

The development of an erosion test to determine the relative erodibility of fine grained forest soils
by James Dennis Hogan

A thesis submitted to the graduate faculty in partial fulfillment of the requirements for the degree of master of science in Civil Engineering
Montana State University
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Abstract:
A tentative standard laboratory erosion test was developed which can be used to determine the relative credibility of fine grained soils.

Eighteen fine grained soils, most of them taken from steep forested slopes of southwestern Montana and north central Idaho, were subjected to laboratory erosion tests. The results of the laboratory tests correlated well with physical soil properties which have been shown to be good erosion indicators based on observed field erosion.

It is believed that the laboratory erosion test, in which actual erosion is measured under standard conditions, is superior to any indirect erosion indicator as a means of classifying soils with respect to their potential susceptibility to erosion.

The laboratory erosion apparatus is also believed to have potential usefulness as an aid in solving specific erosion problems at specific sites. It is easily adjustable in regard to slope, stream size, and soil treatment, which makes it a versatile experimental tool for studying the extent to which various soil treatments might affect erosion.

THE DEVELOPMENT OF AN EROSION TEST TO DETERMINE THE RELATIVE ERODIBILITY OF FINE GRAINED FOREST SOILS

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ABSTRACT

A tentative standard laboratory erosion test was developed which can be used to determine the relative erodibility of fine grained soils.

Eighteen fine grained soils, most of them taken from steep forested slopes of southwestern Montana and north central Idaho, were subjected to laboratory erosion tests. The results of the laboratory tests correlated well with physical soil properties which have been shown to be good erosion indicators based on observed field erosion.

It is believed that the laboratory erosion test, in which actual erosion is measured under standard conditions, is superior to any indirect erosion indicator as a means of classifying soils with respect to their potential susceptibility to erosion.

The laboratory erosion apparatus is also believed to have potential usefulness as an aid in solving specific erosion problems at specific sites. It is easily adjustable in regard to slope, stream size, and soil treatment, which makes it a versatile experimental tool for studying the extent to which various soil treatments might affect erosion.

CHAPTER I

INTRODUCTION

PROBLEM

At present, there is a lack of sufficient reliable fundamental knowledge of soil erodibility to enable engineers to make a reasonably accurate prediction of the erosion which would result from a particular land use operation at a specific site. Numerous studies have been made of the erodibility of soils, but the results, in general, appear to be applicable only to soils and sites which are similar, if not identical in all respects, to those considered in the studies.

This points to the need of a simple soil erodibility classification system which could be used as a guide in land use and road construction on all types of soil. Present soil classification systems such as the AASHO and Unified systems are not suitable as a means of classifying soils with respect to their potential erodibility because soils within the same group classification can and sometimes do exhibit highly different erodibilities. Also, some soils which fall under different classifications show essentially the same erodibility.

OBJECTIVE

The primary objective of this study was to develop a tentative standard laboratory erosion test which would measure the relative erodibility of fine grained forest soils with spe-

cial applicability to bare disturbed soils on steep slopes. It is hoped that the results of this test, or some similar test, will ultimately prove to be superior to indirect erosion indicators and be accepted as a standard general indicator of soil erodibility.

The results of this test were correlated with measured physical soil properties which have been shown to correlate well with actual erosion as it occurs in the field. The correlation compares favorably with the field correlation. This lends support to the assumption that this test, with some limitations, will measure the actual potential erodibility of a soil.

The laboratory erosion apparatus which was developed may also prove to be useful as a tool to study the effects of various soil treatments on the erodibility of a soil, and to make possible an objective study of a particular soil when it is exposed to the specific conditions which a proposed land use would impose upon it.

A BRIEF DESCRIPTION OF THE LABORATORY TEST METHOD

Very briefly, the erosion test procedure which was developed in the course of this research consists of first filling a small steel channel level full with about fifteen pounds of loose, air-dry soil which passes the No. 4 sieve, placing the channel on a slope of 50%, applying a standard jet of water to the soil near the upper end of the channel, and collecting the runoff water and sediment as it comes off the lower end of the

channel.

In the second phase of the test the soil is placed in the channel at its optimum water content and compacted with a compactive energy equal to that used in the standard AASHO compaction test. It is then tested in the same fashion as the air-dry soil.

The proposed soil erodibility classification is then expressed as an Erosion Number, EN, which is equal to 1/10 of the weight, in grams, of the soil eroded from the compacted sample during the first three minutes of runoff, plus 1/100 of the weight of soil eroded from the loose, air-dry sample during the first three minutes of runoff.

A thorough search of the literature failed to reveal any comparable soil erodibility classification system which is based on direct measurements of erosion under standard conditions.

CHAPTER II

REVIEW OF LITERATURE

Soil erosion, defined as the carrying away of soil particles from their place of rest or origin by the action of wind, water, or gravity, has been recognized as a problem for many years and has been the object of a considerable amount of research.

It has generally been found that erosion by either splash action or overland flow is a function of a great number of variables which include rainfall intensity, slope, ground cover such as vegetation and litter, physical properties of the soils, slope aspect, location of the soil in terms of relation to ridge top or creek bottom, rate of overland flow, and numerous others. It appears that the variables investigated in various studies were the ones which happened to be of particular interest to the persons involved. It was found that many people have studied the effects of slope and rate of overland flow or rainfall intensity, but the lack of general agreement among the investigators shows that little real progress of a fundamental unifying nature has been made.

The results of the literature reviewed will be presented by grouping the work into the following categories: erosion indicators based on physical soil properties, erosion prediction equations, and general observations.

EROSION INDICATORS OR INDICES BASED ON PHYSICAL SOIL PROPERTIES

Middleton (15)[1] discovered a definite relationship between certain physical properties of a soil and its erodibility. His studies were done on a number of soils which contained large amounts of fine sand, silt, and clay. The soils were classified as erosive or non-erosive by inspection in the field. Physical properties of the soil were then investigated to ascertain which property or combination of properties was a good indicator of erosion.

Dispersion Ratio

He first developed a Dispersion Ratio which he defined as the ratio of the percentage of silt and clay observed in a non-dispersed sample to the percentage of silt and clay as determined by the standard hydrometer analysis. The silt and clay fraction observed in the non-dispersed sample was determined as follows:

> "A sample of air-dry soil equivalent to 10 grams of ovem-dry soil was placed in a tall cylinder of approximately 1200 cubic centimeter capacity fitted with a rubber stopper. Sufficient distilled water was added to make the volume a liter. The cylinder was closed with the stopper and was shaken end over end twenty times. The suspension was then allowed to settle until a 25 cubic centimeter sample which was pipetted at a depth of 30 centimeters consisted of particles of a maximum diameter of 0.05 mm. A metal tip placed on the end of the pipette with six

---

[1] Numbers in parentheses refer to references listed under LITERATURE CITED.

> radial No. 80 drill holes was used; through it liquid was drawn from the side rather than from directly under the pipette. From the dry weight of the pipetted fraction, the total weight of silt and clay in the suspension was calculated..." (15)

In theory, this silt and clay is the fraction of silt and clay which is not aggregated or which is easily slaked. Silt and clay particles which are aggregated and are therefore larger in size than the individual silt or clay particles are more difficult to bring into suspension. Thus, the greater the percentage obtained in the non-dispersed test, the easier it is to get the silt and clay particles into suspension. Therefore, as the dispersion ratio increases, the erodibility increases.

He also observed that as the ratio of colloid to moisture equivalent decreases, the erodibility increases. Colloid is the fraction of the sample which is finer than 0.001 mm., and the moisture equivalent is defined as the maximum percent of moisture which a soil can retain in opposition to a centrifugal force of 1000 times the force of gravity. The two ratios, which vary inversely, were combined to give an erosion ratio by dividing the dispersion ratio by the ratio of colloid to moisture equivalent. The erosion ratio then increases with an increase in erodibility. For Middleton, this ratio made a more marked distinction between erodible and non-erodible soils than did the dispersion ratio. Middleton emphasized the fact that the erosion ratio is an indicator of erodibility of soils of similar

type which were subjected to essentially the same environment. The results would not necessarily apply to greatly different soils which were eroded under conditions other than those studied by Middleton. Table I gives a partial summary of Middleton's results.

TABLE I: DISPERSION AND EROSION RATIOS OF AN EROSIVE AND A NON-EROSIVE SOIL FROM THE SAME LOCALE. (15)

Soil Character	Soil Type	Dispersion Ratio	Erosion Ratio	Ratio of Clay to Silt
12	Iredell	19.6	24.2	0.43
Erosive 13	Loam	13.0	15.7	0.36
14		20.9	15.0	2.64
15		23.5	22.8	1.24
16	Davidson	13.3	12.2	0.60
Non- 17	Clay	6.1	3.7	2.71
Erosive 18		6.6	4.3	1.65
19		10.6	7.7	0.86

Clay Ratio

In 1935, Bouyoucos (6) proposed a clay ratio, expressed as percent sand and percent silt all divided by percent clay, as an index of erosiveness. He studied a large number of soils which included most of the soils tested by Middleton and compared his clay ratios to the erosion ratios. He found that the clay ratio followed the same trend as the erosion ratio. High and low values indicate high and low erodibilities respectively.

The dispersion and clay ratios as described above apply to fine grained soils only, because they do not include the

effects of varying percentages of coarse material in the total sample. It is possible for two different soils to have the same dispersion ratio and contain vastly different percentages of clay.

Surface Aggregation Ratio

André and Anderson (5) proposed an erosion indicator which they called a surface aggregation ratio. Surface was defined as the amount of surface in square centimeters per gram on particles larger than silt (greater than 0.05 mm.). Particles were considered to be spheres with densities of 2.65, and they were separated into three size ranges--particles larger than 5 mm., between 2 and 5 mm., and between 0.05 and 2 mm. The mean diameters for the size ranges were taken to be 7.5 mm., 3.5 mm., and 0.9 mm. From these assumed data and the fractions of the soil within these size ranges, it was possible to calculate the surface area described above.

Aggregated silt and clay was defined as the total percent of silt and clay observed in a dispersed sample of soil less that observed in a non-dispersed sample of the same soil. The surface aggregation ratio was then expressed as the surface divided by the aggregated silt and clay. Results of a statistical analysis showed that the dispersion ratio and surface aggregation ratio were good indicators of erosion.

From the nature of the erosion indicators reported above, it appears that erodibility is dependent on the relative amount

of silt and clay present, and on the ease with which it may go into suspension.

Erosion Index

A paper published by the Forest Soils Committee of the Douglas-fir Region (4) included a short section on the spacing of lateral drainage culverts which was based, in part, on an Erosion Index. Table II was taken from this paper. In Table II, the standard soil groups from the Unified Soil Classification System as well as the standard soil textural grades were "tentatively" assigned to erosion classes I to X, which have erosion indices from 10 to 100 respectively. Class I is the most erosive, and class X the least erosive.

The soils were placed in the various erosion classes based on the assumption that the soil contained 100% of the specified soil type. If the erosion index of a soil which contains materials from several different erosion classes is desired, it is calculated as illustrated in the following example:

Material	% Content	x	Erosion Index	=	Total Erosion Index
Silt	20	x	10	=	20
Sandy Clay	40	x	50	=	20
Fine Gravel	40	x	90	=	36
					76 = Erosion Class VII

These erosion classes and indices may be satisfactory for the use for which they were developed, but they appear to be based upon arbitrary procedures. It is believed that the tentative standard erosion test, which is the main subject of this

TABLE II - A GUIDE FOR PLACING COMMON SOIL AND GEOLOGIC TYPES INTO EROSION CLASSES. (4)

EROSION CLASS	I	II	III	IV	V	VI	VII	VIII	IX	X
EROSION INDEX	10	20	30	40	50	60	70	80	90	100
Standard soil texture & Unified System Soil Groups	SM ML	SM ML	Silt (Unconsolidated) (B) OL MH	Silt (Consolidated) (B) OL MH CL	Silty Clay Loam (A) Silty Clay (A) Clay, varying with type, cohesiveness & compaction (A) Sandy Clay (B) SC, GM, OH, CH	Clay Loam (A) Silt Loam (A, B) Sandy Clay (B) CH, GM	Loamy Sand (C) Sandy Loam (B) Sand (B) GC	Coarse Sand (C) SW SP Sand (C)	Fine Gravel (C) SW SP	Rock (C) Cobble (D) Gravel (C) GW, GP
Special cases	Decomp. Grano-diorite (C) Highly decomp. granites (C)	Decomp. sand-stone (B, C) Mod'ly decomp. granites (B)	Fine soils derived from rocks high in mica (C)	Coarse soils derived from rocks high in mica (C)	Some volcanic ash or fine pumice (C)					Fractured loose basalt or shale (A)

NOTE: (A) indicates nonporous materials; (B) indicates moderately porous materials; (C) indicates highly porous materials.

thesis, will classify a soil as to its potential erodibility with more certainty than can be done by consulting Table II.

EROSION PREDICTION EQUATIONS

Several equations which express erosion or erodibility as a function of different combinations of variables such as slope and rainfall intensity have been formulated. These equations have been developed by measuring both splash and overland flow erosion.

Eckern (9), by the use of simulated rainfall, made an intensive study of splash erosion and found that erosivity can be expressed as a function of discharge, Q, slope, S, and rainfall intensity, I. The equations which employ these variables are expressed as follows:

$$\text{Erosivity} = f(Q^{1.0}S^{1.0}) \qquad (1)$$

$$\text{Erosivity} = f(I^{1.46}S^{1.0}) \qquad (2)$$

Eckern did not explicitly define f in the above equation, but it was taken to mean function of the variables in parentheses.

In another of Eckern's studies (10), it was found that the amount of soil, in this particular case sand, transported was directly proportional to the rainfall intensity when drop size, shape, and velocity were held constant.

Borst and Woodburn (7), by use of a rainfall simulator, found several expressions for erosion by applying 1" of rain at a rate of 4" per hour to a bed of soil on varying slopes from one to approximately twenty percent. They were studying the

effects of both slope and infiltration rate and found no definite relationship between the two. They also concluded that there was no definite relationship between percent runoff and slope and no consistent relationship between percent runoff and soil moisture content. They did find that the rate of runoff after reaching equilibrium was approximately the same for all soils. It was also found that a wet, lightly compacted soil eroded more than a loose dry soil. Their equations for erosion are:

$$\text{Wet Soil:} \quad E = 8.23\ S^{1.223} \qquad (1)$$

$$\text{Dry Soil:} \quad E = 4.84\ S^{1.298} \qquad (2)$$

where S is % slope and E is pounds of eroded soil. The observations of Free (12) agreed with those of Borst and Woodburn.

A paper by Neal (17) further related erosion to slope, duration of storm, and rainfall intensity. His study, which included effects of infiltration and initial soil moisture content, showed that initial soil moisture content had a greater effect on the rate of infiltration than any other factor. However, for slopes less than 16%, this infiltration was not a function of slope. He found that the relative density of runoff material increased as the slope increased. The main factor influencing erosion and runoff was found to be the rainfall intensity. The intensity had a greater influence on erosion than did the runoff. His equation for erosion for a rain falling on a saturated soil is:

$$E = 0.4\ S^{0.7}\ TI^{2.2}$$

where E is the erosion in pounds from 0.001 acre, I is the rainfall intensity in inches per hour, T is the time in hours, and S is percent slope. He also found that hard dry soil eroded more than either loose dry soil or a moist, slightly compacted soil. It is the writer's opinion that the loose dry soil is least erosive because of its comparatively large permeability which decreases overland flow and thus decreases the erosive action of the water. A soil which has been wetted becomes cohesive, and this cohesiveness increases its resistance to erosion, whereas aggregations on the hard dry surface will slake and go into suspension which will increase the amount of soil eroded.

Slope has an important influence on erosion, as the equations which were previously listed indicate. Some general observations have been made on the effects of slope on erodibility. Gard and Van Doren (13) performed experiments on slopes of 5 to 9% and found steepness to be a dominating factor in soil loss. It was also noted that erosion increased as the length of the plots increased. Zingg (26) found that soil loss per unit area varies as the 0.6 power of the slope length. This is in qualitative agreement with the observations of Gard and Van Doren.

All of the above equations show that an increase in slope or flow increases the erosion. They have very little or no

general quantitative applicability, however, because they merely showed how a few specific soils reacted when one or more of the many factors which influence erosion were varied.

GENERAL OBSERVATIONS

Ellison (11) states that splash erosion consists of two independent actions. The first is the detachment of soil particles from the soil mass, and the second is the transportation as splashes of the detached particles. He found that sands have the highest detachability, while cohesive soils have lower detachabilities. Rose (22) was able to correlate detachability to the plasticity index, PI. He found that detachability increases as PI decreases, and he also observed that the clay ratio of Bouyoucos increased as the PI decreased.

Detachability should not be confused with the ability of a soil particle to go into suspension. Sand particles which show the highest detachability are not as easily brought into suspension as are the silt and clay particles which exhibit low detachabilities. It would appear from the studies of these two characteristics, that a soil, sand for instance, could show the same erodibility as a silt if the velocity of the overland flow common to both soils furnished a force just sufficient to detach the easily suspended silt and just sufficient to suspend the easily detached sand.

Another important factor which affects runoff, which in turn affects erosion, is the permeability of a soil. Musgrave

(16) noted that soils which are readily permeable to water are relatively resistant to erosion. Peele (20) agreed with Musgrave and in addition stated that percolation rate, percent of suspension, and dispersion ratio give a good index of the erodibility of soils.

It is obvious that high infiltration rates or permeability would reduce overland flow by allowing water to drain down through the soil and thus decrease the erosive effect of the overland flow.

In a later study, Peele and others (21) again found that high infiltration rates helped resist erosion. They studied the mechanical analysis, dispersion ratio, degree of aggregation and water imbibition, and specific gravity of various soils and found no single property that would give an index to erodibility. They did conclude that soil cover had a greater effect on erosion than did the physical soil properties.

Craddock and Pearse (8) also investigated the effect of soil cover (range type) and found that it had a greater influence on erosion than did slope, rainfall intensity, and soil disturbance.

Adams, et al. (1) made a detailed study of erosion on small field plots with a rainfall simulating apparatus. These plots were all six inches in diameter and were on a slope of zero percent. As part of his study, he investigated the effects of percent water-stable aggregates greater than 2 mm. in size,

rainfall intensity, and dispersion ratio on wash erosion. Rainfall intensity and percent water stable aggregates greater than 2 mm. were found to be highly significant at the 1% level, while the dispersion ratio was found to be insignificant. He attributed the insignificance of the dispersion ratio to the fact that some of the soils had high dispersion ratios and small percentages of silt and clay. The high dispersion ratios would indicate that the silt and clay could be easily brought into suspension, but the small percentage of silt and clay would not lead to a high degree of erosion. They also concluded that wash erosion rather than splash erosion would be a better measure of natural erosion by water.

In general, it appears that the various indirect erosion indicators such as dispersion ratio, erosion ratio, surface aggregation ratio, clay ratio, etc., do have some merit as qualitative erosion indicators, but they have not proved to be highly dependable.

Effects of Soil Type or Origin on Erosion

Packer (18, 19) has proposed and made several studies directed toward reducing erosion on logging roads and skid trails on various soils in Idaho and Montana. He surmised that most of the erosion in this region was caused by overland flow, and that most of this flow was due to snow-melt. Results of his studies showed that erosion increased with an increase in gradient (slope) and with change in location from ridges to hill

sides to drainage bottoms. He listed the following soil types according to their increasing erodibility.

1. Hard Sediments (slates and shales)
2. Basalt
3. Granite
4. Glacial Silt
5. Andesite
6. Loess

Kidd (14) also studied the erosion which occurs on logging skid trails and his results verified those of Packer. Specifically, erosion is greater on granitic than on basaltic soils, and is greater in ravine bottoms than on side hills.

Wallis (25) determined the surface aggregation ratio for nine different rock types which are common in northwestern California. Of the nine types, he classified a quartz diorite as the most highly erodible, basalt and gabro about half as erodible as the quartz diorite, and Serpentinite as the least erodible. The erodibilities of different soil and rock types as presented above apparently furnish a rough guide to the potential erodibilities of the soils. However, an erodibility classification based upon a quantitative laboratory erosion test would seem to offer a better and more dependable measure of the potential erodibility of a soil.

Effects of Land Use on Erosion

In another study, Anderson (3) studied the effects of land use--logging in particular--on sediment production. He observed that the sediment production increased 800 percent

during the first year of logging and dropped off rapidly in the following years. The chief sources of this sediment were logging roads, skid trails, and landings. This would lead to the conclusion that such disturbances should be kept to a minimum to reduce erosion.

CHAPTER III

MATERIALS AND LABORATORY TESTS

MATERIALS

The main consideration in the choice of soils used in this thesis investigation was that they be fine grained soils from typical sites located on forested land which has a fairly steep slope. It was initially assumed that there might be a strong correlation between erodibility and plasticity index. Thus, with the exception of the six soils described below, the soils were chosen to give as wide a range of plasticity index as possible. It was also decided that most of the soils should be taken from areas which had been logged or where forest access roads had been built.

Eighteen different soil samples were used in the tests. Twelve soil samples were taken from various drainages located on or adjacent to the Gallatin National Forest in southwestern Montana. The remaining six soils were chosen from the six soil groups studied by Packer (19). An attempt was made to obtain the samples from the specific sites studied by him. If the sites were found to be inaccessible, a sample was taken from the general area. Soil samples 1, 7, and 10, as identified in Table III, were obtained from the specific sites studied by Packer, while soils 5, 6, and 9 were taken only from the general areas. It is possible that soils 5, 6, and 9 are quite different from the soils which were included in Packer's study.

TABLE III - SOIL SAMPLE IDENTIFICATION AND LOCATION

SOIL NO.	NAME	LOCATION	FOREST	COUNTY	STATE
1	BITT #21*	NW¼ S21, T10N R20W	Bitterroot	Ravalli	Montana
2	BRACKETT CR.	NE¼ S9, T1N R7E	--	Gallatin	"
3	BRIDGER	NE¼ S17, T1N R7E	Gallatin	"	"
4	CARD #1	Near Cardwell	--	Madison	"
5	CLEAR #6**	NE¼ S6, T34N R6E	Clearwater	Clearwater	Idaho
6	CLEAR #13**	SE¼ S13, T34N R5E	Clearwater	"	Idaho
7	FLAT #13*	NW¼ S14, T32N R24W	Flathead	Flathead	Montana
8	GALL #1	SE¼ S30, T2N R7E	Gallatin	Gallatin	"
9	GALL #2**	NE¼ S5, T4S R6E	"	"	"
10	LOLO #18*	S18, T16N, R22W	Lolo	Missoula	"
11	MOOSE CR.	NE¼ S6, T6S, R5E	Gallatin	Gallatin	"
12	MOOSE CR. #2	SW¼ S5, T6S R5E	"	"	"
13	N. FK. BRACKETT	SE¼ S36, T2N R6E	Gallatin	Gallatin	Montana
14	ORCHID CR.	NE¼ S16, T5S R5E	"	"	"
15	RAT LAKE	SE¼ S1, T5S R5E	"	"	"
16	SQUAW CR.	SW¼ S5, T5S R5E	"	"	"
17	TAYLOR FORK	NW¼ S12, T9S R3E	"	"	"
18	TAYLOR #2	SE¼ S7, T9S R4E	"	"	"

*Denotes soils taken from test sites studied by Packer.
**Denotes soils taken from the general area of the sites studied by Packer. These soils may differ considerably from the soils at Packer's sites.

A two to three hundred pound sample was obtained from each site. The top few inches of litter, organic matter, and leached soil was removed, and the sample was taken at random from a surface area of approximately fifty square feet. The samples were placed in paper sacks and transported to the laboratory where they were spread out to dry.

The soils are tabulated by number, name and location in Table III.

STANDARD TESTS

The five standard tests which are listed below were performed on representative samples of each soil.

1. Mechanical Analysis, AASHO Designation: T88-57
2. Atterberg Limits:
   (a) Liquid Limit, ASTM Designation: D423-61T
   (b) Plastic Limit, ASTM Designation: D424-59
3. Specific Gravity, ASTM Designation: D854-58
4. Moisture-Density Relations of Soils,
   AASHO Designation: T99-57, method A.

The above tests were performed essentially as specified by the above standards; however, in the mechanical analysis test, the constant temperature water bath was not as deep as specified by the standards. The bath maintained the temperature of the suspensions within 2° of the specified 68°F and was considered to be adequate for the test. Results of these standard tests are tabulated in Tables IV and V. The grain size

accumulation curves for the material used in the erosion tests are shown in figures 33 through 37 in appendix E.

TEST FOR AGGREGATED SILT AND CLAY

The dispersion and surface aggregation ratios of each soil were determined. To do this, it was necessary to determine the amount of aggregated silt and clay present in each soil. This aggregation can be described as water stable silt and clay particles which cling together to form particles whose diameters are greater than 0.05 mm., the maximum size for silt.

There is no widely accepted standard procedure for determining the amount of aggregated silt and clay. It can be done by either the pipette method (15) or by the use of a hydrometer. The latter method was used in this case and is described below.

The following procedure differs slightly from the standard hydrometer method of mechanical analysis in which a dispersing agent is used to break up the aggregated silt and clay particles. Since the purpose of this test was to determine the fraction of aggregated silt and clay, no dispersing agent was used.

A representative sample of air-dry material, which passed the No. 4 sieve (4.699 mm.) and was equivalent to 75 grams of oven-dry material, was placed in the bottom of a 1000 ml. cylinder, and water at 68°F was added to fill the graduate to

the 1000 ml. mark. The graduate was then placed in a constant temperature (68°F) water bath for one hour. The cylinder was then picked up and the soil was shaken loose from the bottom. When all of the soil was off the bottom, the contents of the cylinder were thoroughly mixed by turning the cylinder end over end for sixty seconds. The cylinder was then placed in the bath at time zero, and hydrometer readings were taken at the end of one and two minutes.

The calculations for corrected grain sizes, hydrometer readings, and percentage of total sample finer than the specified grain sizes were calculated according to the procedure given in Standard Methods of Mechanical Analysis of Soils, AASHO Designation: T88-57. The results were plotted on semi-log graph paper and the percentage of aggregated silt and clay was determined. The results of this test and the calculation of the dispersion and surface aggregation ratios are given in Table VI.

THE LABORATORY EROSION TEST

A simple and compact device was developed which was used to measure erosion in the laboratory. Pictures and detailed drawings of this device are shown in figures 1 through 6.

The detailed recommended procedure for the Standard Erosion Test is given in appendix A. The procedure used in the laboratory development of the erosion test is described below. The description will cover three different aspects of the test

TABLE IV - RESULTS OF STANDARD TESTS

SOIL NO.	ATTERBERG LIMITS			SPECIFIC GRAVITY	Moisture-Density Relationship		% of Total Sample Passing #4 Sieve
	LL	PL	PI		Optimum M. C., %	Max dry density, pcf.	
1	31.0	21.5	9.5	2.74	12.0	123.0	93.6
2	39.8	20.4	19.4	2.71	21.2	101.4	91.7
3	40.2	21.1	19.1	2.74	20.1	104.1	100.0
4	28.3	23.2	5.1	2.67	17.3	104.7	100.0
5	39.8	23.4	16.4	2.68	19.1	104.7	98.5
6	30.8	23.4	7.4	2.65	12.1	118.3	100.0
7	25.4	19.9	5.5	2.62	14.8	109.0	92.0
8	50.4	24.9	25.5	2.71	22.4	98.7	100.0
9	52.6	40.2	12.4	2.61	34.4	81.6	97.0
10	30.4	19.6	10.8	2.64	17.2	108.8	92.0
11	62.4	23.9	38.5	2.73	29.5	89.2	78.9
12	70.7	24.3	46.4	2.70	30.8	87.1	95.8
13	38.1	18.1	20.0	2.74	17.4	110.2	91.7
14	48.5	21.4	27.1	2.70	25.0	94.7	88.6
15	52.9	34.2	18.7	2.70	28.7	90.9	96.8
16	27.4	24.7	2.7	2.81	13.0	120.8	96.4
17	47.5	27.2	20.3	2.60	22.4	97.1	95.9
18	48.2	19.9	28.3	2.74	20.0	105.5	98.4

TABLE V - MECHANICAL ANALYSIS OF FRACTION USED IN THE EROSION TEST

SOIL NO.	PERCENT PASSING OR SMALLER THAN									
	#4	#8	#10	#20	#40	#100	#200	.05 mm.	.005 mm.	.002 mm.
1	100	93.1	92.4	84.4	74.5	59.1	50.8	40.2	13.2	9.0
2	100	97.2	96.9	94.3	89.0	74.6	67.3	59.2	29.3	22.7
3	100	85.0	82.6	82.4	82.0	78.7	71.4	59.3	23.9	16.0
4	100	100.0	100.0	99.5	98.3	95.3	90.2	69.5	12.0	7.2
5	100	97.6	97.1	91.9	82.3	71.8	68.1	63.6	33.0	24.2
6	100	98.7	98.3	88.4	69.0	44.2	32.9	29.0	12.0	9.2
7	100	97.8	97.7	95.3	94.3	89.9	87.3	81.3	30.0	14.1
8	100	100.0	100.0	97.9	91.5	77.7	68.9	59.6	34.7	27.0
9	100	98.5	98.1	95.5	91.8	82.0	74.3	61.5	15.0	8.3
10	100	95.2	95.0	91.7	89.2	87.0	85.2	78.5	27.2	18.0
11	100	92.3	91.0	89.2	83.5	68.9	60.4	56.2	36.0	30.8
12	100	97.7	93.3	91.1	88.0	82.1	77.9	73.0	48.0	43.2
13	100	86.8	85.3	84.1	82.7	80.2	76.2	71.0	42.5	32.8
14	100	98.3	97.8	97.0	96.0	94.2	92.4	85.0	45.5	37.2
15	100	97.0	96.1	89.4	79.1	53.3	48.0	41.5	15.0	8.3
16	100	96.9	96.0	82.5	59.6	38.9	29.3	22.5	6.3	4.3
17	100	97.8	97.3	95.0	92.0	80.5	71.8	64.1	31.0	20.5
18	100	98.0	96.4	93.9	91.9	89.0	84.0	78.2	53.7	41.0

TABLE VI - SURFACE AGGREGATION AND DISPERSION RATIOS

SOIL NO.	FRACTION OF SAMPLE BETWEEN SIZES, mm.			SURFACE CM^2/GRAM	% FINER THAN 0.05 mm.		AGG. SILT & CLAY	SURFACE AGG. RATIO	DISPERSION RATIO
					DISPERSED	UNDISPERSED			
	>5	2 to 5	.05 to 2	S	D	U	A = D - U	S/A	U/D
1	0	7.3	52.5	22.8	40.2	27.5	12.7	1.80	.68
2	0	3.2	37.8	23.7	59.2	24.1	35.1	0.68	.41
3	0	16.2	24.5	17.7	59.3	23.0	36.3	0.49	.39
4	0	0	30.5	25.2	69.5	59.0	10.5	2.40	.85
5	0	2.7	33.7	23.8	63.6	26.8	36.8	0.65	.42
6	0	1.5	69.5	24.8	29.0	15.3	13.7	1.81	.53
7	0	2.3	16.4	22.8	81.3	65.0	16.3	1.40	.80
8	0	0	40.4	25.2	59.6	17.0	42.6	0.59	.29
9	0	1.7	36.8	24.3	61.5	42.0	19.5	1.24	.68
10	0	4.9	16.6	20.9	78.5	50.0	28.5	0.73	.64
11	0	8.4	35.4	21.6	56.2	24.3	31.9	0.68	.43
12	0	4.5	22.5	22.1	73.0	44.0	29.0	0.76	.60
13	0	14.0	15.0	16.1	71.0	40.0	31.0	0.52	.56
14	0	2.0	13.0	22.7	85.0	37.0	48.0	0.47	.44
15	0	3.4	55.1	24.1	41.5	18.0	23.5	1.03	.43
16	0	3.6	73.9	24.3	22.5	14.3	8.2	2.75	.64
17	0	2.5	33.4	23.9	64.1	18.5	45.6	0.52	.29
18	0	2.8	19.0	22.8	78.2	20.0	58.2	0.39	.26

NOTE: The Surface Aggregation Ratio computations were based on the assumptions stated on page 8.

which are soil and soil bed preparation, apparatus adjustment, and erosion collection and measurement.

Soil Preparation

The soil samples were spread out on the laboratory floor immediately after they were brought in from the field and allowed to air dry. The drying period was quite long in this case (a month or more), but a shorter drying time could have been used.

Sandy and silty soils were sieved through the No. 4 screen. The material retained on the screen was pounded lightly with a rubber mallet until most of the aggregated particles were broken down, was sieved again, and the oversize particles were then discarded.

The clayey soils contained large lumps or clods which were larger than the No. 4 sieve size and were very difficult to break down. Any hand method such as pounding with a rubber mallet or Proctor hammer required an undue amount of time. Consequently, a mechanical method which utilized a Los Angeles Abrasion Machine was used.

The machine was used as a combination rod and ball mill. Ten steel balls, standard for the machine, and four cast iron sash-weight were used to charge the machine. The crushing action, which was caused by the charge being carried almost to the top of the revolution and dropped on the material below, reduced about 80% of a 30 pound sample, in ten minutes, to material

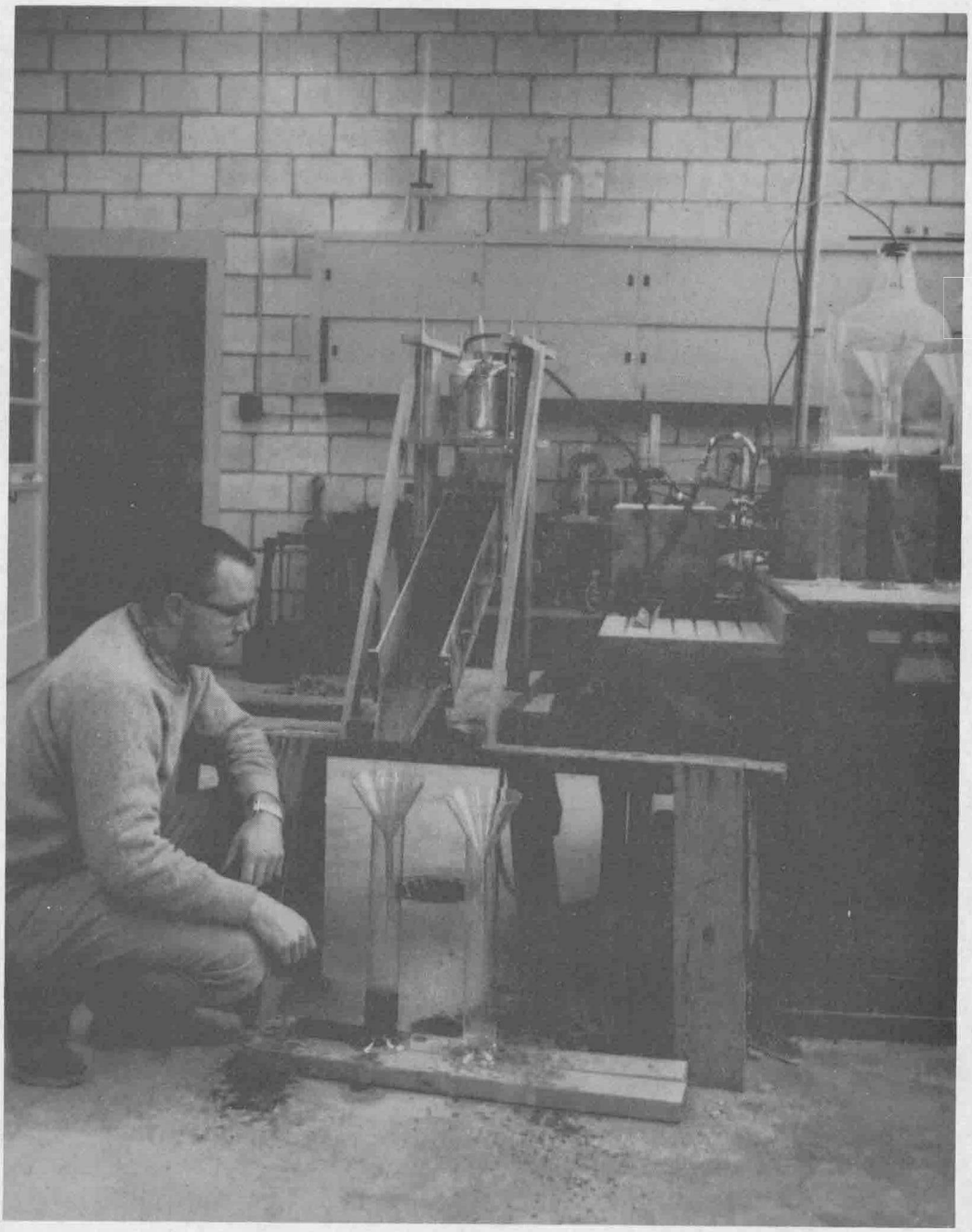


FIGURE 1 — LABORATORY EROSION TEST APPARATUS

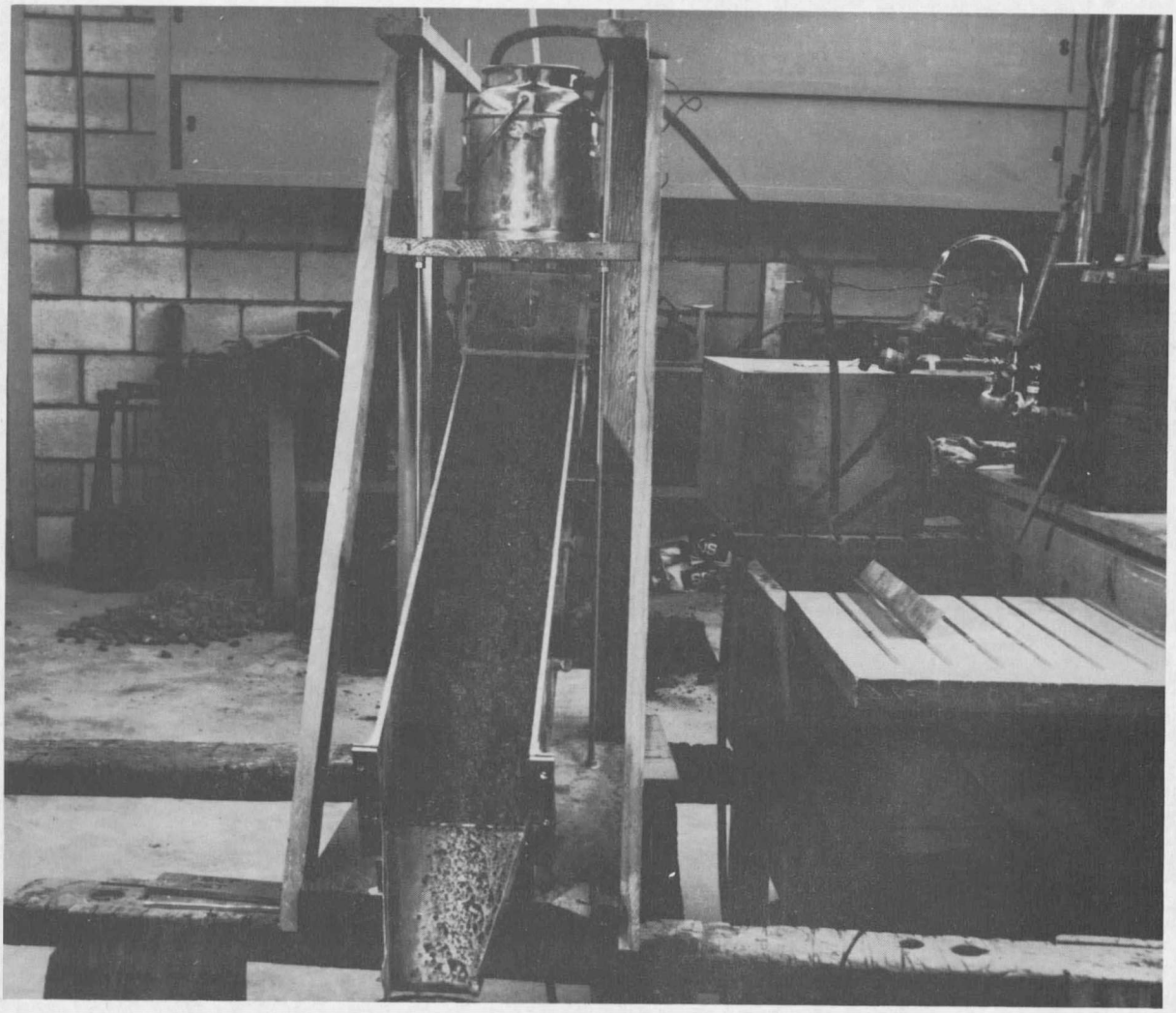


FIGURE 2 — LABORATORY EROSION TEST APPARATUS

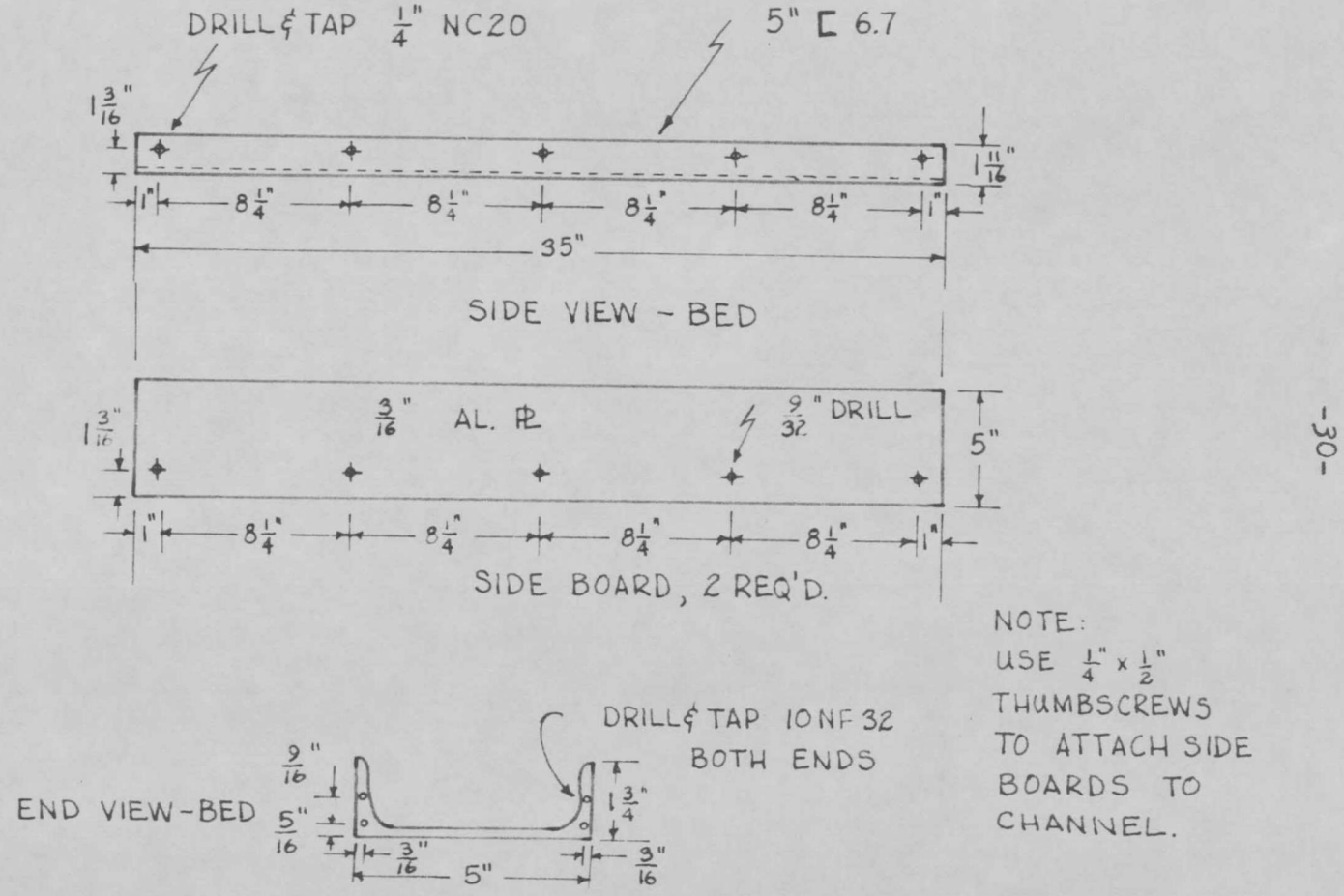


FIGURE 3 - SOIL BED CONSISTING OF A STEEL CHANNEL

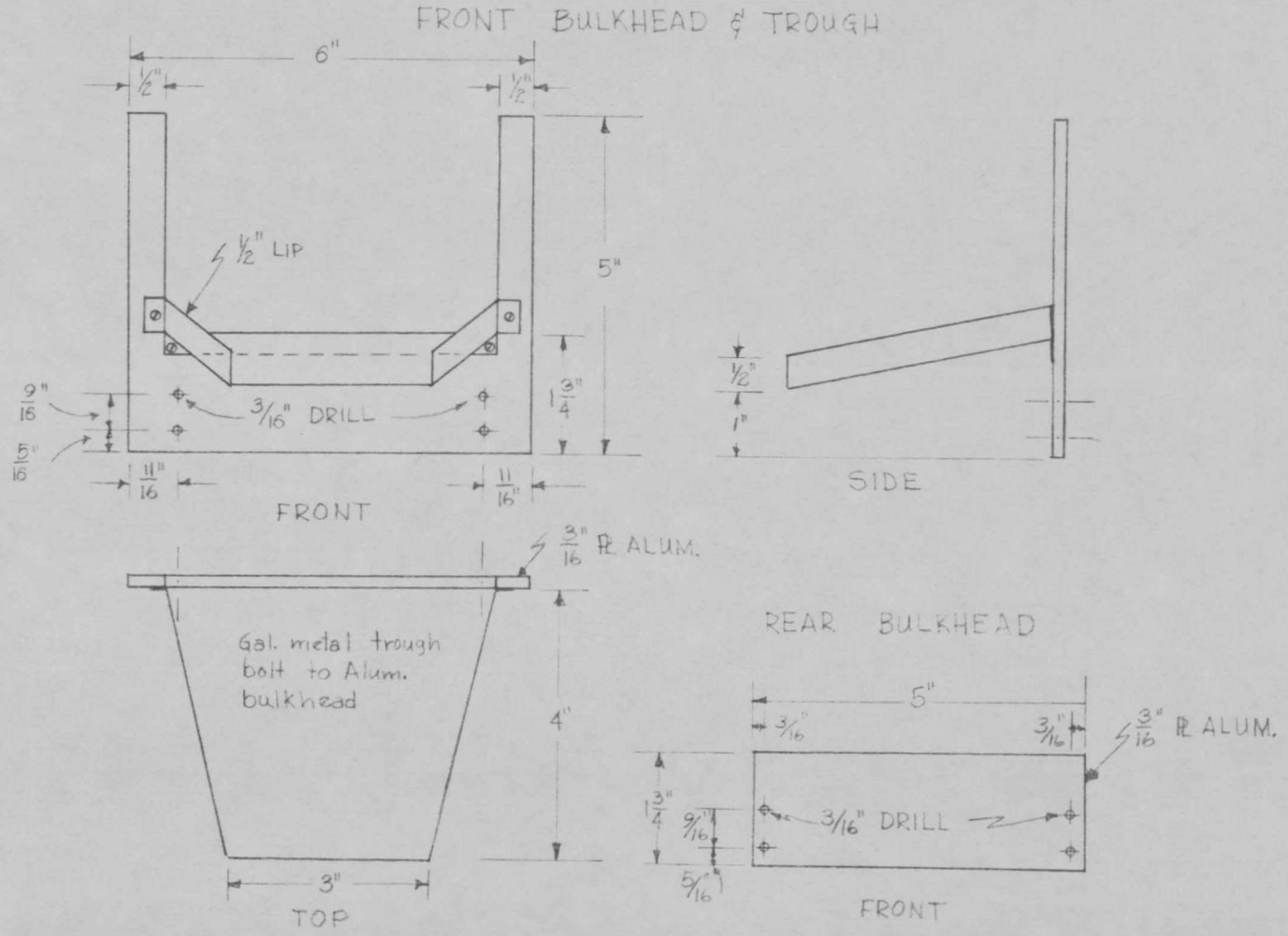
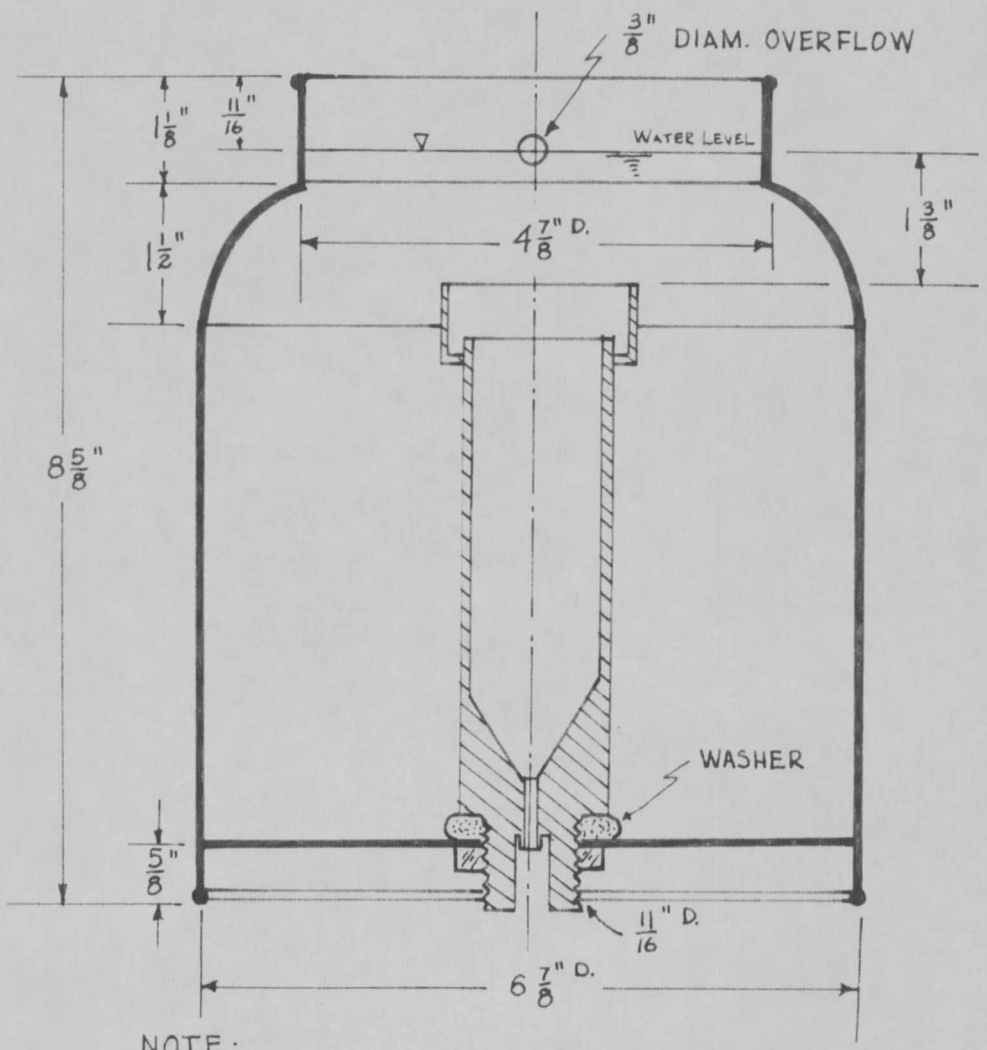


FIGURE 4 - SOIL BED BULKHEADS



NOTE:

THE RESERVOIR WAS MADE FROM A STOCK 4-QT. CREAM CAN. THE ORIFICE IS THE STANDARD ORIFICE AND SUPPORT FROM A SAYBOLT FUROL VISCOMETER.

FIGURE 5 - RESERVOIR ORIFICE

NOTE:
NOT TO SCALE ~ APPROX. DIMENSIONS ONLY

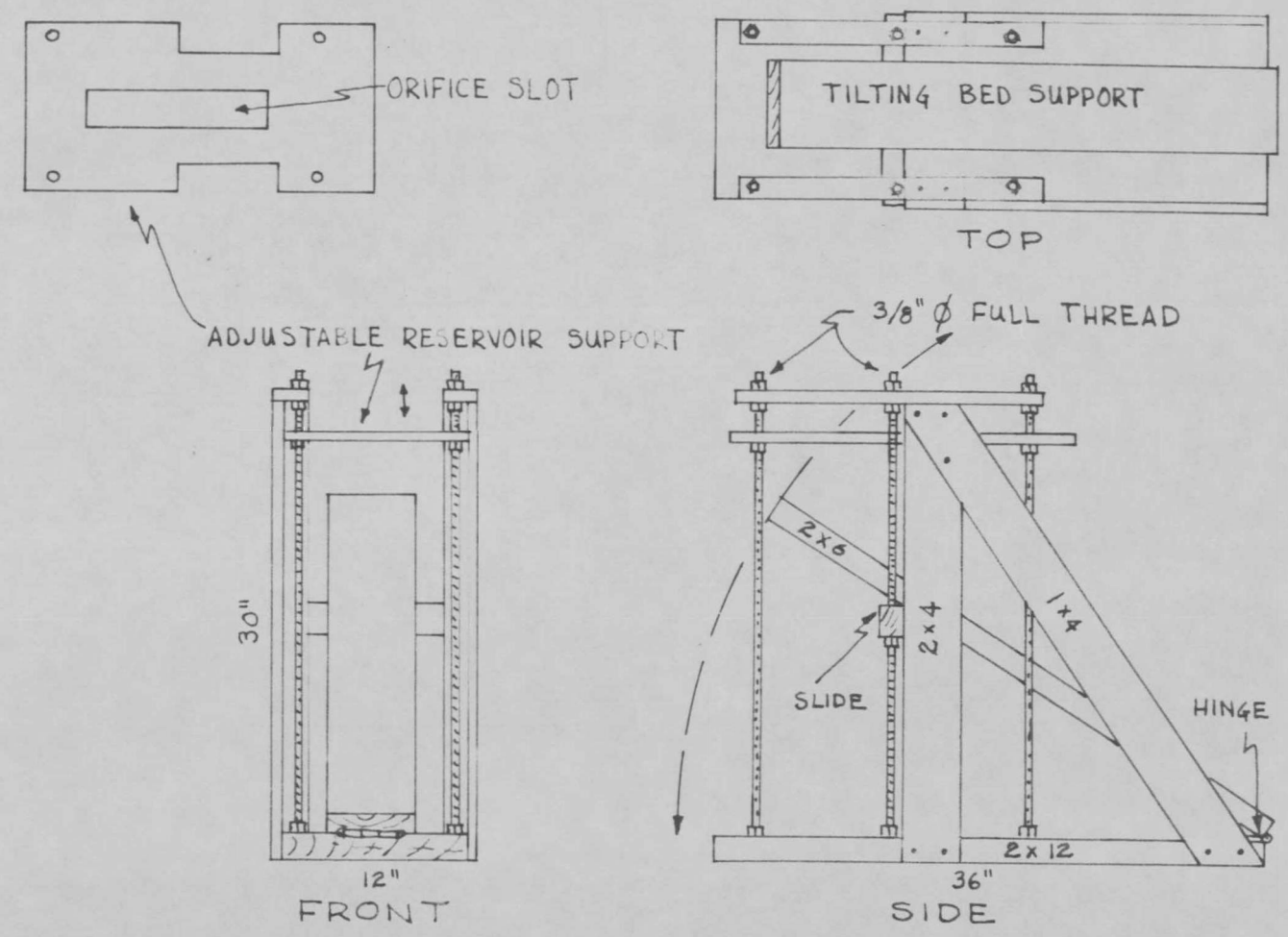


FIGURE 6 - SOIL BED SUPPORT

which would pass the No. 4 sieve. The fraction which passed the No. 4 sieve contained a fair amount of aggregated particles and was not ground down to the fineness of flour. The oversize material left after one 10 minute run in the machine was discarded.

Soil Bed Preparation

For each soil, erosion tests were made with the soil in a loose air-dry state, and also in a dense moist state.

Loose State

For the loose state tests, approximately 12 pounds of air-dry soil, which was prepared as described above, was placed loosely in the steel soil bed and was screeded off level with its top. No packing or compacting was done.

Dense State

For the dense state tests, a water content determination was made for each soil prior to the tests. A 15 to 20 pound air-dry sample of the previously prepared soil was brought up to its optimum AASHO water content, thoroughly mixed, and placed in one even layer in the soil bed. The soil was then compacted in a single lift with 338 uniformly distributed blows from a standard 5.5 pound AASHO compaction hammer. This gives essentially the same compactive energy per unit of soil volume as does the standard AASHO compaction test.

After the soil was compacted in the bed, the side-boards were removed, and the soil was screeded off even with the top

of the steel soil bed. A sample of the screeded off material was then used to check the actual water content of the soil. The bed and soil was then weighed and the weight of the compacted soil, the water content, and the volume of the bed were used to determine the dry density of the soil in the bed.

Soil Bed and Orifice Adjustment

All test runs were conducted with the same standard erosive action on a slope of 50%. The soil bed support was adjusted to the 50% slope and checked periodically between test runs. The soil bed was placed and roughly centered on the support. The reservoir was then adjusted vertically and laterally so that the bottom (lowest extremity) of the standard orifice was 7" above a point centered between the side boards of the soil bed 30" from the downstream end. See figure 7.

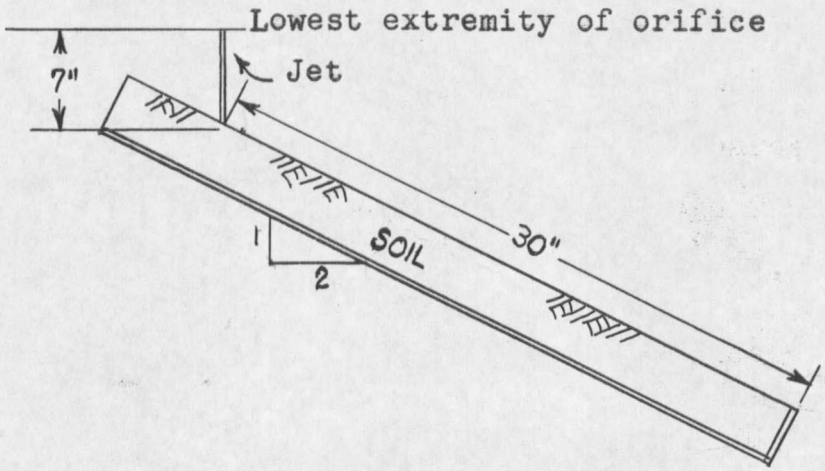


FIGURE 7 - ORIENTATION OF JET AND SOIL BED

The splash protector was then positioned at the upper end of the soil bed as shown in figure 1. The purpose of the splash protector was to divert splashes back to the channel and to keep soil particles detached by the splashing action confined to the soil bed. After the reservoir-orifice was positioned, a diversion chute was placed between the orifice and the soil bed. The head was adjusted so that the water level was near the center of the overflow pipe as shown in figure 5, and the temperature was simultaneously adjusted as close to 70°F as possible. The discharge from the diversion chute was then collected in a 500 ml. graduated cylinder for 30 seconds. Three measurements were made and the average was recorded as the beginning discharge.

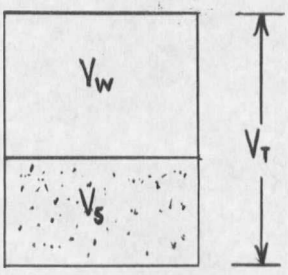
Erosion Collection and Measurement

The first of six 1000 ml. graduates was placed beneath the runoff chute, and the diversion chute was removed. The time between the removal of the diversion chute and first runoff into the graduate was noted, and the graduates were changed at one minute intervals thereafter for six minutes. At the end of the six minutes the diversion chute was replaced under the orifice, and the discharge from the orifice was measured again as previously described.

In order to determine the weight of eroded soil, it was necessary to measure the total volume and weight of the combined sediment and water in each of the six cylinders. The volumes

were read to the nearest milliliter while the weights were determined to the nearest tenth of a gram.

It was necessary to develop an equation to find the dry weight of the eroded material. In the following derivation, V_s is the volume of soil particles, V_t and V_w are the total volume and volume of water respectively, W_t is the total weight of sediment and water, W_s and W_w are the weights of the sediment and water respectively, γ_w is the unit weight of water, and G is the specific gravity of the soil particles.



$$V_t = V_w + V_s \quad (a)$$

$$W_t = W_s + W_w \quad (b)$$

$$V_s = \frac{W_s}{G\gamma_w} \quad (c)$$

FIGURE 8

VOLUME RELATIONSHIP

$$V_t = V_w + \frac{W_s}{G\gamma_w} = \frac{(W_t - W_s)}{\gamma_w} + \frac{W_s}{G\gamma_w} \quad (d)$$

$$\text{whence } W_s = \frac{G(W_t - V_t\gamma_w)}{G - 1} \quad (e)$$

Equation (e) was the working formula used to compute the dry weight of eroded soil. The runoff water volume was then found by taking the difference between W_t and W_s and multiplying that

difference by γ_w.

The results of the erosion test are tabulated in Tables XI through XX in appendix C and are summarized graphically in appendix D.

EROSION TEST DEVELOPMENT

The basic objective of this study was to devise an erosion test which could be used to measure the potential erodibility of a soil and thus serve as a basis for a soil erodibility classification system.

Specifically, the test was intentionally designed to be most applicable to bare, disturbed, fine grained soils of shallow depth on steep slopes, eroded predominately by overland flow. This corresponds to the common field situation where the cover is removed and the soil is disturbed by road building or logging operations on steep forest land. The 50% slope adopted for the test was about as steep as could be used without having many of the highly erodible soils slumping out of the channel. The shallow depth of soil in the channel corresponds closely to a field situation where impervious bedrock exists at a shallow depth, or where the soil is frozen below a thin thawed layer. The loose disturbed air-dry state selected for one phase of the test is very similar to a rather extreme, but not uncommon, soil condition sometimes prevailing on freshly logged off areas. A moist coherent state is undoubtedly more typical, however, and the erosion test on the moist compact

soil was given greater weight than the erosion test on the loose air-dry soil in the tentative erodibility classification system that was developed.

In practical situations where the erosion of loose air-dry soil is the main concern, it would be possible to modify the interpretation of the laboratory tests and give greater weight to the erosion observed on the loose air-dry soil. This is only one of many ways in which the laboratory erosion apparatus usage might be modified to help solve specific problems on specific sites. The flow rate, the slope, and the condition of the soil in the steel channel may all be changed with relative ease.

The apparatus was designed to be simple, easy to use, and to be operated by a single person. Standard items of laboratory equipment were used wherever possible.

The soil bed support was designed to allow tilting of the soil bed from 0 to 100% and to allow vertical and lateral adjustment of the reservoir so that the orifice could be kept in the same position relative to the soil for all slopes.

The method of applying the water to the soil bed was based on the assumption that a greater part of erosion can be attributed to overland flow. Several of the previous researchers, Packer (19) for one, also assumed this to be the case. A standard orifice, the Saybolt Furol Viscosity Orifice, was mounted in a four quart cream can, and an overflow pipe was

mounted so as to maintain a head which would produce a discharge close to 700 ml. per minute. The choice of flow rate was arbitrary, but it was considered to be similar to overland flow due to snowmelt.

This discharge was then applied to what was estimated to be the most erodible soil. It was found that a 1000 ml. graduate would practically fill up with eroded sediment and water in a one minute interval. After six minutes had elapsed most of this soil had run out of the channel. Using this as a guide, the time elements were set for 60 second intervals and a total elapsed time of six minutes.

The temperature of the discharge was held constant within $\pm 3^{\circ}$ of 70° F. The maximum deviation in viscosity, which was 7% over this temperature range, would not seriously affect the erosive action of the water. The change in the discharge which was caused by the change in viscosity was hardly noticeable. This maximum temperature variation of six degrees, combined with fluctuations in head due to pressure changes in the water supply system, caused a fluctuation in discharge from 690 to 705 ml. per minute. For a period of six minutes, the maximum deviation in total runoff volume was 2.1%.

Soil passing the No. 4 sieve was used for all of the erosion tests. This particular fraction corresponds to the fraction used in the AASHO compaction test.

The test was performed on the soils in both the loose

and dense conditions. The loose condition could be expected to compare to the disturbance caused by one pass of a log skidded along the ground, and the compacted condition could be compared to a damp road surface or to the moist compact soil beneath a loose dry surface layer. The 338 blows applied to the soil in the channel deliver the same energy per cubic foot as that used in the standard AASHO compaction test. It was observed that the actual water content varied no more than 1% from the optimum. However, the dry density was always lower than the maximum dry density as determined by the AASHO test. This compactive effort was not expected to produce the same density that it produces in the standard compaction mold but was employed merely as a standard method of compaction.

Comments on the reproducibility of the erosion tests are included in chapter IV.

In addition to the tests on the eighteen soils, loose erosion tests were also conducted on three different fractions of a standard concrete sand which was available in the Montana State College concrete laboratory. The sand appeared to contain approximately equal amounts of angular and rounded particles.

The different size fractions were:

Group 1: 1.651 to 4.699 mm.; between No. 4 and No. 10 sieves

Group 2: .833 to 1.651 mm.; between No. 10 and No. 20 sieves

Group 3: .417 to .833 mm.; between No. 20 and No. 40 sieves.

Groups 1 and 2 showed no erosion at all. The first runoff from these groups was a little milky, but after the first minute it cleared up. It took 2¼ minutes for the first runoff to take place for the group 3 sand, but ninety percent of the sand then eroded within four minutes after the first runoff. These results suggest that the fraction of soil larger than the No. 20 sieve size (.833 mm.) is relatively resistant to erosion for this particular slope and overland flow.

CHAPTER IV

TEST RESULTS AND ANALYSIS

The following physical soil characteristics, which are the liquid limit, plasticity index, mechanical analysis, aggregated silt and clay, the percentage of material passing the No. 20 sieve, or the percentage of material passing the No. 40 sieve, were used to formulate the ratios described below. These ratios were examined to determine the extent of their correlation with erosion.

Modified Dispersion Ratio, DR20

The dispersion ratio, DR, as defined by Middleton (15), was modified so as to include the effects of the larger size fractions on erodibility. The fraction of soil which passes the No. 20 sieve was considered to be the erodible fraction. The modified dispersion ratio was expressed as DR x (% passing No. 20 sieve) or DR20.

Surface Aggregation Ratio, S/A

The surface aggregation ratio, S/A, is defined as the ratio of particle surface area, in square centimeters per gram, to the amount of aggregated silt and clay in percent. Table VI shows the determination of the aggregated silt and clay and the calculation of the dispersion and surface aggregation ratios.

Modified Clay Ratio, MCR

A modified clay ratio has been formulated which is:

MCR = [(% sand + % silt) x (percent passing No. 20 sieve] ÷

TABLE VII - RATIOS USED IN STATISTICAL ANALYSES

SOIL NO.	SURFACE AGGREGATION RATIO, S/A	DISPERSION RATIO DR20	MODIFIED CLAY RATIO MCR	LL/PI RATIO LPR	PI RATIO PIR
1	1.80	0.57	5.56	2.43	0.78
2	0.68	0.39	2.27	1.82	0.46
3	0.49	0.32	2.62	1.72	0.43
4	2.40	0.85	7.29	5.44	1.93
5	0.65	0.39	1.88	2.00	0.50
6	1.81	0.47	6.49	2.87	0.93
7	1.40	0.76	2.22	4.43	1.71
8	0.59	0.28	1.84	1.81	0.36
9	1.24	0.65	5.41	3.89	0.74
10	0.73	0.59	2.46	2.51	0.82
11	0.68	0.38	1.58	1.35	0.22
12	0.76	0.55	0.98	1.34	0.19
13	0.52	0.47	1.13	1.57	0.41
14	0.47	0.43	1.16	1.72	0.35
15	1.03	0.38	5.07	2.24	0.42
16	2.75	0.53	12.07	6.06	2.21
17	0.52	0.28	2.12	2.15	0.45
18	0.39	0.24	0.81	1.56	0.33

TABLE VIII - EROSION DATA SUMMARY

SOIL NUMBER	CUMULATIVE SOIL RUNOFF, gms. AT 3 MINUTES			EROSION NUMBER	RATIO $\frac{E_1}{E_d}$
	LOOSE, E_1	DENSE, E_d	$E = E_d + .1E_1$	EN = E/10	
1	431.80	241.50	284.70	28.5	1.79
2	465.70	69.20	115.80	11.6	6.73
3	408.70	107.20	148.10	14.8	3.81
4	298.30	434.10	463.90	46.4	.69
5	526.70	171.80	224.50	22.5	3.07
6	1036.60	271.10	374.80	37.5	3.83
7	284.40	73.60	102.00	10.2	3.87
8	767.20	101.50	178.20	17.8	7.56
9	408.40	348.20	389.00	38.9	1.18
10	298.40	121.80	151.60	15.2	2.45
11	432.30	87.50	130.70	13.1	4.94
12	271.70	61.80	89.00	8.9	4.40
13	198.80	43.90	63.80	6.4	4.52
14	370.20	38.20	75.20	7.5	9.69
15	599.40	226.10	286.00	28.6	2.65
16	1483.90	211.00	359.40	35.9	7.04
17	255.70	113.40	139.00	13.9	2.25
18	295.10	29.90	59.40	5.9	9.88

Average Ratio $\frac{E_1}{E_d} = 4.46$

times from one to six minutes. The results of the individual tests were combined to give the average erosion for each elapsed time.

In most cases, it was noted that the results started to show greater variation after three minutes had elapsed. Usually, a channel eroded through the soil down to the surface of the steel channel between an elapsed time of two and three minutes. From this point on, sloughing into the eroded channel was a random process and was the major cause of the sometimes erratic results evident during the last three minutes of the test.

It was interesting to note the differences in behavior of the soils during the loose test. The water cut a channel down the center of the bed of soil when a silt, soil No. 4 particularly, was used. The soils which contained a large percentage of fine soil eroded the entire width of the channel from the upper end of the soil bed downstream; almost all of the soil was carried out of the channel.

Dense Test Results

At least two runs were made on each soil in the dense condition. If the results of the two tests varied more than about 15% from their mean, a third test was run. In either case, the results were combined, and an average cumulative erosion was computed for each elapsed time.

Generally, the water flowed over the entire width of the soil surface. Clays, which possessed high or medium plasticity,

showed no definite channels after being subjected to the water jet for six minutes. The silty soils all exhibited a tendency for a channel to form. Clays showed a higher resistance to erosion than did the silts.

After all of the erosion tests were completed, the results were studied, and it was found that the three-minute cumulative dense erosion showed a maximum variation of about 12% about its mean. For fourteen of the soils, this variation was 8% or less. The variation at six minutes showed a maximum variation of approximately 16%. The three minute test results showed the least variation in both the loose and dense states. Thus, the three minute values were used in the statistical analysis.

Prior to making the statistical analysis, graphs of the ratios versus dense erosion were plotted. It was observed that several of the ratios, especially MCR and S/A, appeared to correlate quite well with erosion. However, in the case of MCR, soil No. 16 did not appear to follow the same trend as did the seventeen other soils.

All of the soil was observed to wash completely out of the channel in less than five minutes during one of the three loose erosion tests which were run on soil No. 16, and erosion measurements for this test were not obtained. It was apparent that the three-minute erosion was much larger than that of the other two test runs. For this reason, the average result of the

two measurable runs, as tabulated in Table XIX, should be considered as the minimum loose erosion value. It is possible that this value should be as much as 50% larger than the tabulated value. Because of the different behavior of soil No. 16, the statistical analyses were run with this soil included and then omitted in order to determine what effect this soil had on the overall correlation between erosion and the various ratios.

Erosion was expressed as three different quantities which are:

1.) E_d = cumulative erosion, in grams, at the end of three minutes with the soil in the dense moist state.

2.) E_l = cumulative erosion, in grams, at the end of three minutes with the soil in the loose air-dry state.

3.) $E = E_d + 0.1E_l$

It was observed that the graphs of E_l versus the various ratios did not exhibit linear correlations which were as good as the correlations between E_d and the various ratios. However, it was felt that the loose erosion test results have some significance and should be included in the erosion results. Equation 3, which includes 10% of the loose erosion results, was proposed.

LINEAR REGRESSION ANALYSIS

Linear regression analysis, which involved one independent and one dependent variable, were performed to determine the extent of the linear correlation between erosion and the

various ratios. Equations for expressing erosion as a function of a variable were developed in each case and took the form of Erosion = A + B(Ratio). These equations were fitted to the data by using the least squares criterion which requires the sum of the square of the deviations of the observed points from the straight-line moving average to be a minimum.

Analyses of variance for regression were performed in order to determine the effect of each ratio on erosion. The linear correlation was determined by examining the correlation coefficient r. According to Steel (25), "A value of 1 for r would indicate perfect linear correlation or a functional relation between the two variables." The square of the correlation coefficient, r^2, called the determination coefficient, was also examined. The value of r^2, in this case, is the proportion of a total sum of squares which is attributable to the variation of the independent variable. High values of r^2 then indicate that a large portion of the variation of erosion is due to the variation of the particular ratio under study.

The equations of lines which express erosion as a function of a particular ratio are given, along with the analysis of variance tables and values of r and r^2, in Tables XXI through XXV in appendix F.

Linear Correlation and the Effects of the Ratios on Erosion

MCR and S/A were the only two ratios which exhibited linear correlation with loose erosion when soil No. 16 was

included. The exclusion of soil No. 16 in the analyses showed that none of the ratios exhibited an acceptable degree of correlation with loose erosion.

The value of $\underline{r}$ for the correlation between MCR and E_1, soil No. 16 included, was .736, while the value of $\underline{r}^2$ was 0.542. This $\underline{r}^2$ value indicated that only about 54% of the variation in E_1 was due to the variance of MCR. The $\underline{r}$ and $\underline{r}^2$ value for the correlation between E_1 and S/A were .583 and .340. Obviously, MCR exhibits the better correlation with E_1.

Of all the ratios, the modified clay ratio, MCR, was found to have the most significant effect on E_d, E_1, and E. It exhibited the best linear correlation when erosion was expressed as either E or E_d. When soil No. 16 was included in the analysis, the $\underline{r}$ values were .8447 when E was used and .7319 when E_d was used. The $\underline{r}^2$ values indicated that about 71% of the variation in E and 54% of the variation in E_d could be attributed to the variation in MCR. The omission of soil No. 16 resulted in an improvement of the linear correlation. In this case, the $\underline{r}$ values were .9480 and .9372 when E and E_d were used. The $\underline{r}^2$ values indicated that 90% of the variation in E and 88% of the variation in E_d could be attributed to the variation in MCR.

The analysis of variance for regression showed that the surface aggregation ratio, S/A, had a very significant effect on both E and E_d, but the linear correlation was not as good as

that exhibited by MCR when soil No. 16 was omitted. The r values were .8050 and .7309 for E and E_d respectively. These values were nearly the same as those obtained when MCR was used and soil No. 16 was included.

It was found that the liquid limit-plasticity index ratio, LPR, did not exhibit as good a linear correlation with E or E_d as did MCR or S/A. In this case, soil No. 16 included, the r values were .7012 and .6530 for E and E_d. The analysis of variance for regression showed that LPR had a significant effect on E and E_d.

The plasticity index ratio had a significant effect on E at the 1% level when soil No. 16 was included, but the r value was only .5921. The modified dispersion ratio also exhibited poor linear correlation with erosion. The highest r value in this case was .5575 when E_d was used with soil No. 16 omitted. The analysis of variance indicated that DR20 had a significant effect on E_d, soil 16 omitted, at the 5% level.

After reviewing the above analyses, a multiple linear regression analysis was run to determine the effects of four of the ratios, MCR, S/A, LPR, and DR20, and several combinations of these ratios, on erosion. It was found that the MCR was responsible for almost all of the linear correlation, and the inclusion of S/A, LPR, and DR20 did very little to improve this correlation.

The graphs and equations for erosion expressed as

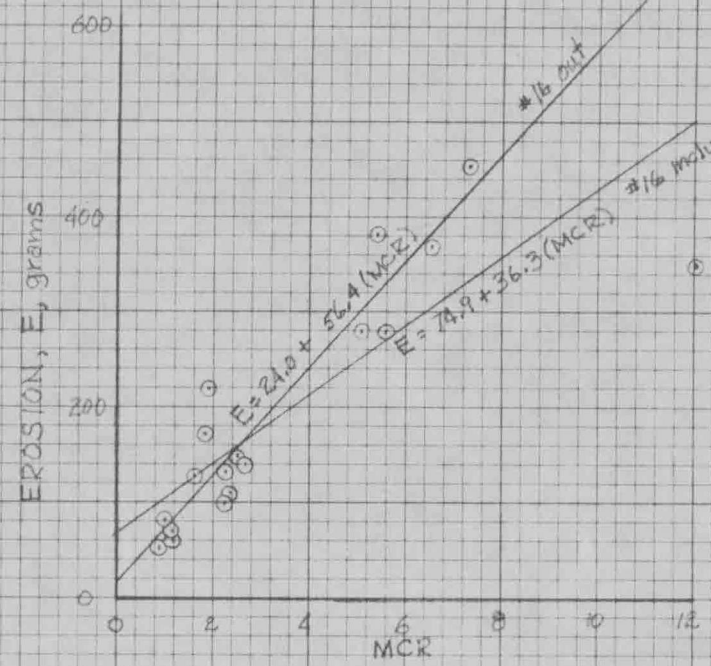


FIGURE 9 - MCR vs. EROSION, E

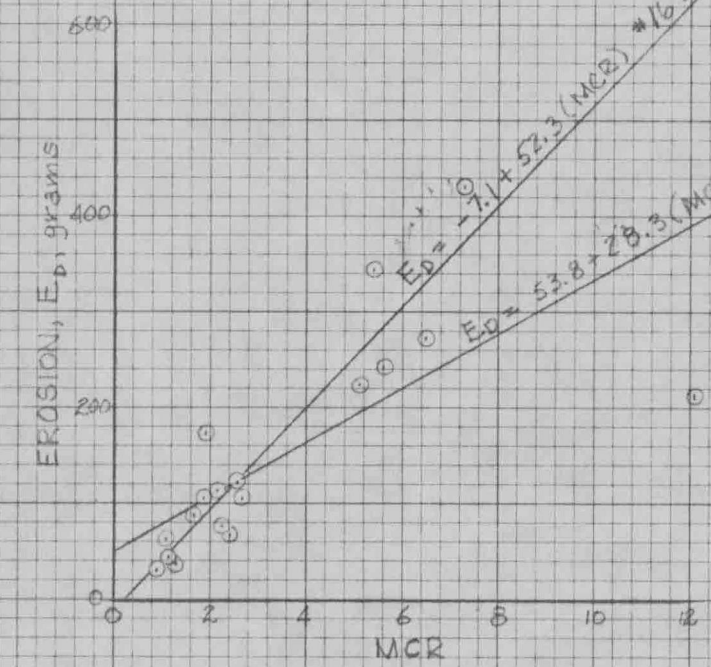


FIGURE 10 - MCR vs. EROSION, E_D

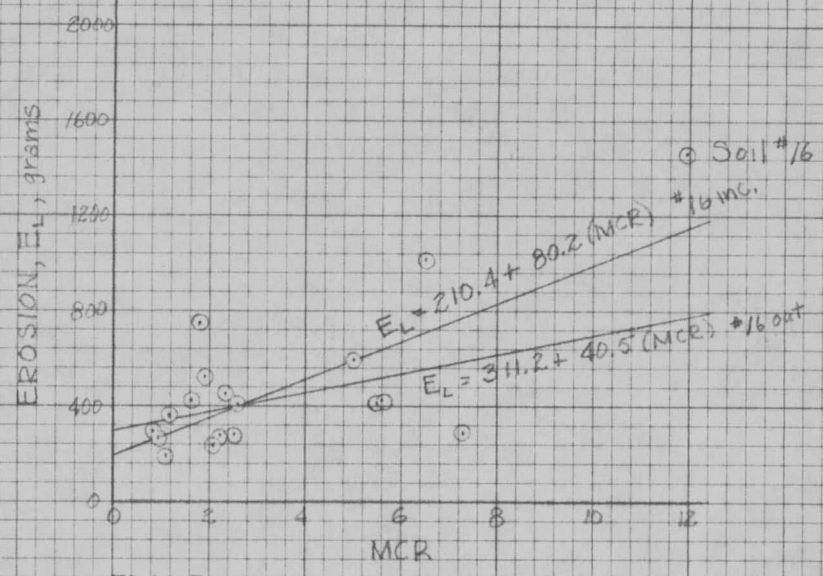


FIGURE 11 - MCR vs. EROSION, E_L

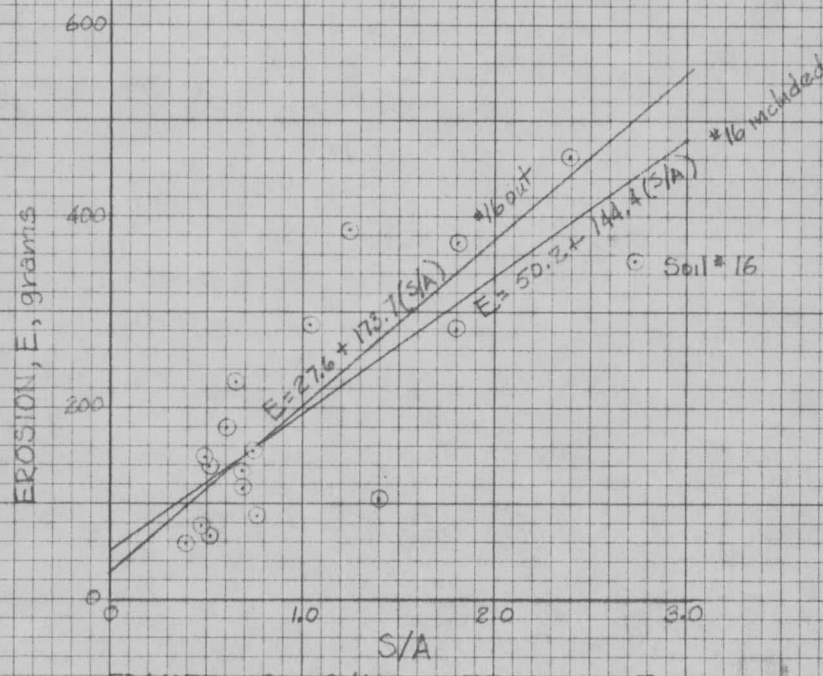


FIGURE 12 - S/A vs. EROSION, E

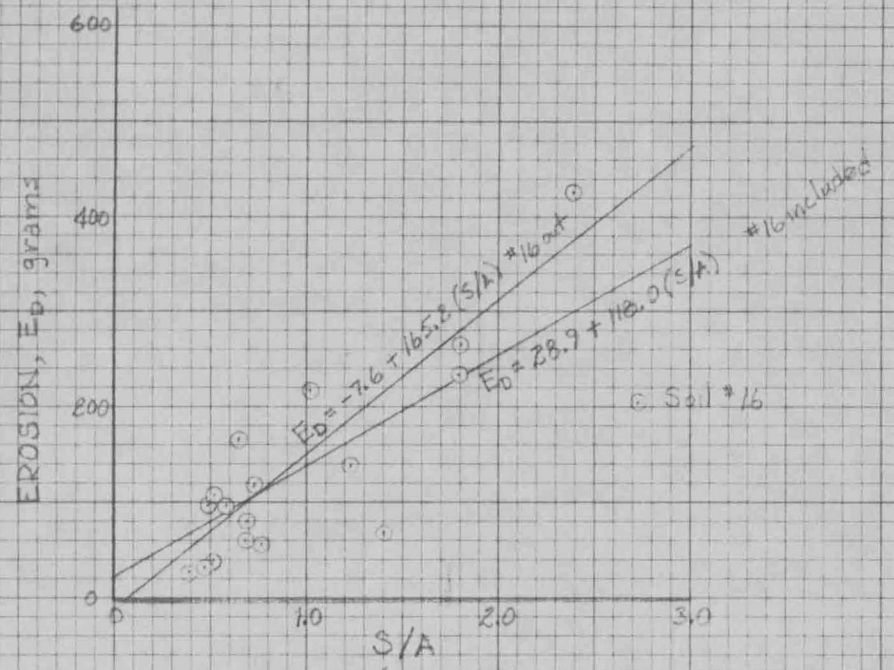


FIGURE 13 - S/A vs. EROSION, E_D

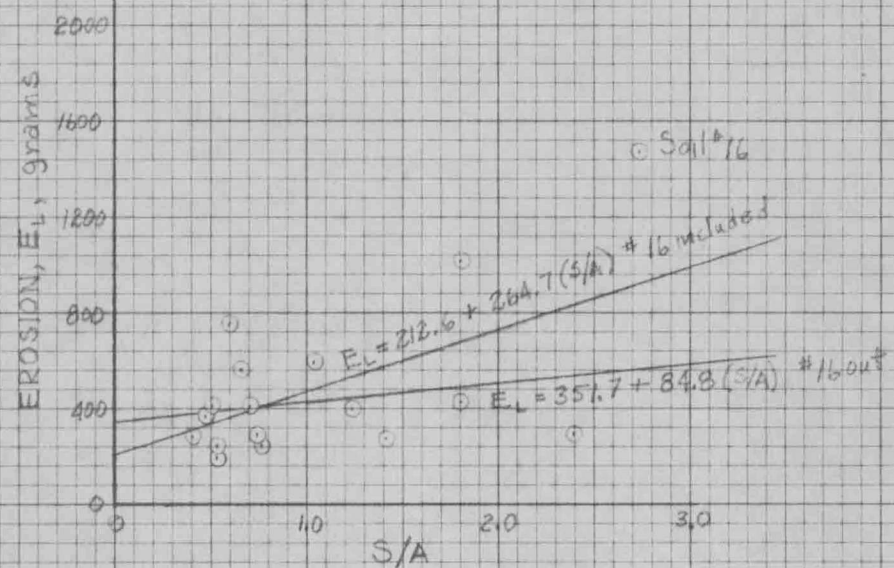


FIGURE 14 - S/A vs. EROSION, E_L

functions of MCR and S/A are shown in figures 9 through 14.

For the dense condition, the results of tests on soil 16 were reproducible. Examination of figures 10 and 13 will show that soil 16 does not appear to follow the general trend shown by the other seventeen soils.

As mentioned before, the E_1 value for soil 16 should be considered to be a minimum value. If this value were to be increased by 50% to 2230 grams, the resultant value of E would be 434 grams. This would raise soil 16 above its location as shown in figure 9 and would result in a better degree of linear correlation.

The evidence that an occasional soil exhibits an erodibility which deviates widely from that predicted by indirect indicators lends further support to the argument that a direct erosion test is a superior basis for a soil erodibility classification system.

DISCUSSION

The graphs of erosion as measured in the laboratory versus the surface aggregation ratio and the modified clay ratio show that erosion increases as the ratios increase. These observed relationships follow the same trend as the relationship between erosion measured in the field and essentially the same two ratios as observed by Anderson (3) and Bouyoucos (6).

The modified dispersion ratio seemed to show very little correlation with erosion as it was measured in the laboratory.

This is not in agreement with the findings of Middleton (15), but it does agree with the findings of Adams (1) and Peele, et al. (21). Bouyoucos suggested that his clay ratio might be a better erosion indicator than the dispersion ratio. This has been shown to be definitely so in this study.

At the beginning of this study it was hypothesized that the PI would correlate well with erosion and could then be used as an erosion indicator. The PI, as such, showed very poor correlation with erosion. However, the plasticity index ratio showed a fair correlation with erosion. The liquid limit-plasticity index ratio exhibited a slightly better correlation with erosion than did the plasticity index ratio. However, neither of the ratios exhibited the degree of correlation with erosion that was shown by the MCR and S/A ratios.

The correlation of laboratory erosion with essentially the same factors that have been shown by others to correlate well with field erosion indicates that the laboratory erosion test is furnishing results which compare qualitatively, at least, with field erosion. This suggests that the laboratory erosion test can be used to determine the relative erodibility of soils, or in other words, to classify soils directly as to their potential erodibility.

It is the writer's belief that, by using the standard erosion test, or some similar direct erosion test, to measure the erodibility of the fine grained soil in question, the

engineer or land manager will have a better and more dependable estimate of the potential erodibility of the soil than he would if he utilized the surface aggregation ratio, clay ratio, or some other indirect erosion indicator.

Utilization of the Laboratory Erosion Test

It is proposed that the results of the laboratory erosion test be used to determine an erosion number for any particular soil. This number is expressed as EN = $\frac{E}{10}$. The EN would range from 0 to 50 or more (46.4 was the largest of the 13 erosion numbers determined in this investigation), with 0 indicating no erodibility and 50 or more indicating extremely high erodibility. The erosion numbers of the soils studied in this investigation are given in Tables VIII and XI. The erosion number is believed to provide a better measure of relative erodibility than any indirect erosion indicator or predictor such as surface aggregation ratio, clay ratio, dispersion ratio, or erosion index.

As an example of how the erosion number is used to classify soils, consider soils 5, 10 and 18. The erosion numbers for these three soils, which are 22.4, 15.2, and 5.9, show 5 to be about four times as erodible as 18, and soil 10 to be about three times as erodible as 18. These soils are all classified as CL under the Unified Soil Classification System. Erosion indices for these three soils were calculated according to the method illustrated on page 9. All three of the indices

fell under the same erosion class.

The equations for erosion which have been developed could be used in lieu of the actual erosion test to get a rough estimate of the erosion number. The best estimate would be obtained by determining the MCR and using the equation EN = 24 / 56(MCR) ÷ 10. This equation cannot be considered applicable to all soils, but it will produce a reasonable estimate of EN when applied to soils similar to the soils upon which the equation is based. The use of the equation would not, of course, evaluate the erosion number as accurately as the actual performance of the erosion test.

It was found that all but one of the soils tested eroded more in the dry loose test than in the dense test. This suggests that soil moisture and density have, in some instances, a significant effect on soil erodibility. Borst and Woodburn (7), and Free (12) found that a wet, slightly compacted soil eroded more than a loose dry soil. In their case, the loose dry soil apparently absorbed most of the applied moisture. This would reduce the amount of overland flow and thereby decrease the erosive action of the water. In this investigation, a comparatively large flow of water was applied to the soil. The shallow depth of soil and the ability of the comparatively large flow rate to transport the soil was responsible for the high erosion rate of the loose air-dry soils.

The cohesion of the soil in the moist dense condition

accounted for the comparatively low erosion rates of the soils in this condition.

The ratios of $\frac{E_l}{E_d}$, which are tabulated in Table VIII, for each soil were examined and were found to range between 0.69 and 9.88. The average values for all of the soils tested was 4.46. This means that, on the average, the soils were about 4.5 times as erodible in the loose air-dry state as they were in the dense moist state.

The writer feels that the ratio of $\frac{E_l}{E_d}$ has some value in pointing out the influence of compaction and moisture on erodibility. This ratio could be used by engineers to estimate the feasibility of compacting fill slopes for erosion reduction purposes. Values of $\frac{E_l}{E_d}$ near 1 indicate that nothing would be gained by compacting the fill slopes, while a value of 10 indicates that compaction would be highly desirable. It is significant that all but one of the soils studied in this investigation had a value of $\frac{E_l}{E_d}$ greater than 1.

Comparison with Packer's Test Results

The six soil types which were studied by Packer and were included in this study are listed in Table IX by number, sample name, and soil type.

Soil 5 was taken from the overburden at the top of a road cut through basalt. It is possible that this soil differs from that studied by Packer. Soil 9 was taken from a site which was a considerable distance from Packer's site, and there is no

assurance that this soil is similar to the soil at his site.

TABLE IX: SOILS STUDIED BY PACKER AND HOGAN

SOIL NO.	SOIL NAME	EN	SOIL TYPE
1	BITT #21	28.5	GRANITIC
5	CLEAR #6	22.5	BASALTIC
6	CLEAR #13	37.5	LOESSIAL
7	FLAT #13	10.2	GLACIAL SILT
9	GALL #2	38.9	ANDESITIC
10	LOLO #18	15.2	HARD SEDIMENTARY

Table X lists the soils described in Table IX in the order of increasing erodibility as determined by Packer and Hogan. With the exception of the glacial silt, the agreement is probably as good as can be expected, for reasons that are explained below.

TABLE X: COMPARISON OF RELATIVE SOIL ERODIBILITY AS DETERMINED BY PACKER AND HOGAN

PACKER	THIS STUDY	
SOIL TYPE	SOIL TYPE	EROSION NO., EN
Hard Sedimentary	Glacial Silt	10.2
Basaltic	Hard Sedimentary	15.2
Granitic	Basaltic	22.5
Glacial Silt	Granitic	28.5
Andesitic	Loessial	37.5
Loessial	Andesitic	38.9

The sites which Packer studied were actual road bed cross-sections, some of which contained large amounts of coarse rock particles larger than the No. 4 sieve size. The erosion test was conducted on material which passed the No. 4 sieve, and consequently the erosion retarding effect of the coarse

particles was not included in the test results. This may be the cause of some of the lack of agreement as shown in Table X.

Soils 5, 6, and 9 were taken from the general area of Packer's test sites, and it is quite possible that these soils are entirely different from the soils which occupy the actual test sites. This could account for some of the lack of agreement shown above.

There is also the possibility that Packer's test sites were subjected to different amounts of precipitation or snowmelt runoff which could also account for some of the disagreement evident in Table X.

General Observations

The conditions under which the laboratory test was run can be compared to the following field conditions:

1. No ground cover at all.
2. Fine grained surface layer of soil.
3. No physical obstructions in the path of eroding water.
4. A thin layer of soil ($1\frac{1}{2}$") over an impermeable stratum which might be bedrock or frozen soil.

The above conditions approximate the worst conditions that occur in the field. This suggests that the test results give the maximum erodibility under the standard test conditions. An increase in ground cover, percentage of coarse particles, number of obstructions, and thickness of soil layer are expected to decrease the erodibility of the soils.

CHAPTER V

SUMMARY AND CONCLUSIONS

SUMMARY OF TEST RESULTS

A practical and simple laboratory erosion test for determining the relative erodibility of fine grained soils has been developed. The results of this erosion test have been correlated with several physical soil characteristics, two of which are the modified clay ratio and the surface aggregation ratio. The clay ratio and surface aggregation ratio have been found by others to correlate well with actual field erosion. It has been found that the laboratory erosion test results, as well as field erosion measurements, display an increase in erodibility with an increase in either ratio.

The dispersion ratio and two other ratios based on the liquid limit and plasticity index were also investigated; however, the correlation with erosion was quite poor.

Several equations were developed to express the laboratory erosion as a function of either the modified clay ratio, MCR, or the surface aggregation ratio, S/A. The equations which will most satisfactorily describe these inter-relationships are:

$$E = 24 \neq 56(MCR), \text{ or } EN = 2.4 \neq 5.6(MCR) \quad (1)$$
$$E = 28 \neq 174(S/A), \text{ or } EN = 2.8 \neq 17.4(S/A) \quad (2)$$

In these expressions, the erosion, E, for a given soil is described as the cumulative weight, in grams, of soil runoff

at the end of a three minute test on the soil in the loose, air-dry condition. The erosion number, EN, is merely $\frac{E}{10}$.

Equation (1) showed the best linear correlation, and the MCR was found to have the most significant effect on the erodibility of fine grained soils.

CONCLUSIONS

The results of the proposed standard laboratory erosion test, when expressed as an erosion number, EN, provide a basis for classifying disturbed fine grained soils as to their relative erodibility. The modified clay ratio, MCR, and the surface aggregation ratio, S/A, correlate quite well with standard laboratory erosion. Both of these ratios increase with an increase in erodibility.

The liquid limit and plasticity index, when expressed as LPR or PIR, and the modified dispersion ratio do not correlate well with standard laboratory erosion.

RECOMMENDATIONS

It is recommended that the proposed standard laboratory erosion test, or some similar test, be used to classify fine grained soils as to their relative erodibility.

If facilities for performing the standard erosion test are not available, it is recommended that the modified clay ratio be determined for the soil in question. The erosion number may be estimated by using the following formula:

$$EN = 2.4 + 5.6\ (MCR)$$

It is emphasized that the use of the formula is an alternate method and will not evaluate EN as accurately as the actual performance of the test. The above equation is applicable only to fine grained soils which are similar to soils upon which the equation is based.

The use of the standard laboratory erosion test to classify soils as to their relative erodibility is considered to be superior to the use of indirect erosion indicators for a similar purpose.

RECOMMENDATIONS FOR FURTHER STUDY

It is recommended that the next step in the further development of a standard erosion test should be the investigation of the effects of coarse material on erodibility. The first phase of this investigation would involve the study of soils which contain widely varying amounts of coarse sand. The second phase sould involve the study of the erosion retarding effects of coarse material which is larger than coarse sand. Then, field test sites should be established and erosion on these sites measured and compared to the erosion as predicted by the use of the standard laboratory erosion test. A similarity in trends or results between laboratory and field erosion would verify the validity of the test. It will then be necessary to develop transfer coefficients which will directly relate the laboratory and field erosion results.

The dense moist phase of the erosion test is complicated

and time consuming and appears to be a serious disadvantage of the proposed standard test. It is recommended that the use of a moist loose, or lightly compacted soil condition, in place of the dense moist soil condition, be investigated. If results indicate that the moist loose or lightly compacted state will furnish satisfactory results, then the test procedure would be simplified, and the time required to perform the test would be greatly reduced.

It is further recommended that the apparatus be used to study the effects of slope changes, change in discharge rate, different soil treatments, different soil conditions, and varying amounts of ground cover.

APPENDICES

APPENDIX A

PROPOSED STANDARD EROSION TEST PROCEDURE

The special apparatus necessary for the performance of the laboratory erosion test is illustrated in figures 1 through 6 in the text.

Sample

Obtain approximately 100 pounds of disturbed soil from the field and spread it out to air dry in the laboratory. After the soil has become thoroughly air-dried, set aside a representative sample, about 15 pounds, which will be used for tests other than the erosion test.

Sieve the remainder of the sample over the No. 4 sieve. Break up the aggregations which are larger than the No. 4 sieve with a rubber mallet and sieve the material again. Repeat this process until only coarse gravel and rock particles remain on the sieve. Discard the oversize material. The aggregations should be reduced in size so that they will just pass through the No. 4 sieve. It is not necessary or desirable to reduce the aggregations to the individual particles of which they are comprised. Perform the standard AASHO Moisture-Density Relationship test (AASHO Designation T99-57, Method A) on a representative sample of the prepared soil.

Test Procedure

Place approximately 12 pounds of the air-dry soil, which has been prepared as described above, loosely in the steel

channel. Screed the soil surface off level with the top of the channel.

Adjust the soil bed support to a 50% slope. Place the soil bed on the support and adjust the reservoir both vertically and laterally so that the lowest extremity of the standard orifice is 7" above a point on the soil bed which is 30" from the downstream end and centered between the side-boards.

Place the splash protector at the upper end of the channel and place the diversion chute beneath the orifice. Adjust the water temperature to 70° F $\pm$ 1° and adjust the head for a discharge of 700 $\pm$ 5 ml/minute.

Place a 1000 ml. cylinder below the runoff chute and remove the diversion chute. Note the time to first runoff and change cylinders at one minute intervals thereafter for three minutes.

If the soil is highly erodible, it is possible that the 1000 ml. cylinders will not be sufficient to contain all of the runoff water and eroded sediment. In this case, the runoff can be collected for the entire three minutes in a large container such as a pail.

Determine the tare weights of each of the cylinders to the nearest 0.1 gram. Determine the total volume and weight of the combined sediment and water in each of the three cylinders to the nearest milliliter and nearest 0.1 gram respectively. Compute the dry weight of the sediment as follows:

$$W_s = \frac{G\,(W_t - V_t \gamma_w)}{G - 1}$$

W_s = dry weight of sediment

W_t = combined weight of sediment and water

V_t = total volume of sediment and water

γ_w = unit weight of water

G = specific gravity of the soil particles

Erosion is then expressed as the cumulative W_s at the end of three minutes. If a large container is used to collect the soil runoff, determine the total weight of the combined sediment and water; pour the mixture into graduated cylinders and determine the total volume to the nearest milliliter.

At least two loose erosion tests should be made on each soil. Run a third test if the results of the first two tests vary more than 15% about their mean. Erosion, E_1, is then expressed as an average of the individual test results.

Next, perform phase two of the test. This phase is performed exactly as described above except for the placement of the soil in the soil bed.

Add enough water to about 16 pounds of the prepared air-dry soil to bring it up to its optimum AASHO water content. Mix the soil and water thoroughly and place it in the steel channel in one uniform lift. Compact the soil with 338 uniformly distributed blows of a standard 5.5 lb. AASHO compaction

hammer. Remove the side-boards from the channel, screed the excess material off even with the top of the channel, and replace the side-boards. Check the water content of the soil by taking a sample of the excess material which has been screeded off. Place the soil bed on the soil bed support and proceed as described above.

If the result of two repetitions of the dense test vary more than 15% about their mean, repeat the test a third time. Erosion, E_d, is expressed as an average of the individual test results.

The final results of the laboratory erosion tests are expressed as an erosion number which is:

$$EN = 0.1E_d + 0.01 E_l.$$

APPENDIX B

TABLE XI, SOIL CLASSIFICATION

SOIL NO.	NAME	LL	PI	CLASSIFICATION		EROSION NO. EN
				AASHO	UNIFIED	
1	BITT #21	31.0	9.5	A-4 (3)	CL, SC	28.5
2	BRACKETT CR.	39.8	19.4	A-6 (10)	CL	11.6
3	BRIDGER	40.2	19.1	A-6,A-7 (11)	CL	14.8
4	CARD #1	28.25	5.1	A-4 (8)	ML	46.4
5	CLEAR #6	39.8	16.4	A-6 (9)	CL	22.5
6	CLEAR #13	30.8	7.4	A-2-4 (0)	SM	37.5
7	FLAT #13	25.35	5.5	A-4 (8)	ML-CL	10.2
8	GALL #1	50.4	25.5	A-7-6 (15)	CL-CH	17.8
9	GALL #2	52.6	12.4	A-7-5 (11)	MH	38.9
10	LOLO #18	30.4	10.8	A-4 (8)	CL	15.2
11	MOOSE CR.	62.4	38.5	A-7-6 (16)	CH	13.1
12	MOOSE #2	70.7	46.4	A-7-6 (20)	CH	8.9
13	N. FK. BRACKETT	38.1	20.0	A-6 (12)	CL	6.4
14	ORCHID CR.	48.5	27.1	A-7-6 (17)	CL	7.5
15	RAT LAKE	52.9	18.7	A-7-5 (7)	SM, MH	28.6
16	SQUAW CR.	27.4	2.7	A-2-4 (0)	SM	35.9
17	TAYLOR FORK	47.5	20.3	A-7-6 (13)	ML-CL	13.9
18	TAYLOR #2	48.2	28.3	A-7-6 (17)	CL	5.9

APPENDIX C

EROSION TEST RESULTS

TABLE XII - EROSION TEST RESULTS

SOIL NO.	COND. LOOSE, DENSE	TIME, min.	RUN NUMBER ACCUMULATIVE SOIL RUNOFF, GMS. 1	2	3	4	TOTAL	AVERAGE
1	L	1	126.7	109.2	130.6		366.5	122.2
		2	257.7	231.8	313.1		802.6	267.5
		3	403.3	375.6	516.6		1295.5	431.8
		4	553.1	581.9	643.4		1778.4	592.8
		5	600.2	740.4	852.6		2193.2	731.1
		6	678.8	983.4	1210.1		2872.3	957.4
	D	1	103.6	96.2			199.8	99.9
		2	175.2	169.9			345.1	172.5
		3	248.7	234.3			483.0	241.5
		4	303.3	292.1			595.4	297.7
		5	377.8	354.6			732.4	366.2
		6	445.7	416.3			872.0	436.0
2	L	1	126.8	147.8			274.6	137.3
		2	307.3	328.4			635.7	317.9
		3	464.1	467.3			931.4	465.7
		4	577.8	598.1			1175.9	587.9
		5	698.8	721.0			1419.8	709.9
		6	804.2	834.7			1638.9	819.4
	D	1	32.9	41.0			73.9	36.9
		2	43.0	50.7			93.7	46.8
		3	63.5	74.9			138.4	69.2
		4	74.0	85.4			159.4	79.7
		5	89.7	97.1			186.8	93.4
		6	110.6	119.4			230.0	115.0

TABLE XIII - EROSION TEST RESULTS

SOIL NO.	COND. LOOSE, DENSE	TIME, min.	RUN NUMBER ACCUMULATIVE SOIL RUNOFF, GMS. 1	2	3	4	TOTAL	AVERAGE
3	L	1	134.3	159.0	159.0		452.3	150.8
		2	249.6	304.6	279.2		833.4	277.8
		3	385.3	438.8	401.9		1226.0	408.7
		4	511.3	580.4	507.6		1599.3	533.1
		5	641.6	771.7	770.6		2183.9	724.6
		6	1026.6	1352.7	1291.6		2318.2	1159.1
	D	1	47.4	48.2			95.6	47.8
		2	68.1	73.7			141.8	70.9
		3	100.2	114.3			214.5	107.2
		4	130.6	142.0			272.6	136.3
		5	170.3	174.4			344.7	172.3
		6	218.8	224.6			443.4	221.7
4	L	1	79.4	56.2	71.7		207.3	69.1
		2	175.8	153.2	164.4		493.4	164.5
		3	341.8	291.0	262.0		894.8	298.3
		4	590.4	404.8	486.6		1481.8	493.9
		5	917.4	517.0	610.2		2044.6	681.5
		6	1314.9	803.2	755.9		2874.0	958.0
	D	1	150.7	131.7			282.4	141.2
		2	284.9	260.9			545.8	272.9
		3	423.9	444.2			868.1	434.1
		4	553.4	600.5			1153.9	576.9
		5	681.2	748.0			1429.2	714.6
		6	816.2	982.5			1798.7	899.3

TABLE XIV - EROSION TEST RESULTS

SOIL NO.	COND. LOOSE, DENSE	TIME, min.	RUN NUMBER ACCUMULATIVE SOIL RUNOFF, GMS. 1	2	3	4	TOTAL	AVERAGE
5	L	1	138.3	124.6			262.9	131.5
		2	342.3	336.6			678.9	339.4
		3	527.7	525.8			1053.5	526.7
		4	683.1	748.3			1431.3	715.6
		5	973.0	1095.3			2068.3	1034.1
		6	1229.7	1307.8			2537.5	1268.7
	D	1	91.5	73.2	70.1		234.8	78.3
		2	156.9	108.4	100.4		365.7	121.9
		3	230.2	150.2	135.0		515.4	171.8
		4	286.1	184.0	155.7		625.8	208.6
		5	353.6	219.2	178.2		751.0	250.3
		6	423.0	254.9	210.6		888.5	296.2
6	L	1	266.0	221.4	236.0		723.4	241.1
		2	526.0	518.9	501.0		1545.9	515.3
		3	1092.0	1062.9	955.0		3109.9	1036.6
		4	1483.5	1516.9	1377.0		4377.4	1459.1
		5	1767.5	1932.9	1639.1		5339.5	1779.8
		6	2073.5	2475.9	2051.1		6600.5	2200.2
	D	1	141.4	129.6	134.0		405.0	135.0
		2	211.6	184.9	216.6		613.1	204.4
		3	276.8	239.7	297.6		813.2	271.1
		4	335.1	278.3	349.3		962.7	320.9
		5	397.1	322.3	452.0		1171.4	390.5
		6	467.3	376.3	505.5		1349.1	449.7

TABLE XV - EROSION TEST RESULTS

SOIL NO.	COND. LOOSE, DENSE	TIME, min.	RUN NUMBER ACCUMULATIVE SOIL RUNOFF, GMS. 1	2	3	4	TOTAL	AVERAGE
7	L	1	85.7	71.0			156.7	78.3
		2	175.3	153.5			328.8	164.4
		3	283.6	285.2			568.8	284.4
		4	390.5	409.2			799.7	399.9
		5	482.6	513.4			996.0	498.0
		6	580.4	615.8			1196.2	598.1
	D	1	37.0	32.5			69.5	34.7
		2	52.4	57.6			110.0	55.0
		3	74.4	72.8			147.2	73.6
		4	87.5	87.7			175.2	87.6
		5	107.2	105.8			213.0	106.5
		6	129.7	132.2			262.0	131.0
8	L	1	107.7	187.2	205.0	185.0	685.3	171.3
		2	313.7	367.2	425.0	513.9	1619.8	405.0
		3	740.7	729.2	774.0	824.9	3068.8	767.2
		4	1098.7	1037.7	1034.0	1179.9	4350.3	1087.6
		5	1344.2	1453.7	1211.6	1551.5	5561.0	1390.2
		6	1532.8	1798.7	1360.1	1976.0	6667.6	1666.9
	D	1	56.7	45.0			101.7	50.9
		2	83.2	65.0			148.2	74.1
		3	113.6	89.3			202.9	101.5
		4	138.0	103.4			241.4	120.7
		5	165.1	124.0			289.1	144.5
		6	193.8	145.7			339.5	169.8

TABLE XVI - EROSION TEST RESULTS

SOIL NO.	COND. LOOSE, DENSE	TIME, min.	RUN NUMBER ACCUMULATIVE SOIL RUNOFF, GRAMS 1	2	3	4	TOTAL	AVERAGE
9	L	1	112.6	112.2	89.0		313.8	104.6
		2	260.1	285.0	246.2		791.3	263.8
		3	436.1	422.3	366.8		1225.2	408.4
		4	595.3	588.7	460.7		1644.7	548.2
		5	890.8	880.7	644.6		2416.1	805.4
		6	1176.3	1059.2	973.6		3209.1	1069.7
	D	1	110.2	108.6			218.8	109.4
		2	221.5	230.1			451.6	225.8
		3	349.2	347.3			696.5	348.2
		4	496.7	459.0			955.7	477.9
		5	629.0	578.8			1207.8	603.9
		6	773.7	697.5			1471.2	735.6
10	L	1	78.1	77.5			155.6	77.8
		2	179.4	170.9			350.3	175.1
		3	292.4	304.4			596.8	298.4
		4	369.6	396.1			765.7	382.8
		5	439.1	487.4			926.5	463.3
		6	510.4	576.6			1087.0	543.5
	D	1	56.2	50.1			106.3	53.1
		2	81.6	79.9			161.5	80.7
		3	126.5	117.1			243.6	121.8
		4	154.0	152.8			306.8	153.4
		5	183.1	174.1			357.2	178.6
		6	218.5	204.7			423.2	211.6

TABLE XVII - EROSION TEST RESULTS

SOIL NO.	COND. LOOSE, DENSE	TIME, min.	RUN NUMBER ACCUMULATIVE SOIL RUNOFF, GMS. 1	2	3	4	TOTAL	AVERAGE
11	L	1	132.0	131.0	136.7		399.7	133.2
		2	271.3	291.1	272.3		834.7	278.2
		3	402.8	484.7	409.5		1297.0	432.3
		4	641.8	748.2	684.7		2074.7	691.6
		5	868.8	913.8	856.2		2638.8	879.6
		6	973.0	1288.8	1064.8		3326.6	1108.9
	D	1	38.1	33.6			71.7	35.8
		2	57.4	55.1			112.5	56.2
		3	86.5	88.6			175.1	87.5
		4	106.2	110.4			216.6	108.3
		5	130.7	135.7			266.4	133.2
		6	161.6	163.2			324.8	162.4
12	L	1	58.5	69.1			127.6	63.8
		2	148.7	167.4			316.1	158.1
		3	258.4	285.0			543.4	271.7
		4	357.6	391.5			749.1	374.5
		5	448.3	478.2			926.5	463.2
		6	536.6	555.2			1091.8	545.9
	D	1	19.7	19.4			39.1	19.5
		2	35.6	35.9			71.5	35.8
		3	60.9	62.8			123.7	61.8
		4	79.8	76.0			155.8	77.9
		5	100.9	93.6			194.5	97.2
		6	116.8	112.8			229.6	114.8

TABLE XVIII - EROSION TEST RESULTS

SOIL NO.	COND. LOOSE, DENSE	TIME, min.	RUN NUMBER ACCUMULATIVE SOIL RUNOFF, GMS. 1	2	3	4	TOTAL	AVERAGE
13	L	1	85.5	84.2			169.7	84.8
		2	137.1	136.4			273.5	136.7
		3	203.0	194.7			397.7	198.8
		4	257.8	245.4			503.5	251.7
		5	332.1	297.2			629.3	314.6
		6	402.0	365.9			767.9	383.9
	D	1	23.5	18.4			41.9	20.9
		2	30.3	23.4			53.7	26.8
		3	49.2	38.7			87.9	43.9
		4	56.0	43.9			99.9	50.0
		5	63.1	48.0			111.1	55.5
		6	80.4	63.9			144.3	72.1
14	L	1	101.7	81.8			183.5	91.7
		2	232.9	241.8			474.7	237.3
		3	370.3	370.2			740.5	370.2
		4	468.9	463.9			932.8	466.4
		5	564.1	566.3			1130.4	565.2
		6	670.4	662.6			1333.0	666.5
	D	1	13.2	14.2			27.4	13.7
		2	20.7	24.2			44.9	22.4
		3	37.1	39.3			76.4	38.2
		4	40.0	44.3			84.3	42.1
		5	48.8	50.6			99.4	49.7
		6	66.9	74.6			141.5	70.7

TABLE XIX - EROSION TEST RESULTS

SOIL NO.	COND. LOOSE, DENSE	TIME, min.	RUN NUMBER ACCUMULATIVE SOIL RUNOFF, GRAMS 1	2	3	4	TOTAL	AVERAGE
15	L	1	141.0	127.7			268.7	134.3
		2	293.5	294.4			587.9	293.9
		3	593.5	605.4			1198.9	599.4
		4	854.5	891.9			1746.4	873.2
		5	1132.0	1228.9			2360.9	1180.4
		6	1597.0	1476.2			3073.2	1536.6
	D	1	101.0	94.5			195.5	97.7
		2	166.6	149.5			316.1	158.1
		3	236.9	215.3			452.2	226.6
		4	297.6	275.2			572.8	286.4
		5	363.5	330.4			693.9	346.9
		6	427.6	393.3			820.9	410.5
16	L	1	165.0	All of	67.2		232.2	116.1
		2	709.0	soil	610.2		1319.2	659.6
		3	1276.5	slumped	1691.2		2967.7	1483.9
		4	1513.5	out by 3^m	2632.2		4145.7	2072.9
		5	1882.5	50^s. No				
		6	2297.5	meas. made				
	D	1	101.4	105.5			206.9	103.4
		2	146.8	154.4			301.2	150.6
		3	204.8	217.2			422.0	211.0
		4	260.2	266.7			526.9	263.4
		5	299.8	317.4			617.2	308.6
		6	360.8	372.0			732.8	366.4

TABLE XX - EROSION TEST RESULTS

SOIL NO.	COND. LOOSE, DENSE	TIME, min.	RUN NUMBER ACCUMULATIVE SOIL RUNOFF, GMS. 1	2	3	4	TOTAL	AVERAGE
17	L	1	75.5	55.2			130.7	65.3
		2	173.7	162.5			336.2	168.1
		3	259.5	251.9			511.4	255.7
		4	311.5	308.5			620.0	310.0
		5	377.8	358.7			736.5	368.2
		6	435.6	425.5			861.1	430.5
	D	1	57.0	61.0			118.0	59.0
		2	77.5	89.7			167.2	83.6
		3	105.8	121.0			226.8	113.4
		4	121.9	142.6			264.5	132.3
		5	137.2	163.5			300.7	150.3
		6	158.1	188.0			346.1	173.1
18	L	1	68.2	57.6			125.8	62.9
		2	192.5	142.9			335.4	167.7
		3	321.1	269.1			590.2	295.1
		4	442.1	335.9			798.0	399.0
		5	547.9	429.9			977.8	488.9
		6	644.1	508.2			1152.3	576.1
	D	1	9.0	11.5			20.5	10.2
		2	11.8	15.8			27.6	13.8
		3	27.5	32.3			59.8	29.9
		4	29.2	36.9			66.1	33.1
		5	36.1	48.1			84.2	42.1
		6	52.6	65.7			118.3	59.1

APPENDIX D

GRAPHICAL PRESENTATION OF EROSION TEST RESULTS

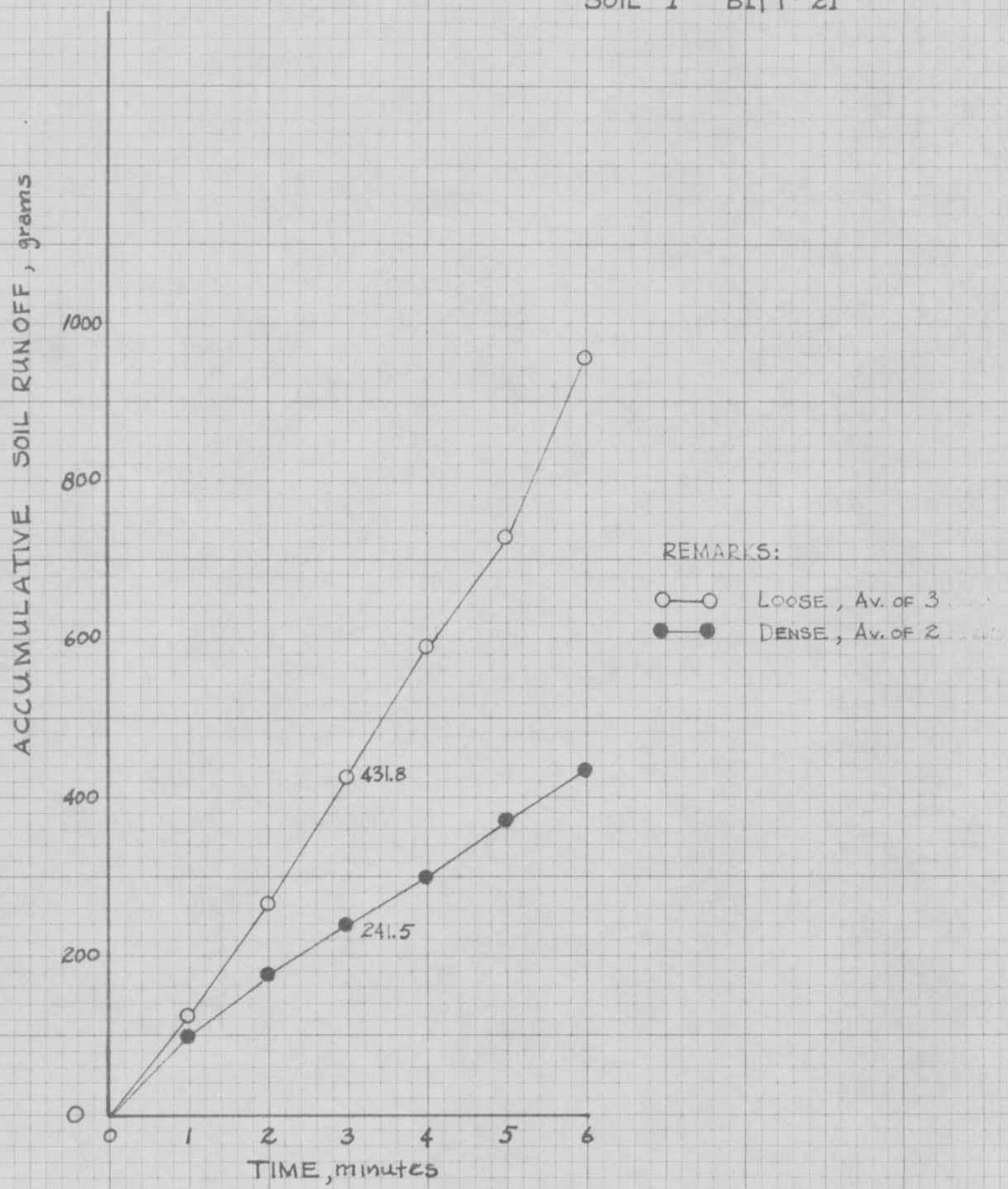


FIGURE 15 - EROSION TEST RESULTS

SOIL #2 BRACKETT CR.

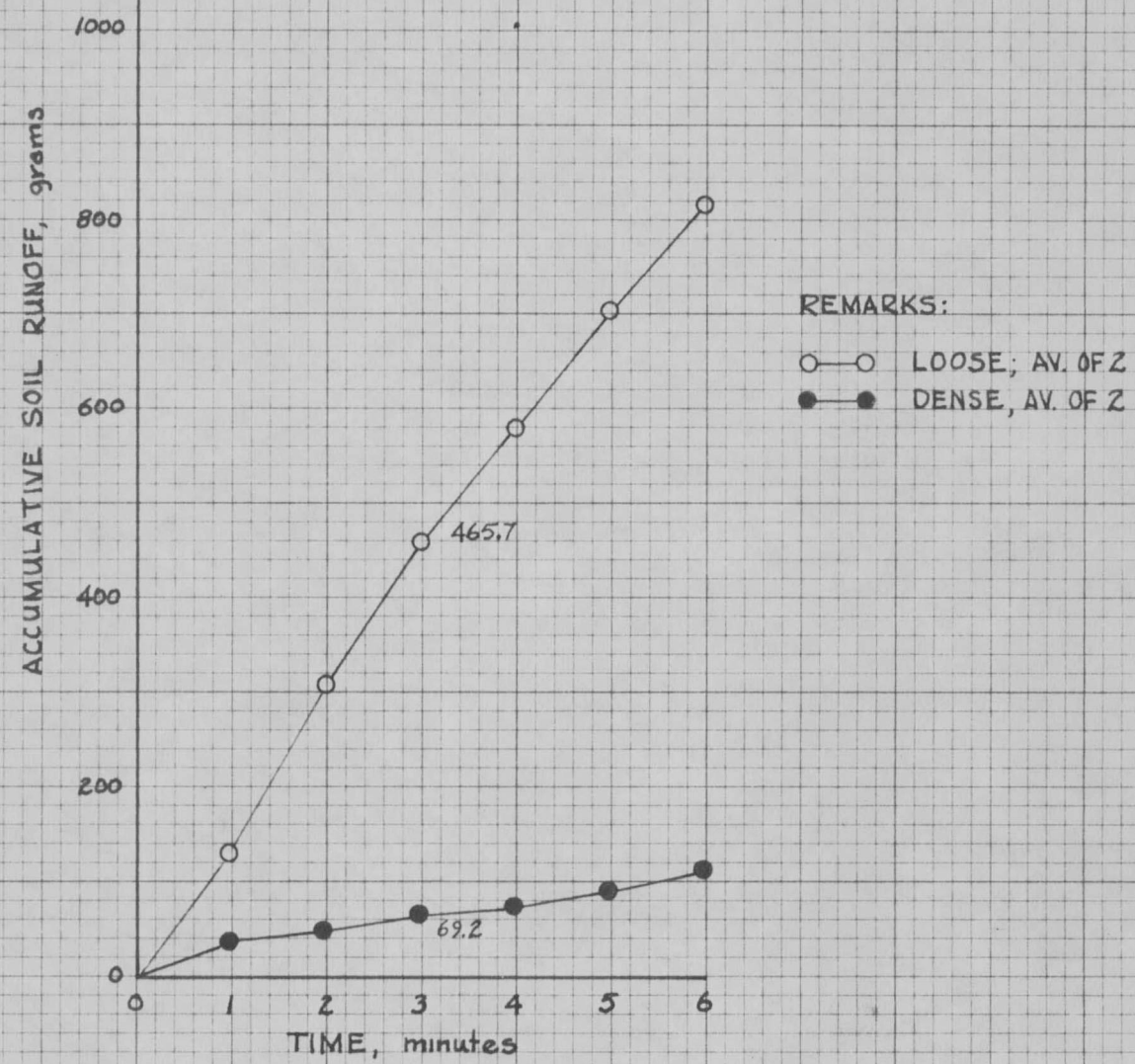


FIGURE 16 - EROSION TEST RESULTS

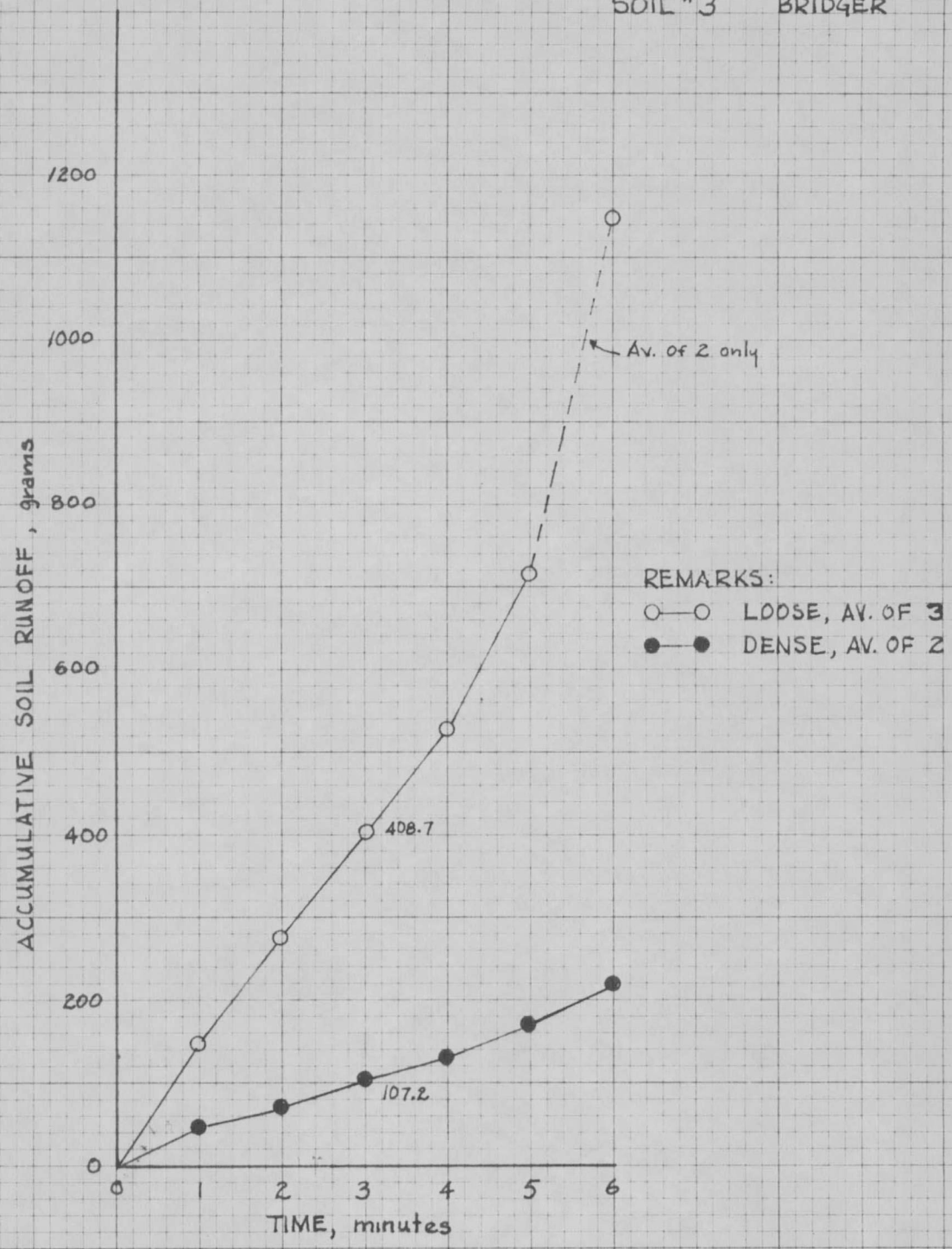


FIGURE 17 - EROSION TEST RESULTS

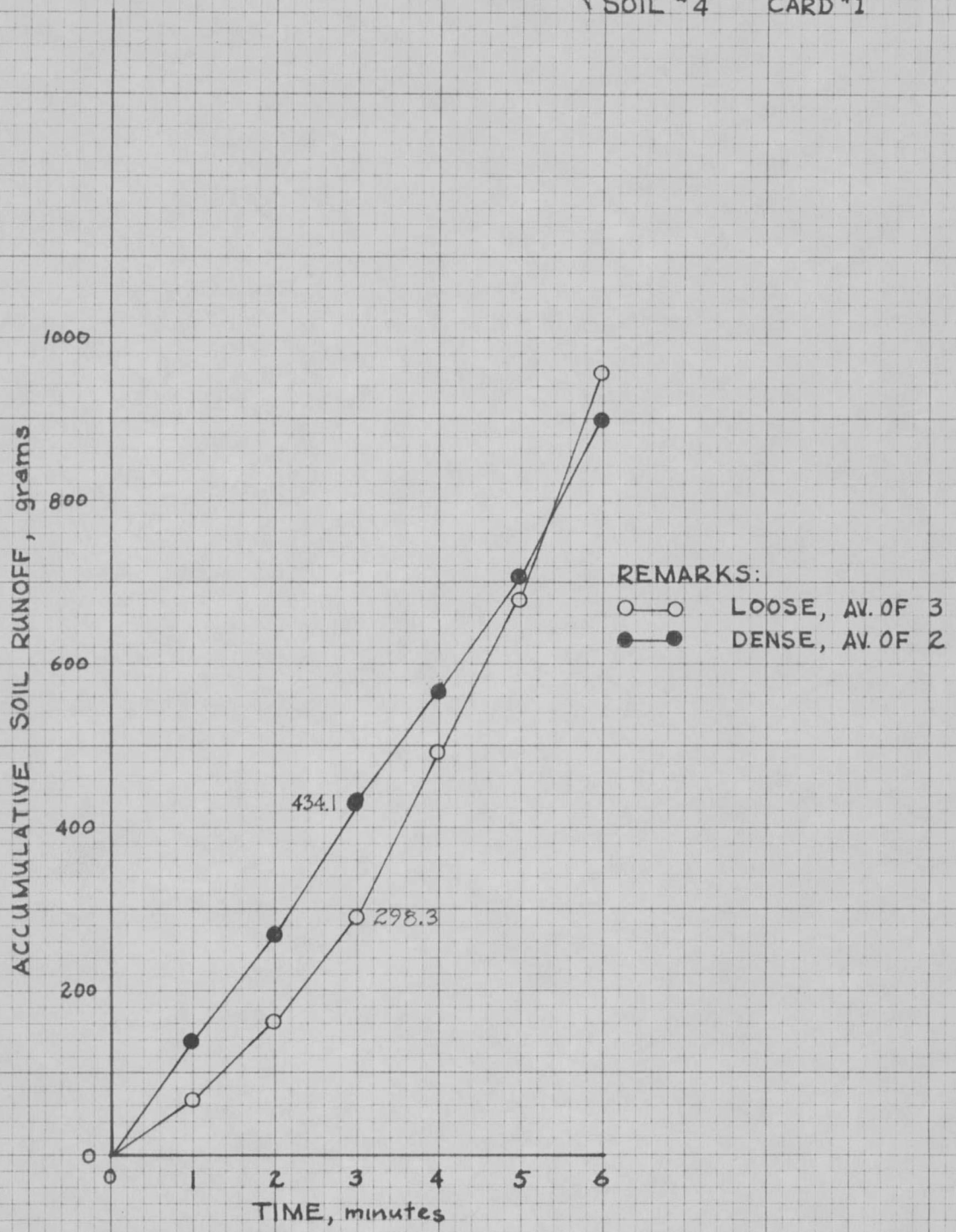


FIGURE 18 - EROSION TEST RESULTS

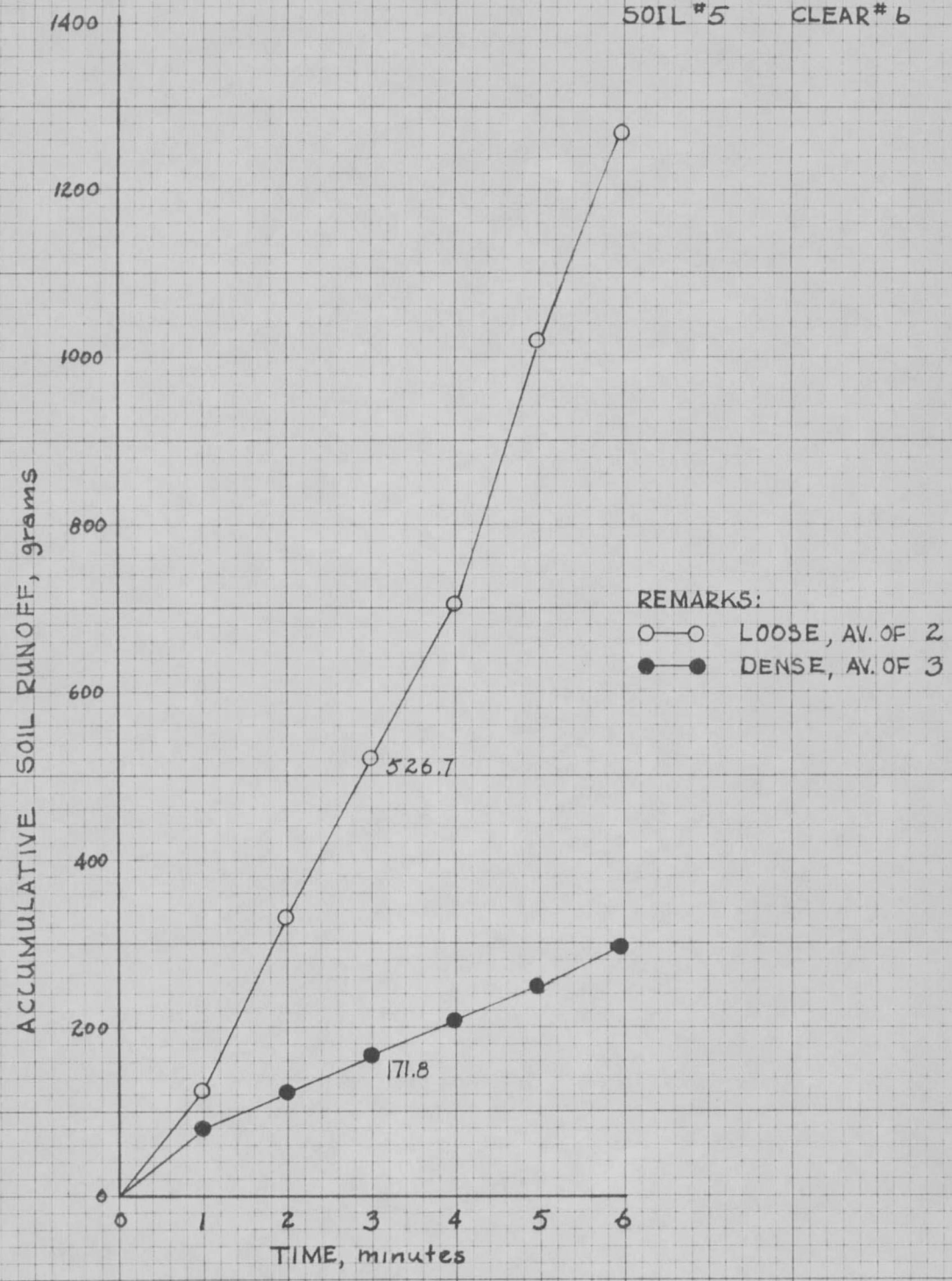


FIGURE 19 - EROSION TEST RESULTS

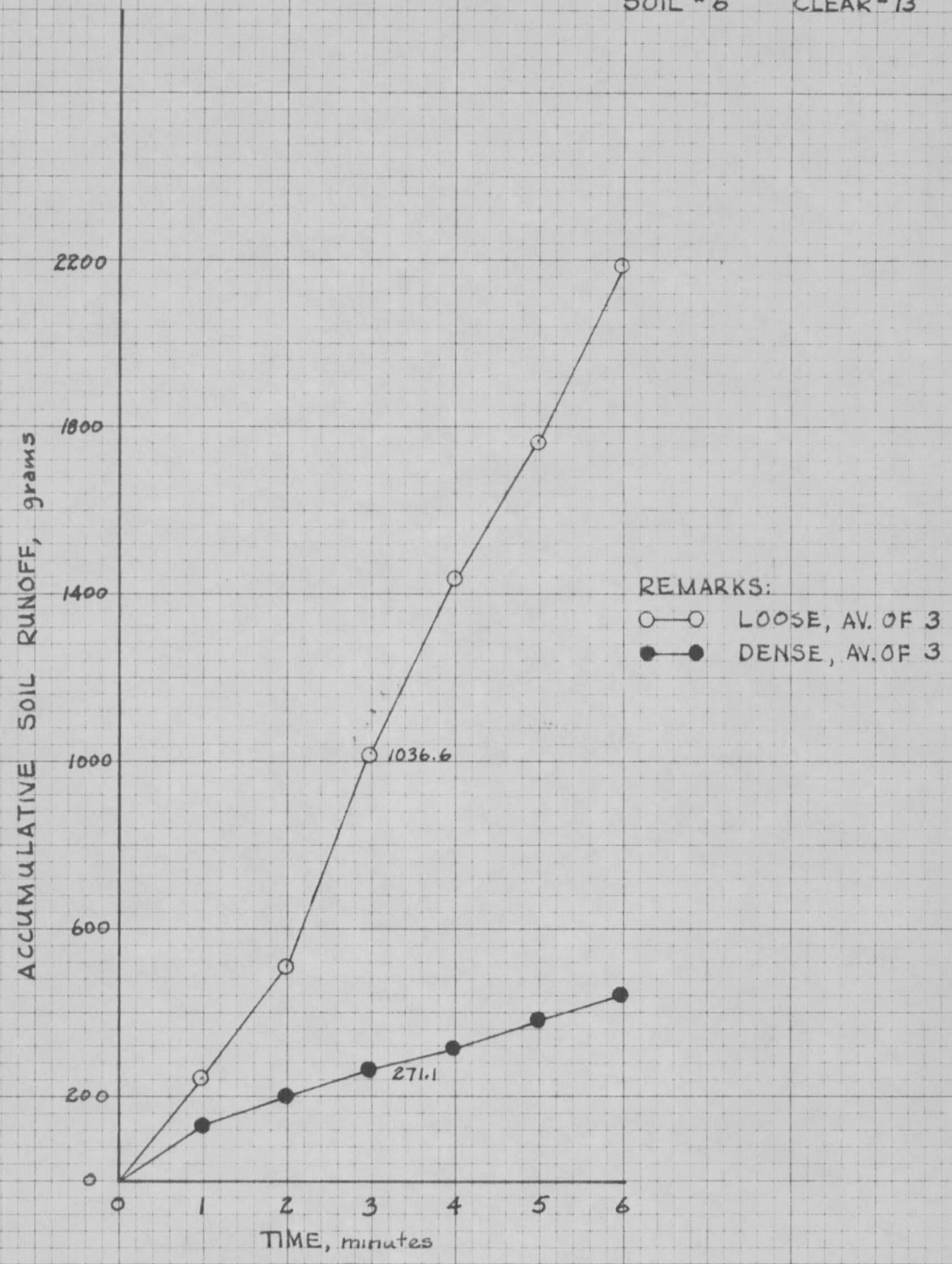


FIGURE 20 - EROSION TEST RESULTS

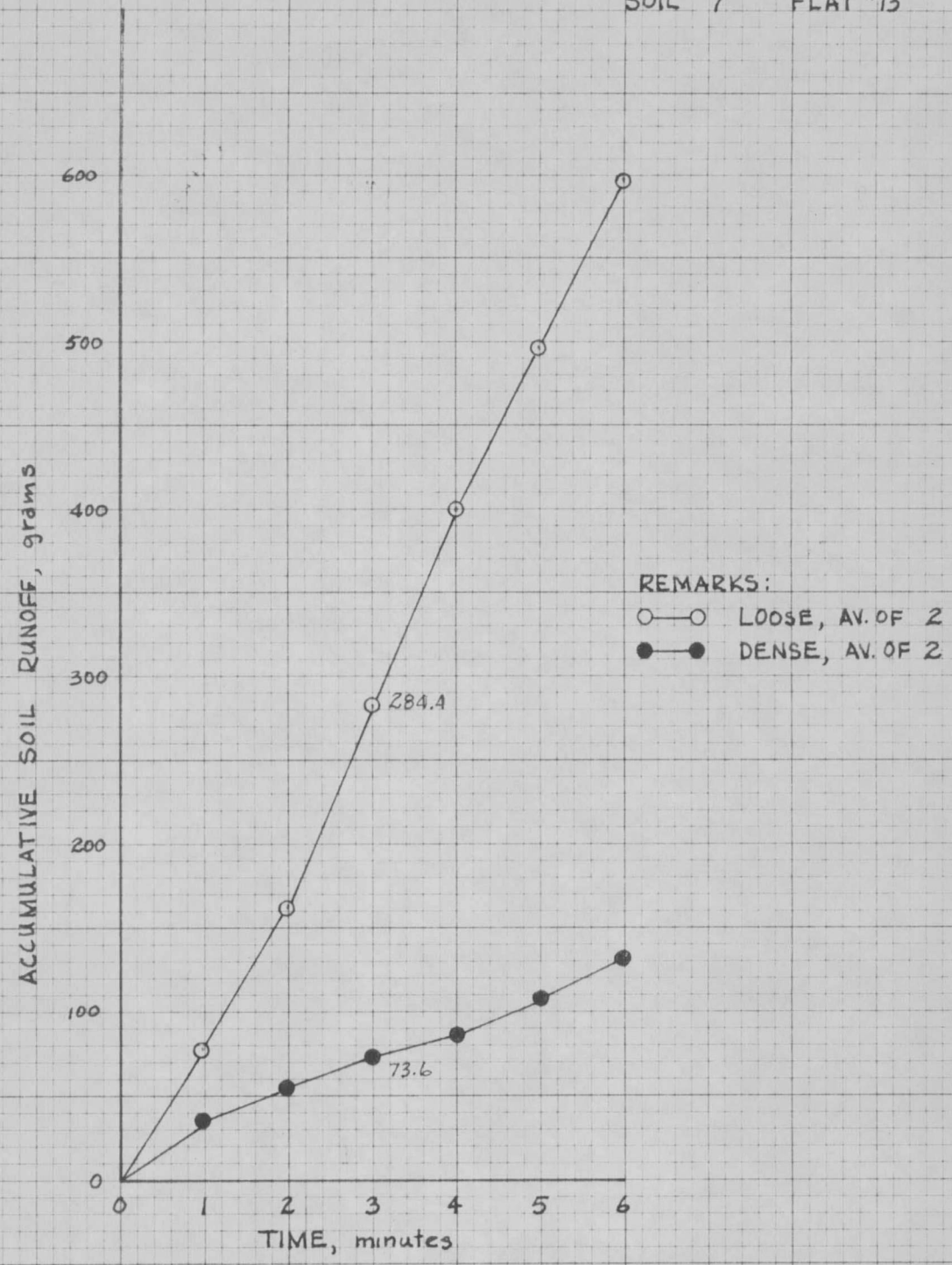


FIGURE 21 - EROSION TEST RESULTS

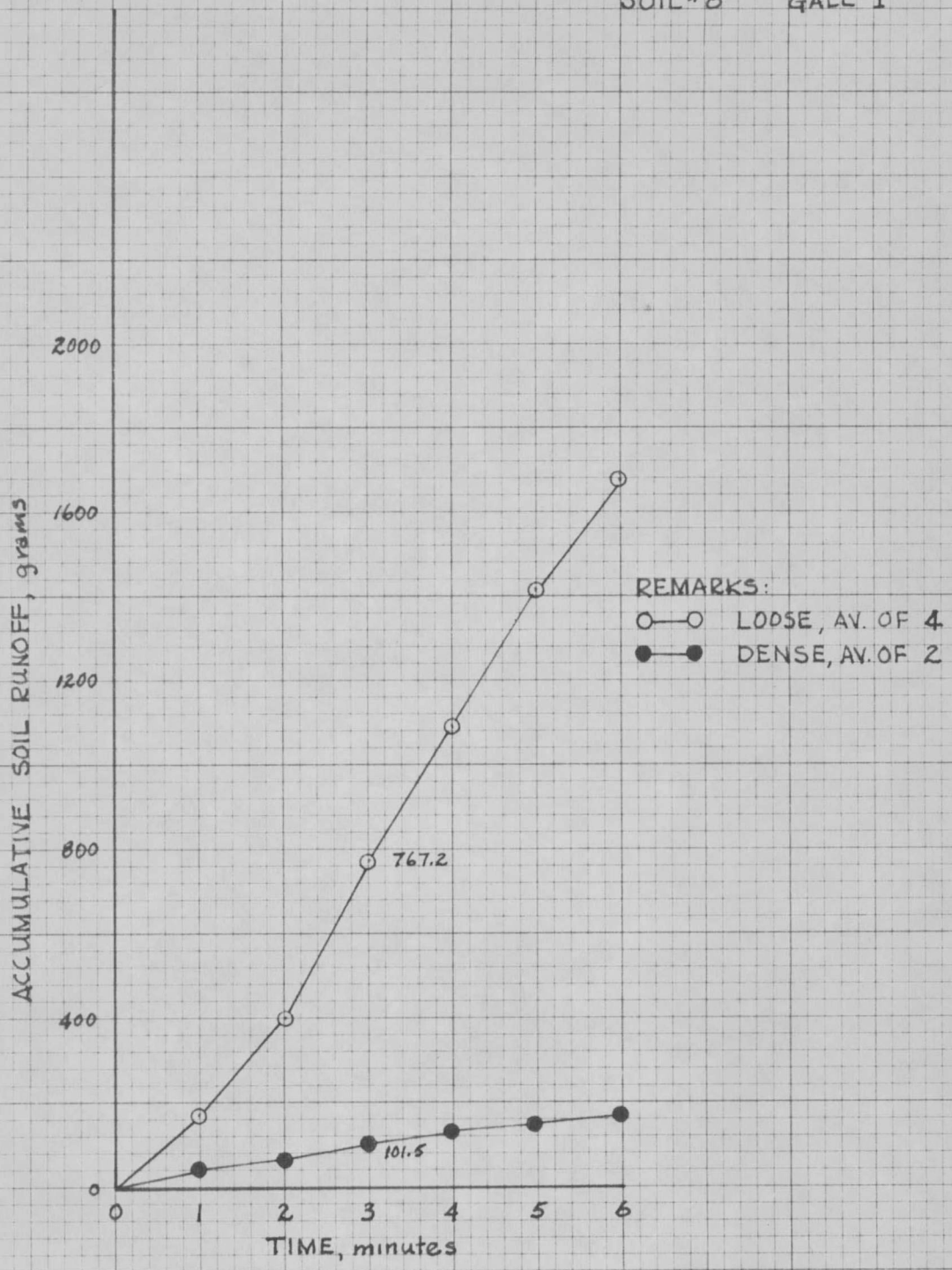


FIGURE 22 - EROSION TEST RESULTS

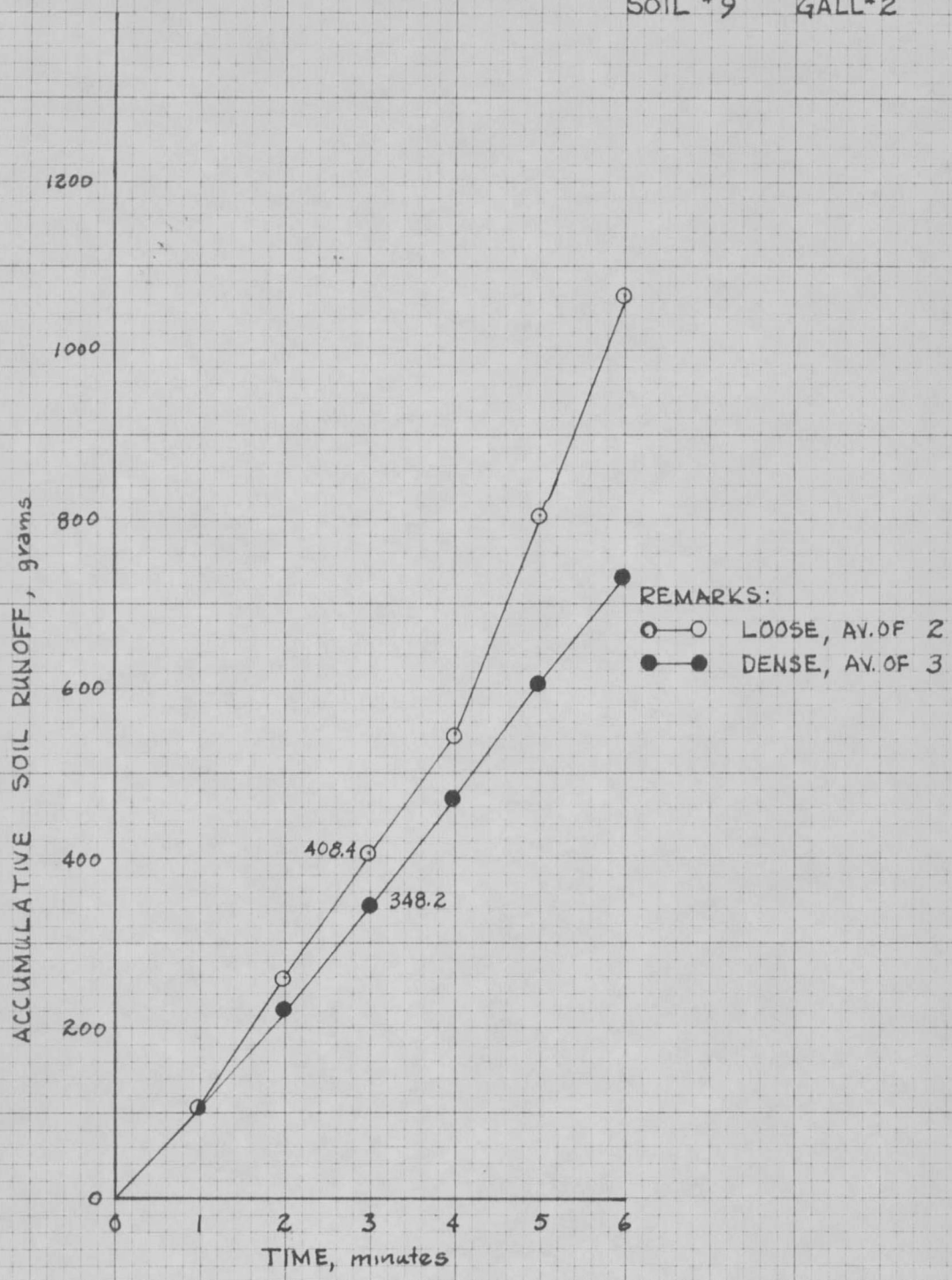


FIGURE 23 - EROSION TEST RESULTS

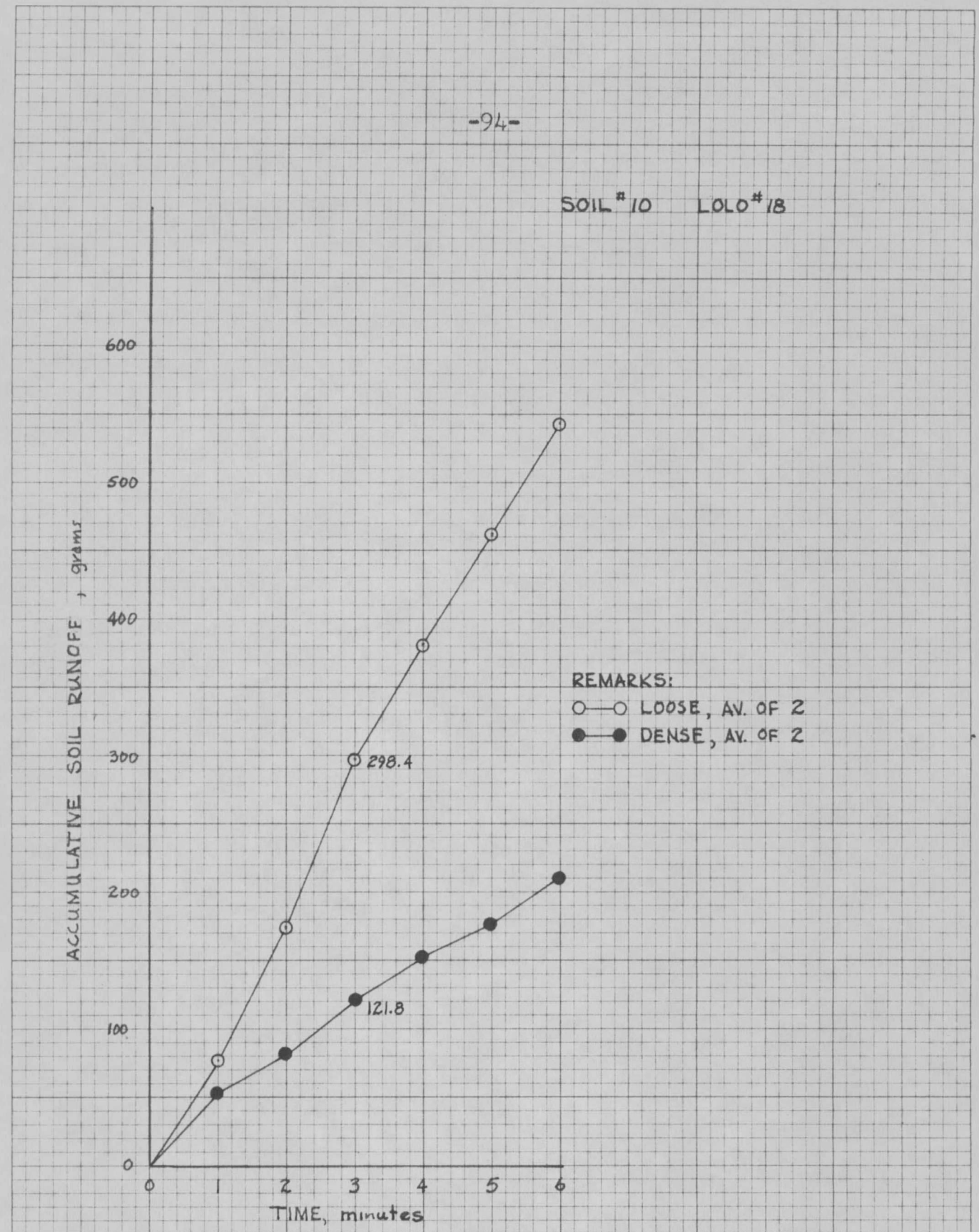


FIGURE 24 - EROSION TEST RESULTS

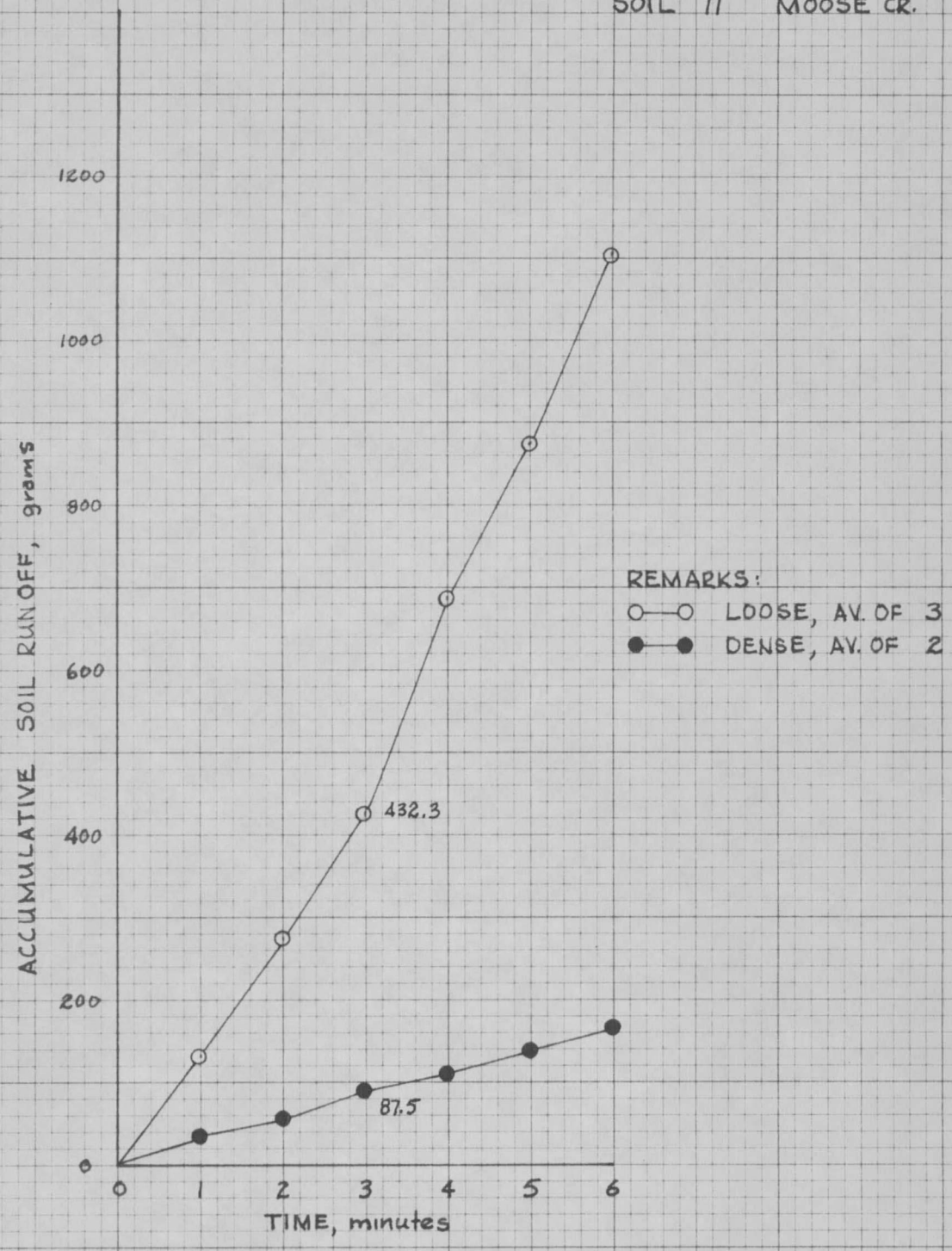


FIGURE 25 - EROSION TEST RESULTS

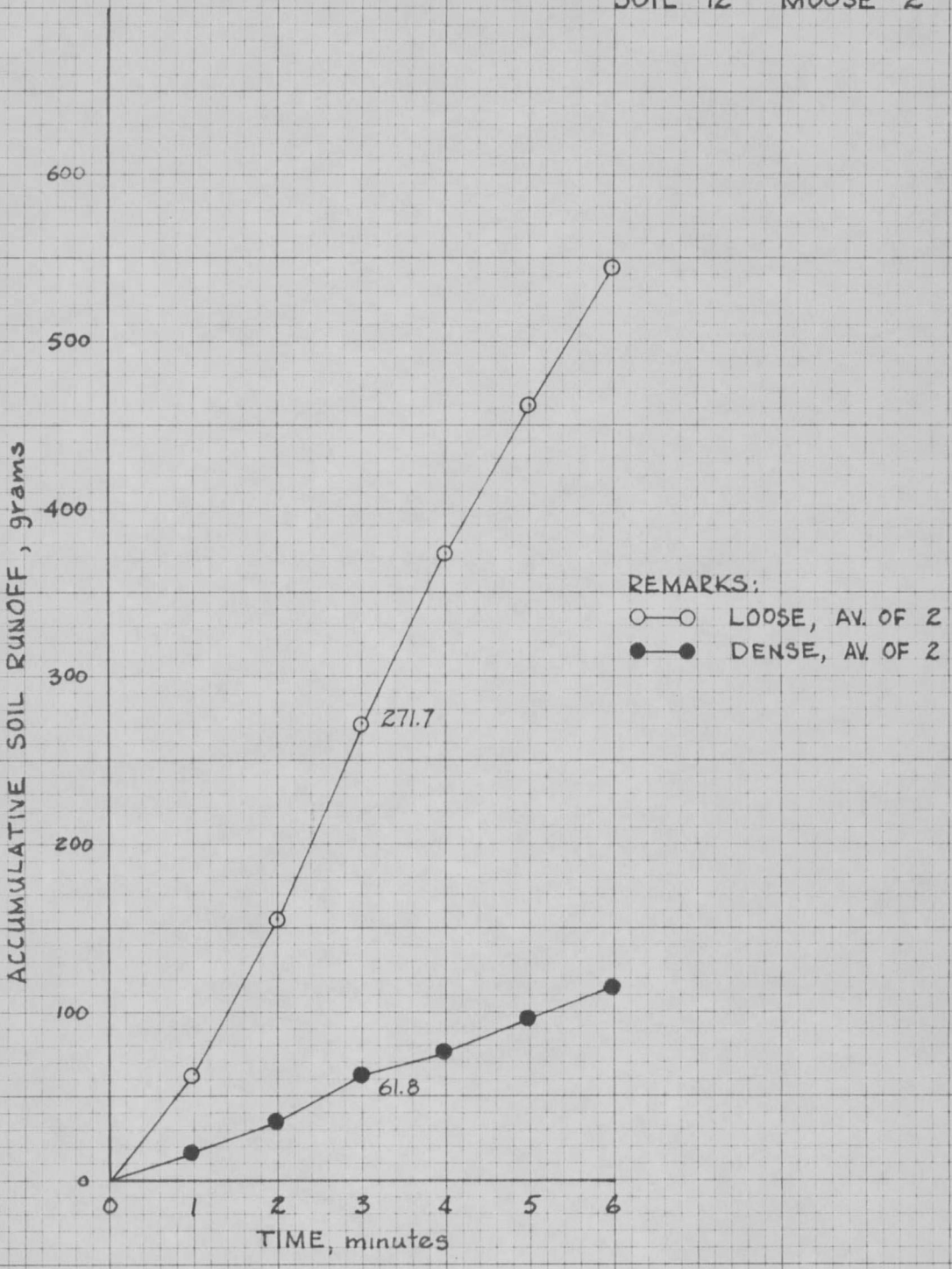


FIGURE 26 - EROSION TEST RESULTS

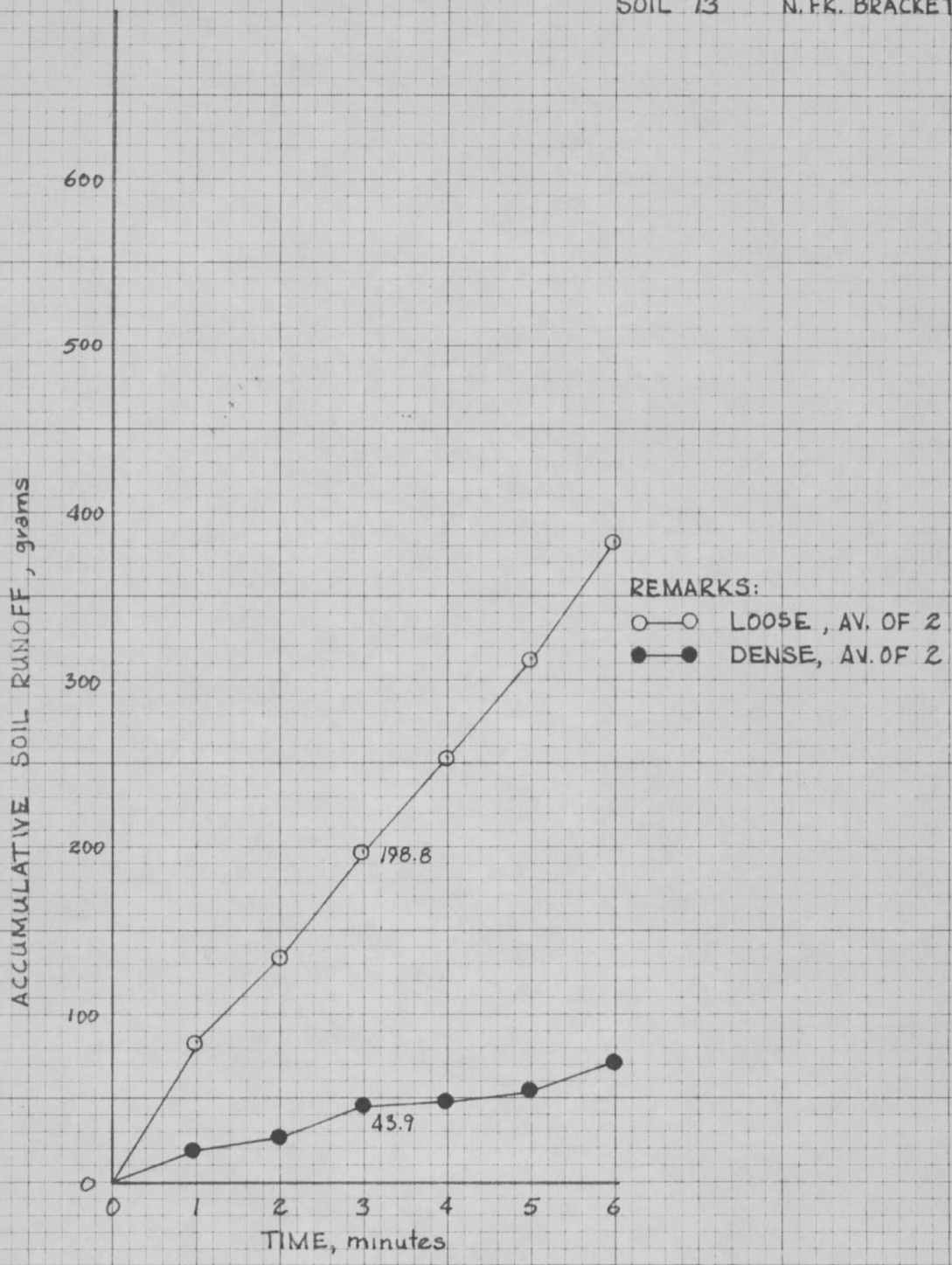


FIGURE 27 - EROSION TEST RESULTS

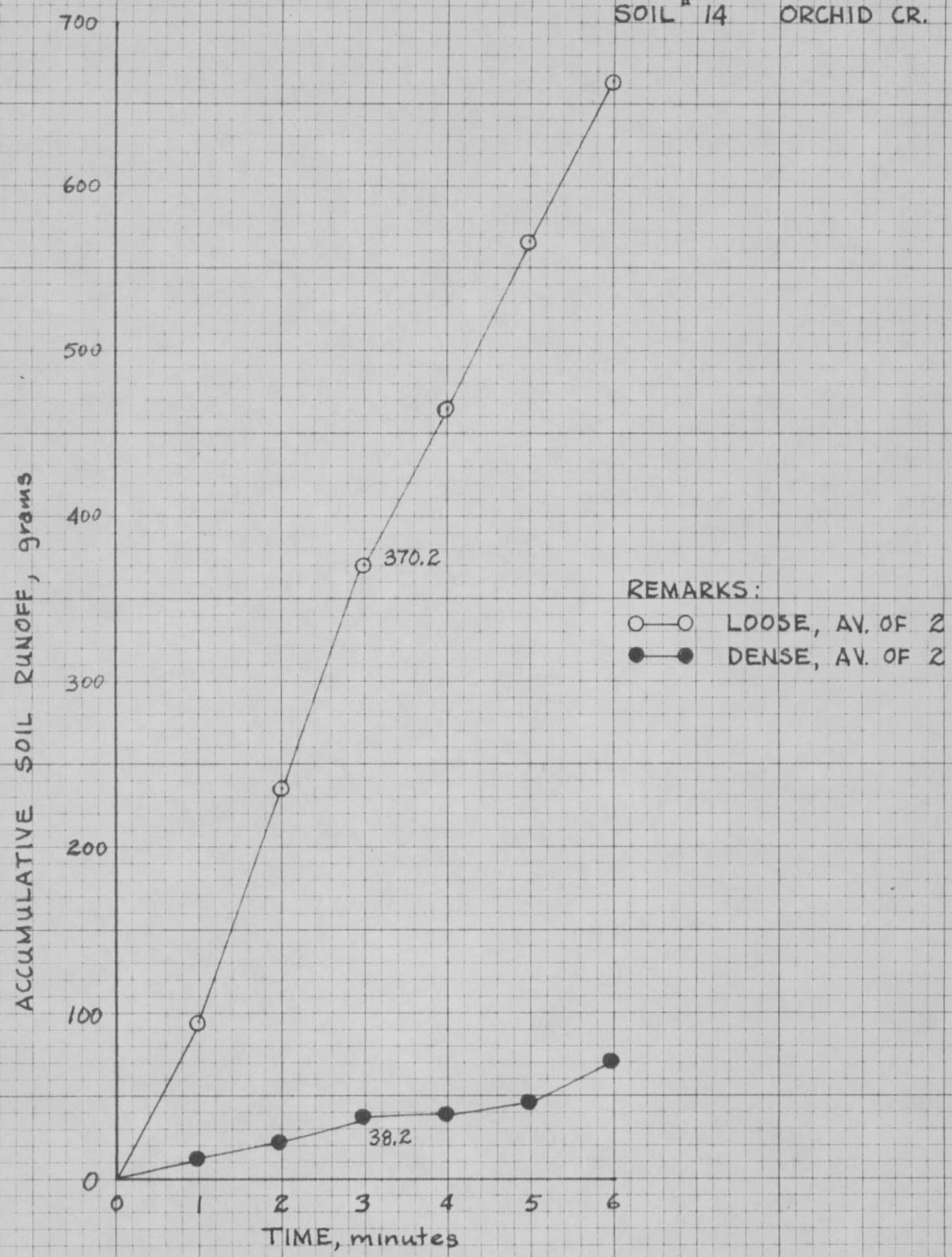


FIGURE 28 - EROSION TEST RESULTS

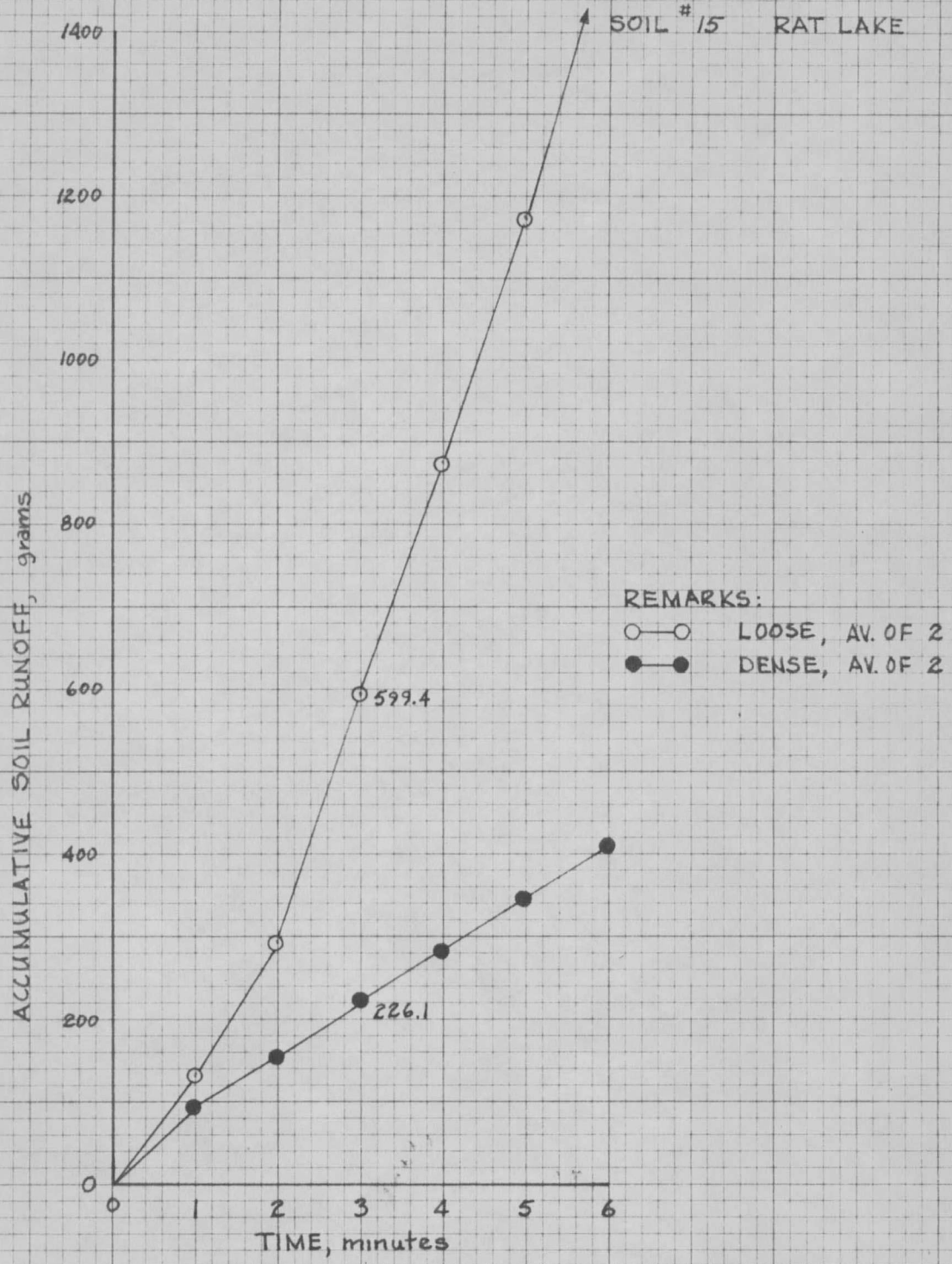


FIGURE 29 - EROSION TEST RESULTS

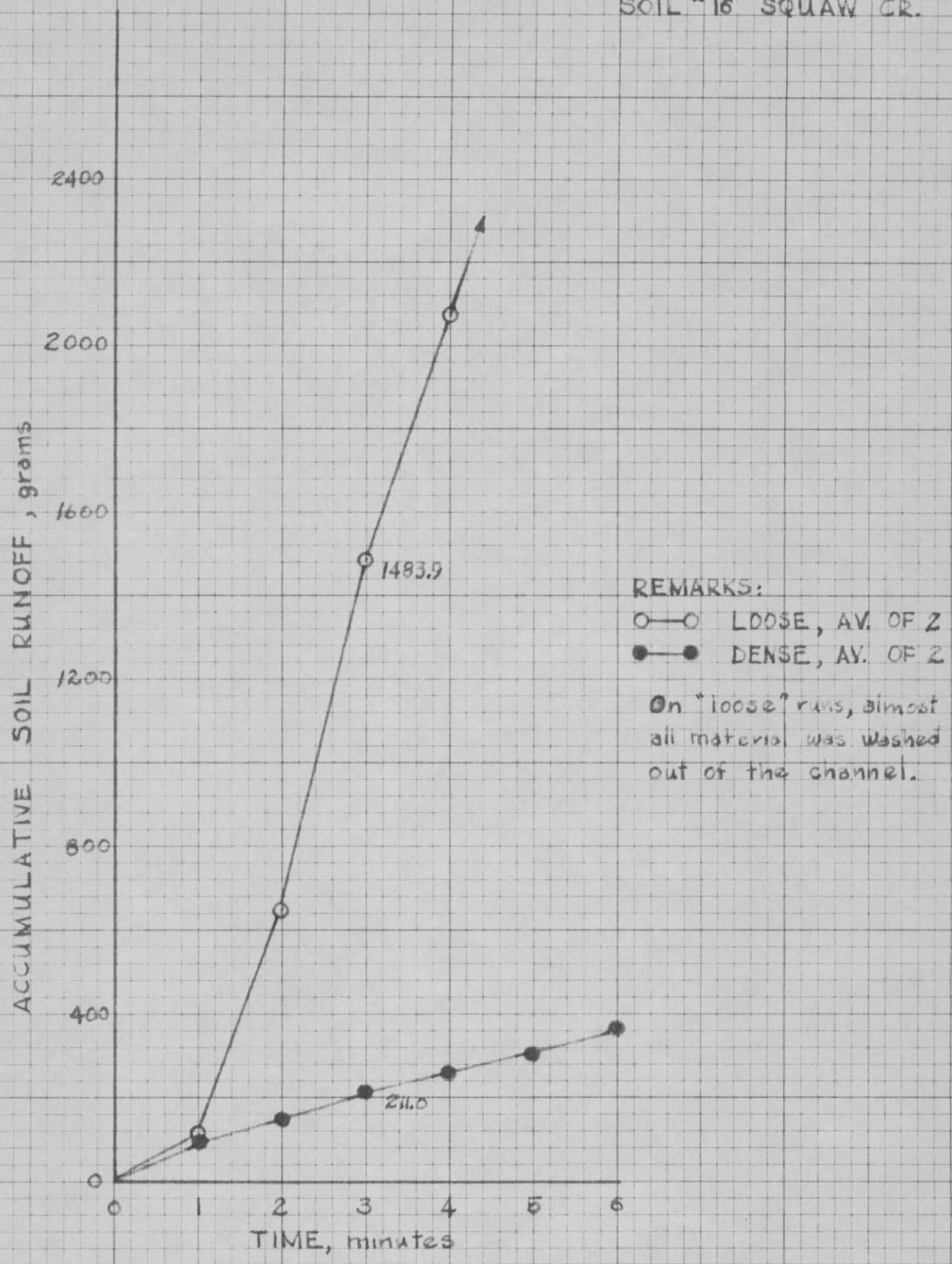


FIGURE 30 - EROSION TEST RESULTS

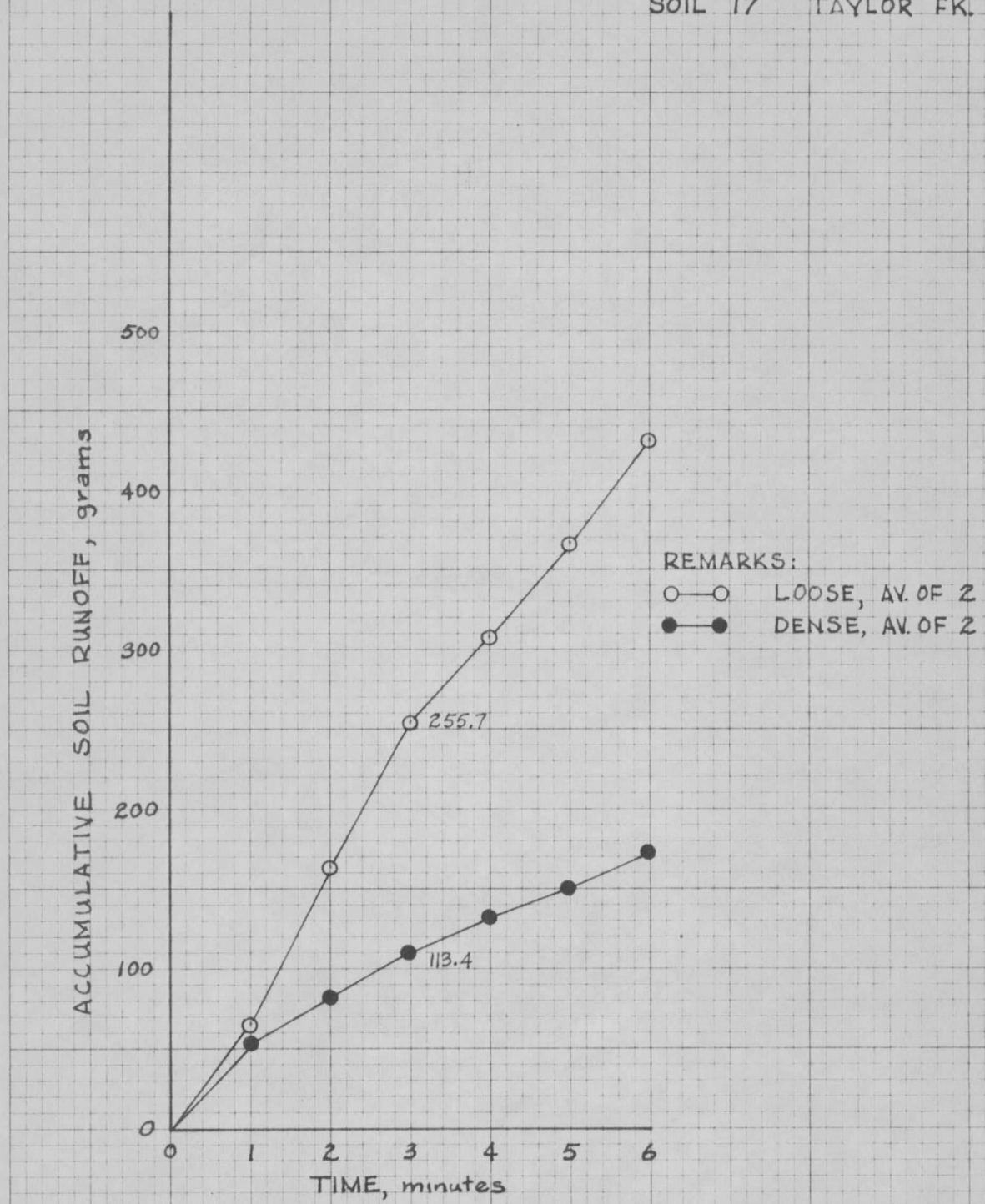


FIGURE 31 - EROSION TEST RESULTS

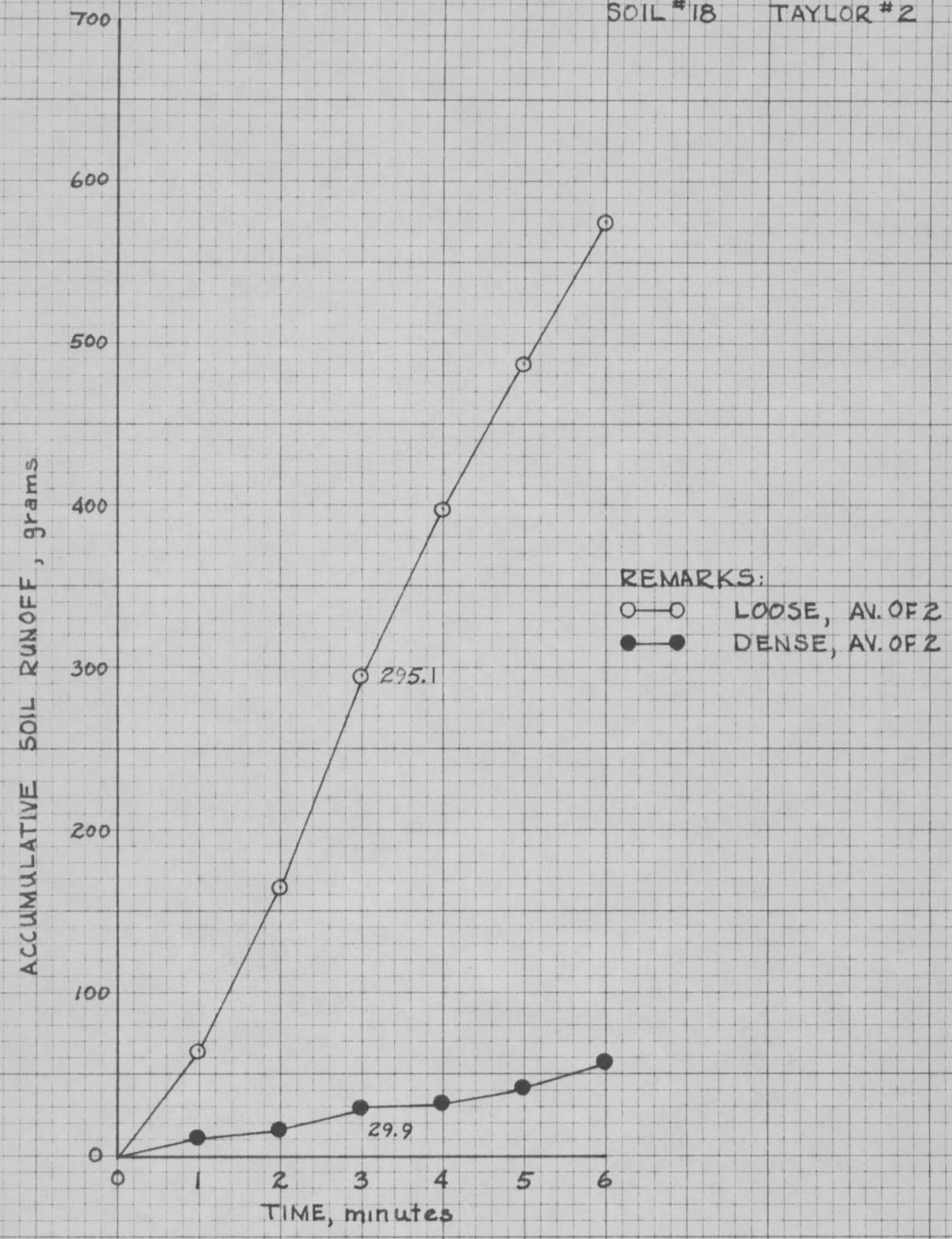


FIGURE 32 - EROSION TEST RESULTS

APPENDIX E

GRAIN SIZE ACCUMULATION CURVES

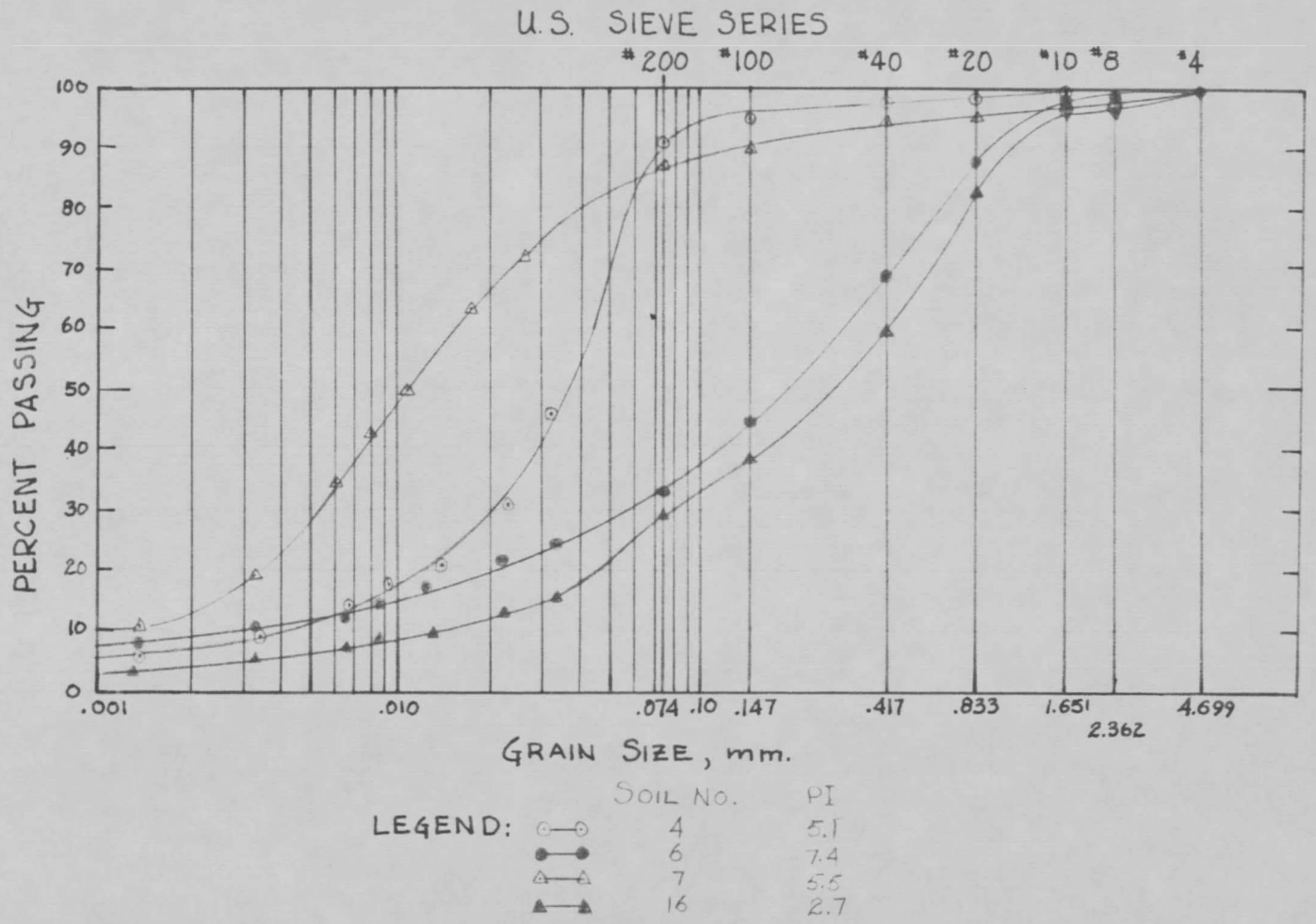


FIG 33 - GRAIN SIZE ACCUMULATION CURVE

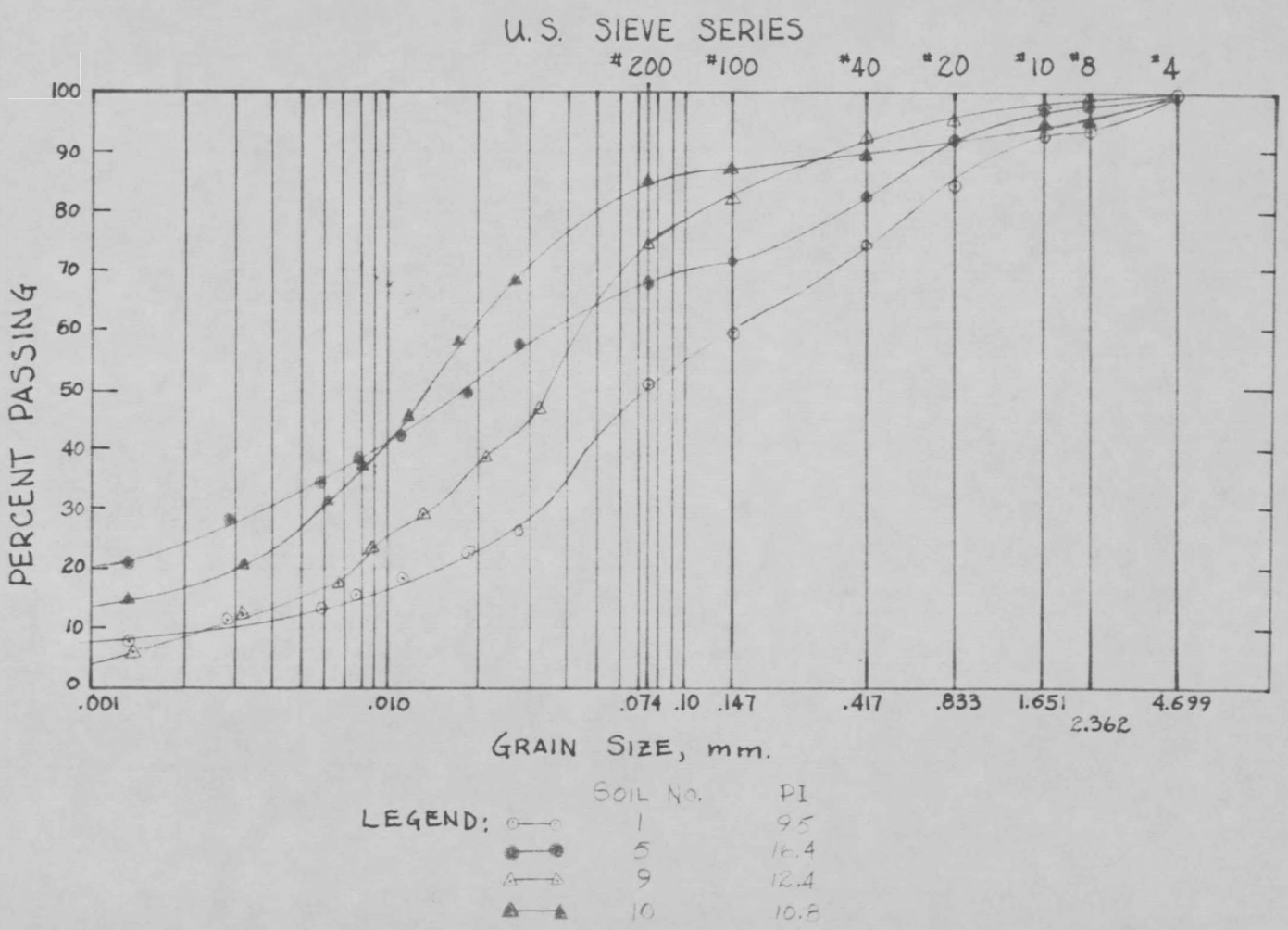


FIGURE 34 - GRAIN SIZE ACCUMULATION CURVE

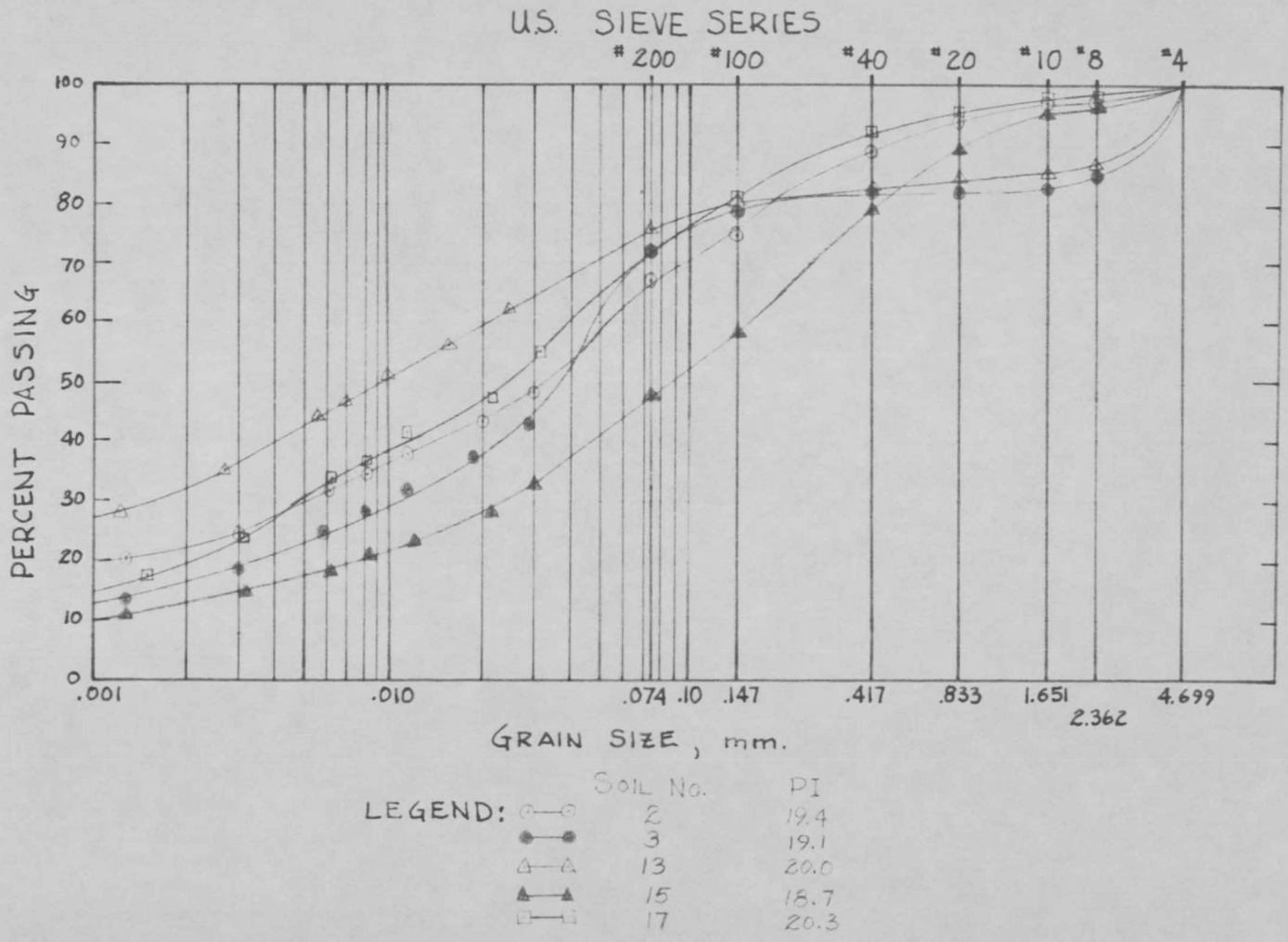


FIGURE 35 - GRAIN SIZE ACCUMULATION CURVE

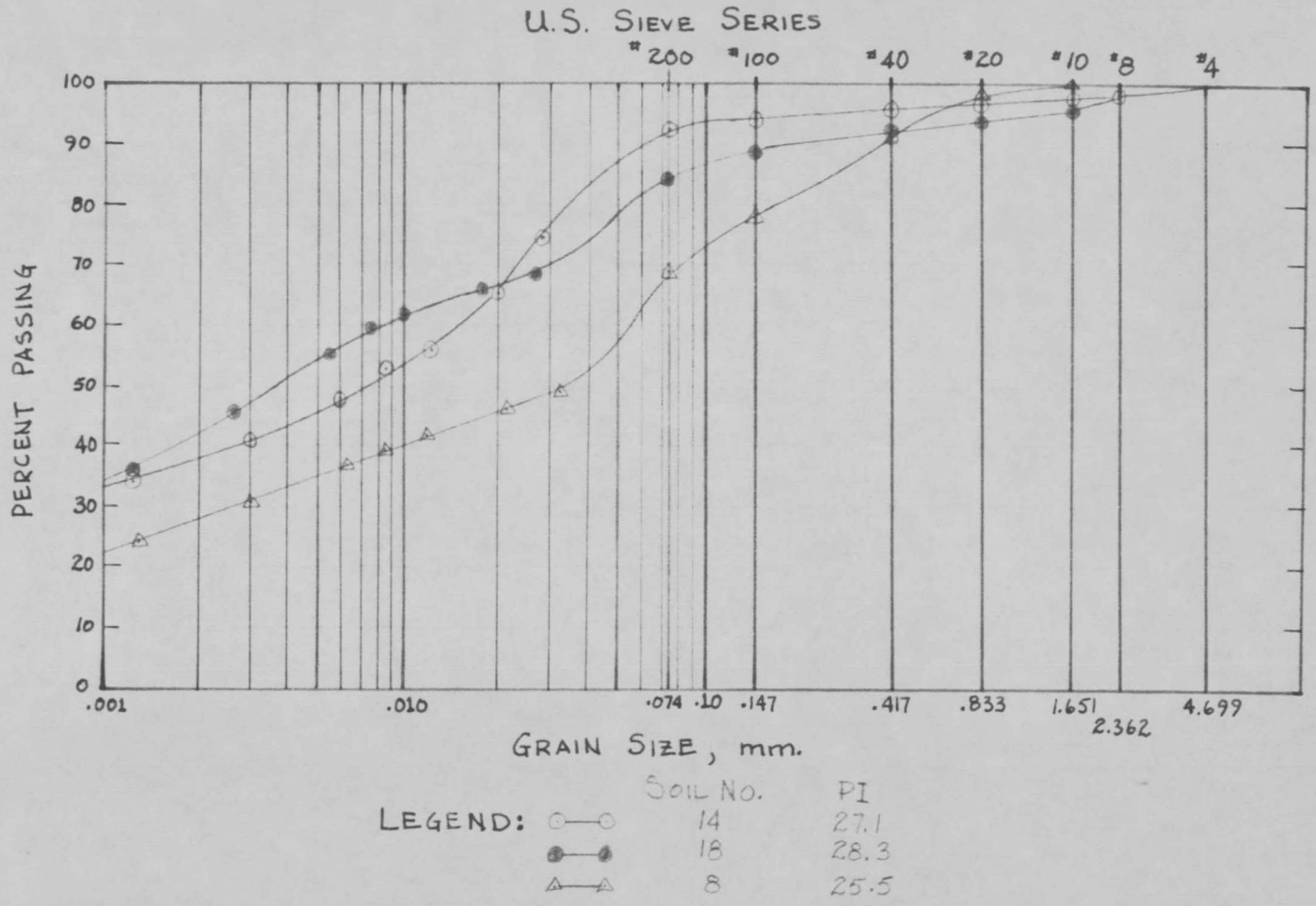


FIGURE 36 - GRAIN SIZE ACCUMULATION CURVE

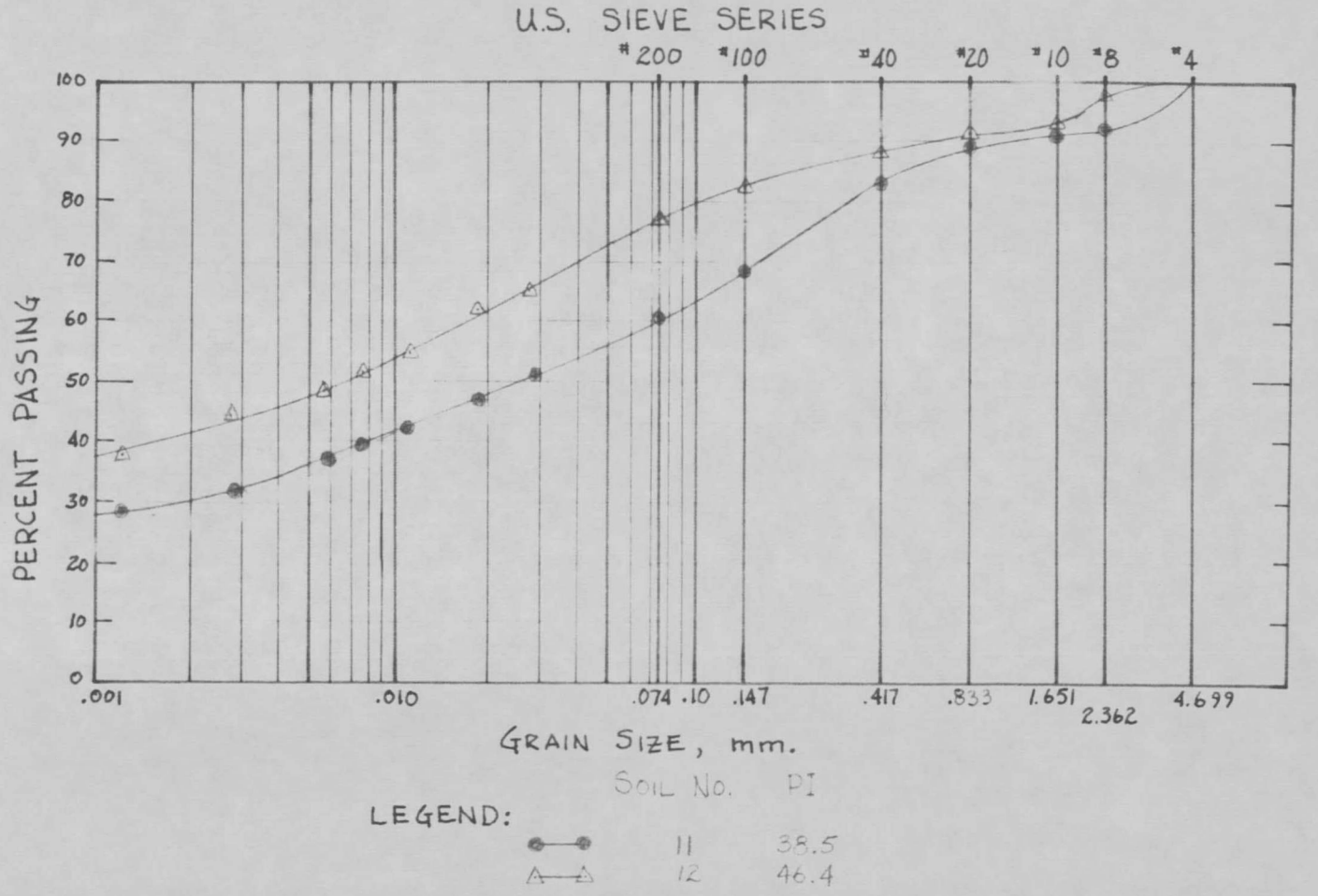


FIGURE 37 - GRAIN SIZE ACCUMULATION CURVE

APPENDIX F

ANALYSIS OF VARIANCE TABLES

TABLE XXI - ANALYSIS OF VARIANCE FOR REGRESSION - MCR

EROSION		SOURCE OF VARIATION	df	SUM OF SQUARES	MEAN SQUARE	F
E	#16 IN (a)	REGRESSION	1	194,978.11	194,978.11	39.86**
		ABOUT REG.	16	78,268.99	4,891.81	
		TOTAL	17	273,247.10		
		r = .8447	r^2 = .7135			
	#16 OUT (b)	REGRESSION	1	222,113.12	222,113.12	133.21**
		ABOUT REG.	15	25,011.03	1,667.40	
		TOTAL	16	247,124.15		
		r = .9480	r^2 = .8987			
E_d	#16 IN (c)	REGRESSION	1	118,615.21	118,615.21	18.46**
		ABOUT REG.	16	102,807.13	6,245.45	
		TOTAL	17	221,422.34		
		r = .7319	r^2 = .5356			
	#16 OUT (d)	REGRESSION	1	191,375.05	191,375.05	108.45**
		ABOUT REG.	15	26,470.38	1,764.69	
		TOTAL	16	217,845.43		
		r = .9372	r^2 = .8784			
E_l	#16 IN (e)	REGRESSION	1	949,491.04	949,491.04	18.91**
		ABOUT REG.	16	803,255.40	50,203.46	
		TOTAL	17	1,752,746.44		
		r = .7360	r^2 = .5417			
	#16 OUT (f)	REGRESSION	1	114,515.80	114,515.80	2.89
		ABOUT REG.	15	593,839.90	39,589.33	
		TOTAL	16	708,355.70		
		r = .4020	r^2 = .1616			

** - Significant at 0.5% level.

EQUATIONS:
(a) $E = 74.9 \pm 36.3(MCR)$
(b) $E = 24.0 \pm 56.4(MCR)$
(c) $E_d = 53.8 \pm 28.3(MCR)$
(d) $E_d = -7.1 \pm 52.3(MCR)$
(e) $E_l = 210.4 \pm 80.2(MCR)$
(f) Not significant

TABLE XXII - ANALYSIS OF VARIANCE FOR REGRESSION - S/A

EROSION		SOURCE OF VARIATION	df	SUM OF SQUARES	MEAN SQUARE	F
E	#16 IN (a)	REGRESSION	1	177,100.01	177,100.01	29.47**
		ABOUT REG.	16	96,147.09	6,009.19	
		TOTAL	17	273,247.10		
		r = .8050	r^2 = .6481			
	#16 OUT (b)	REGRESSION	1	163,898.20	163,898.20	29.54**
		ABOUT REG.	15	83,225.95		
		TOTAL	16	247,124.15		
		r = .8143	r^2 = .6632			
E_d	#16 IN (c)	REGRESSION	1	118,288.50	118,288.50	18.35**
		ABOUT REG.	16	103,133.84	6,445.87	
		TOTAL	17	221,422.34		
		r = .7309	r^2 = .5342			
	#16 OUT (d)	REGRESSION	1	148,297.52	148,297.52	31.98**
		ABOUT REG.	15	69,547.91	4,636.53	
		TOTAL	16	217,845.43		
		r = .8250	r^2 = .6807			
E_l	#16 IN (e)	REGRESSION	1	595,098.57	595,098.57	8.22*
		ABOUT REG.	16	1,157,647.90	72,352.99	
		TOTAL	17	1,752,746.47		
		r = .5826	r^2 = .3395			
	#16 OUT (f)	REGRESSION	1	39,077.43	39,077.43	.88
		ABOUT REG.	15	669,278.28	44,618.55	
		TOTAL	16	708,355.71		
		r = .2348	r^2 = .0551			

** - Significant at 0.5% level; * - Significant at 2.5% level

EQUATIONS: (a) $E = 50.2 + 144.4(S/A)$
(b) $E = 27.6 + 173.7(S/A)$
(c) $E_d = 28.9 + 118.0(S/A)$
(d) $E_d = -7.6 + 165.2(S/A)$
(e) $E_l = 212.6 + 264.7(S/A)$
(f) Not Significant

TABLE XXIII - ANALYSIS OF VARIANCE FOR REGRESSION - LPR

EROSION		SOURCE OF VARIATION	df	SUM OF SQUARES	MEAN SQUARE	F
E	#16 IN (a)	REGRESSION	1	134,434.14	134,434.14	15.48**
		ABOUT REG.	16	138,938.66	8,683.67	
		TOTAL	17	273,372.80		
		r = .7012	r^2 = .4917			
	#16 OUT (b)	REGRESSION	1	114,252.12	114,252.12	12.90**
		ABOUT REG.	15	132,872.03	8,858.14	
		TOTAL	16	247,124.15		
		r = .6799	r^2 = .4623			
E_d	#16 IN (c)	REGRESSION	1	94,441.04	94,441.04	11.90**
		ABOUT REG.	16	126,981.31	7,936.33	
		TOTAL	17	221,422.34		
		r = .6530	r^2 = .4265			
	#16 OUT (d)	REGRESSION	1	116,847.71	116,847.71	17.35**
		ABOUT REG.	15	100,997.72	6,733.18	
		TOTAL	16	217,845.43		
		r = .7323	r^2 = .5363			
E_l	#16 IN (e)	REGRESSION	1	352,548.01	352,548.01	4.03
		ABOUT REG.	16	1,400,198.40	87,512.40	
		TOTAL	17	1,752,746.41		
		r = .4484	r^2 = .2011			
	#16 OUT (f)	REGRESSION	1	1,416.48	1,416.48	0.03
		ABOUT REG.	15	706,939.23	47,129.28	
		TOTAL	16	708,355.71		
		r = .0447	r^2 = .002			

** - Significant at 0.5% level

EQUATIONS:
(a) E = 37.9 + 62.9(LPR)
(b) E = 16.7 + 73.3(LPR)
(c) E_d = 15.4 + 52.8(LPR)
(d) E_d = -28.5 + 74.1(LPR)
(e) = Not significant
(f) = Not significant

TABLE XXIV - ANALYSIS OF VARIANCE FOR REGRESSION - PIR

EROSION		SOURCE OF VARIATION	df	SUM OF SQUARES	MEAN SQUARE	F
E	#16 IN (a)	REGRESSION	1	96,629.96	96,629.96	8.64**
		ABOUT REG.	16	178,958.05	11,184.88	
		TOTAL	17	275,588.01		
		$r = .5921$	$r^2 = .3506$			
	#16 OUT (b)	REGRESSION	1	71,656.03	71,656.04	6.05
		ABOUT REG.	15	177,660.96	11,844.06	
		TOTAL	16	249,616.99		
		$r = .5361$	$r^2 = .2874$			
E_d	#16 IN (c)	REGRESSION	1	63,249.80	63,249.80	6.40*
		ABOUT REG.	16	158,172.54	9,885.78	
		TOTAL	17	221,422.34		
		$r = .5344$	$r^2 = .2856$			
	#16 OUT (d)	REGRESSION	1	73,931.66	73,931.66	7.71*
		ABOUT REG.	15	143,913.78	9,594.25	
		TOTAL	16	217,845.44		
		$r = .5825$	$r^2 = .3393$			
E_1	#16 IN (e)	REGRESSION	1	340,024.76	340,024.76	3.85
		ABOUT REG.	16	1,412,721.70	88,295.11	
		TOTAL	17	1,752,746.46		
		$r = .4404$	$r^2 = .1939$			
	#16 OUT (f)	REGRESSION	1	3,002.71	3,002.71	.06
		ABOUT REG.	15	705,353.00	47,023.53	
		TOTAL	16	708,355.71		

** - Significant at 1% level; * - Significant at 2.5% level.

EQUATIONS: (a) $E = 109.1 \pm 125.6(PIR)$
(b) Not significant
(c) $E_d = 78.1 \pm 101.6(PIR)$
(d) $E_d = 59.3 \pm 139.0(PIR)$
(e) Not significant
(f) Not significant

TABLE XXV - ANALYSIS OF VARIANCE FOR REGRESSION - DR20

EROSION		SOURCE OF VARIATION	df	SUM OF SQUARES	MEAN SQUARE	F
E	#16 IN (a)	REGRESSION	1	63,399.11	63,399.11	4.83*
		ABOUT REG.	16	209,973.69	13,123.36	
		TOTAL	17	273,372.80		
		$r = .4815$	$r^2 = .2319$			
	#16 OUT (b)	REGRESSION	1	57,138.77	57,138.77	4.51
		ABOUT REG.	15	189,985.38	12,665.69	
		TOTAL	16	247,124.15		
		$r = .4808$	$r^2 = .2312$			
E_d	#16 IN (c)	REGRESSION	1	55,509.62	55,509.62	5.35*
		ABOUT REG.	16	165,912.72	10,369.55	
		TOTAL	17	221,422.34		
		$r = .5006$	$r^2 = .2506$			
	#16 OUT (d)	REGRESSION	1	67,711.21	67,711.21	6.77**
		ABOUT REG.	15	150,134.22	10,008.95	
		TOTAL	16	217,845.43		
		$r = .5575$	$r^2 = .3108$			
E_l	#16 IN (e)	REGRESSION	1	15,568.45	15,568.45	.143
		ABOUT REG.	16	1,737,178.00	108,573.62	
		TOTAL	17	1,752,746.45		
		$r = .0942$	$r^2 = .0088$			
	#16 OUT (f)	REGRESSION	1	44,644.86	44,644.86	1.01
		ABOUT REG.	15	663,710.84	44,247.39	
		TOTAL	16	708,355.70		
		$r = .2510$	$r^2 = .0630$			

** - Significant at 2.5% level; * - Significant at 5% level.

EQUATIONS:
(a) $E = 28.5 + 366.0(DR20)$
(b) Not significant
(c) $E_d = 0.3 + 331.8(DR20)$
(d) $E_d = -29.2 + 379.6(DR20)$
(e) Not significant
(f) Not significant

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