in per cent

x = length of furrow in meters

q = furrow input in liters per second

t = time the water requires to travel distance $\underline{x}$

K, C = coefficients depending on furrow input.

Philip (14) has also proposed a logarithmic expression for the rate of advance of a wetted front applicable to soils of Australia:

$$X = A\, q^{0.72}\, S^{0.20} \log (1 + B\, t) \qquad \text{(Eq. 9)}$$

where:

X = length of furrow in feet

q = furrow input in cubic feet per minute

S = slope of the furrow expressed as a decimal

t = time in minutes for water to travel distance $\underline{X}$

A, B = coefficients depending on soil type and furrow geometry.

The design of surface irrigation systems involves extremely complex flow phenomena. Myers (11) stated that the major errors can result from the use of flow equations that do not apply to the situation at hand. Basic research to develop equations applicable to flow in irrigation furrows is needed.

Powell (15) (16) studied flow in smooth and rough channels with subcritical and supercritical flow regimes. Powell examined the effect of discharge, roughness, and slope on the flow, but he stated that other factors, such as the angle between channel sidewalls and bottom, need to be studied. Powell also did not include in his studies the extreme magnitude of relative roughness likely to be encountered in irrigation furrows.

Hall (5) developed an equation that considered a variable infiltration rate and nonuniform depth of water, the latter reflecting the slope and hydraulic roughness of the soil surface.

Bouwer (2) considered variable infiltration rates in his equations which were solved simultaneously to determine field infiltration rates in borders. This method offers some advantages in its simplicity and may be quite valuable for determining infiltration rates in irrigation furrows.

Philip (13) stated that the initial moisture content of a soil was one of the major factors influencing its infiltration characteristics. High infiltration rates are associated with low initial moisture content and low rates with high moisture content.

Thornton (21) suggested that if the rate of advance when plotted against time is a straight line, there should theoretically be uniform flow. He also suggested that the intake rate of a soil should increase with an increase in temperature as a result of the decrease in the viscosity of the water. The flow into the soil is usually approximately laminar for compact, finely textured soils. The rate of intake should therefore vary inversely as the kinematic viscosity. On this basis, an increase in water temperature of 50 degrees F. should approximately double the intake rate.

The stream width for a given soil has a great effect on the intake rate due to the wetted perimeter. Little (10) pointed out that the depth of the surface head has very little effect on the infiltration. The volume of storage on the surface has a great effect on the rate of advance of the wetted front. Thus for a given furrow size and shape, the stream size or volume of storage should be determined.

The Agriculture Handbook No. 107, Conservation Irrigation, (22) states that the intake rate at which water enters the soil is dependent upon soil-surface conditions and upon the rate at which the absorbed water can pass through the successive soil layers and make room for more water to be absorbed. The soil layer with the lowest transmission rate, whether at the surface or in the subsoil, sets the limit on the intake rate. Regardless of the intake rate or opportunity for water to enter a soil, limiting factors below the surface, such as a hardpan, claypan, rock layer, sand layer, or a heavy clay subsoil, may restrict the downward movement of water.

Holtan (6) discussed the possibility of relating the potential infiltration, that may be expected to occur before a constant rate is reached, to the available porosity and the vegetal cover. Holtan suggested that it may be possible to estimate the potential infiltration by multiplying the available porosity by the basal area of the vegetation. The basal area is the percentage of the ground surface area occupied by roots and stems.

Shockley (18) gave a method of approximating the average intake rate over the time of irrigation. His method was to multiply the final intake rate by a factor that depended on the soil type. Shockley gave the following table of factors for soils of different textures:

Table 1. Soil Infiltration Factors

Soil texture	Soil factor
Fine and moderately fine clays and clay loams	1.50
Medium and moderately coarse silt loam to sandy loam	1.33
Coarse and very coarse loamy sands and sands	1.20

Frevert (4) stated that the infiltration rate of a soil was dependent on the size of the passageways between the soil particles. These passageways were dependent upon the size of the soil particles, the degree of aggregation between the individual particles and the arrangement of the particles. The infiltration rate was affected by antecedent soil moisture conditions. Moisture caused the soil colloids to swell and close the passageways.

Israelsen (7) suggested that the basic variables involved in the hydraulics of surface irrigation are:

1. size of streams
2. rate of advance
3. length of run and time required
4. depth of flow
5. intake rate
6. slope of land surface
7. surface roughness
8. erosion hazard
9. shape of flow channel
10. depth of water to be applied.

The result of improper consideration of these variables will produce nonuniform distribution of water over the field, runoff from the lower end of the fields, and over-irrigation with a loss of water and plant nutrients by deep percolation.

The design of an efficient and practical surface irrigation system should give consideration in some way to each of the basic variables. Proper design and operation can result in saving water, soil, labor, and overall economy.

LAYOUT AND PROCEDURE

The increase of irrigation agriculture in southeastern South Dakota during the past decade brought with it a definite need for more concrete recommendations as to design, layout, and construction of an irrigation system. This investigation was, therefore, designed to aid in answering some of the problems and questions that have arisen.

In the fall of 1962, a plot was selected near Meckling, South Dakota, in Clay County. This location was selected because it was assumed that this soil was representative of much of the soil in the Missouri Valley area suitable for irrigation. Irrigation management practices have not been satisfactorily developed for this area, and climate and soil conditions are not exactly analogous to other areas where irrigation practices have been developed and practiced.

In order to satisfy the objectives of this problem, the experimental plot was designed in a manner so analysis of the data collected would evaluate the following items:

1. furrow infiltration rate
2. rate of advance of wetted front
3. soil moisture percentage.

The plot was approximately 1150 feet in length and 264 feet in width. The plot had been previously leveled to the extent of having furrows of all gradients between 0.10 per cent and 0.25 per cent. It was assumed that the length of 1150 feet would be sufficient to determine maximum length permissible for varying conditions encountered.

The plot was planted to sugar beets on April 6th with 22-inch row spacings. The plot was then laid out as shown in Figure II.

Soil moisture samples were then taken approximately every week at twelve locations on the plot, as shown by Figure III. These samples were then oven dried and a record kept of the moisture percentage in the top four feet of soil. The moisture samples were taken at each foot interval.

Approximately the first of June, after the field had been cultivated once, two-inch Parshall flumes were installed at the lower end of each slope strip. The flumes were installed to obtain a record of any excess runoff that might occur. The runoff was recorded by installing Leupold & Stevens Type F stage recorders above the flumes with a float placed in the wells attached to the side of the Parshall flumes. It was decided to direct three furrows into each two-inch Parshall flume to obtain a better average of the runoff. Figure IV shows a two-inch Parshall flume and recorder installed at the lower end of the plot. The taller white instrument in Figure IV is a three-point temperature recorder.

Soil tension samples were secured at each location where soil moisture samples were taken, in order to obtain wilting point and field capacity percentage. This made it possible to estimate when the soil moisture was reaching the wilting point and when to irrigate.

About the 15th of June, construction was completed on several tensiometers which were installed at the locations shown by Figure V. The tensiometers were installed at four locations and at depths of

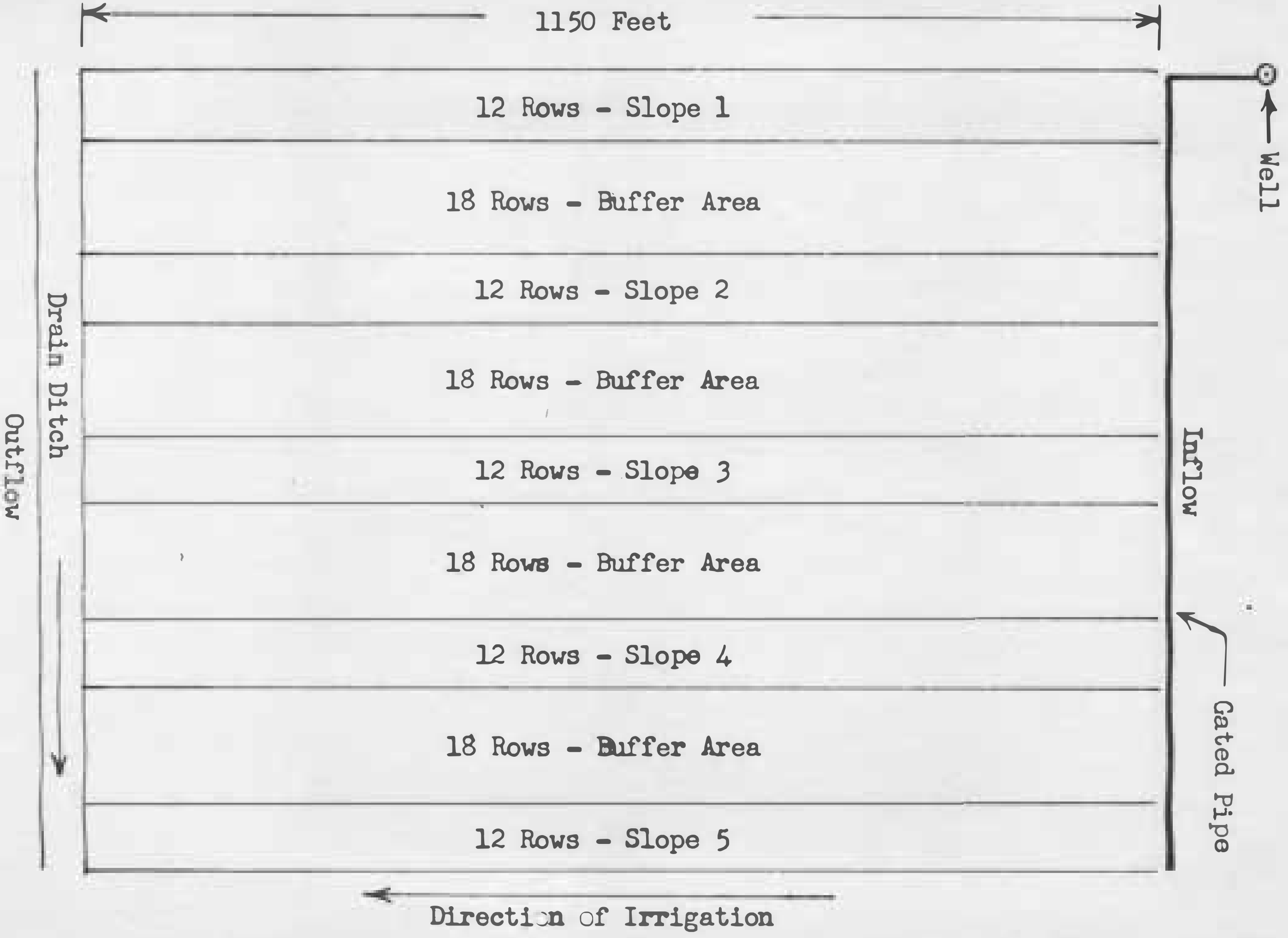


Figure II. Plot Layout

Figure III. Location of Soil Moisture Samples

Figure IV. Two-inch Parshall Flume and Recorder

Figure V. Location of Tensiometers

6 inches, 12 inches, 18 inches, 36 inches, and 48 inches. Figure VI illustrates one of the constructed tensiometers, and Figure VII shows a group of tensiometers installed in the field. It can be noted that the tensiometers were installed in the beet row to make it possible to cultivate the beets without disturbing them. Readings were then made periodically and records kept to indicate when to irrigate.

The first irrigation, July 1, was used as a trial irrigation. The water was supplied to the head of each furrow by gated pipe with 22-inch gate spacing. Figure VIII shows the gated pipe supplying water to the furrows at the upper end of the field. Figure IX illustrates the tractor and pump used to supply water to the gated pipe.

The second irrigation, July 22, was used for furrow infiltration and advance studies. Before the second irrigation the field was again furrowed. Figure X shows the cultivator used for furrowing. Four-inch diameter pipes were pulled behind the Planter Junior furrow openers.

The grade of each individual test furrow was then secured by bench leveling to obtain a more accurate reading of the slope of each furrow. The results are shown in Figure XI. The five test furrows were selected in the center of each slope study strip. This made it possible to use the remainder of each strip for border or buffer furrows.

Before irrigation, soil moisture samples were secured at locations stationed along the test furrow of each slope. It was assumed that this would make it easier to estimate how much water would be

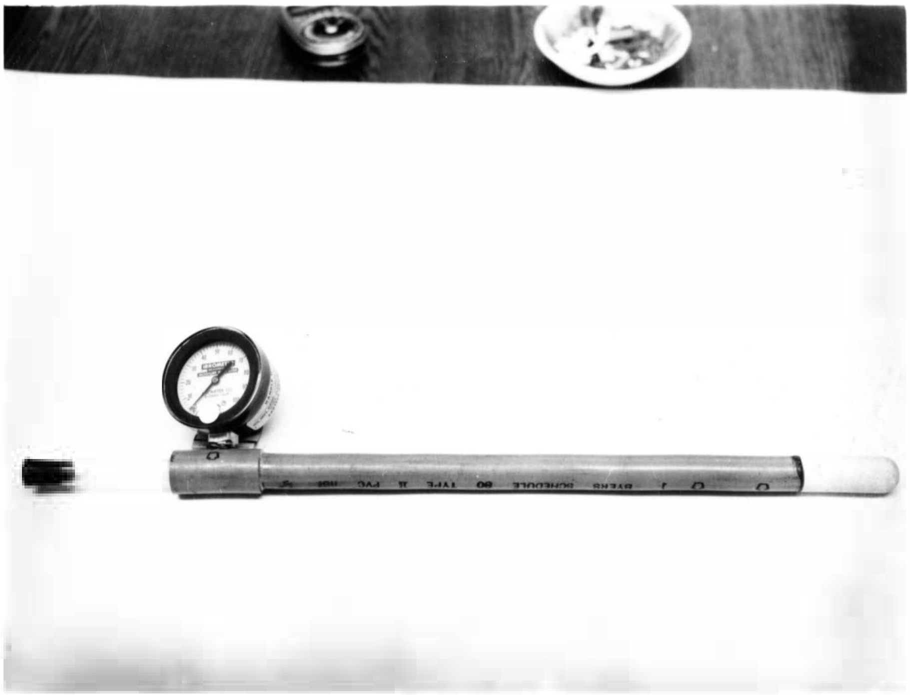


Figure VI. Constructed Tensiometer

Figure VII. Tensiometers Installed in the Field

Figure VIII. Gated Pipe Supplying Water to Furrows

Figure IX. Tractor and Pump Supplying Water

Figure X. Furrowing Cultivator

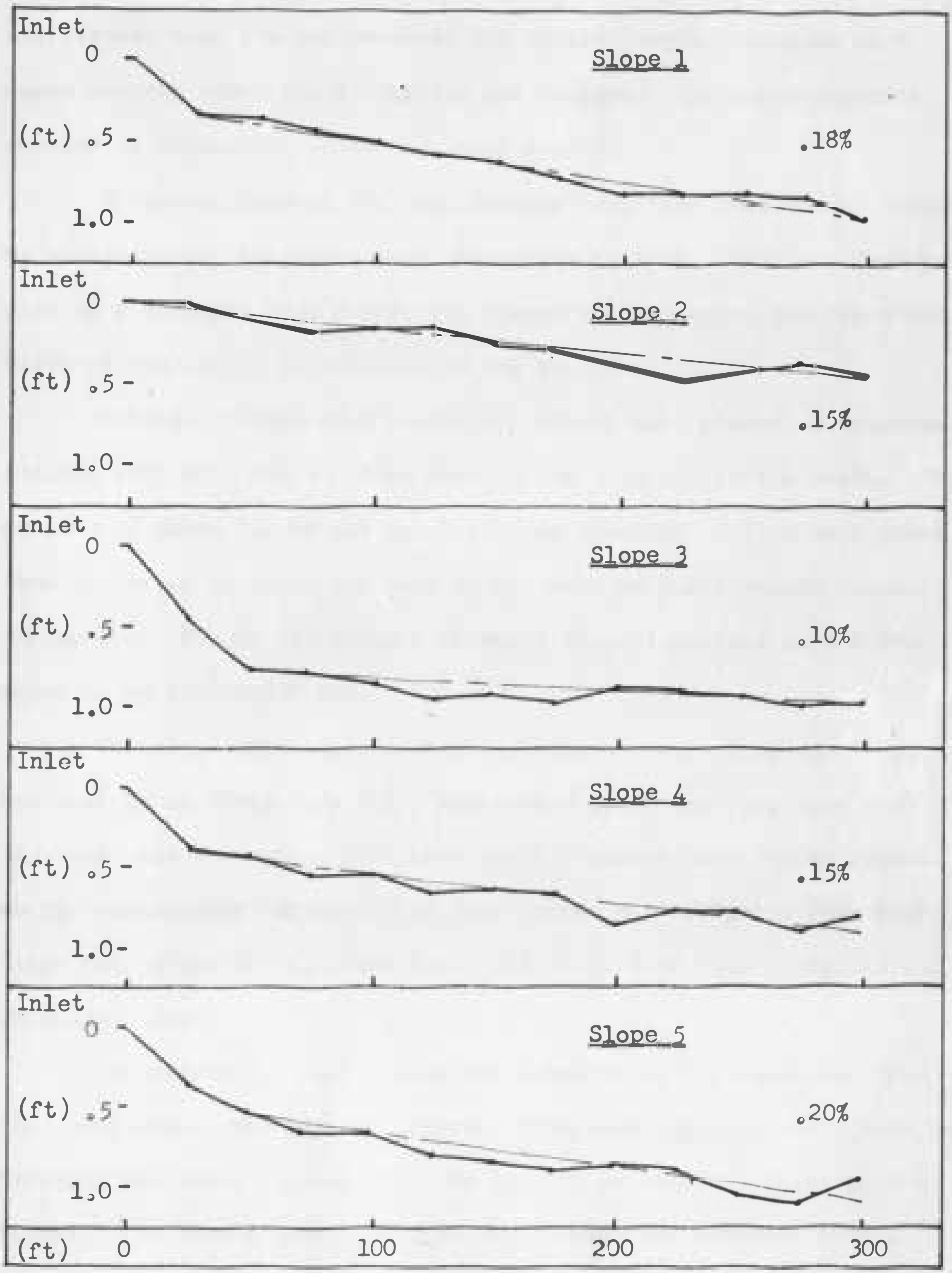


Figure XI. Furrow Slopes

infiltrated into the furrow along its entire length. Samples were again secured after the irrigation and compared with pre-irrigation samples to obtain the amount of water stored.

Cross-sections of the test furrows were then recorded to assist in analyzing the hydraulic characteristics of each. This was done by placing a straight edge across the furrow and measuring the depth and width of the furrow in relation to the straight edge.

Parshall flumes with a one-inch throat were placed at stations located 100, 200, and 300 feet down furrow from the furrow inlet. The purpose of these flumes was to obtain the quantity of flow at a given time to assist in obtaining data on the rate of infiltration during irrigation. Figure XII shows a Parshall flume installed in a furrow prior to an irrigation run.

The slopes were then irrigated, each on succeeding days. It was decided to irrigate a strip approximately twelve rows wide each day, with the assumption that this would eliminate any border effects on the center test furrows. The first slope was irrigated July 22nd. Slope two, slope three, slope four, and slope five were irrigated on succeeding days.

The stream for each furrow was supplied to the upper end from the gated pipe. The stream flow-rate from each gate was calculated by catching the water flowing from the gate in an ordinary three-gallon bucket. The time required to fill each bucket was recorded with a stopwatch.

Figure XII. Parshall Flume Installed Prior to an Irrigation Run

As the wetting front advanced down the furrow, the time was recorded as it passed the individual stations staked out and marked prior to irrigation. As the water front reached one of the one-inch Parshall flumes, depth readings were started and continued until the depth flowing reached a constant rate.

When it could be determined, by observations of tensiometers and by use of a probe, that the soil reservoir was full, the inflow stream was shut off and the irrigation was completed.

The amount of water stored in the soil reservoir was then determined by taking moisture samples again and relating them to the samples taken prior to each irrigation.

Periodically after irrigation, soil moisture samples were taken and the tensiometers read so that the "consumptive use" could be approximated and the time of the next irrigation determined. The term "consumptive use" may also be termed evapo-transpiration, or the sum of transpiration and evaporation. In simple terms, the "consumptive use" applies to the water requirements of a crop, field, or entire area.

DISCUSSION OF FIELD PROCEDURES

A more detailed discussion of the field procedures seems advantageous, due to the varied problems encountered.

The plot was leveled in the fall of 1962 to grades ranging from 0.10 per cent to 0.25 per cent. Due to settling of the fill areas and normal cultivation procedures, the grades were much flatter and very uneven when the field was furrowed. Figure XI illustrates the furrow slopes recorded before irrigation and just after it had been furrowed. The areas of settlement can be noted very readily. These areas formed pockets, and on the very flat slopes these areas caused problems in maintaining flow in the furrows without overtopping or flooding.

The plot was approximately 1150 feet in length. The upper 400 feet were used basically for the infiltration and rate-of-advance studies due to the difficulty of maintaining good flow characteristics in the lower ends of the furrows. This extra length was also beneficial in that it provided an opportunity to extend the area of study if necessary, while it also eliminated the effect of the outflow conditions normally encountered at the lower ends of furrows.

Sugar beets were planted on the plot since this crop was the crop normally irrigated in this area by the furrow method. The tillage operations, weed control, thinning, and harvesting were all done by the farmer in a recommended manner. The fertilization was the farmer's responsibility and was done as recommended along with the Agronomy Department at South Dakota State College.

The plot was laid out as shown by Figure II. The rows were spaced 22 inches apart to correspond with the tillage equipment used in this area. The areas used for the investigation consisted of five areas, each 12 rows wide. The four areas, 18 rows wide, between each of the slope study areas were used for moisture studies on another phase of the overall project. The center five rows of each slope area were used for the infiltration and rate-of-advance study. The remaining rows in each slope strip were used as border rows to eliminate any outside effects from irrigation of the moisture areas between the slope areas.

After the plot was planted to sugar beets on April 6th, soil moisture samples were taken approximately every week at the locations shown by Figure III. The samples were taken at 12 locations and at each foot interval down to a depth of four feet. The samples were then taken to the laboratory where they were oven dried and moisture content determined. It is understandable that if the field capacity and wilting point percentage are not known for the particular soil, the moisture content will be almost meaningless. To obtain the wilting point and field capacity percentages, samples of soil were removed at the same depths as the moisture samples. The samples were then taken to the laboratory where the wilting point and field capacity percentages were approximated by applying fifteen atmospheres and one-third atmosphere of tension respectively.

The runoff at the lower end of the slope strips was obtained by Parshall measuring flumes with side stilling wells. Water level recorders were placed on the flumes to record the time and volume of water flowing. It was assumed when the recorders were installed that normal rainfall may cause runoff from the strips, but available rainfall during the investigation produced no runoff. The only recordings obtained at the outlet end were during the actual irrigation period. It was decided to direct three furrows into each two-inch Parshall flume; the resultant volume was then averaged for the three furrows. Figure XIII illustrates the total flow recorded from three furrows.

When the construction of the tensiometers was completed in June, they were installed at four locations and at depths of 6 inches, 12 inches, 18 inches, 36 inches, and 48 inches. The readings were taken daily and recorded. The daily loss of moisture was plotted as shown by Figure XIV. The tensiometer readings were used only as a guide in determining when the soil moisture was reaching the wilting point. When the tensiometers began to read high, soil moisture samples were secured and the moisture content determined by drying. The results could then be compared with the wilting point percentage determined in the laboratory to determine how near the soil moisture was to the wilting point. This also offered a rough check as to the value the tensiometers would read at wilting point.

The plot was furrowed before the first trial irrigation. The first trial irrigation gave an indication of many of the problems that should be corrected before the experimental irrigation. The range of inflow and the furrow carrying capacities were also estimated during this time. Another important factor noted during the trial irrigation

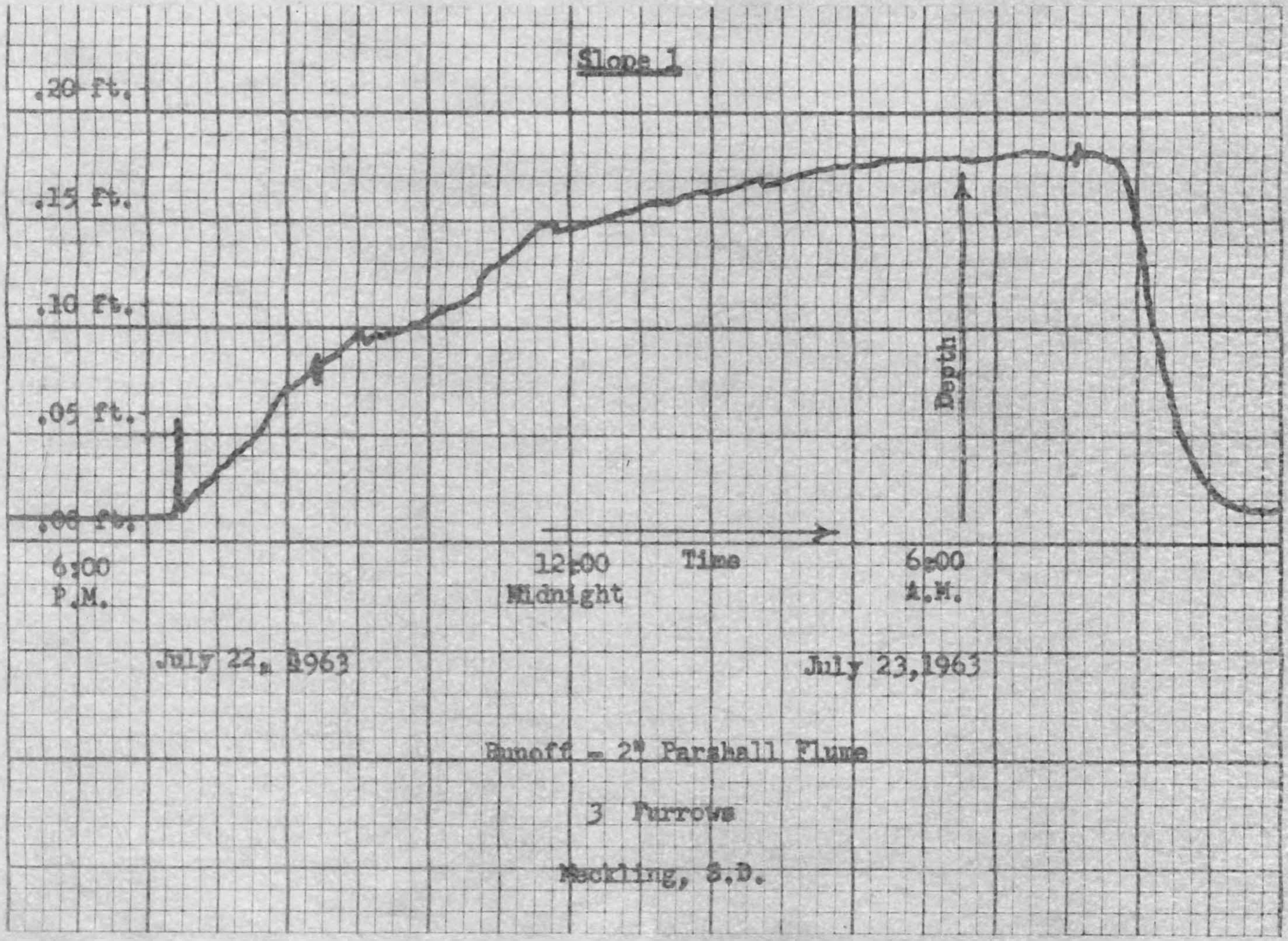


Figure XIII. Total Flow Recorded From Three Furrows

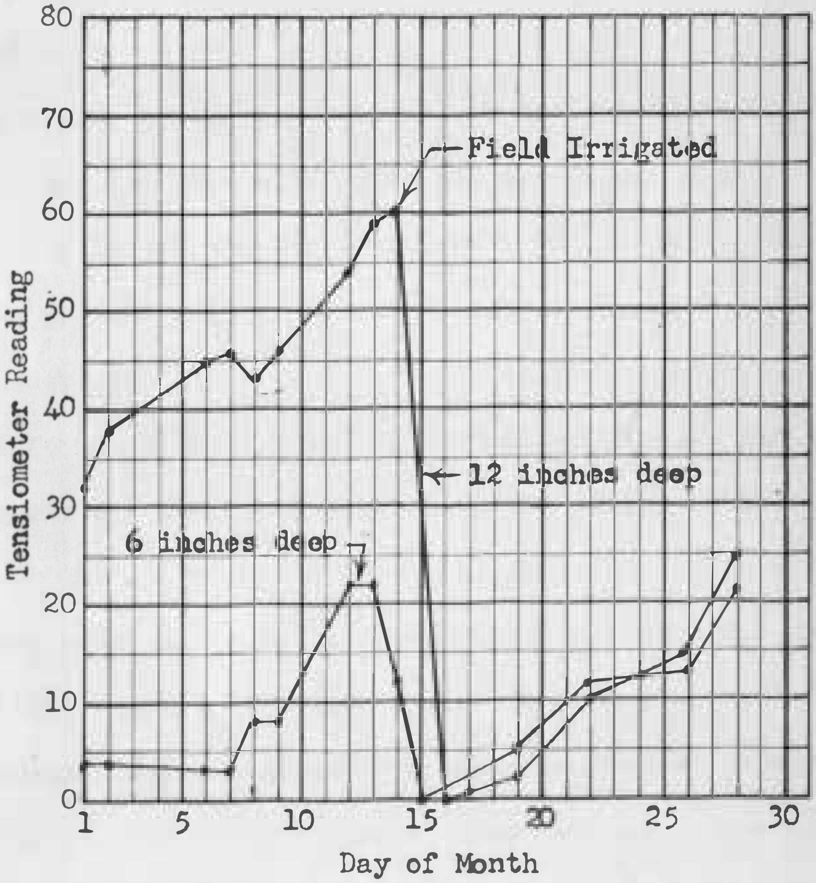
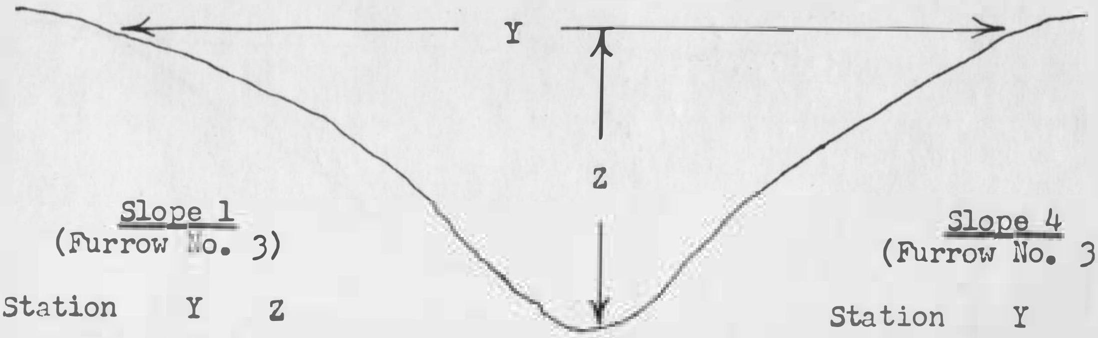


Figure XIV. Daily Loss of Soil Moisture

was the reaction of the furrow sides and bottom to wetting. It was observed that the soft sides of the furrows did not hold their shape when the water soaked into them. Upon wetting, the soil lost its structure and the sides, very noticeably, silted downward forming a very flat-bottomed furrow. This changed the hydraulic characteristic of the furrow.

The second irrigation was used as the experimental irrigation for determining the rate of advance and the furrow infiltration. The problem of the furrow structure was reviewed and it was decided to examine the possibility of pulling four-inch diameter pipes behind the Planter Junior furrow openers to aid in firming the bottom of the furrow and to help form a better and smoother channel for flow. Figure XV illustrates the four-inch diameter pipes pulled behind the furrow openers. It was also decided that a slightly deeper furrow might be advantageous with the very flat slopes on the plot. The depth of the furrows were increased from four inches deep on the trial irrigation to approximately six inches deep on the experimental irrigation. Figure XVI illustrates the approximate cross-sections recorded before the experimental irrigation. Figure XVII shows the approximate cross-sections recorded after the experimental irrigation. Generally, the furrow sides lost their structure, giving a more gradual slope to the sides and a flat bottom ranging from approximately four inches to eight inches wide. The exception seemed to be at the upper end where the width stayed approximately the same, but the bottom of the furrow had washed out slightly. This washing was probably caused by the

Figure XV. Four-inch Diameter Pipes and Furrow Openers



Slope 1
(Furrow No. 3)

Station	Y	Z
0 + 25	12"	4.0"
0 + 50	15"	4.5"
1 + 00	13"	5.0"
1 + 50	14"	4.5"
2 + 00	11"	5.0"
2 + 50	13"	4.0"
3 + 00	12"	4.5"

Slope 2
(Furrow No. 3)

Station	Y	Z
0 + 25	11"	4.0"
0 + 50	12"	5.5"
1 + 00	15"	4.0"
1 + 50	14"	4.0"
2 + 00	12"	4.5"
2 + 50	13"	5.0"
3 + 00	13"	5.5"

Slope 3
(Furrow No. 3)

Station	Y	Z
0 + 25	13"	4.0"
0 + 50	11"	5.0"
1 + 00	12"	4.5"
1 + 50	11"	5.0"
2 + 00	15"	5.0"
2 + 50	13"	4.5"
3 + 00	13"	5.5"

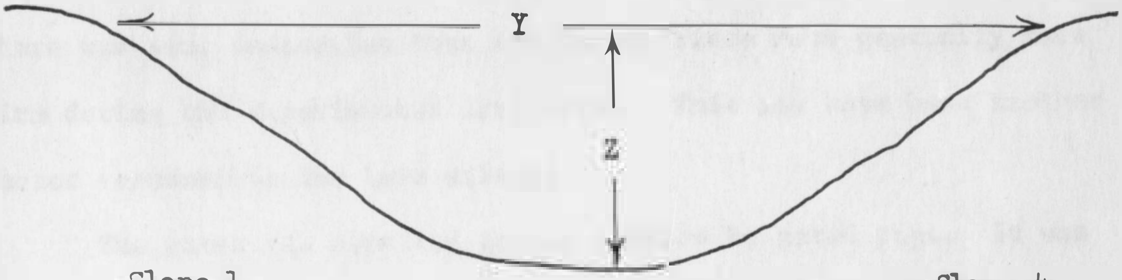
Slope 4
(Furrow No. 3)

Station	Y	Z
0 + 25	12"	5.0"
0 + 50	11"	6.0"
1 + 00	11"	5.5"
1 + 50	13"	5.5"
2 + 00	12"	6.0"
2 + 50	14"	5.0"
3 + 00	15"	5.0"

Slope 5
(Furrow No. 3)

Station	Y	Z
0 + 25	13"	6.0"
0 + 50	15"	5.5"
1 + 00	15"	5.0"
1 + 50	14"	7.0"
2 + 00	15"	6.5"
2 + 50	16"	6.0"
3 + 00	15"	6.0"

Figure XVI. Furrow Cross-Sections Before Irrigation



Slope 1
(Furrow No. 3)

Station	Y	Z
0 + 25	12"	5.0"
0 + 50	15"	5.5"
1 + 00	13"	4.5"
1 + 50	15"	4.0"
2 + 00	12"	4.0"
2 + 50	13"	3.0"
3 + 00	13"	3.0"

Slope 2
(Furrow No. 3)

Station	Y	Z
0 + 25	11"	5.0"
0 + 50	12"	6.0"
1 + 00	15"	4.0"
1 + 50	15"	3.5"
2 + 00	13"	3.5"
2 + 50	14"	3.0"
3 + 00	14"	4.0"

Slope 3
(Furrow No. 3)

Station	Y	Z
0 + 25	13"	6.0"
0 + 50	11"	6.0"
1 + 00	12"	4.0"
1 + 50	12"	4.0"
2 + 00	15"	4.0"
2 + 50	14"	3.0"
3 + 00	14"	4.0"

Slope 4
(Furrow No. 3)

Station	Y	Z
0 + 25	12"	6.0"
0 + 50	11"	7.0"
1 + 00	12"	5.5"
1 + 50	14"	5.0"
2 + 00	12"	4.0"
2 + 50	16"	3.0"
3 + 00	16"	3.0"

Slope 5
(Furrow No. 3)

Station	Y	Z
0 + 25	13"	6.5"
0 + 50	15"	5.5"
1 + 00	15"	4.5"
1 + 50	15"	5.0"
2 + 00	15"	4.0"
2 + 50	17"	4.5"
3 + 00	16"	4.5"

Figure XVII. Furrow Cross-Sections After Irrigation greater slope of each furrow in the first 50 feet of the furrow. There was some indication that the furrow sides were generally more firm during the experimental irrigation. This may have been another factor responsible for less silting.

The water was supplied to the furrows by gated pipe. It was decided to keep the stream size for the five test furrows of each slope approximately the same. The stream size for each furrow was set so that the maximum flow occurred without erosion or overtopping of each furrow. The stream size or flow-rate from each gate was determined by catching the outflow from a gate in a calibrated bucket. The flow-rate was calculated by recording the time with a stopwatch. Several checks were made to obtain an accurate average of the flow from a particular gate. The flow was checked several times during the irrigation to record any change in flow-rate.

As the wetting front advanced down the furrow and reached one of the one-inch Parshall flumes, depth readings were started and continued until the depth flowing through the flume became constant. Figure XVIII shows the streams flowing in the five test furrows of a test slope. An attempt was made to place the flumes level with the furrow bottom in such a manner as to least interfere with the normal flow of water in the furrow channel. Figure XIX illustrates a furrow stream flowing through a one-inch Parshall flume. The depth flowing in the Parshall flumes was measured by using a rule and placing it upright in the flume throat. The inflowing stream was left constant until the wetting front reached the lower end of the plot. The furrow

Figure XVIII. Streams Flowing in Five Test Furrows of a Slope

Figure XIX. Furrow Stream Flowing Through a One-inch Parshall Flume stream was then cut back to allow the stream front to just reach the lower end of the plot and thus eliminate much unnecessary waste runoff. If any runoff did occur, it was automatically recorded by the Parshall flumes and recorders at the lower end of the test furrows.

The advance rate of the wetting front was also recorded along with the depth reading in the one-inch Parshall flumes. The depth readings in the flumes were continued until the flow through the flumes became constant or submerged flow existed in the flume.

The cut-back stream was approximately one-fourth the flow-rate of the original stream that was used while the wetting front was advancing across the plot. When the wetting front reached the lower end of the furrow, the inflow stream was normally shut down to eliminate excess runoff. The time for the stream to advance the total 1150 feet was quite long. It was observed that when the wetting front reached the lower end of the plot, the irrigation was approximately 50 per cent completed. When the wetting front reached the lower end of the plot, it was also observed that there were many areas of ponded water located on the plot. This was probably due to the fact that there were many low areas or areas where the landleveling fill had settled. Figures XX and XXI illustrate the flooding and overtopping that occurred in the low areas.

The tensiometers were observed and a soil probe was used to determine when the soil reservoir was completely replenished. When it was assumed that the reservoir was full, the inflow stream was shut off and the irrigation was completed.

Figure XX. Flooding and Overtopping

Figure XXI. Flooding and Overtopping

The amount of water stored in the soil reservoir was determined by taking moisture samples, oven-drying them, and relating them to the samples taken prior to the irrigation.

DERIVATION OF EQUATIONS

Water flowing into a furrow usually goes into three types of storage in the furrow. They are (1) volume infiltrated, (2) surface storage, and (3) surface detention volume. The volume infiltrated is the volume infiltrated into the soil during a period of time. The surface storage is the volume of water stored above the soil surface during a period of time, and surface detention is the volume necessary to fill the surface depressions and irregularities before flow can occur. In equation form, it may be expressed as:

$$V_A = V_I + V_S + V_D \qquad \text{(Eq. 10)}$$

where:

V_A = total volume flowing into furrow

V_I = volume infiltrated

V_S = surface storage volume

V_D = surface detention volume.

As previously stated, the rate of intake of water into the soil under furrow conditions may be expressed as:

$$I = K\, t^n \qquad \text{(Eq. 1)}$$

where:

I = intake rate per unit length of furrow

t = time after infiltration begins, in minutes

K, n = constants

A discussion of Eq. (1) seems in order since it is very important to the approach considered here. Eq. (1) is an empirical equation and is generally evaluated by the inflow-outflow method.

Data on the rate of advance of the wetting front in furrow irrigation can generally be expressed by:

$$t = a\ x^b \qquad \text{(Eq. 11)}$$

where:

x = length of furrow wetted

t = time required to wet the length

a, b = constants

Eq. (11) is also empirical and does not have physical significance. However, it is indicated by field data that the rate of advance of the wetting front is adequately expressed by Eq. (11), if the intake data are of the form of Eq. (1).

Smerdon (20) indicated that if the preceding statements are to be assumed, the assumptions must also be made that the furrow slope is constant, the furrow stream is constant, the intake characteristics do not change along the furrow, and the furrow shape is constant along the furrow.

It seems logical to express the quantity of water that will infiltrate over a unit length of furrow after a period of time (t) by integrating Eq. (1) over the time from $\underline{t = 0 \text{ to } t = t}$.

Let this total infiltration equal V_I; then we have:

$$V_I = \int_{t=0}^{t=t} I\ dt \qquad \text{(Eq. 12)}$$

substituting:

$$V_I = \int_{t=0}^{t=t} K\ t^n\ dt \qquad \text{(Eq. 13)}$$

integrating:

$$V_I = \frac{K\ t^{n+1}}{n+1}\Bigg]_{t=0}^{t=t} \qquad \text{(Eq. 14)}$$

$$= \frac{K\ t^{n+1}}{n+1} \qquad \text{(Eq. 15)}$$

If this Eq. (15) expresses the volume infiltrated, then it seems practical to express the total volume infiltrated into the furrow when a length x is wetted by integrating this equation again from $x = 0$ to $x = x$. We can express this total volume by V_T:

$$V_T = \int_{x=0}^{x=x} V_I\ dx \qquad \text{(Eq. 16)}$$

substituting:

$$V_T = \int_{x=0}^{x=x} \frac{K\ t^{n+1}}{n+1}\ dx \qquad \text{(Eq. 17)}$$

We also assume that if this expression is applicable to a particular soil, then Eq. (11) should also be applicable. By substituting Eq. (11):

$$V_T = \int_{x=0}^{x=x} \frac{K}{n+1}\ (a\ x^b)^{n+1}\ dx \qquad \text{(Eq. 18)}$$

integrating:

$$V_T = \int_{x = 0}^{x = x} \frac{K}{n + 1} a^{n + 1} x^{b (n + 1)} dx$$

$$= \frac{K}{n + 1} a^{n + 1} \left. \frac{x^{b (n + 1) + 1}}{b (n + 1) + 1} \right]_{x = 1}^{x = x} \qquad \text{(Eq. 19)}$$

It can be easily seen that an equation relating both <u>t</u> and <u>x</u> would be advantageous.

We know that, at any time, the sum of the volume of water in surface storage, detention storage, and the total volume infiltrated must equal the volume which has been applied to the furrow, providing there is no water loss by other means, such as evaporation. Expressed in equation form:

$$Q\ t = V_T + V_S \qquad \text{(Eq. 20)}$$

where:

Q = rate of flow into furrow

t = time

V_S = volume of surface storage after time (t)

V_T = given by Eq. (19) and is a direct function of <u>x</u>.

If we assume a constant or nearly constant depth of flow, we may then say that:

$$V_S = V_{Sa}\ x \qquad \text{(Eq. 21)}$$

where $\underline{V_{Sa}}$ is the unit-length surface storage in the furrow.

The surface storage is indirectly a function of the length of furrow, but is generally dependent on the depth of flow, the furrow shape, and the shape of the surface profile of the advance wetting front.

If we combine Eq. (19), (20), and (21), we get:

$$Q\,t = \frac{K\,a^{n+1}}{(n+1)\left[b\,(n+1)+1\right]}\,x^{b\,(n+1)+1} + V_{Sa}\,x \qquad \text{(Eq. 22)}$$

If the rate-of-advance data from a given furrow is plotted on log-log paper, the constants $\underline{a}$ and $\underline{b}$ can be determined. The method of least squares can be applied to the data to obtain the line of best fit and the values of $\underline{a}$ and $\underline{b}$.

If $\underline{Q}$ and $\underline{V_{Sa}}$ are determined and the constants $\underline{K}$ and $\underline{n}$ evaluated, we can get an expression for the particular soil involved.

RESULTS

The experimental results of this investigation are part of an overall study to determine the best criteria for furrow irrigation development and management in southeastern South Dakota. The purpose of this investigation was to determine a relationship for the rate of advance of the wetting front in an irrigation furrow and for the intake rate of the particular soil involved.

The rate of advance of a wetted front down a furrow is a function of the soil type, moisture content of the soil, furrow input, and furrow grade. As indicated previously, this study was limited to the soil type that had been graded for furrow irrigation.

The soil on this plot was classified as Blencoe silty clay loam. The bulk density of the soil was determined in the field by the balloon method. Table 2 illustrates the bulk densities:

Table 2. Bulk Densities

Location	Depth	Bulk density
Upper end of plot	surface	1.245 gr/cm^3
Upper end of plot	1 foot	1.395 gr/cm^3
Lower end of plot	surface	1.183 gr/cm^3
Lower end of plot	1 foot	1.493 gr/cm^3

The control of the moisture variable was difficult due to the fact that the farmer's irrigation equipment had to be used when available. Therefore, an analysis of the soil moisture was secured just before irrigation. The soil was sampled at four stations along each of the five slopes. The soil was sampled at six-inch intervals down to a depth of four feet. The top 18 inches are illustrated in Table 3. The percentage of moisture before and after irrigation are given in the table.

Rate of Advance

Many efforts have been made to predict the rate of advance of wetting surfaces in furrow irrigation. Most of these procedures require that the intake characteristics of the soil be known. This would be relatively simple to do if it were not for the fact that most fields are not homogeneous. The variations within fields due to cut and fill areas, resulting from land forming and from persistent cracking of some soils, make determination of infiltration from infiltrometer observations difficult. Another factor that can not be evaluated by a furrow infiltrometer is the effect of water movement in the furrow on infiltration.

It seems that if the intake characteristics of a soil could be determined by taking measurement of the wetting front during actual irrigation, the results may be more reliable. By observing an entire furrow, the size of the area being used for the infiltration determination is made sufficiently large so that the variability caused by badly cracked soils is reduced.

The rate-of-advance curves are very important in determining the size furrow stream and length of run to use. The rate-of-advance

Table 3. Moisture Percentage*

	Before irrigation			After irrigation		
Location	6 in.	12 in.	18 in.	6 in.	12 in.	18 in.
Slope 1						
0 + 10	26	27	22	33	32	31
1 + 00	24	23	22	35	33	33
2 + 00	23	26	25	36	35	35
3 + 00	26	28	27	36	35	34
Slope 2						
0 + 10	19	20	23	29	29	26
1 + 00	23	21	22	31	30	31
2 + 00	24	24	23	31	33	32
3 + 00	23	21	22	33	34	29
Slope 3						
0 + 10	22	21	22	32	28	27
1 + 00	23	22	23	37	32	31
2 + 00	24	24	26	34	34	35
3 + 00	25	25	27	35	33	39
Slope 4						
0 + 10	22	21	19	33	32	33
1 + 00	25	24	27	36	33	36
2 + 00	24	27	27	36	34	35
3 + 00	24	24	27	37	33	33
Slope 5						
0 + 10	20	22	21	32	32	29
1 + 00	23	23	25	33	33	33
2 + 00	26	25	28	35	36	36
3 + 00	24	26	26	35	29	36

*Second irrigation, July 22, 1963; taken along test furrow data is summarized in Table 11 of Appendix B for each slope. In order to arrive at the most accurate rate-of-advance curve, the time distance measurements for the center test furrow of each slope were plotted on logarithmetic paper. The method of least squares was then applied to the data to determine the curve of best fit for the points. The log plot of these points suggested a straight line on log paper of the form:

$$t = a\,x^{b} \qquad \text{(Eq. 11)}$$

The advance curves and equations are shown in Figures XXIX, XXX, XXXI, XXXII, and XXXIII of Appendix A.

The equation determined for each slope was then used to plot the rate-of-advance curves on rectangular coordinates. Figure XXII. The set of rate-of-advance curves were generally parabolic in shape and followed the expected pattern with respect to the furrow inputs. It can be noted that the smaller stream size produced a steeper line on the graph. If the rate-of-advance curves of Figure XXII are compared to the slope of the lines of Figures XXIX, XXX, XXXI, XXXII, and XXXIII of Appendix A, it can be seen that the rate-of-advance curves of Figure XXII that tend to straighten are the same furrows that give the greater slope to the lines of Figures XXIX, XXX, XXXI, XXXII, and XXXIII of Appendix A. This indicates continued advancement of the wetted front at a more rapid rate.

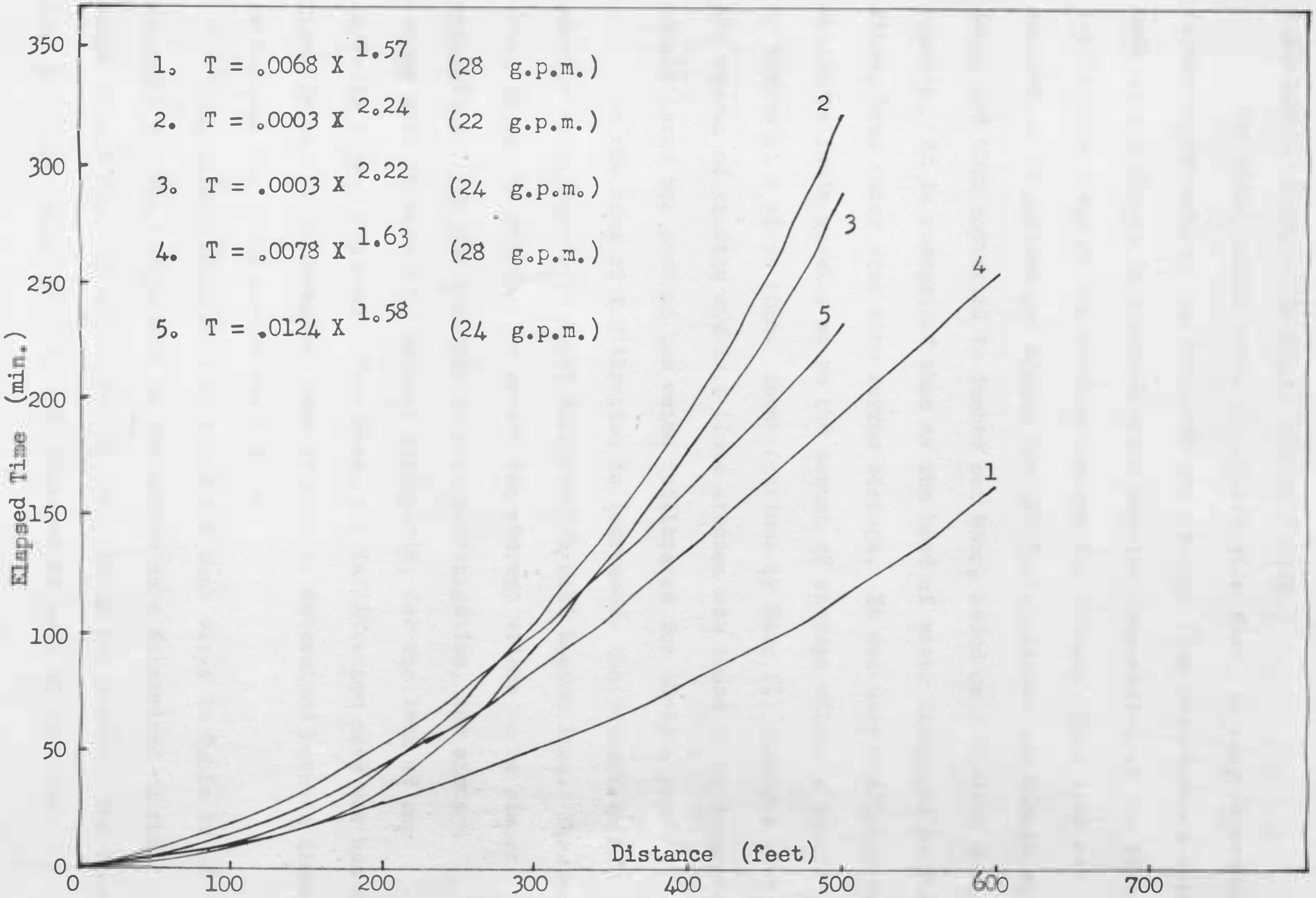


Figure XXII. Rate-Of-Advance Curves on Rectangular Coordinates

Infiltration From Differential Between Flumes

The field intake rate, or infiltration rate, is very important in design procedure. As indicated previously, flow measurements were made at the flumes in a manner which enabled computation of the furrow infiltration rate in the section between the flumes. This rate was determined in gallons per minute per 100 feet, gallons per minute per foot, and then converted to inches per hour, based on a 22-inch furrow spacing. It is recognized that as the head of water increased in the flume, some water went into furrow storage. It was very difficult to obtain reliable results as to the amount of storage within a section of furrow at a given time. Investigations by Beer (1) indicate that the amount of storage within a flume station was found to be approximately three per cent of the water infiltrated for 40-inch rows.

As the time of infiltration is increased, the percentage of storage with respect to total infiltration will become less. Therefore, it may be possible to assume the storage volume to be almost negligible. For the analysis of this investigation, the storage volume will therefore be assumed negligible, for the lack of any definite supporting data. Therefore, the infiltration rate was based directly on the differential rate of flow as determined between flumes or between the water source and a flume.

The infiltration data is shown for each slope in Table 12 of Appendix B. The inflow rate is the inflow rate determined as the water flowed from the gated pipe at the head of the furrow. The readings are illustrated as they were recorded at each of the three

100-foot stations down furrow. The data for each slope was then plotted on log-log paper in inches per hour as the ordinate and elapsed time in minutes as the abscissa. It has been pointed out by many investigators that the intake rate for most soils can be adequately expressed in the form:

$$I = K\ t^{n} \tag{Eq. 1}$$

if the rate of advance of the wetting front is adequately expressed by the equation:

$$t = a\ x^{b} \tag{Eq. 11}$$

Both of these equations are empirical and do not have theoretical significance. With this assumption, that the infiltration fits the form of the equation ($I = K\ t^{n}$), the data for each slope was analyzed by the method of least squares to determine an equation for the curve of best fit. The data is plotted in Figures XXXIV, XXXV, XXXVI, XXXVII, and XXXVIII of Appendix A for each slope.

In general, the greater the slope of the infiltration curve, the steeper the slope of the graph for the rate-of-advance curves. This is in agreement with the theory that with a given constant inflow, the rate of advance should be related to the infiltration if all other factors are constant.

Infiltration From Rate of Advance of Wetting Front

The intake of the soil may also be approximated from the rate of the advance of the wetting front alone, assuming no storage. The data and computations are shown in Table 13 of Appendix B. The data was then analyzed by the method of least squares and the line of best fit was plotted on log-log paper. Figures XXXIX, XL, XLI, XLII, and XLIII of Appendix A. In comparison of the graphic plot of the infiltration determined by the flumes (Figures XXXIV, XXXV, XXXVI, XXXVII, and XXXVIII of Appendix A) and the graphic plot determined by the rate of advance (Figures XXXIX, XL, XLI, XLII, and XLIII of Appendix A), it can be observed that the infiltration data from the flume determination is much more scattered than the infiltration data from the advance rate alone.

Infiltration From Rate of Advance as a Border

It is the observation of the author that the equations obtained by these two methods indicate relatively high infiltration rates. Therefore, it was decided to analyze each slope as a border in an attempt to obtain more supporting evidence. The total inflow to the center five furrows of each slope was used to calculate the infiltration in a similar manner as was done with the individual furrows previously. The advance times of the five furrows for each slope were averaged and this time was used for figuring the infiltration in inches per hour. The data is illustrated in Table 14 of Appendix B. It was analyzed by the method of least squares and the line of best fit was plotted in Figures XLIV, XLV, XLVI, XLVII, and XLVIII of Appendix A. It can be noted that the infiltration rates obtained by considering the slopes as a border are lower and generally fall less scattered than those of the previous two methods: by flumes and advance in individual furrows. The rate-of-advance curves are plotted in Figures XLIX, L, LI, LII, and LIII of Appendix A for each border.

The following tables are a summary of the infiltration equations obtained by each of the three methods:

Table 4. Determination by Differential of Flow Between Flumes

Slope	Equation
1	$I = 9.91\ T^{-.1552}$
2	$I = 44.10\ T^{-.6640}$
3	$I = 158.00\ T^{-1.2300}$
4	$I = 13.45\ T^{-.3390}$
5	$I = 53.00\ T^{-.7109}$

Table 5. Determination by Rate of Advance of Wetting Front in Individual Test Furrow of Each Slope

Slope	Equation
1	$I = 83.9\ T^{-.7609}$
2	$I = 32.1\ T^{-.4640}$
3	$I = 31.2\ T^{-.4316}$
4	$I = 40.0\ T^{-.4733}$
5	$I = 84.5\ T^{-.6650}$

Table 6. Determination by Rate of Advance Considering the Flow in Five Furrows of Each Slope as a Border

Slope	Equation
1	$I = 13.70\ T^{-.5875}$
2	$I = 8.82\ T^{-.4390}$
3	$I = 8.90\ T^{-.4650}$
4	$I = 11.70\ T^{-.5080}$
5	$I = 18.00\ T^{-.5930}$

The equations were averaged for each method and the standard deviations calculated for K and n:

Table 7. Summary of Equations

Method	Average equations	Standard deviations	
		K	n
Flume data	$I = 55.69\ T^{-.6198}$	53.81	.3878
Advance single furrow	$I = 54.34\ T^{-.5896}$	24.58	.2053
Advance by border	$I = 12.22\ T^{-.5185}$	3.42	.1975

The following tables show the rate-of-advance equations of the wetting front for the two methods:

Table 8. Determination by Individual Test Furrows

Slope	Equation
1	$T = .0068\ x^{1.57}$
2	$T = .0003\ x^{2.24}$
3	$T = .0003\ x^{2.22}$
4	$T = .0078\ x^{1.63}$
5	$T = .0124\ x^{1.58}$

Table 9. Determination by Considering Five Furrows of Each Slope as a Border

Slope	Equation
1	$T = .0062\ x^{1.68}$
2	$T = .0012\ x^{2.12}$
3	$T = .0004\ x^{2.27}$
4	$T = .0096\ x^{1.67}$
5	$T = .0142\ x^{1.64}$

The rate-of-advance equations were averaged and the standard deviation calculated for each of the two methods:

Table 10. Summary of Equations

Method	Average equations	Standard deviations	
		a	b
Single furrow	$T = .0055\ x^{1.85}$	.0047	.3128
Border	$T = .0063\ x^{1.88}$	.0052	.2650

The values obtained for the infiltration rate and rate of advance do not correlate with the actual slopes of the study area. The values in Tables 4, 5, and 6 for infiltration, and Tables 8 and 9 for rate of advance do not follow the slope trend of the test furrows as illustrated in Figure XI. It is difficult to distinguish any trend or correlation between the degree of slope of the furrows and the equations obtained. This lack of trend may lie in the fact that the slopes in general are relatively flat and there are many low areas of settlement where water ponded. The first 50 feet of each slope strip was also relatively steep, which can be seen in Figure XI. This may have also been a factor in removing a trend or correlation between the slope and rate of advance and infiltration.

Application to a Specific Design Problem

The application of the infiltration and advance equations may best be illustrated by a typical design problem:

> Problem: Determine an approximate furrow length and irrigation time to replace five inches of moisture on this type of Blencoe soil. The furrow input will be approximately 23 - 28 gallons per minute.

The average rate-of-advance equation will be used:

$$T = .0063\, x^{1.88} \qquad \text{(Eq. 23)}$$

The average infiltration equation for the border-flow method was:

$$I = 12.22\, T^{-.5185} \qquad \text{(Eq. 24)}$$

where $\underline{I}$ is in inches per hour and $\underline{T}$ is in minutes.

Eq. (4), page 6, and Eq. (15), page 51, may now be applied to find the total time to replace five inches of moisture.

Eq. (15) may be obtained by considering the area under the curve of the inches per hour of infiltration.

The expression for the area under the curve is:

$$\text{Area} = \int_0^T K\, T^n\, dt \qquad \text{(Eq. 25)}$$

and:

$$\frac{\text{Area}}{60} = D = \text{Surface inches of water applied} \qquad \text{(Eq. 26)}$$

If the value of Area is substituted and the integration performed from T = 0 to T = T, we obtain:

$$60\ D = \frac{K\ (T)^{n+1}}{n+1} \qquad \text{(Eq. 3, 15)}$$

or:

$$T = \left[\frac{60\ D\ (n+1)}{K}\right]^{\frac{1}{n+1}} \qquad \text{(Eq. 4)}$$

where T = time in minutes.

Applying:

$$T = \left[\frac{(60)\ (5\text{ in.})\ (-.5185+1)}{12.22}\right]^{\frac{1}{-.5185+1}}$$

$$= (11.82)^{2.08}$$

$$= 172 \text{ minutes.}$$

The criteria that the wetted front should reach the end of the furrow in approximately 1/4 of the total irrigation may now be applied:

$$1/4 \text{ of } 172 \text{ minutes} = 43 \text{ minutes}$$

172 + 43 = 195 minutes that water is applied to head of furrow.

The design furrow length may now be determined from the rate-of-advance equation:

$$T = .0063\ x^{1.88}$$

$$43 = .0063\ x^{1.88}$$

$$x = (6830)^{.5320}$$

$$= 110 \text{ feet.}$$

This illustrates the method used for design procedure using the infiltration and advance equations. The value obtained for design furrow length is obviously too limited for any practical value.

The use of this design method also verifies the assumption that excessive lateral subsurface movement probably occurred. This is largely evidenced in the fact that the constant $\underline{b}$ of the advance equation:

$$T = a\ x^{b} \qquad \text{(Eq. 11)}$$

is too large. The large value of $\underline{b}$ indicates too great a slope of the advance line on log paper, or an advance rate that is too slow to be practical. It can be seen that the constant $\underline{b}$, or advance rate, has the greatest influence on Eq. (11) in the determination of the design length.

The use of a cutback stream makes the application time of 195 minutes slightly impractical. When the furrow stream reaches the lower end of the furrow, the inflow stream is usually cut back to approximately 1/4 the normal inflow rate. This will increase the time that it takes to fill the soil reservoir but will economize on water.

Investigations by Beer (1) in Harrison County, Iowa, on Blencoe soils with a slope of .1 per cent, obtained an infiltration equation of:

$$I = 15.5\ T^{-0.33} \qquad \text{(Eq. 27)}$$

and an advance equation of:

$$T = .0001\ x^{2.50} \qquad \text{(Eq. 28)}$$

Using these equations (Eq. 27, 28) obtained by Beer and applying the preceding method, the results obtained for Beer's equations give approximately the same design length as that obtained for the investigated plot in southeastern South Dakota.

Infiltration From Rate of Advance With and Without Infiltration

The infiltration rate for a given furrow may also be determined if the rate of advance can be determined with little or no infiltration in the furrow. By using equations for the rate of advance of the wetted fronts with infiltration and without infiltration, the infiltration rate of the soil may be determined. The biggest obstacle in this analysis was to determine the rate of advance for no infiltration. Several methods could possibly be employed to estimate this non-infiltration flow, such as sealing the furrow with a spray or using a liner in the furrow. Neither of these methods was employed in this investigation. It was noted during field tests that the advance of the wetted front was quite rapid for the first 25 to 50 feet of the furrow. This was assumed to be a period of little infiltration, due to the fact that the input is high relative to the rate at which water can be infiltrated into the soil. It was therefore assumed that a straight line tangent to the curve of the rate of advance of the wetting front at this point should be the approximate curve of a wetting front with little or no infiltration. The best estimate of this tangent line was obtained by using the origin and the first station at which the rate of advance was determined. A straight line was drawn through these two points and the equation of this line was assumed to be the equation of a wetting front in a furrow with little infiltration. The equation of the line was determined to be of the form:

$$T_o = a' x \qquad \text{(Eq. 29)}$$

We now have two equations for each furrow. They are:

$$T = a x^b \qquad \text{(Eq. 11)}$$

for a furrow with infiltration, and:

$$T_o = a' x \qquad \text{(Eq. 29)}$$

for a furrow with no infiltration.

It seems logical to assume that the easiest way to find the infiltration would be in quantity of infiltration per length of furrow. We then can use the expression:

$$\frac{Q}{L} = \frac{(T_1 - T_o)\, Q}{T_1\, (x/100)} \qquad \text{(Eq. 30)}$$

where:

Q/L = average infiltration rate in gallons per minute per 100 feet of furrow

T_1 = time at which infiltration rate is desired

x = distance front would travel in time T_1 with infiltration

T_o = time for front to travel distance x with little or no infiltration.

Thus an average infiltration-rate curve may be determined for the soil.

An example will be given to clarify the procedure. It is desired to know the average furrow infiltration rate at $T_1 = 60$ minutes for slope three. The rate-of-advance equation for slope three is:

$$T = .0003\ x^{2.22}$$

If $T_1 = 60$ minutes is substituted in this equation, the distance can be computed.

$$60 = .0003\ x^{2.22}$$

$$x = \left[\frac{60}{.0003}\right]^{.45} = 250 \text{ feet.}$$

The equation $T = a^1\ x$ can be obtained by using the origin and the first control point and drawing a straight line tangent to the curve through these two points. Figure XXIII. The equation obtained was found to be:

$$T_o = .067\ x \qquad \text{(Eq. 31)}$$

Substitution of x into this equation yields the time T_o:

$$T_o = .067\ (250)$$

$$= 17 \text{ minutes.}$$

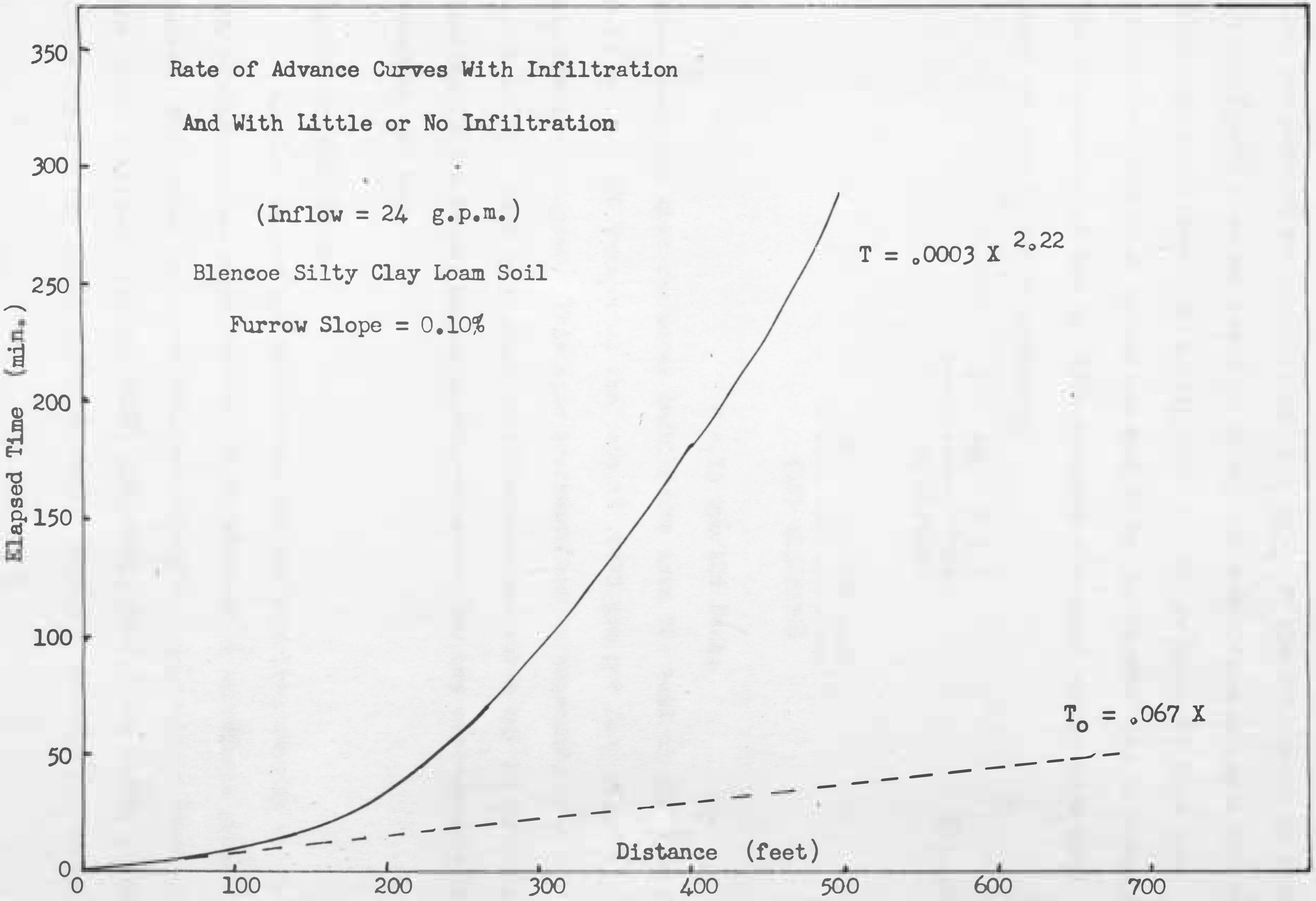


Figure XXIII. Rate-Of-Advance Curves - Slope 3

This now permits the calculation of $T_1 - T_o$ or the difference in time it would take a wetted front to travel the same distance under the two different conditions. By multiplying the furrow input by this time difference, the total volume assumed to be infiltrated can be computed. The denominator of the Eq. (30) converts the total volume to a rate based on time T_1 and a distance x:

$$\frac{Q}{L} = \frac{(T_1 - T_o)\,Q}{T_1\,(x/100)} \qquad \text{(Eq. 30)}$$

$$= \frac{(60 - 17)\,(24\ \text{gpm})}{(60)\,(250/100)}$$

$$= 6.75\ \text{gpm}/100\ \text{feet.}$$

This indicates that the water infiltrates into the soil at the rate of 6.75 gpm per 100 feet or at the rate of .0675 gpm per foot when 60 minutes have elapsed. This same procedure may be repeated for any value of T_1. Thus an average infiltration-rate curve may be determined for any furrow input, providing the constants for the rate-of-advance equation are known.

Discharge-Time Curves

Another method for determining the infiltration rate is to plot the discharge-time curve for each flume station on coordinate graph paper. The curves for lower stations should be successively lower than the upper stations. Figures XXIV, XXV, XXVI, XXVII, and XXVIII illustrate the plotted curves for each slope. The area between the curves

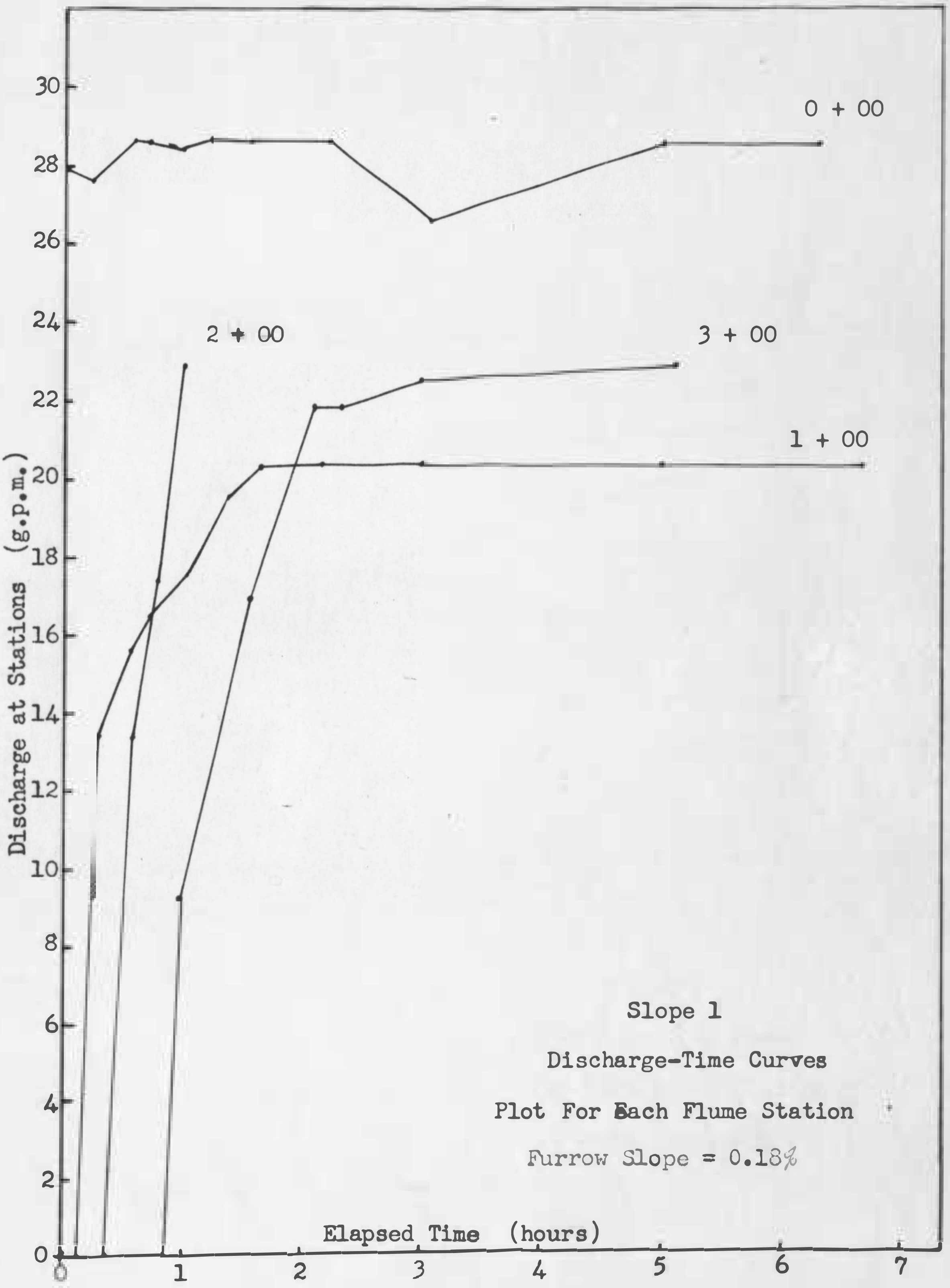


Figure XXIV. Discharge - Time

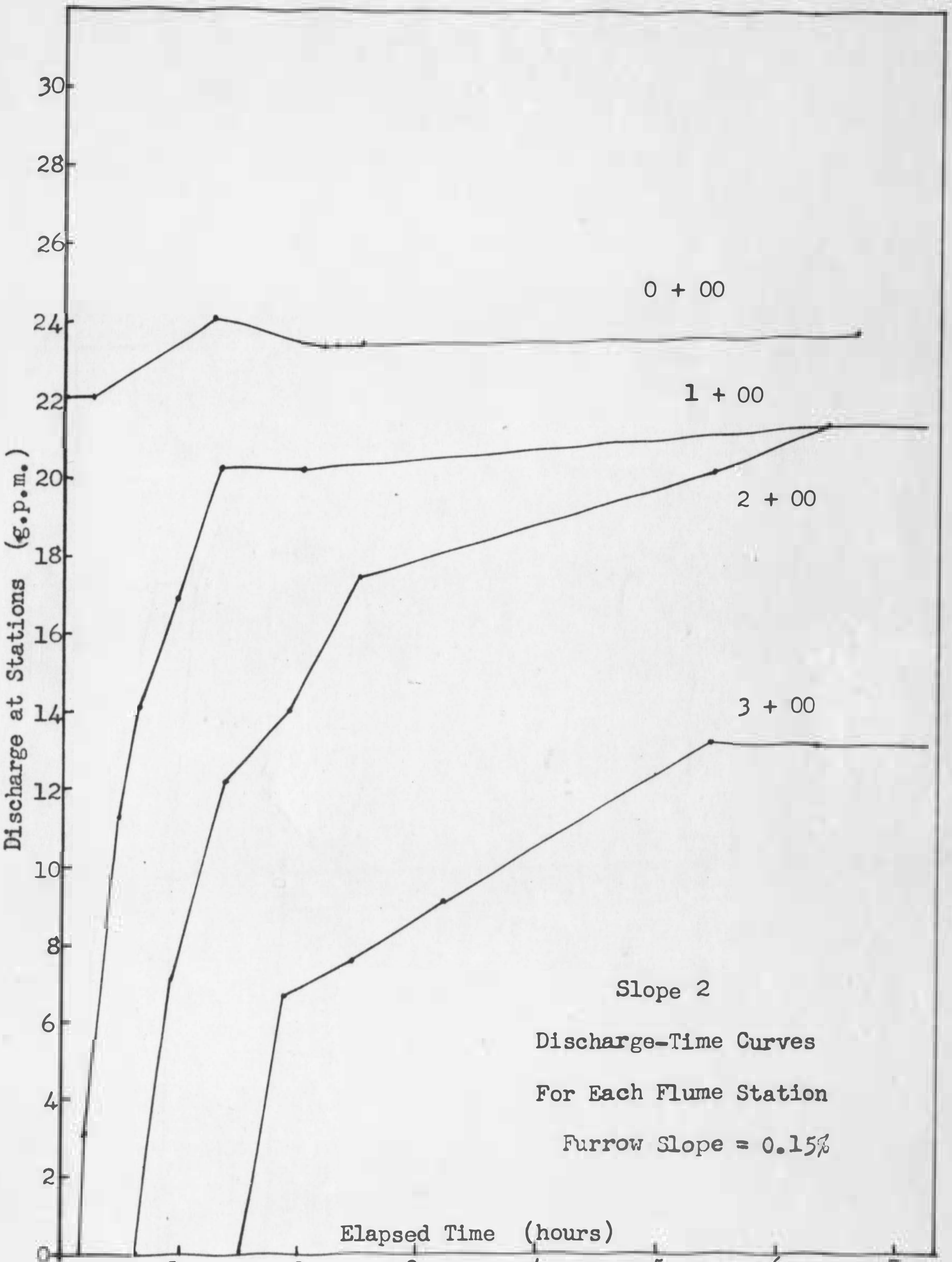


Figure XXV. Discharge - Time Curves

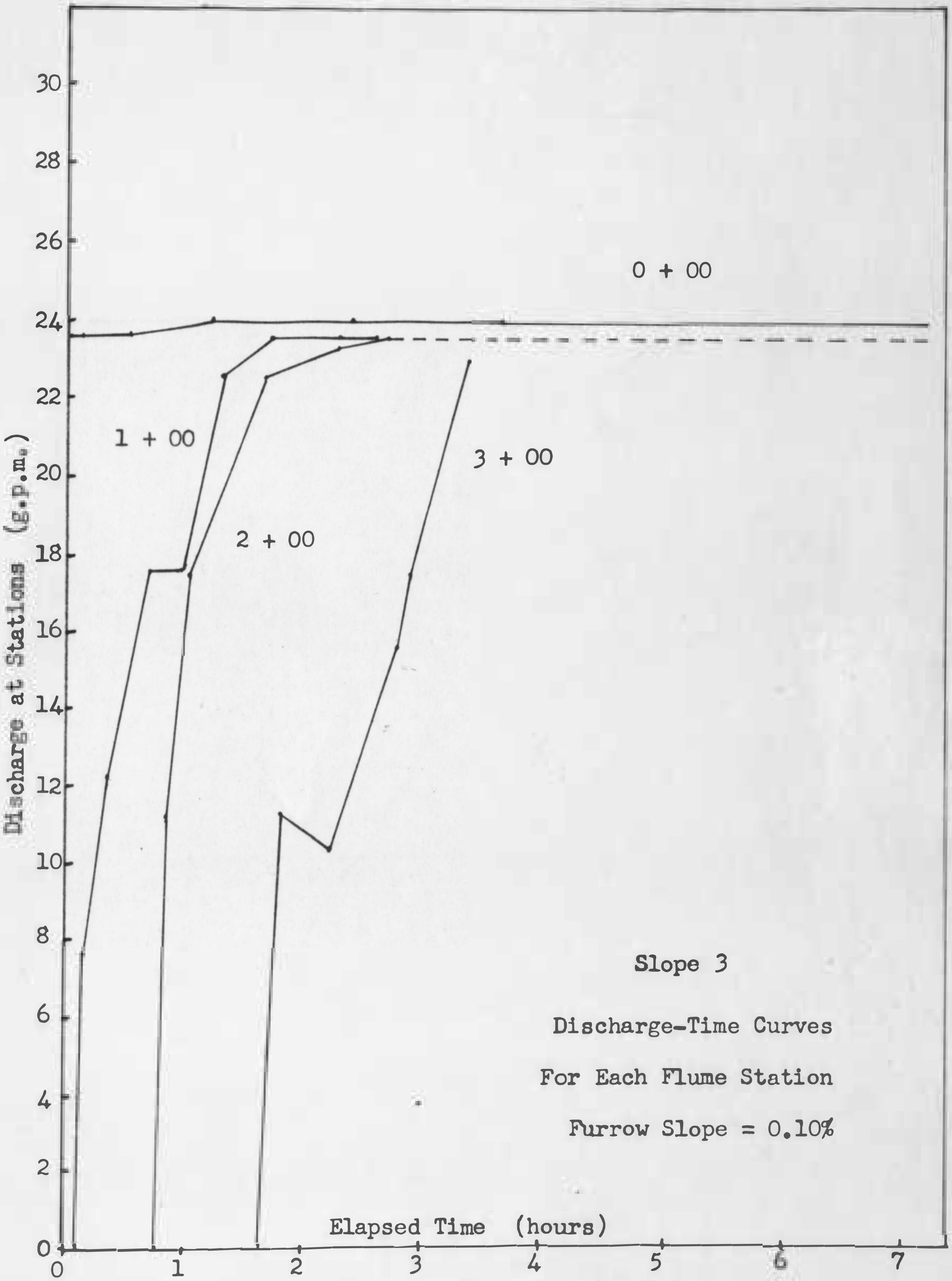


Figure XXVI. Discharge - Time Curves

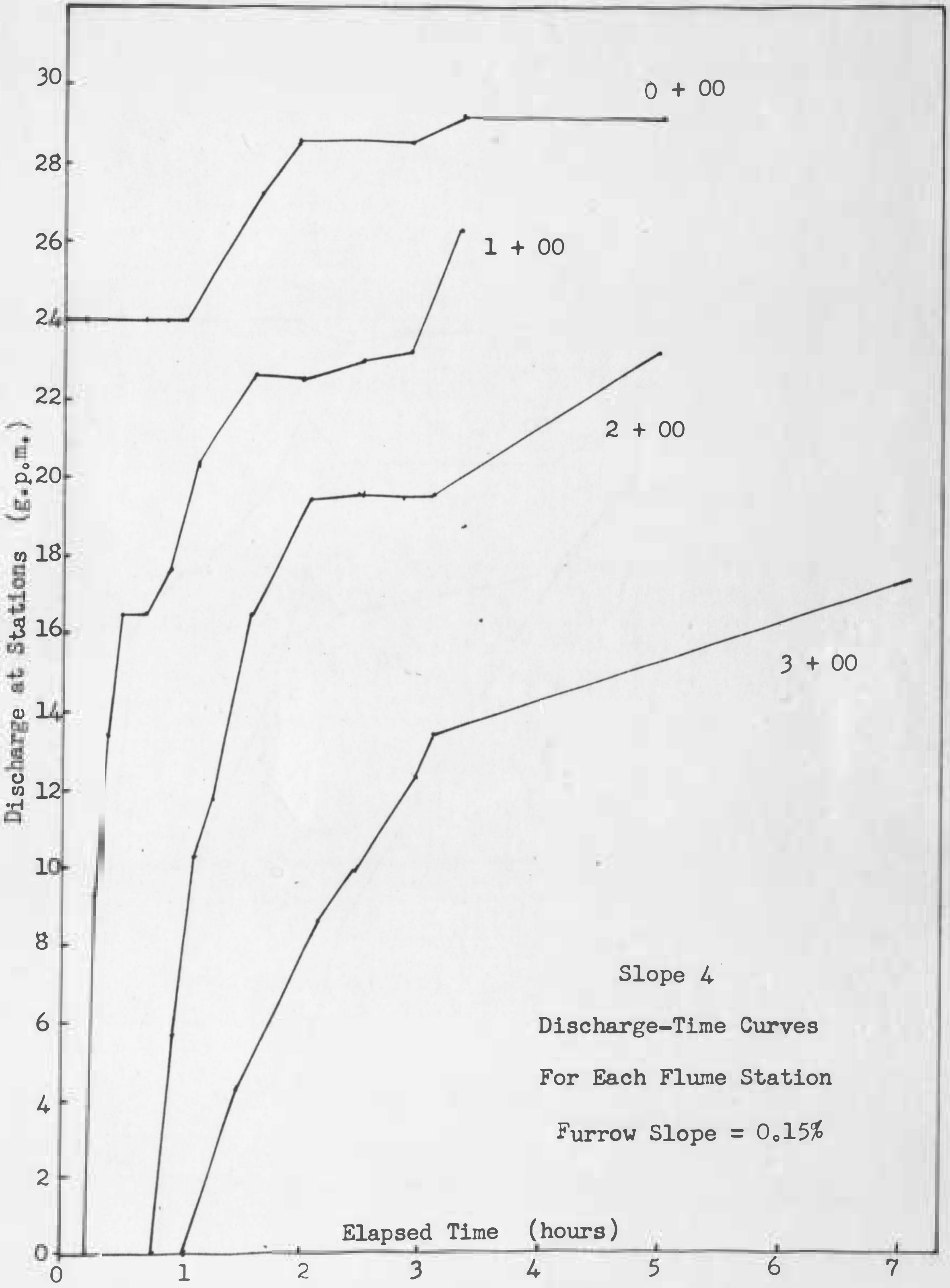


Figure XXVII. Discharge - Time Curves

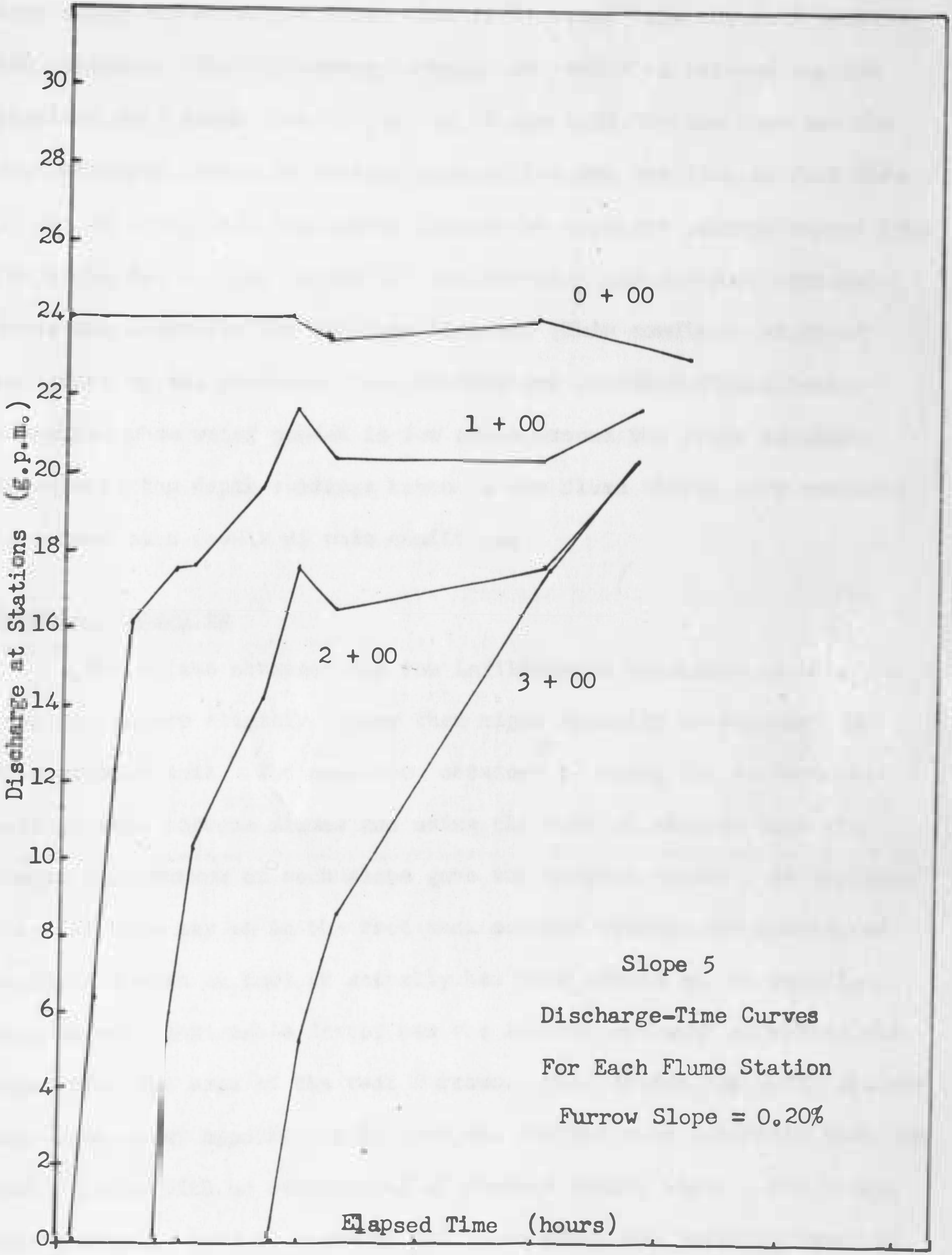


Figure XXVIII. Discharge - Time Curves

represents the amount of water that infiltrated into the soil between the stations. The difference between the ordinates between any two stations at a given time is the sum of the infiltration rate and the instantaneous change in storage between the two stations at that time. It can be noted that the curves follow the expected pattern except that for slope No. 1. The curves for the 200-foot and 300-foot stations cross the curve for the 100-foot station. This condition might be explained by the fact that the 200-foot and 300-foot flumes became submerged when water ponded in low areas around the flume stations. Therefore, the depth readings taken in the flume throat were probably increased as a result of this condition.

General Discussion

The values obtained for the infiltration equations in this investigation are slightly higher than might normally be expected for this type of soil. The equations obtained by using the differential rate of flow between flumes and using the rate of advance from the single test furrow of each slope gave the largest values. An explanation for this may be in the fact that surface storage was considered negligible when in fact it actually has some effect on the equation. Another very noticeable factor was the lateral movement of subsurface water from the area of the test furrows. This factor was quite noticeable when water appeared in furrows six - eight rows laterally from the test furrows with no overtopping of furrows taking place. The theory that extensive lateral movement had taken place was verified somewhat when the adjacent areas to the test furrows were irrigated. The rate of advance of the wetting front in these areas was generally more rapid than on the previously irrigated test areas. This indicated that some water probably moved laterally from the test areas.

The slope areas were analyzed as a border and the infiltration figured from the advance of the border wetting front. The equations obtained by this method indicated a more practical infiltration rate for this soil type. It was assumed by this method that more of the lateral movement effect of the subsurface water could be eliminated. When the equations considering border flow were analyzed, the standard deviations of the constants $\underline{K}$ and $\underline{n}$ of Eq. (11) were noticeably smaller. This would indicate that the results obtained by the border method were more consistent and less variance occurred between the results for each of the test slopes.

The relative agreement of the results in this investigation and by Beer (1) in Harrison County, Iowa, on Blencoe soils indicates that the values obtained may be approximately representative of the Blencoe soil type.

SUMMARY

A furrow-irrigated plot has been investigated for the purpose of obtaining relationships for the rate of advance of the wetting front and for the rate of infiltration.

An efficient furrow-irrigation system requires a properly designed length of furrow and knowledge of the average furrow infiltration rate over the entire length of furrow.

It was shown that for a given furrow grade, furrow input, and soil type the wetted front moved through the furrow according to the equation $\underline{T = a x^{b}}$ where $\underline{T}$ is the time in minutes after furrow input has been introduced, and $\underline{x}$ is the distance in feet down the furrow that the wetted front has progressed in time $\underline{T}$. It was also shown that two slightly different systems of equations can be developed by first determining the rate-of-advance equations in a single test furrow and by secondly considering a system of five adjacent furrows as a border. The average equations for the five slopes studied are:

Single test furrow --- $T = .0055\, x^{1.85}$ (Eq. 32)
Five furrows as a border --- $T = .0063\, x^{1.88}$ (Eq. 33)

The rate of advance of the wetting front was expressed as a straight line on log-log paper and as a parabolic curve on rectangular graph paper.

Several approaches for determining the furrow infiltration rate of the Blencoe soil were presented. They were:

Method 1. Using the differential rate of flow as determined between Parshall flumes placed at measured stations in the test furrows.

Method 2. Using the rate of advance of the wetting front in the test furrow, assuming no storage.

Method 3. Using the rate of advance of the wetting front considering five adjacent furrows of each slope as a border, assuming no storage.

Method 4. Using the discharge-time curves plotted for each station of the test furrow on each slope.

Method 5. Using the two conditions: rate of advances with infiltration and rate of advance with little or no infiltration.

The infiltration curves for the differential rate of flow between flumes were plotted on log-log paper. They are illustrated in Figures XXXIV, XXXV, XXXVI, XXXVII, and XXXVIII of Appendix A. The average infiltration equation obtained by this method was:

$$I = 55.69\ T^{-.6198} \qquad \text{(Eq. 34)}$$

The infiltration rates as determined from the rate of advance of the wetting front in the single test furrow of each slope are illustrated in Figures XXXIX, XL, XLI, XLII, and XLIII of Appendix A. The average equation obtained was:

$$I = 54.34\ T^{-.5896} \qquad \text{(Eq. 35)}$$

The infiltration rates as determined from the rate of advance of five adjacent furrows of each slope are illustrated in Figures XLIV, XLV, XLVI, XLVII, and XLVIII of Appendix A. The average equation obtained was:

$$I = 12.22\ T^{-.5185} \qquad \text{(Eq. 36)}$$

When the results obtained for the rate of advance and for the rate of infiltration are correlated with the five different slopes, there seems to be no well defined correlation. This indicates that the slopes were too flat and uneven and that there was not enough distinction between slopes in this investigation to make a definite correlation of these factors possible.

The discharge-time curves can be used to obtain the amount of water that infiltrated between stations. The difference between the ordinates between any two stations at a given time is the sum of the infiltration rate and the instantaneous change in storage at that time.

The infiltration rate may be determined at any desired time if the advance rate can be found with infiltration and without infiltration. The furrow input multiplied by the difference in time that each wetted front passes a particular distance gives the volume that has infiltrated. The equation for this application is:

$$\frac{Q}{L} = \frac{(T_1 - T_o)\ Q}{T_1\ (x/100)} \qquad \text{(Eq. 30)}$$

Therefore, an average infiltration equation can be determined for any furrow input, providing the constants for the rate-of-advance equations are known.

The variations within the plot due to cut and fill areas, which resulted from land forming, made reliable infiltration studies very difficult. There was no doubt that the infiltration results were affected somewhat by uneven field conditions.

CONCLUSIONS

The following conclusions can be drawn from the preceding investigation:

1. It can be concluded that the average rate-of-advance equations obtained by the single furrow method and the border method are approximately similar. They may be assumed to be approximately representative of the Blencoe soil under conditions similar to those of this investigation. The equations obtained were:

   Single test furrow $T = .0055\ x^{1.85}$ (Eq. 32)

   Five furrows as a border $T = .0063\ x^{1.88}$ (Eq. 33)

2. It can be concluded that the infiltration equations obtained by considering the five furrows of each slope as a border are most representative of the Blencoe soil involved. The average equation for the borders was:

   $$I = 12.22\ T^{-.5185} \qquad \text{(Eq. 36)}$$

3. It can be concluded that the infiltration equations obtained by the differential rate between Parshall flumes and by the rate of advance in the single test furrows produced rates impractical to this soil type and soil conditions. The average equations were:

   Differential between flumes $I = 55.69\ T^{-.6198}$ (Eq. 34)

   Advance in single test furrow $I = 54.34\ T^{-.5896}$ (Eq. 35)

   It can also be concluded that these high values obtained may be due to the unevenness of the furrow grade and the excessive lateral movement of subsurface water.

4. It can be concluded that the slopes were too flat and uneven in this investigation to obtain a correlation between the different slopes and the values obtained for the rate of advance and the rate of infiltration.

5. It can be concluded that the discharge-time curves plotted for each station of the test furrow on each slope resulted in an approximate figure for the quantity of water infiltrated at a particular time. This procedure illustrated trends between flume stations along the test furrow.

6. It can be concluded that the procedure using the two conditions--rate of advance with infiltration and rate of advance with little or no infiltration--produced a relatively accurate value for the infiltration rate. The expression:

$$\frac{Q}{L} = \frac{(T_1 - T_o)\,Q}{T_1\ (x/100)} \qquad \text{(Eq. 30)}$$

requires only a knowledge of the furrow inflow rate and the rate-of-advance equation with infiltration. The rate-of-advance equation for little or no infiltration may be approximated by graphical methods.

SUGGESTIONS FOR FURTHER INVESTIGATIONS

1. Investigate the volume of surface storage in the furrows and attempt to find a surface storage function applicable to the conditions in the irrigation furrows encountered in southeastern South Dakota.

2. Investigate the possibility of lateral subsurface movement of water and the extent to which it affects the infiltration and the rate-of-advance equations for the furrows on the Blencoe silty clay loam.

3. Investigate methods and procedures for obtaining irrigation furrows with better hydraulic characteristics and stability on flat slopes and on Blencoe silty clay loam soils.

4. Investigate the use of different size furrow inflow streams to:

   (a) determine the optimum stream size,

   (b) determine the relationship between the stream sizes and the infiltration rates,

   (c) obtain data so that the infiltration and rate of advance can be determined for a given time, stream size, and length of furrow.

5. Investigate the effects of initial moisture content on the infiltration rate and the rate of advance of the water in the furrows with Blencoe silty clay loam soil.

6. Investigate the change in the infiltration rate of the soil due to change of temperature of the soil and water. Determine the

amount of increase of the intake rate with increase in temperature on the Blencoe silty clay loam.

7. Investigate the methods for obtaining more uniform slopes on the very flat grades. Attempt to eliminate the problem of ponded areas.

8. Investigate the use of modified borders for irrigation in this area of southeastern South Dakota.

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APPENDICES

APPENDIX A. FIGURES

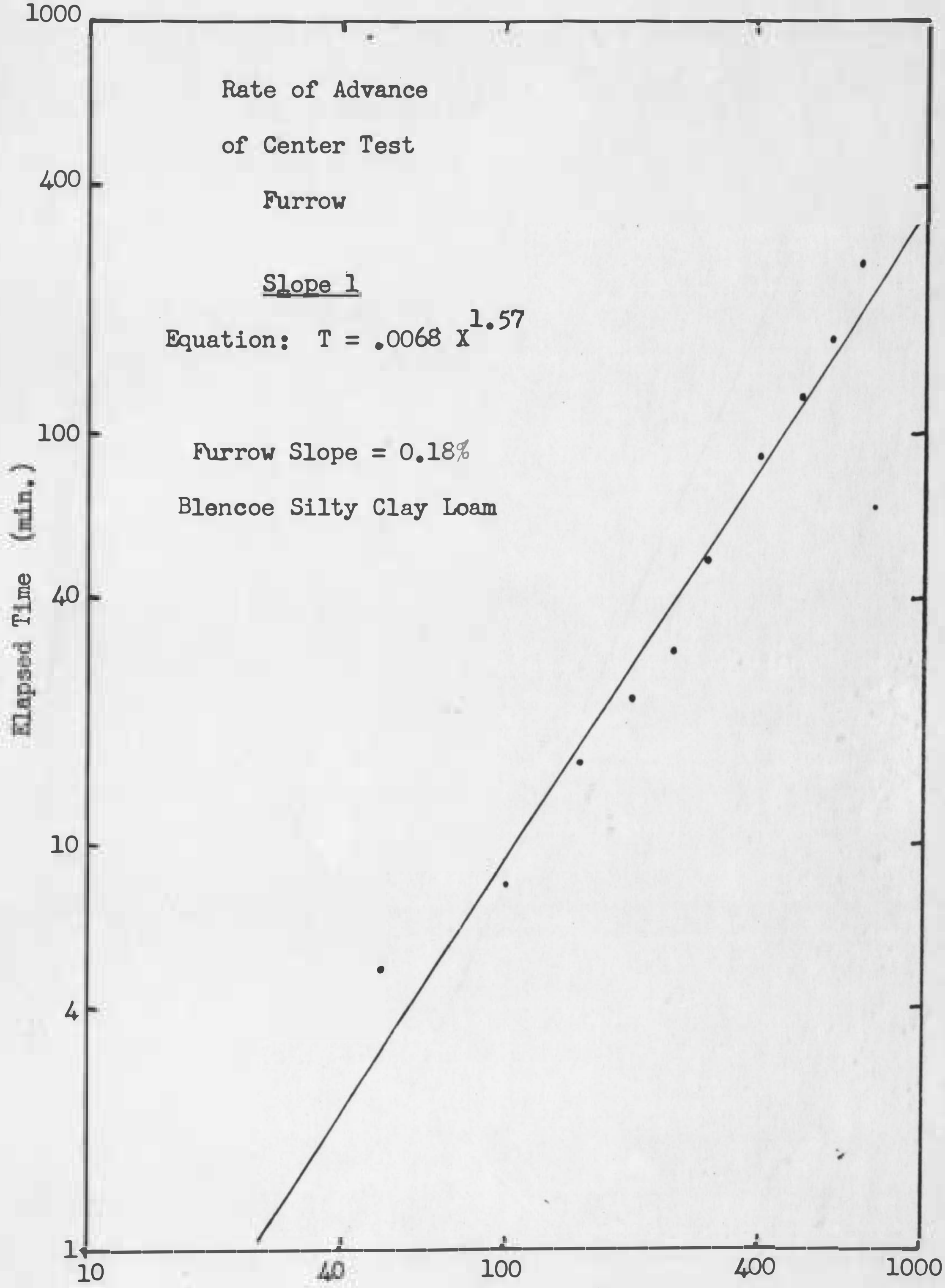

Figure XXIX. Rate of Advance of Center Test Furrow

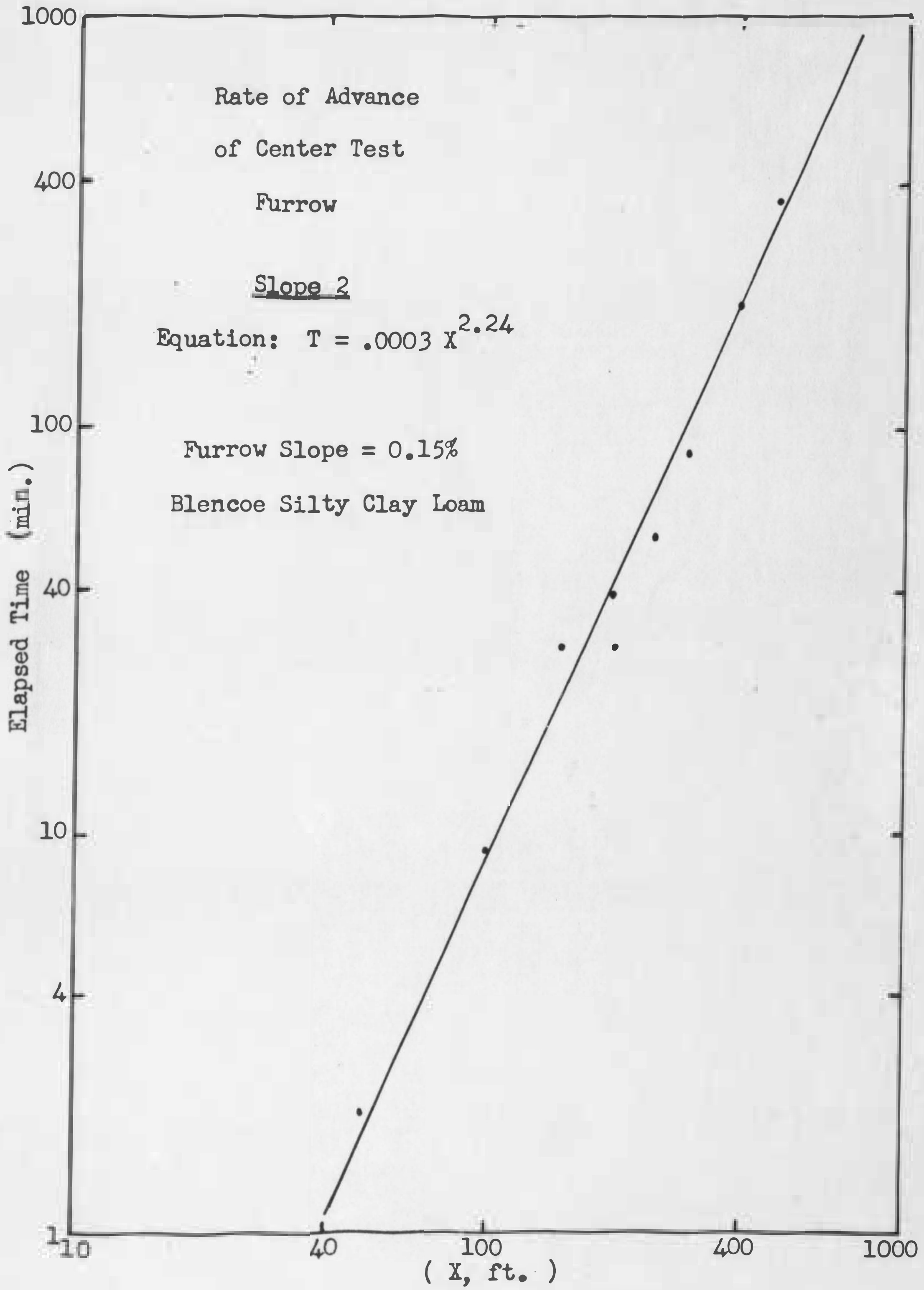

Figure XXX. Rate of Advance of Center Test Furrow

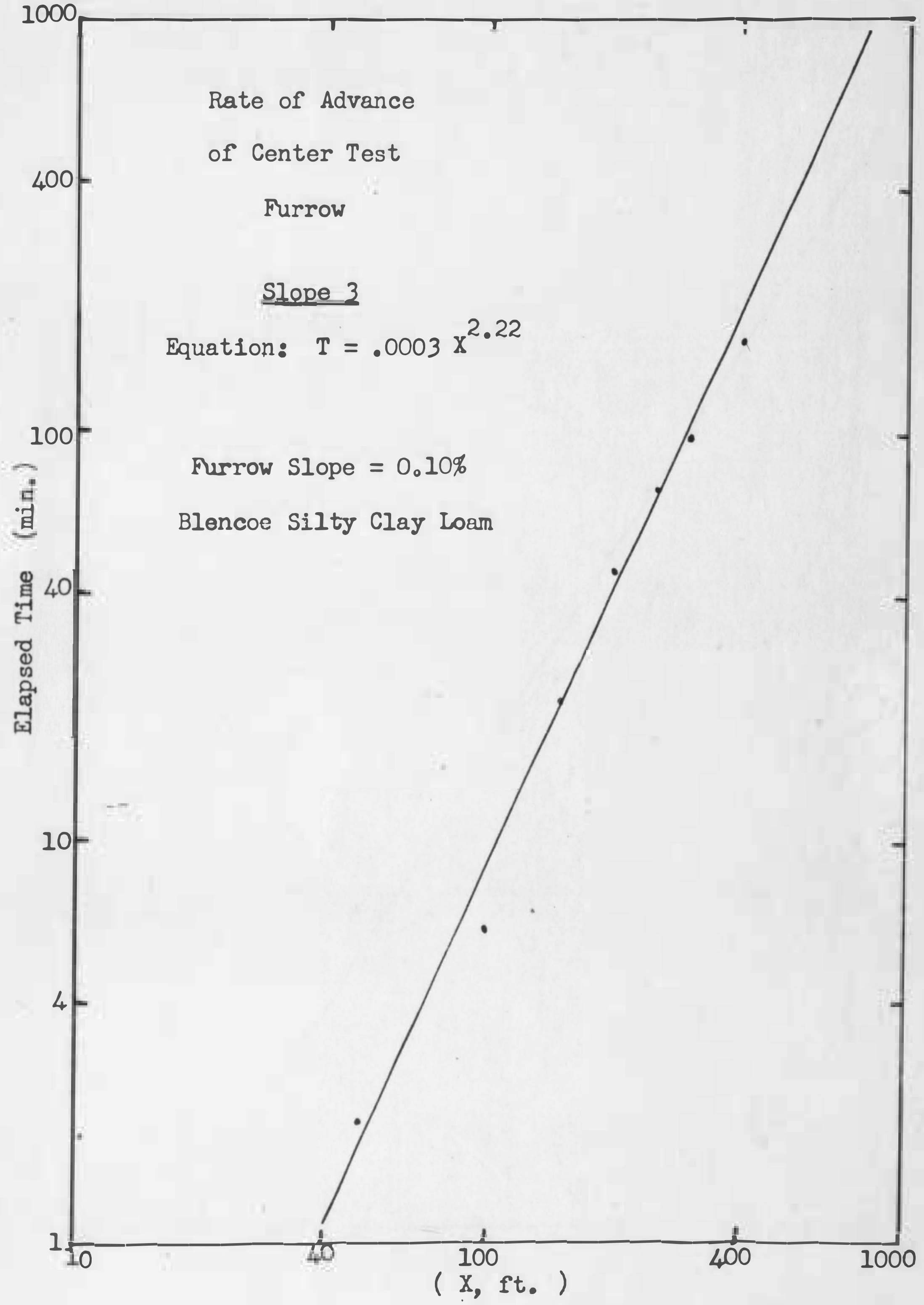

Figure XXXI. Rate of Advance of Center Test Furrow

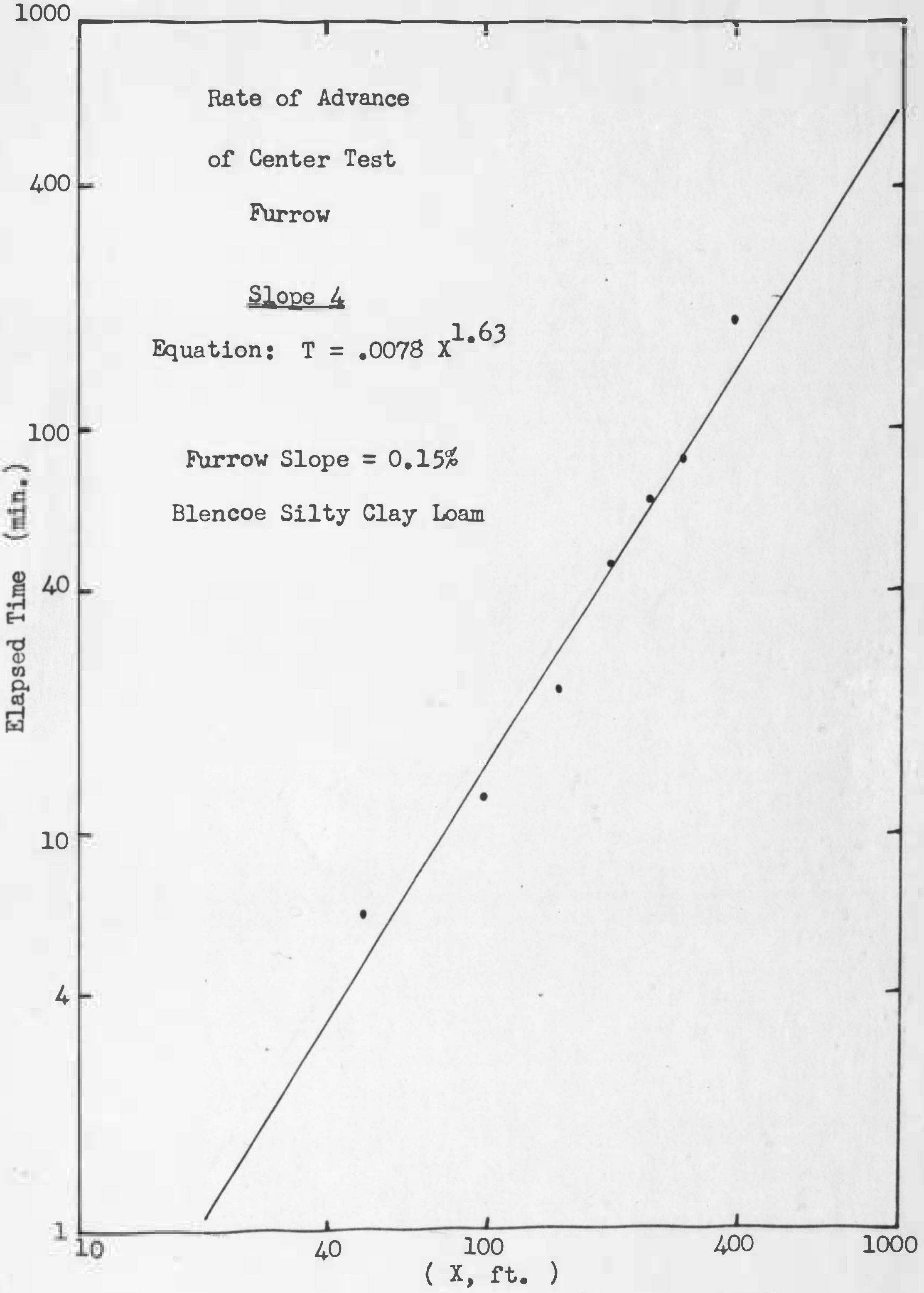

Figure XXXII. Rate of Advance of Center Test Furrow

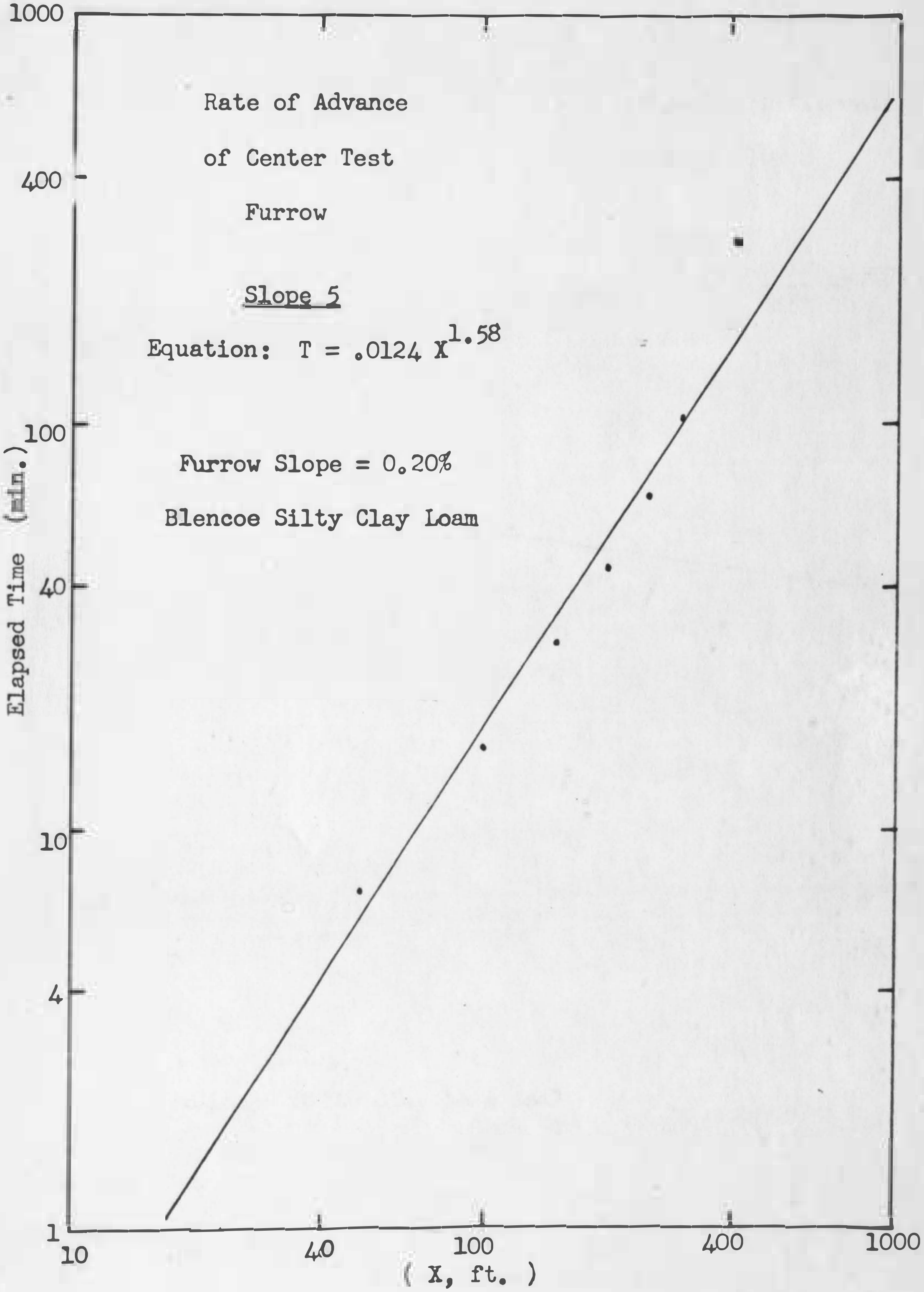

Figure XXXIII. Rate of Advance of Center Test Furrow

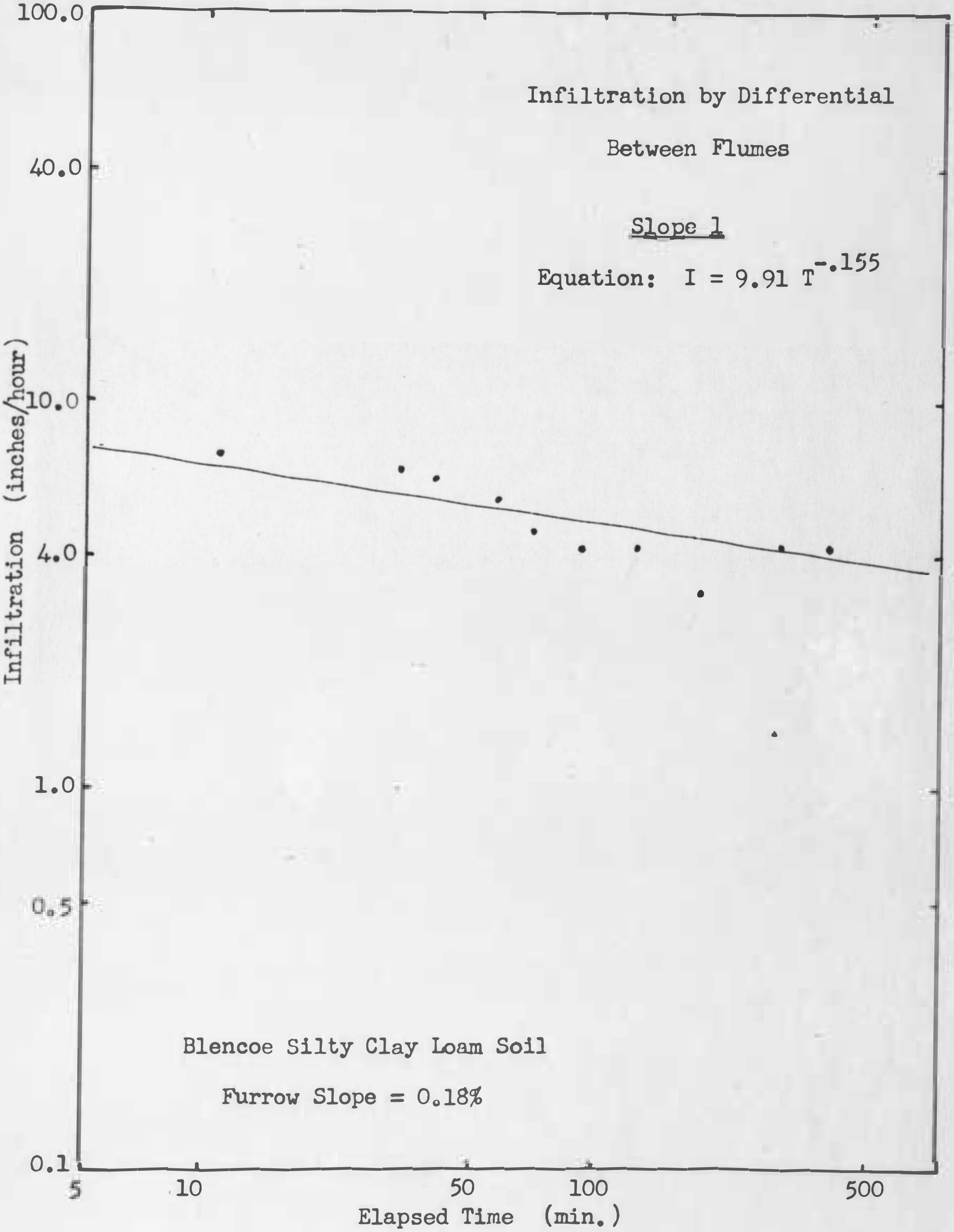

Figure XXXIV. Infiltration by Flumes

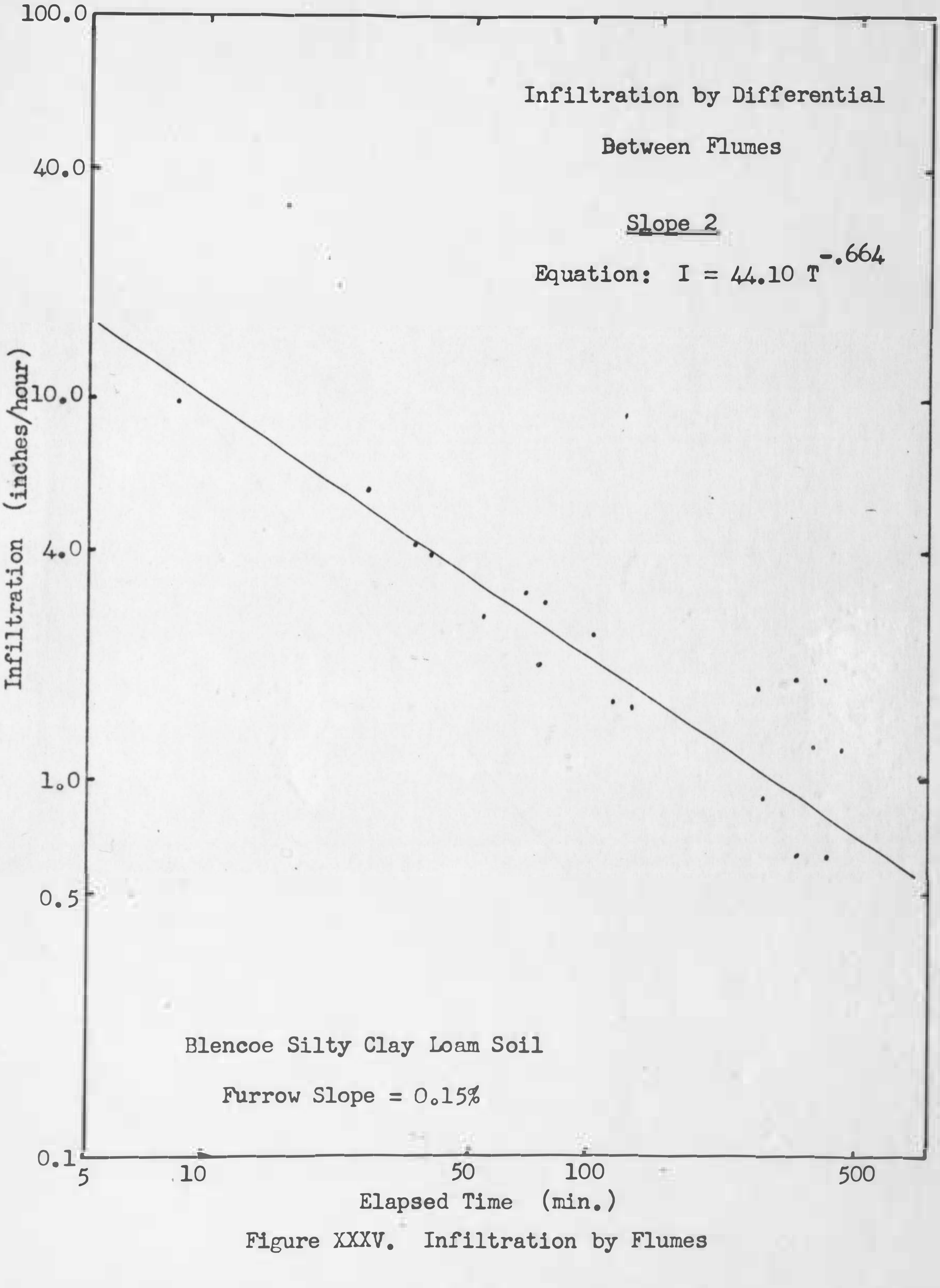

Figure XXXV. Infiltration by Flumes

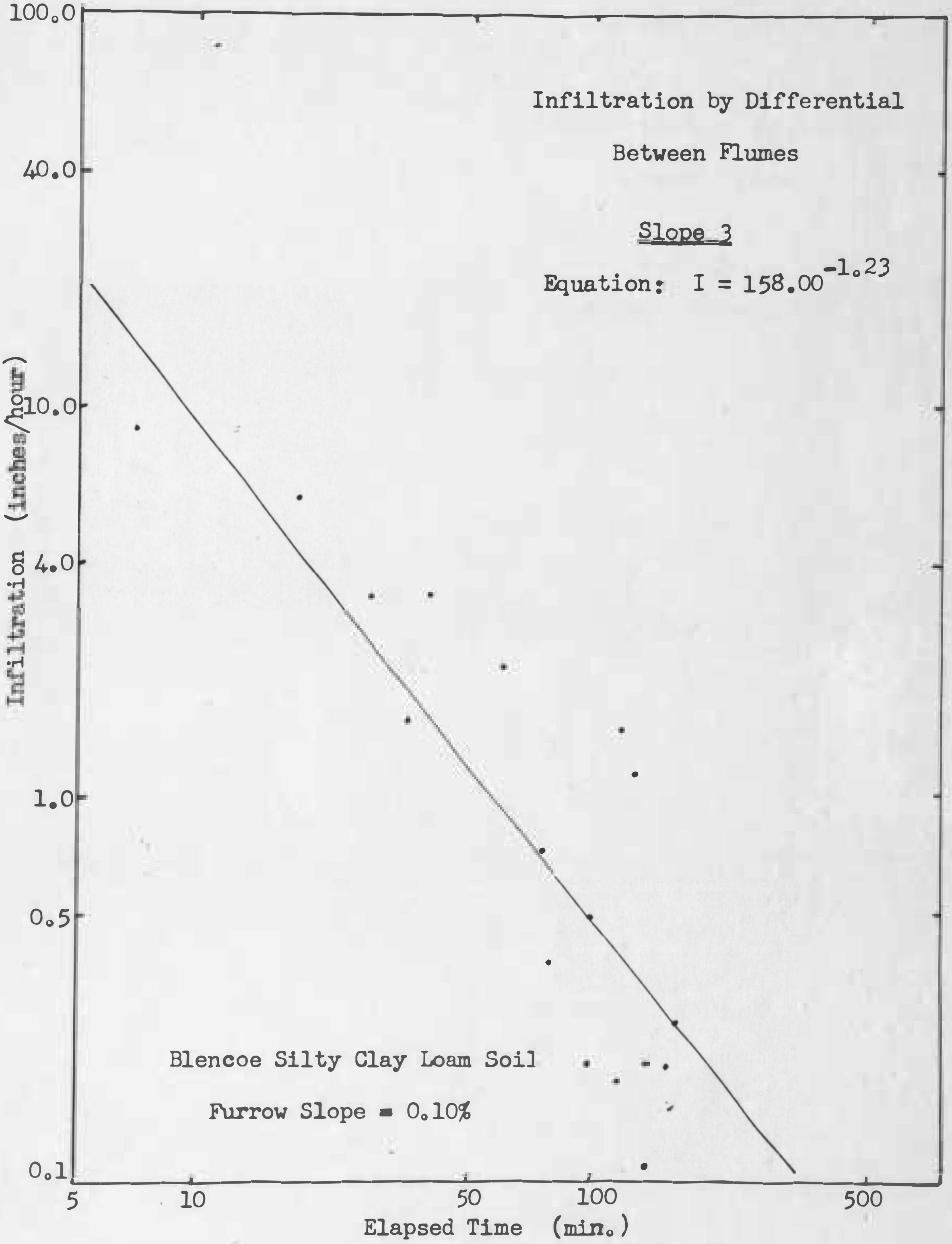

Figure XXXVI. Infiltration by Flumes

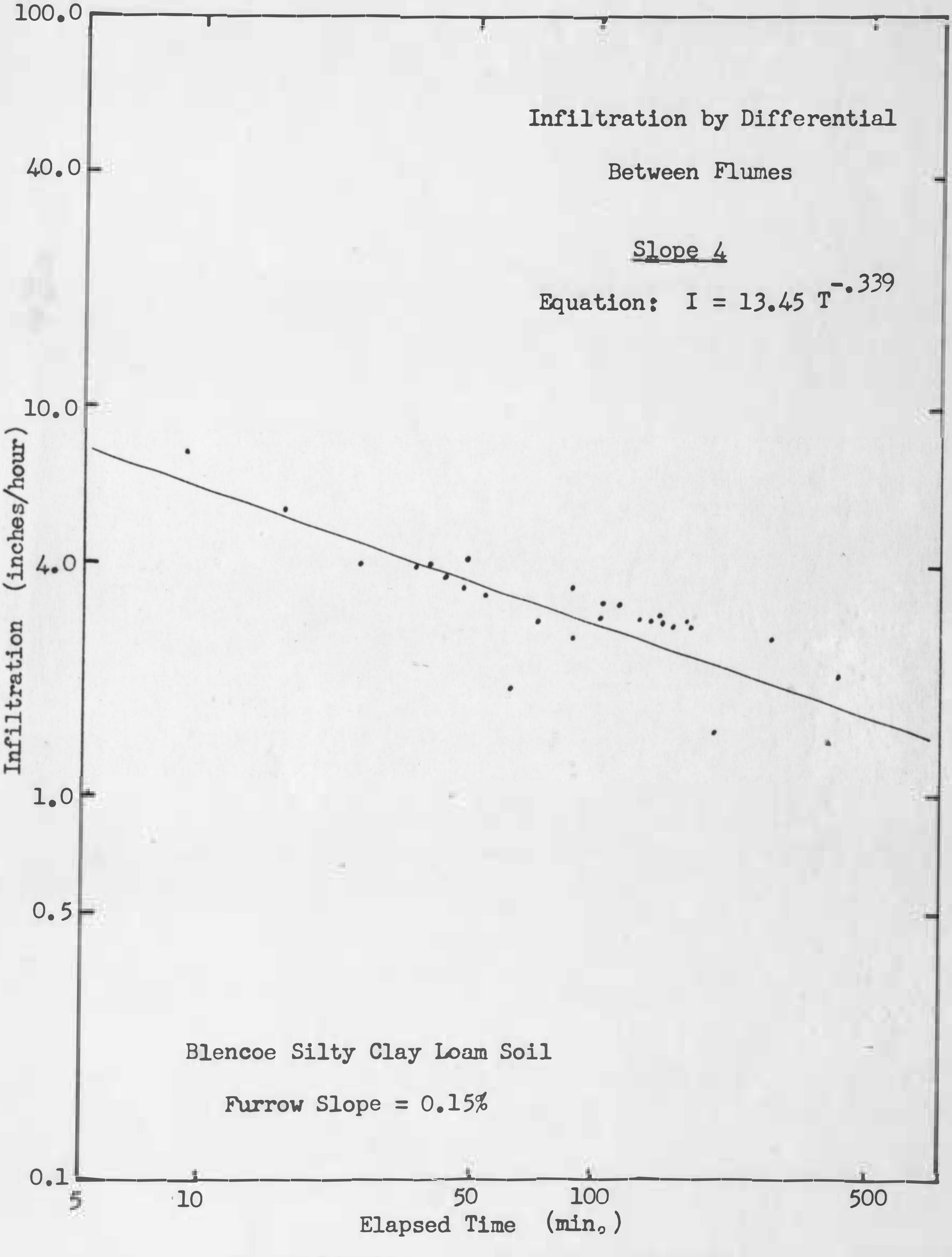

Figure XXXVII. Infiltration by Flumes

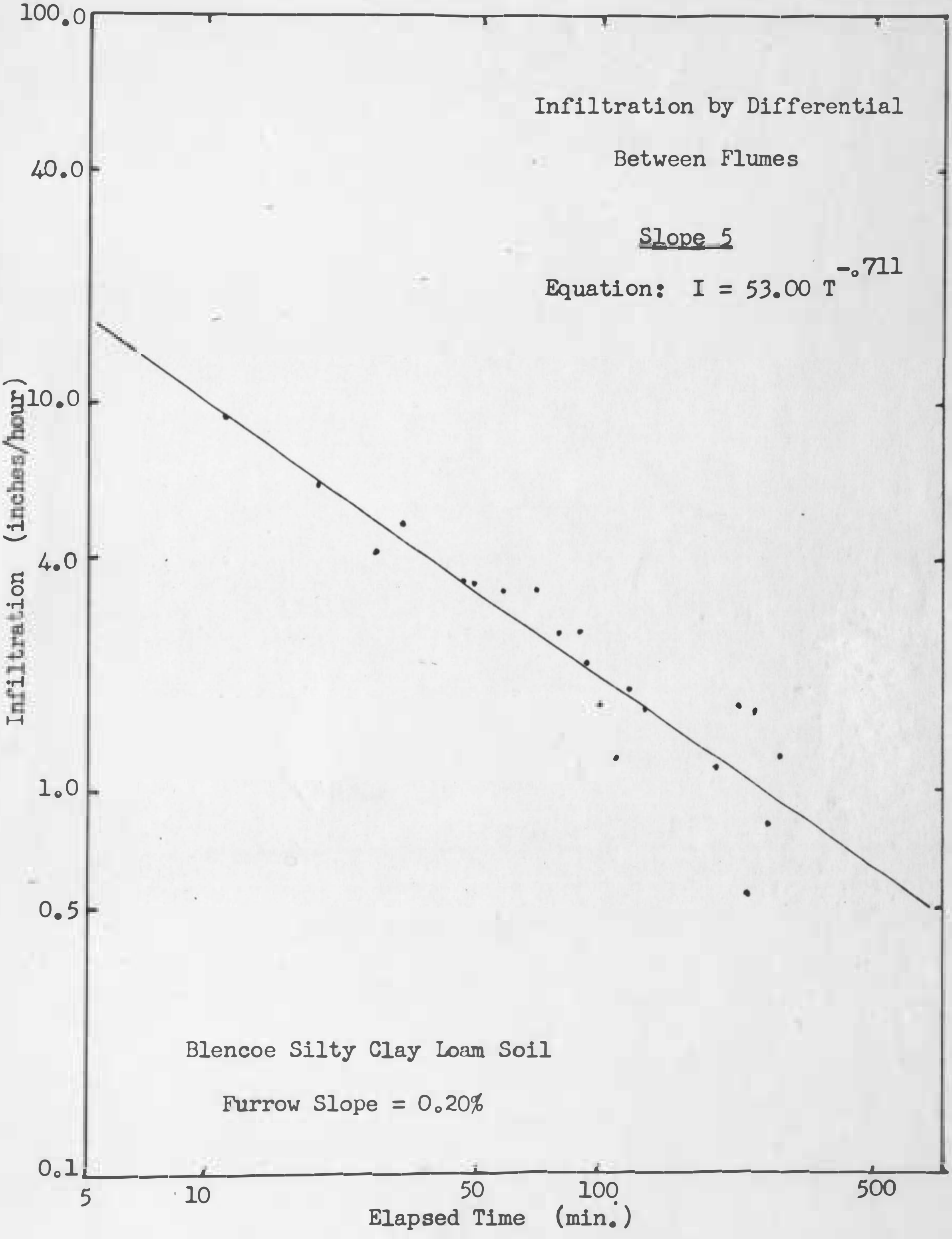

Figure XXXVIII. Infiltration by Flumes

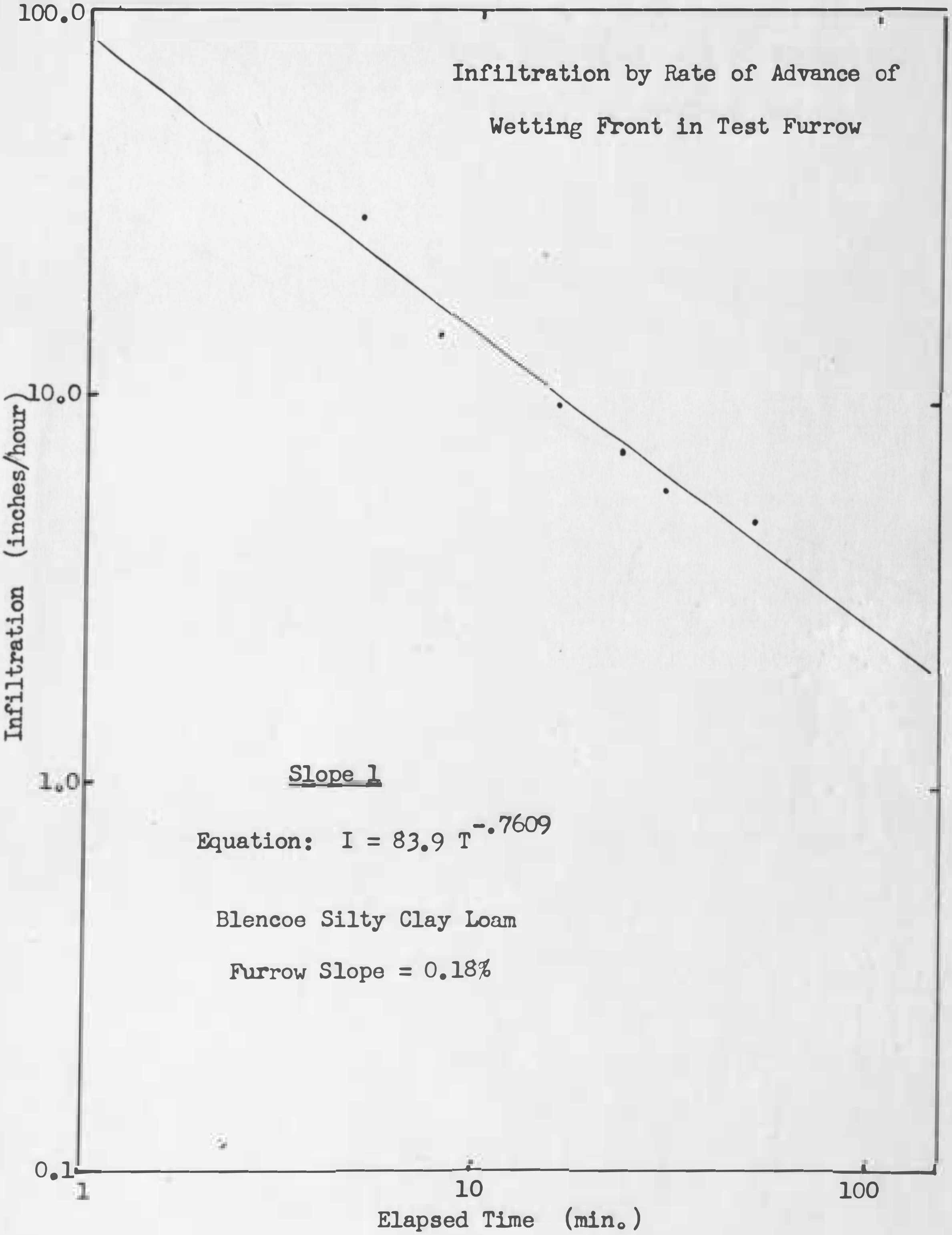

Figure XXXIX. Infiltration From Rate of Advance

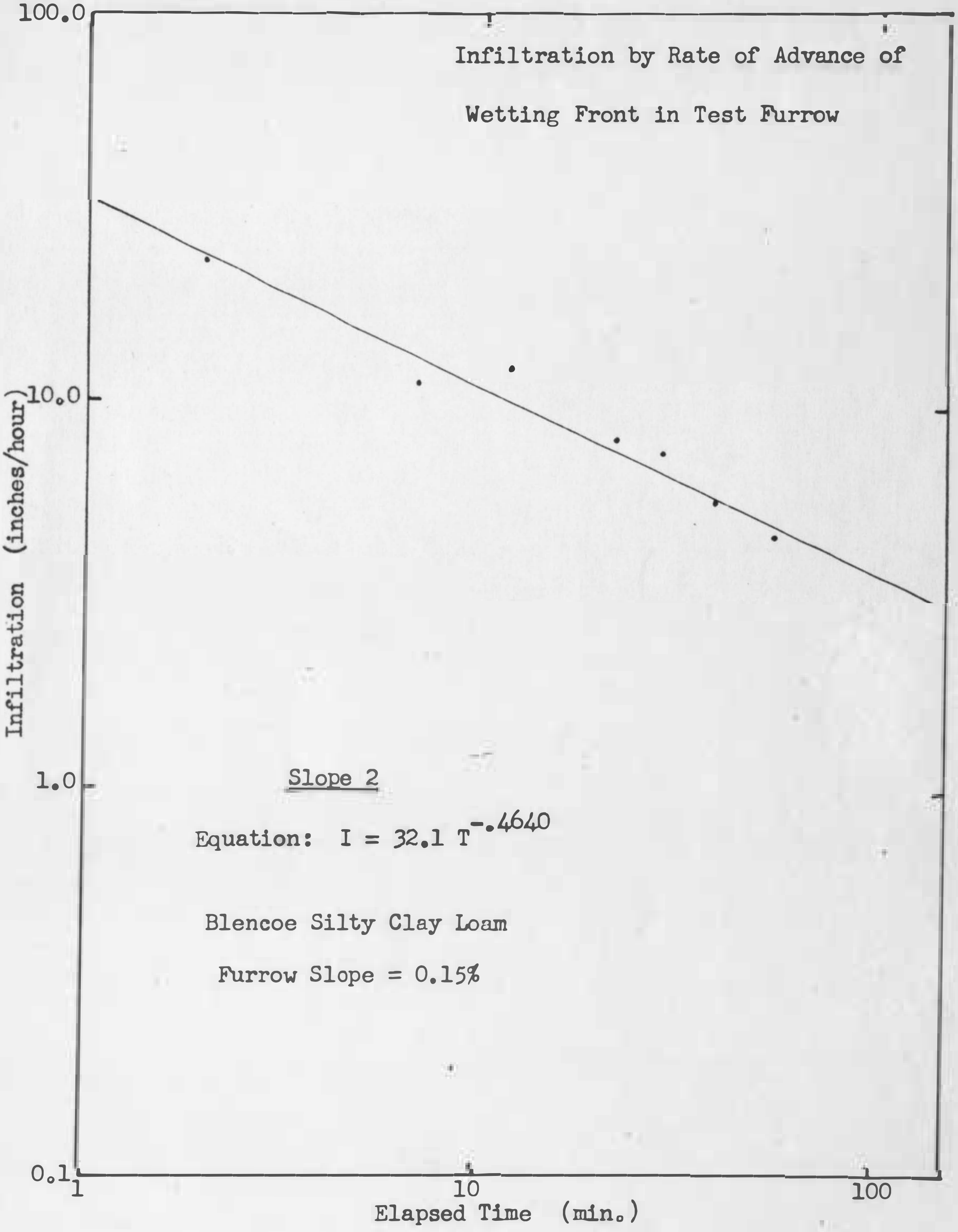

Figure XL. Infiltration From Rate of Advance

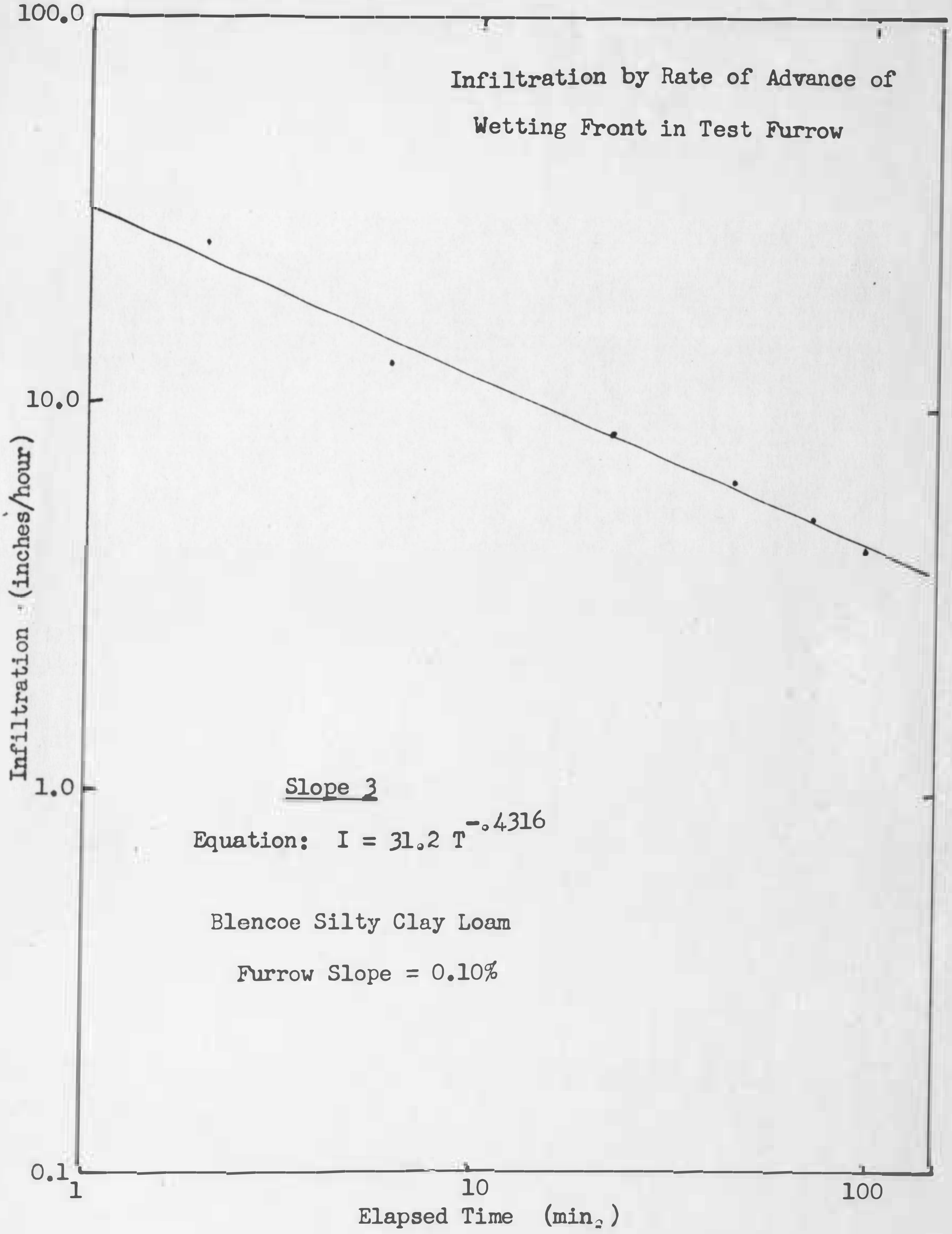

Figure XLI. Infiltration From Rate of Advance

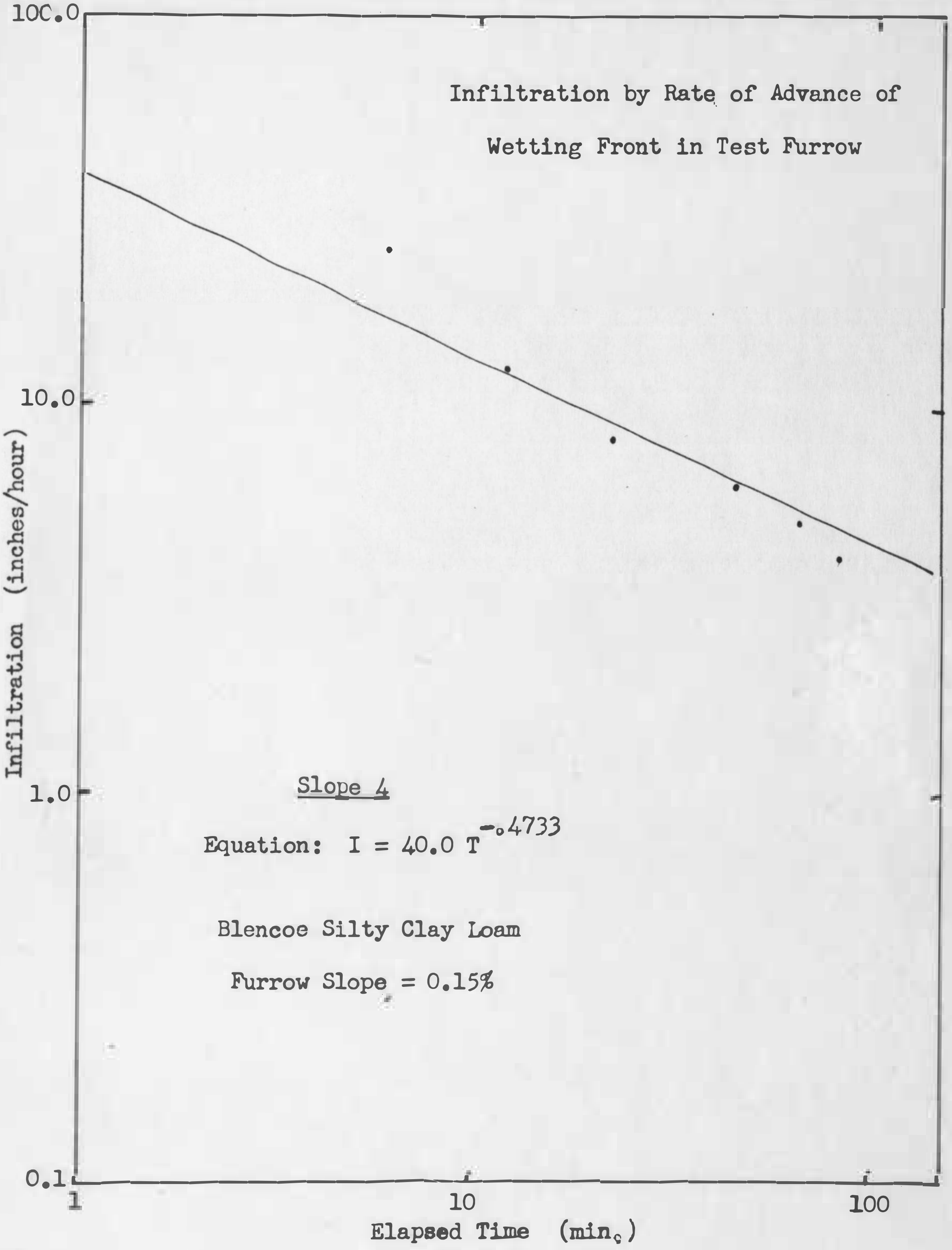

Figure XLII. Infiltration From Rate of Advance

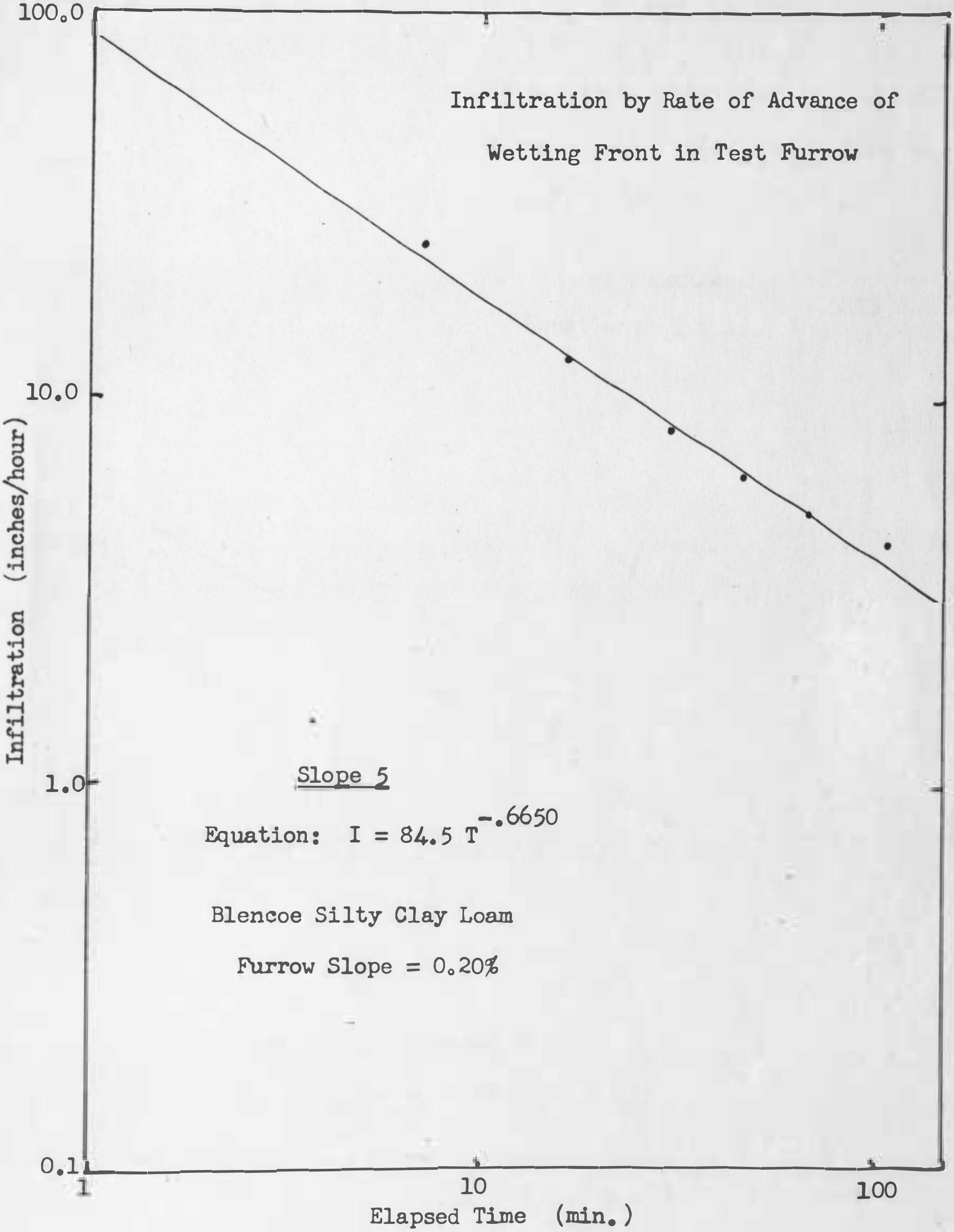

Figure XLIII. Infiltration From Rate of Advance

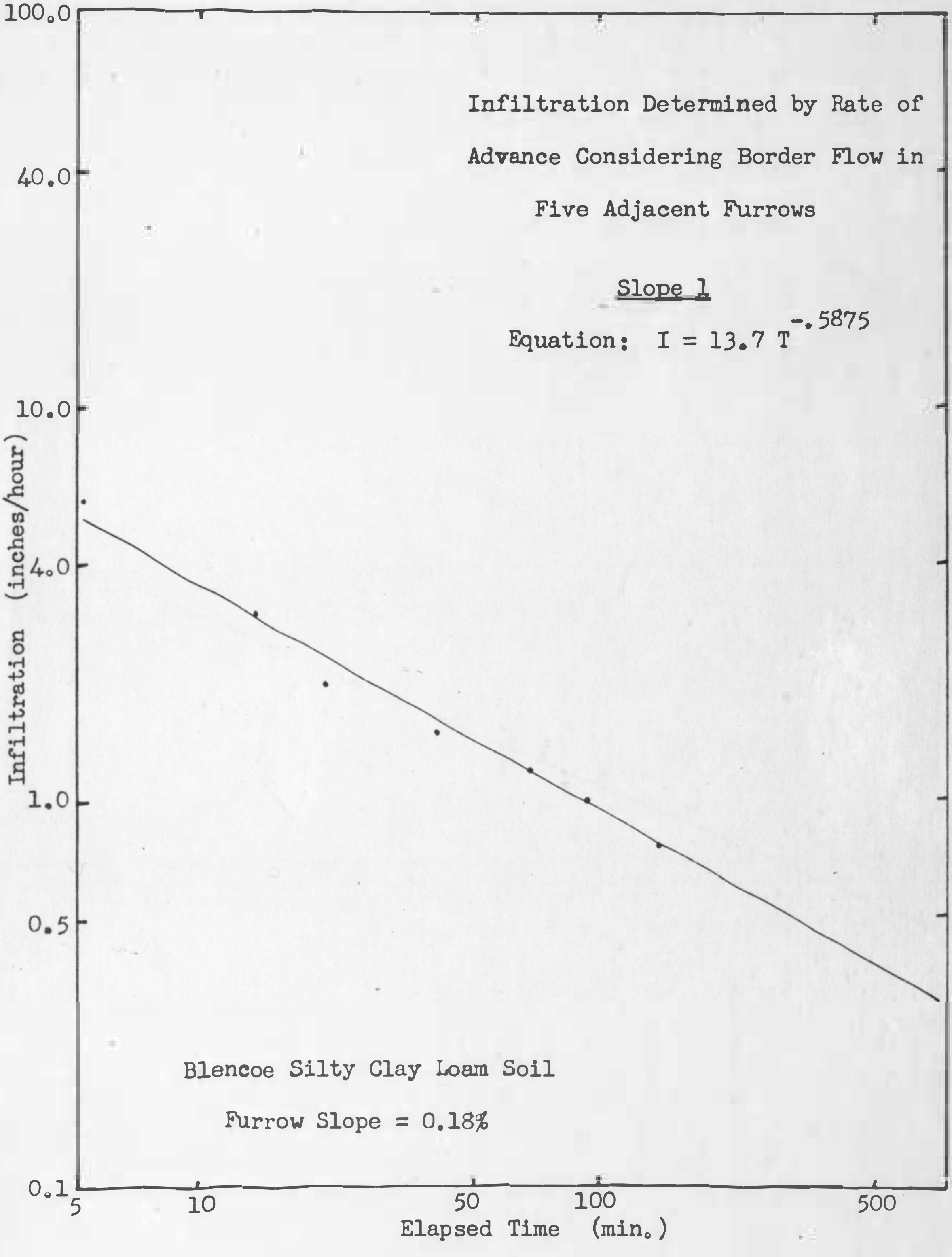

Figure XLIV. Infiltration From Border Flow

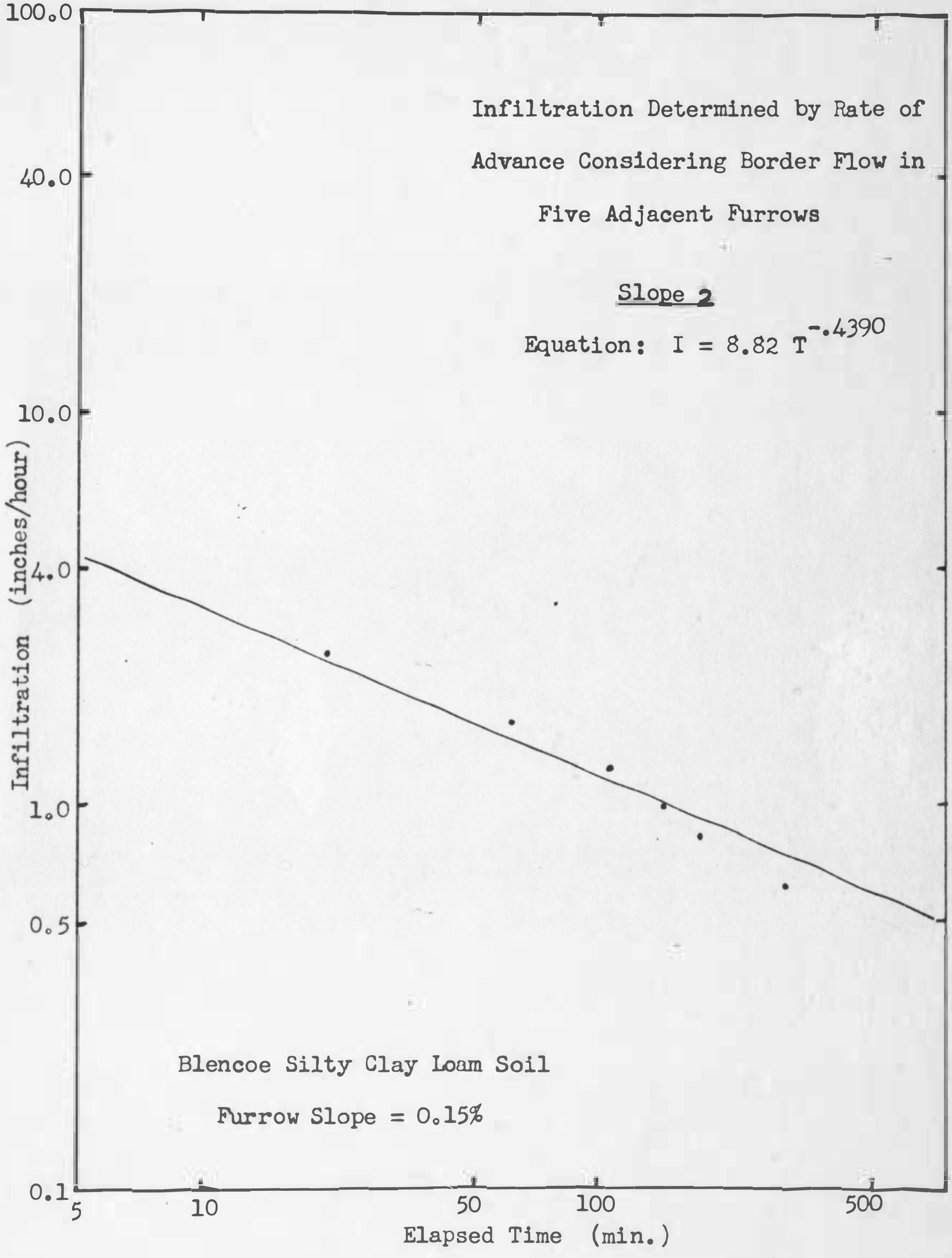

Figure XLV. Infiltration From Border Flow

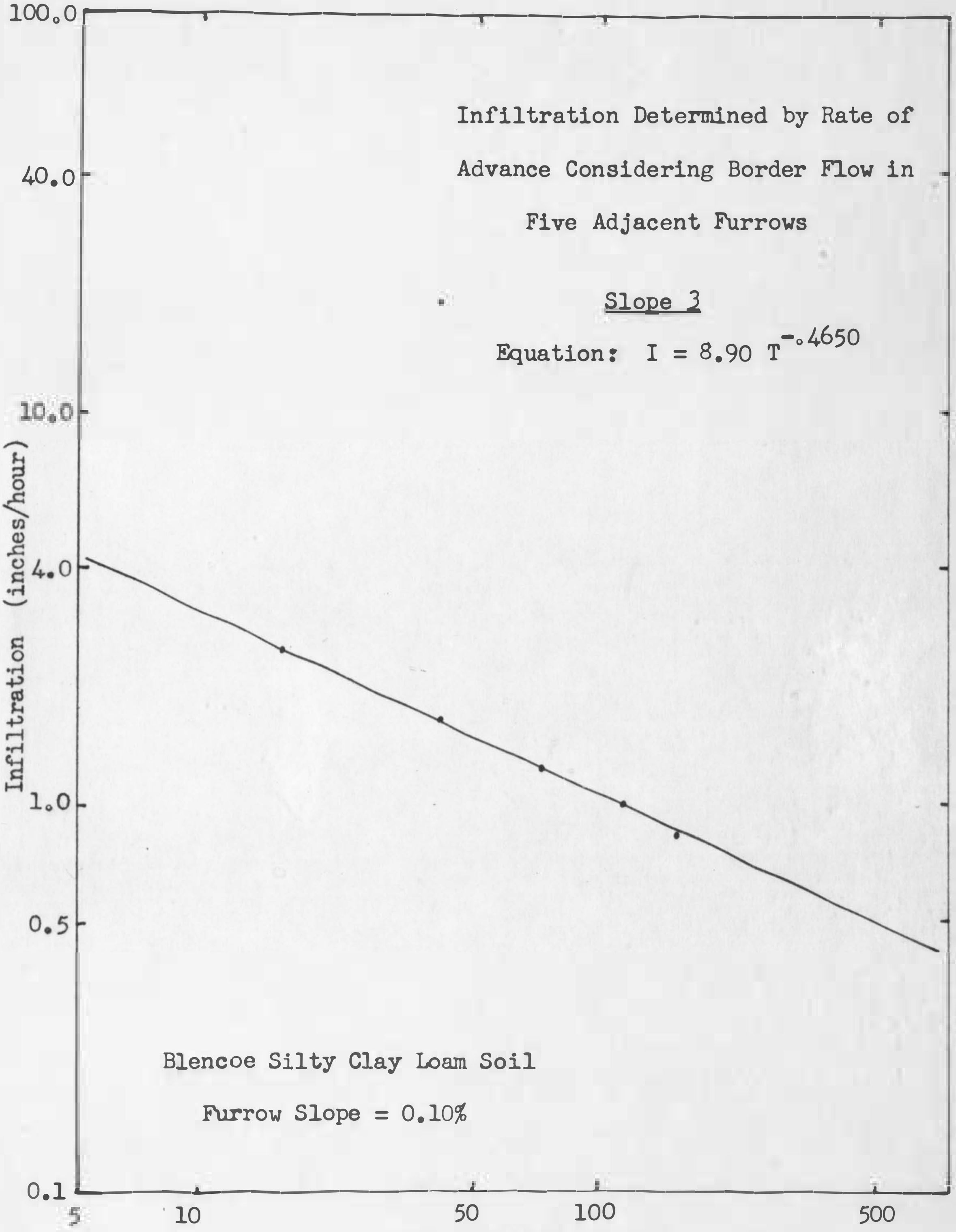

Figure XLVI. Infiltration From Border Flow

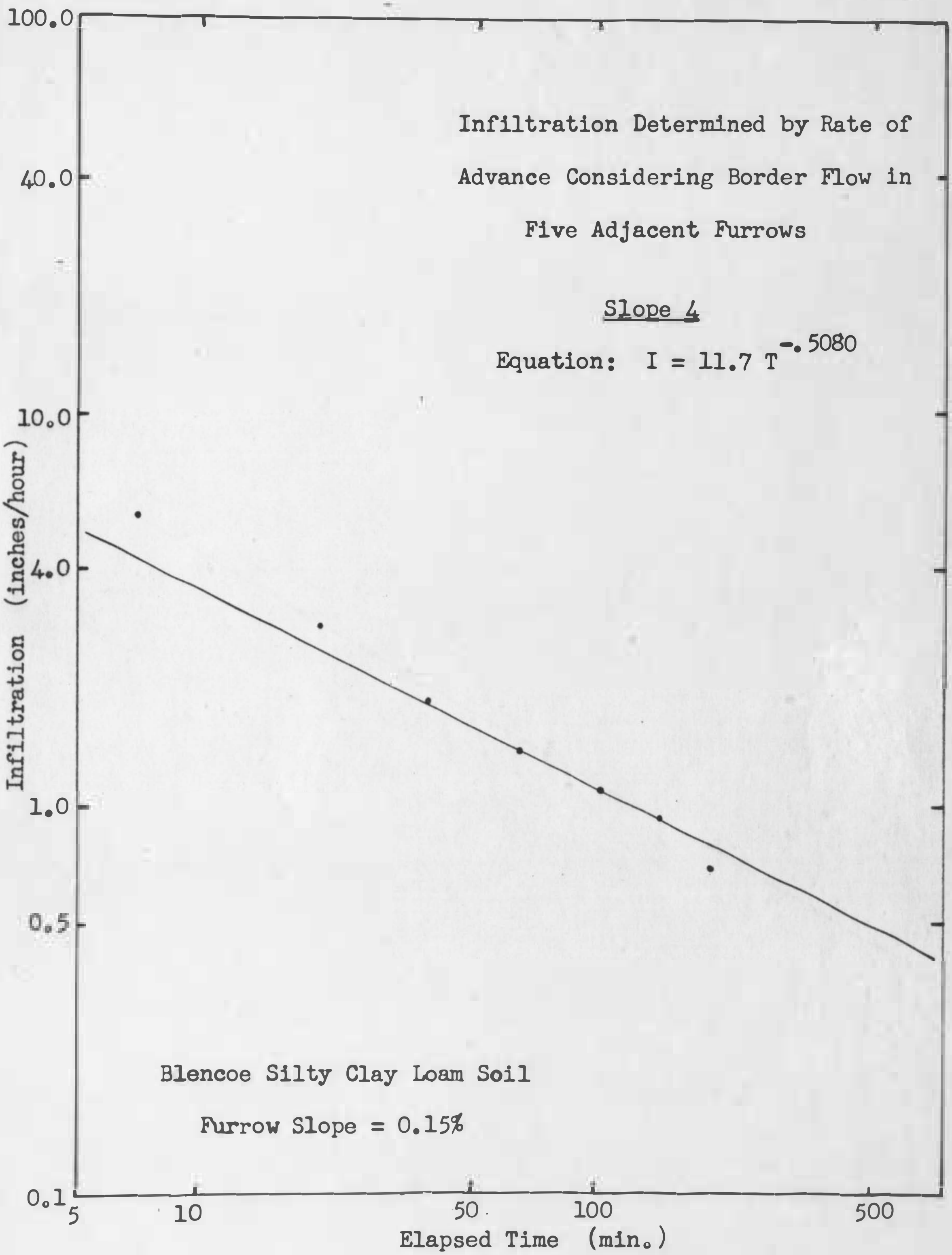

Figure XLVII. Infiltration From Border Flow

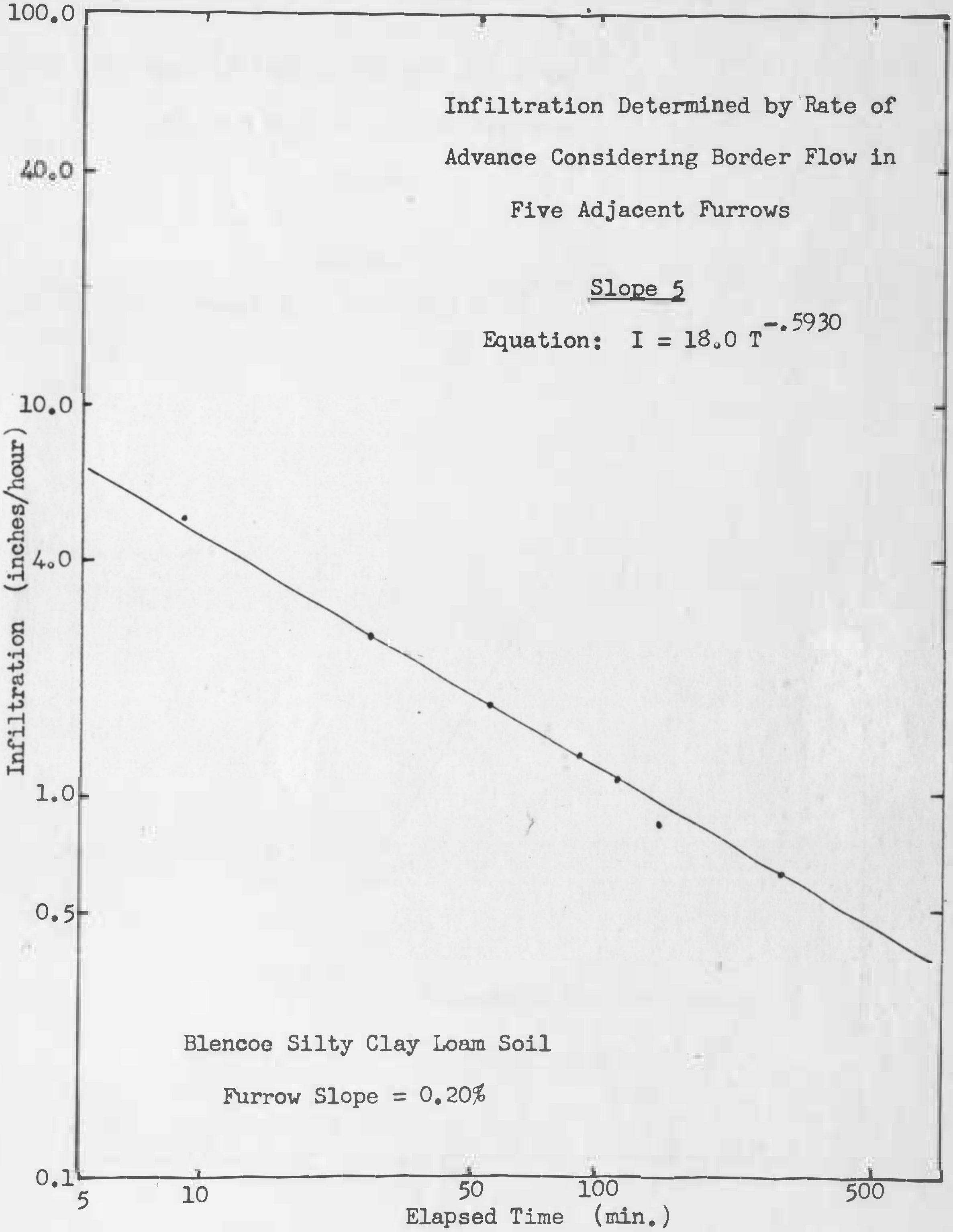

Figure XLVIII. Infiltration From Border Flow

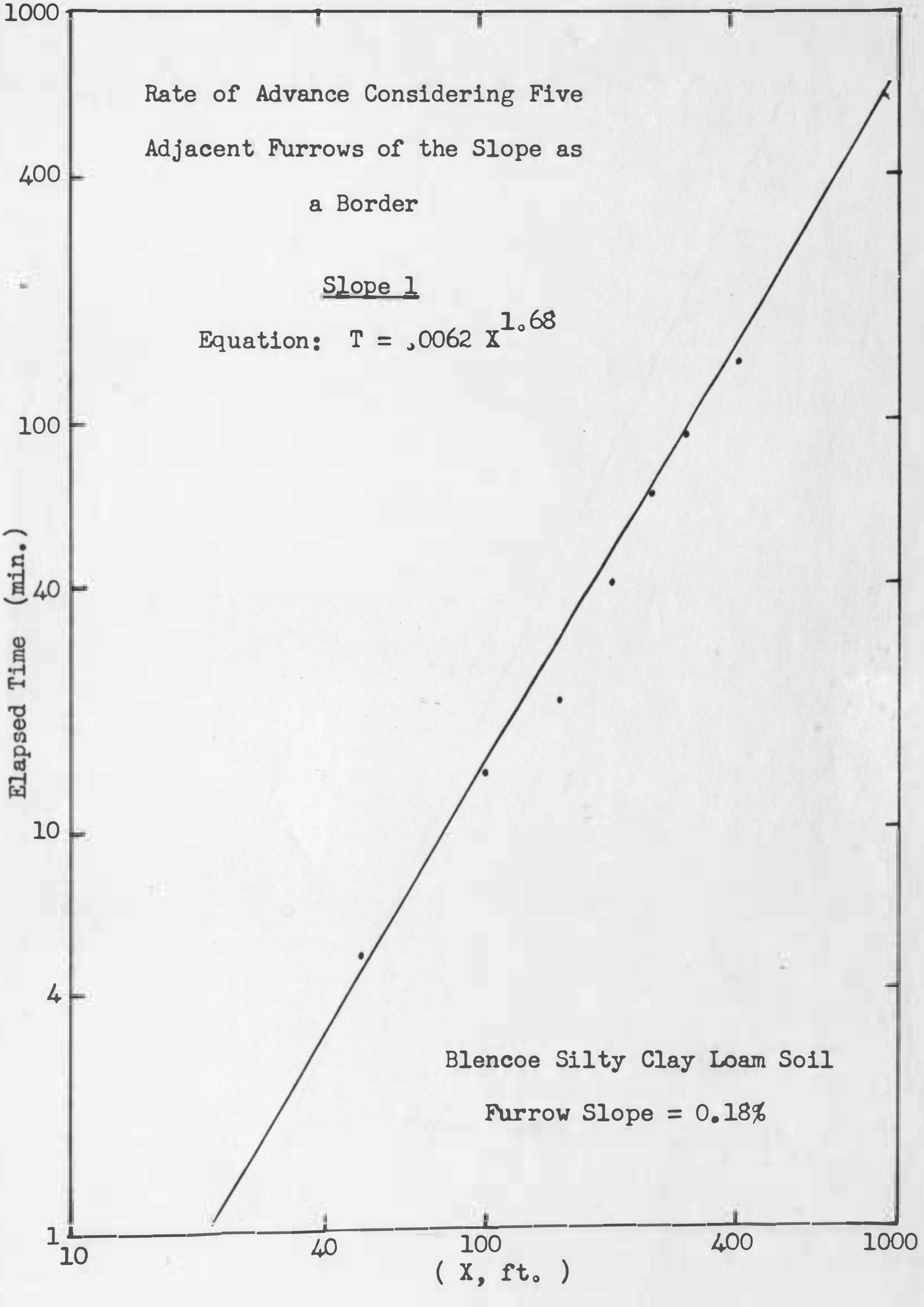

Figure XLIX. Rate of Advance From Border Flow

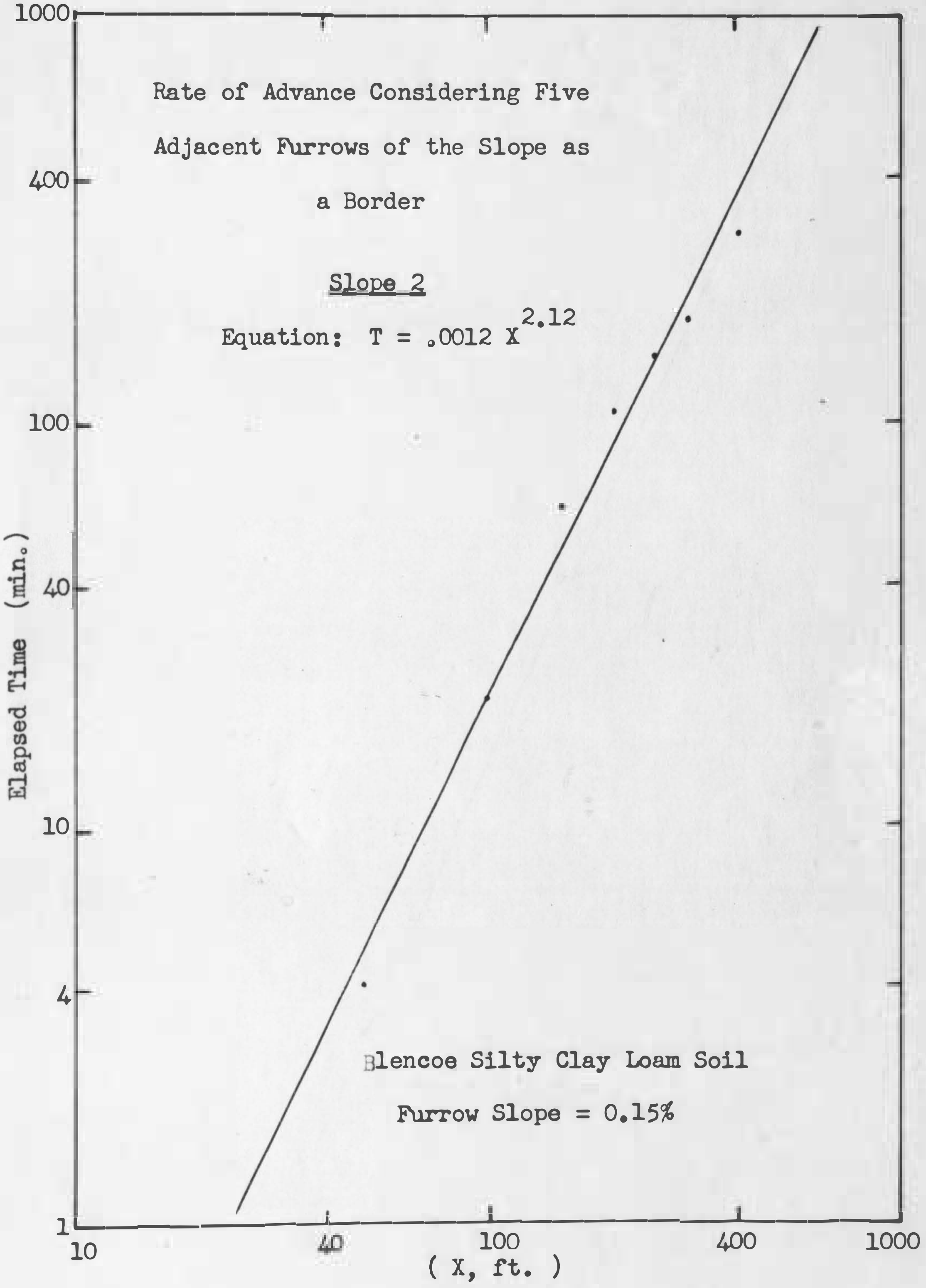

Figure L. Rate of Advance From Border Flow

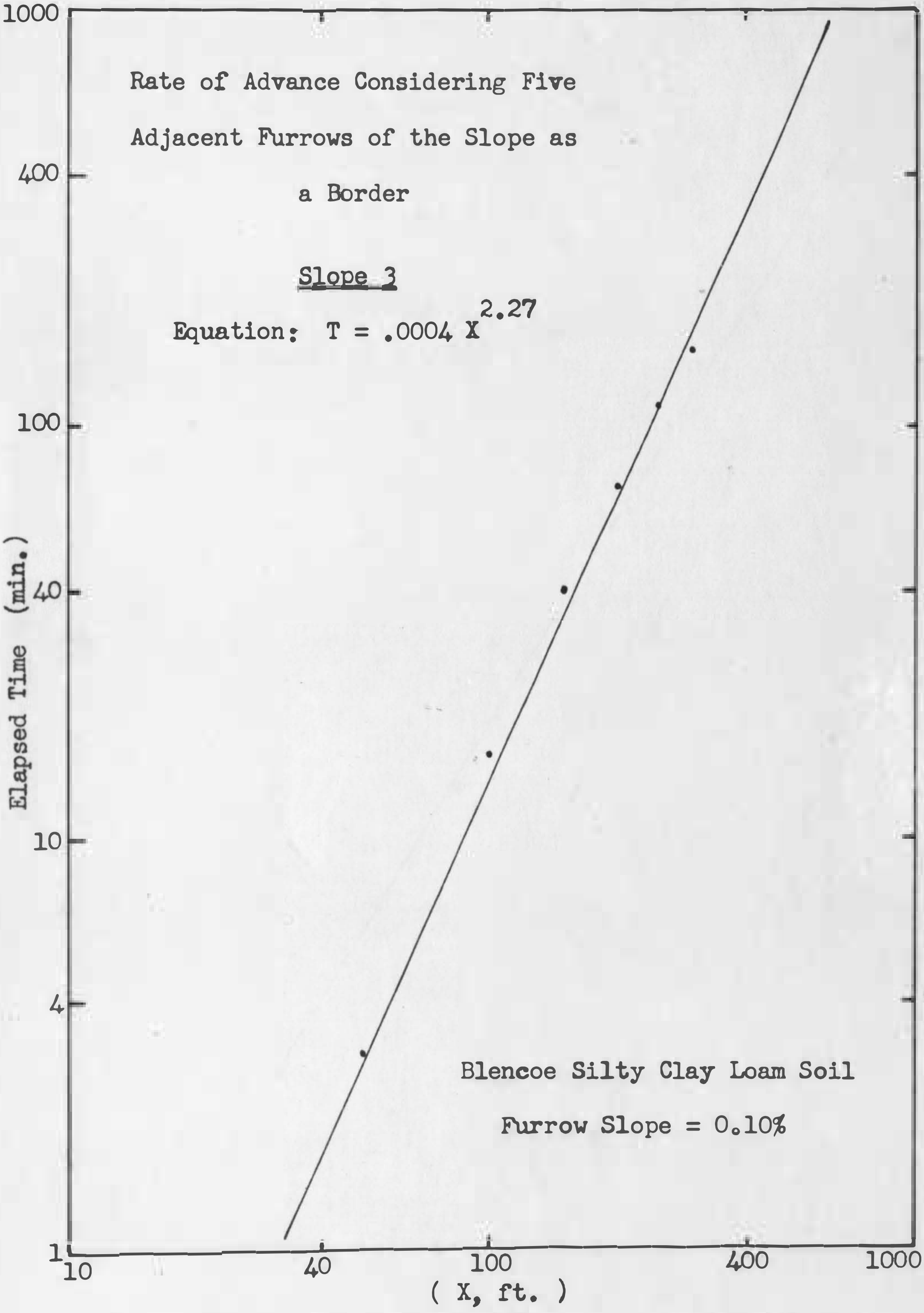

Figure LI. Rate of Advance From Border Flow

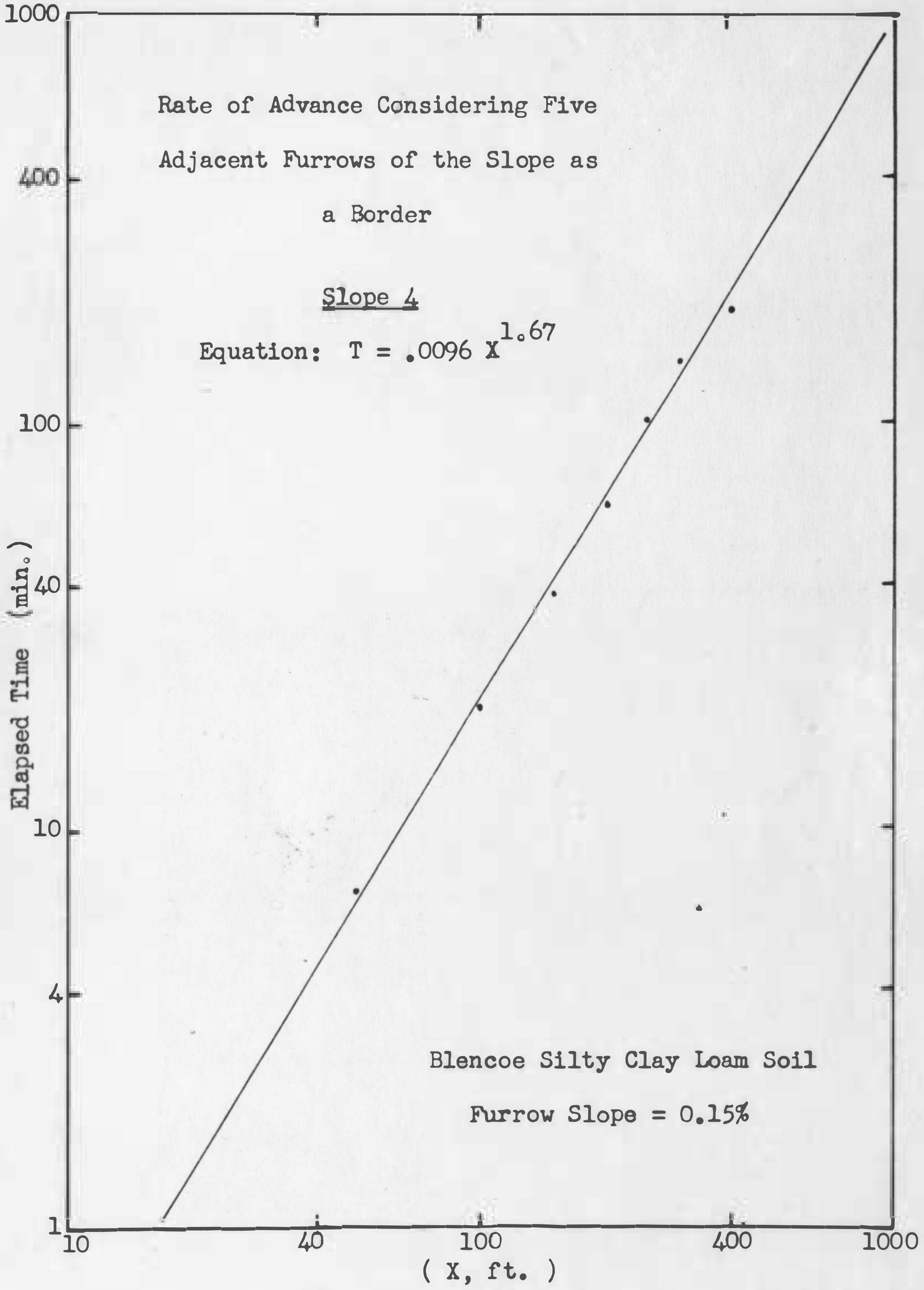

Figure LII. Rate of Advance From Border Flow

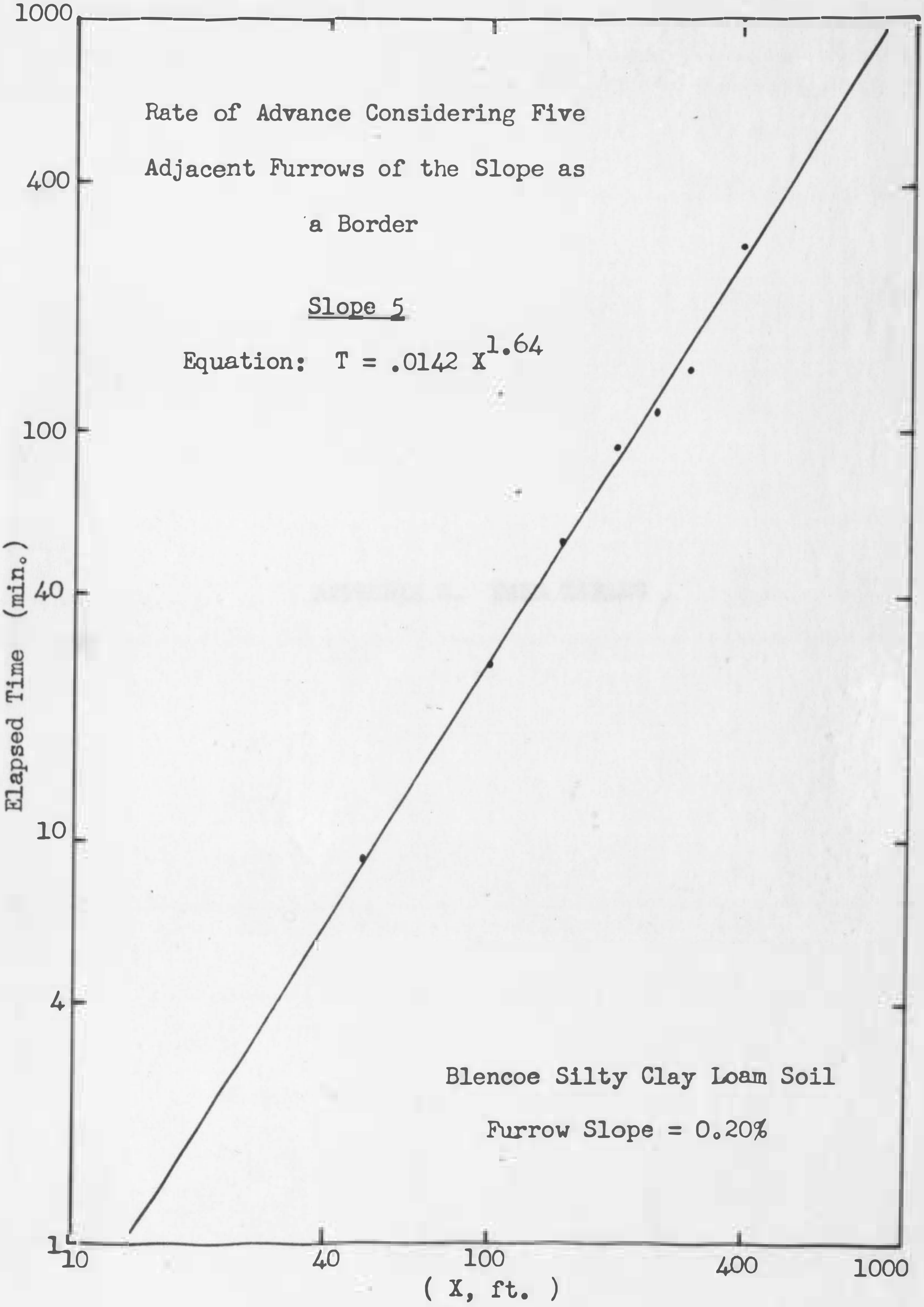

Figure LIII. Rate of Advance From Border Flow

APPENDIX B. DATA TABLES

Table 11. Rate of Advance Data

	Furrow number				
Station	1 Elapsed time (min.)	2 Elapsed time (min.)	3 Elapsed time (min.)	4 Elapsed time (min.)	5 Elapsed time (min.)
Slope 1					
0 + 00	start	start	start	start	start
0 + 50	5	5	5	6	6
1 + 00	10	26	8	12	14
1 + 50	20	45	16	22	30
2 + 00	45		23	45	50
2 + 50	80	85	30		80
3 + 00	116	115	50	85	110
4 + 00			90	150	190
5 + 00			128		
6 + 00	280		173		317
7 + 00	350		270	390	
8 + 00	480	510		515	
Slope 2					
0 + 00	start	start	start	start	start
0 + 50	4	4	2	4	4
1 + 00	11	31	9	27	24
1 + 50	41	74	29	87	81
2 + 00	84	129	39		174
2 + 50	139	179	55	204	
3 + 00	194		89		
4 + 00	384		204		
5 + 00			379		
Slope 3					
0 + 00	start	start	start	start	start
0 + 50	2	5	2	3	4
1 + 00	5	26	6	22	23
1 + 50	19	53	22	52	55
2 + 00	47	77	45	89	99
2 + 50	82		72	142	153
3 + 00	114	162	97	188	198
4 + 00			168		

Table 11. (Continued)

	Furrow number				
Station	1 Elapsed time (min.)	2 Elapsed time (min.)	3 Elapsed time (min.)	4 Elapsed time (min.)	5 Elapsed time (min.)
<u>Slope 4</u>					
0 + 00	start	start	start	start	start
0 + 50	5	9	6	7	8
1 + 00	12	23	12	21	30
1 + 50	30	40	22	45	51
2 + 00	50	62	45	75	90
2 + 50	80	85	65	140	135
3 + 00	110	135	82	188	195
4 + 00	200		180		
<u>Slope 5</u>					
0 + 00	start	start	start	start	start
0 + 50	8	9	7	15	6
1 + 00	25	14	16	35	45
1 + 50	53	52	29	60	75
2 + 00	95	90	45	105	120
2 + 50	110	115	67	120	145
3 + 00	150	152	105	165	
4 + 00	290		285		

Table 12. Infiltration Data by Differential Between Flumes

Elapsed time (min.)			Inflow at head (gpm)	Outflow (gpm)	Loss in furrow (gpm)	gpm/ft.	in./hr.
Station	Station	Average					
Slope 1							
0 + 00	1 + 00						
start			27.9				
15	7	11	27.6	13.4	14.2	.142	7.45
36	28	32	28.6	15.6	13.0	.130	6.82
43	35	39	28.6	16.5	12.1	.121	6.35
60	52	56	28.4	17.6	10.8	.108	5.65
74	66	70	28.6	19.6	9.0	.090	4.71
95	87	91	28.6	20.4	8.2	.082	4.27
133	125	129	28.6	20.4	8.2	.082	4.27
185	177	181	28.6	20.4	6.2	.062	3.26
300	292	296	28.6	20.4	8.2	.082	4.27
401	393	397	28.6	20.4	8.2	.082	4.27
0 + 00	2 + 00						
start			27.9				
15			27.6				
36	13	24.5	28.6	13.4	15.2	.076	4.71
43	20	31.5	28.6	17.5	11.1	.056	2.94
60	37	48.5	28.4	23.0	5.4	.027	1.41
74	51	62.5	28.6	28.6*	0.0		
95	72	83.5	28.6	30.2*	-1.6		
133	110	121.5	28.6	33.0*	-4.4		
185	162	173.5	26.6	33.0*	-6.4	*Submergence	
0 + 00	3 + 00						
start							
15							
36							
43							
60	10	35	28.4	9.3	19.1	.064	3.37
95	45	70	28.6	17.0	11.6	.039	2.04
133	83	108	28.6	21.9	6.7	.022	1.14
185	135	160	28.6	22.6	4.0	.013	0.66
300	250	275	28.6	23.0	5.6	.019	0.98

Table 12. (Continued)

Elapsed time (min.)			Inflow at head (gpm)	Outflow (gpm)	Loss in furrow (gpm)	gpm/ft.	in./hr.
Station	Station	Average					
Slope 2							
0 + 00	1 + 00						
start			22.2				
13	4	8.5	22.2	3.2	19.0	.190	9.95
31	22	26.5	22.2	11.3	10.9	.109	5.73
40	31	35.5	22.2	14.2	8.0	.080	4.19
58	49	53.5	22.2	17.0	5.2	.052	2.70
79	70	74.5	24.2	20.4	3.8	.038	2.00
121	112	116.5	23.5	20.4	3.1	.031	1.61
385	376	380.5	24.0	21.7	2.3	.023	1.21
449	440	444.5	24.0	21.7	2.3	.023	1.21
0 + 00	2 + 00						
start							
13			22.2				
31			22.2				
58	19	38.5	22.2	7.2	15.0	.075	3.92
79	40	59.5	24.2	12.3	11.9	.059	3.10
121	82	101.5	23.5	14.2	9.3	.047	2.47
149	110	129.5	23.6	17.6	6.0	.030	1.57
325	286	305.5	23.7	20.4	3.3	.017	0.90
385	346	365.5	24.0	21.7	2.3	.012	0.63
454	415	434.5	24.0	21.7	2.3	.012	0.63
0 + 00	3 + 00						
start							
13							
31							
58							
79							
121	32	76.5	23.5	6.8	16.7	.056	2.94
149	60	104.5	23.6	7.7	15.9	.053	2.78
325	236	280.5	23.7	13.4	10.3	.034	1.76
385	296	340.5	24.0	13.4	10.6	.035	1.84
454	365	409.5	24.0	13.4	10.6	.035	1.84

Table 12. (Continued)

Elapsed time (min.)			Inflow at head (gpm)	Outflow (gpm)	Loss in furrow (gpm)		
Station	Station	Average				gpm/ft.	in./hr.
Slope 3							
0 + 00	1 + 00						
start			23.6				
10	4	7	23.6	7.7	15.9	.159	8.82
21	15	18	23.6	12.3	11.0	.110	5.77
42	36	39	23.6	17.6	6.0	.060	3.14
57	51	54	23.6	17.6	6.0	.060	3.14
78	72	75	24.0	22.6	1.4	.014	0.71
102	96	99	24.0	23.6	0.4	.004	0.20
138	132	135	24.0	23.6	0.4	.004	0.20
157	151	154	24.0	23.6	0.4	.004	0.20
0 + 00	2 + 00						
start							
10							
21			23.6				
42			23.6				
50	5	27.5	23.6	11.3	12.3	.062	3.22
57	12	34.5	23.6	17.5	6.1	.031	1.59
102	57	79.5	24.0	22.6	1.4	.007	0.37
138	93	115.5	24.0	23.3	0.7	.004	0.18
157	112	134.5	24.0	23.6	0.4	.002	0.11
0 + 00	3 + 00						
start							
10							
21							
42							
50							
57							
102	5	53.5	24.0				
108	11	59.5	24.0	11.3	12.7	.042	2.22
138	41	89.5	24.0	10.3	13.7	.046	2.40
167	70	118.5	24.0	15.6	8.4	.028	1.47
173	76	124.5	24.0	17.5	6.5	.022	1.14
212	115	163.5	24.5	23.0	1.5	.005	0.26

Table 12. (Continued)

Elapsed time (min.)			Inflow at head (gpm)	Outflow (gpm)	Loss in furrow (gpm)	gpm/ft.	in./hr.
Station	Station	Average					
Slope 4							
0 + 00	1 + 00						
start							
15	3	9	24.0	9.3	14.7	.147	7.72
22	10	16	24.0	13.4	10.6	.106	5.56
31	19	25	24.0	16.5	7.5	.075	3.92
41	29	35	24.0	16.5	7.5	.075	3.92
52	40	46	24.0	17.6	6.4	.064	3.37
67	55	61	24.0	20.4	3.6	.036	1.88
95	83	89	27.2	22.6	4.6	.046	2.55
120	108	114	28.6	22.6	6.0	.060	3.14
150	138	144	28.6	23.0	5.6	.056	2.94
175	163	169	28.6	23.3	5.3	.053	2.78
200	188	194	29.2	26.4	2.8	.028	1.45
0 + 00	2 + 00						
start							
52	7	29.5	24.0	5.7	18.3	.092	4.78
65	20	42.5	24.0	10.3	13.7	.069	3.63
75	30	52.5	24.0	11.8	12.2	.061	3.22
93	48	70.5	27.2	16.5	10.7	.054	2.78
123	78	100.5	28.6	17.5	11.1	.056	2.90
150	105	127.5	28.6	17.6	11.0	.055	2.86
172	127	149.5	28.6	17.6	11.0	.055	2.86
194	149	171.5	29.2	17.6	11.6	.052	2.77
300	255	277.5	29.2	23.3	5.9	.030	1.53
0 + 00	3 + 00						
start							
88	6	47	27.2	4.2	23.0	.077	4.04
128	46	87	28.6	8.6	20.0	.067	3.49
146	64	105	28.6	9.9	18.7	.062	3.16
178	96	135	28.6	12.3	16.3	.054	2.84
195	113	154	29.2	13.4	15.8	.053	2.76
425	443	402	29.2	17.5	11.7	.039	2.04

Table 12. (Continued)

Elapsed time (min.)			Inflow at head	Outflow	Loss in furrow		
Station	Station	Average	(gpm)	(gpm)	(gpm)	gpm/ft.	in./hr.
Slope 5							
0 + 00	1 + 00						
start			24.0				
19	3	11	24.0	6.4	17.6	.176	9.20
27	11	19	24.0	12.3	11.7	.117	6.11
35	19	27	24.0	16.1	7.9	.079	4.17
56	40	48	24.0	17.5	6.5	.065	3.41
65	49	57	24.0	17.6	6.4	.064	3.35
100	84	92	24.0	19.6	4.4	.044	2.30
118	102	110	24.0	21.7	2.3	.023	1.21
137	121	129	23.5	20.4	3.1	.031	1.62
242	226	234	24.0	20.4	3.6	.036	1.89
290	274	282	24.0	21.7	2.3	.023	1.21
0 + 00	2 + 00						
start							
54	9	31.5	24.0	5.3	18.7	.093	4.88
67	22	44.5	24.0	10.3	13.7	.069	3.48
101	56	78.5	24.0	14.2	9.8	.049	2.56
120	75	97.5	24.0	17.6	6.4	.032	1.68
138	93	117.5	23.5	16.5	7.0	.035	1.83
243	198	220.5	24.0	17.6	6.4	.032	1.68
288	243	265.5	23.5	20.4	3.1	.016	0.81
0 + 00	3 + 00						
start							
121	16	68.5	24.0	5.3	18.7	.062	3.26
140	35	87.5	23.5	8.6	14.9	.050	2.60
245	140	192.5	24.0	17.5	6.5	.022	1.14
286	181	233.5	23.5	20.4	3.1	.010	0.54

Table 13. Infiltration From Rate of Advance of Wetting Front

X	t	Qt	Intake (assuming no storage)		
(ft.)	(min.)	(ft.^{3})	(ft.^{3}/ft.)	(ft.^{3}/min./ft.)	(in./hr.)
Slope 1					
Q = 28 gpm = 3.74 ft.^{3}/min.					
50	5	18.6	.372	.0745	29.29
100	8	29.9	.299	.0374	14.70
150	16	60.0	.400	.0250	9.81
200	23	86.1	.431	.0188	7.38
250	30	112.1	.449	.0149	5.84
300	50	187.0	.623	.0125	4.91
Slope 2					
Q = 22.2 gpm = 2.97 ft.^{3}/min.					
50	2	5.9	.119	.0594	23.29
100	8	23.8	.238	.0298	11.69
150	29	86.1	.574	.0198	7.77
200	39	115.8	.578	.0148	5.81
250	55	163.3	.653	.0119	4.66
300	89	264.1	.880	.0099	3.88
Slope 3					
Q = 24 gpm = 3.21 ft.^{3}/min.					
50	2	6.4	.128	.0640	25.10
100	6	19.3	.193	.0322	12.62
150	22	70.6	.472	.0214	8.40
200	45	144.5	.722	.0161	6.32
250	72	231.0	.923	.0128	5.02
300	97	311.5	1.038	.0107	4.21
Slope 4					
Q = 24 gpm = 3.21 ft.^{3}/min.					
50	6	19.2	.384	.0640	25.10
100	12	38.6	.386	.0322	12.61
150	22	70.6	.471	.0214	8.39
200	45	144.5	.723	.0161	6.31
250	65	208.5	.834	.0128	5.02
300	82	263.4	.878	.0107	4.19

Table 13. (Continued)

X	t	Qt	Intake (assuming no storage)		
(ft.)	(min.)	($ft.^3$)	($ft.^3$/ft.)	($ft.^3$/min./ft.)	(in./hr.)
Slope 5					
Q = 24 gpm = 3.21 $ft.^3$/min.					
50	7	22.4	.448	.0641	25.75
100	16	51.4	.514	.0321	12.59
150	29	93.2	.622	.0214	8.39
200	45	144.5	.723	.0161	6.31
250	67	215.0	.861	.0129	5.06
300	105	337.8	1.124	.0112	4.39

Table 14. Infiltration From Rate of Advance as a Border

X	t*	Qt	Intake (assuming no storage)		
(ft.)	(min.)	(gal.)	(gal./ft.)	(gal./min./ft.)	(in./hr.)
Slope 1 Average Q = 28.3 gpm					
50	5	142	2.83	.566	5.94
100	14	396	3.96	.283	2.97
150	21	595	3.97	.189	1.98
200	41	1160	5.80	.141	1.48
250	69	1953	7.82	.113	1.17
300	95	2685	8.95	.094	0.99
400	143	4050	10.13	.071	0.75
Slope 2 Average Q = 23.3 gpm					
50	4	93	1.86	.465	4.88
100	21	489	4.89	.233	2.45
150	62	1445	9.63	.155	1.63
200	107	2493	12.47	.117	1.23
250	144	3355	13.42	.093	0.98
300	180	4194	13.98	.078	0.82
400	294	6850	17.10	.058	0.61
Slope 3 Average Q = 23.8 gpm					
50	3	71	1.43	.476	5.00
100	16	381	3.81	.238	2.50
150	40	952	6.35	.159	1.67
200	71	1690	8.50	.119	1.25
250	112	2666	10.66	.095	1.00
300	152	3618	12.06	.079	0.83

Table 14. (Continued)

X	t*	Qt	Intake (assuming no storage)		
(ft.)	(min.)	(gal.)	(gal./ft.)	(gal./min./ft.)	(in./hr.)
Slope 4 Average Q = 26.0 gpm					
50	7	182	3.64	.520	5.46
100	20	520	5.20	.260	2.73
150	38	988	6.59	.173	1.86
200	64	1664	8.32	.130	1.37
250	101	2626	10.50	.104	1.09
300	142	3692	12.31	.087	0.91
400	190	4940	12.35	.065	0.68
Slope 5 Average Q = 24.0 gpm					
50	9	216	4.32	.480	5.04
100	27	648	6.48	.240	2.52
150	54	1296	8.64	.160	1.68
200	91	2184	10.92	.120	1.26
250	111	2664	10.66	.096	1.08
300	143	3432	11.44	.080	0.84
400	288	6912	17.28	.060	0.63

t* = average time (min.) for five test furrows of each slope