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Title: A STUDY OF THE COEFFICIENT OF DRAG RESISTANCE IN YARDING LOGS

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This study was conducted to examine the coefficient of drag resistance (μ) between a log and bare forest soil during partial suspension yarding. Drag resistance in this study was defined as the resistance due to friction between the soil and the log plus the resistance due to the plowing action of the log in the soil. The coefficient of drag resistance is the ratio of the drag resistance forces parallel to the ground and the normal support force between the log and the ground.

Data were collected on four test plots on Paul Dunn and McDonald State Forests located in the foothills of the Coast Range in Oregon. A photographic technique was developed to measure the value of the drag resistance coefficient during yarding. This method used angles measured from a photograph of a yarded log and the logs dimensions to calculate μ. The method is based on the equilibrium of the forces on the log at the instant the photographic sample was taken. Data were taken to determine both the static and dynamic drag resistance coefficient for uphill yarding of young growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) logs.

Regression equations were developed to predict the static μ as a function of log geometry, ground slope, soil texture, soil moisture, and soil density. These equations suggest that soil moisture and ground slope are the most significant variables in explaining μ, with log geometry, soil texture and soil density playing a less important role. The equations developed were verified using a chi-square test for goodness-of-fit to compare predicted and observed values of μ on additional data. Analysis of the data collected for the dynamic drag resistance coefficient revealed that the assumptions of the measurement method were violated so no regression equations were developed. Suggestions were given on the conditions required for the method to work.

A load factor was developed which indicates the increase in log load capacity for a skyline logging system when dragging rather than flying a log load. The calculations for the load factor were based on the results of the study.

A Study of the Coefficient of Drag Resistance in Yarding Logs

by

John Robinson Henshaw

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A STUDY OF THE COEFFICIENT OF DRAG RESISTANCE IN YARDING LOGS

INTRODUCTION

In the logging industry today there is an increasing need to fit the optimal yarding system to each logging operation due to increasing costs and environmental constraints. When the logging engineer is comparing cable systems for a specific show, he must be able to determine the load carrying capacity of each system under consideration. These calculations are often simplified by assuming that the load on a system such as a skyline is fully suspended (e.g. Carson and Mann, 1971). However, when dealing with situations that require or may require partial suspension of logs, the calculations are more difficult and require that the coefficient of drag resistance between the logs and the ground be known (Carson, 1975). It is possible to support larger loads on a cable logging system when the log load is partially suspended rather than fully suspended because part of the load's weight is supported by the ground. The amount of this increase may be calculated by knowing the load factor which is multiplied by the fully suspended net load capacity to determine the net load capacity under partial suspension. Figure 1 illustrates the sensitivity of the load factor to changes in the coefficient of drag resistance for a set of typical log geometry situations in cable yarding.

Drag resistance in this study is defined as the resistance due to friction between the ground and the log plus the resistance due to the plowing action of the log in the ground. The coefficient of drag resistance is the ratio of the drag resistance forces parallel to the ground and the normal support force between the log and the ground. The free body diagram in Figure 2 shows the two drag resistance forces which occur during yarding. The sum of the plow force (P) plus the friction force (F) is divided by the normal

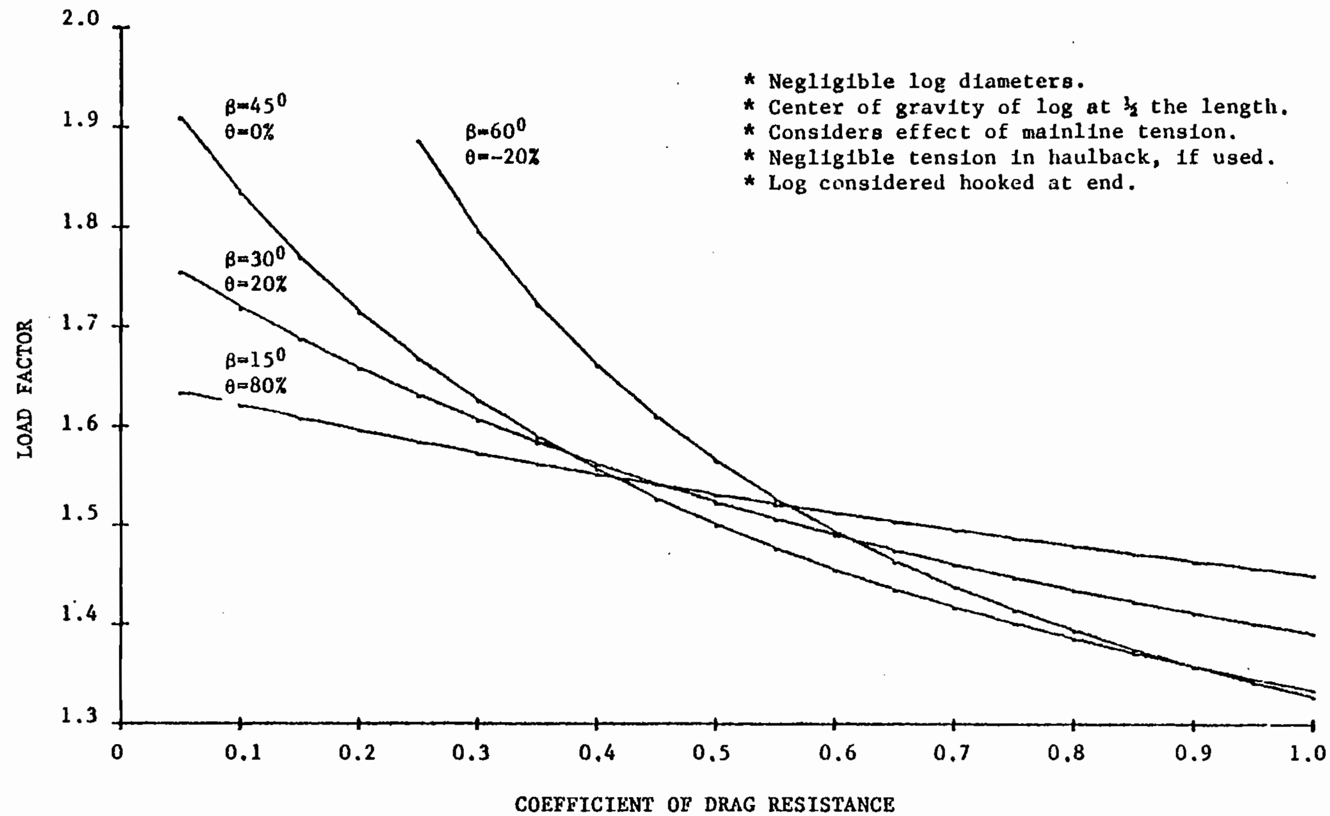


Figure 1 The sensitivity of the coefficient of drag resistance on load capacity for a skyline system during partial suspension yarding of logs for typical geometry situations. The load factor is multiplied by the full suspension capacity of the skyline to determine load capacity under partial suspension. β = log to ground angle in degrees, θ = ground slope in percent. Appendix I has the formulation of the load factor equation used in this figure.

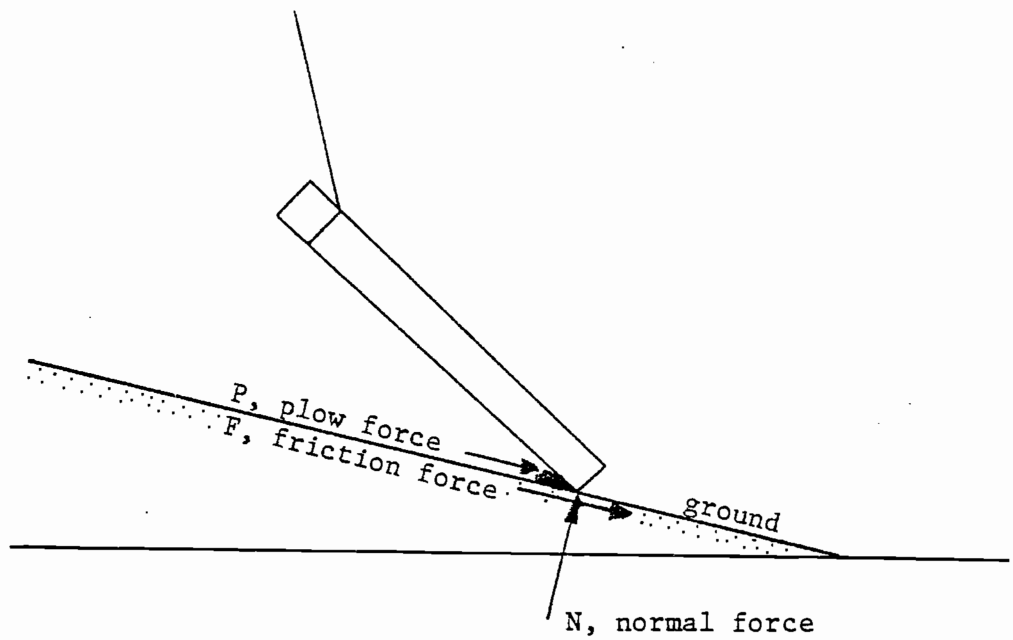


Figure 2. Free body diagram of the soil-log contact during yarding.

force (N) to obtain the coefficient of drag resistance. The coefficient of drag resistance is symbolized by the Greek letter "μ" (mu); therefore:

$$\mu = \frac{P+F}{N}$$

The study described here was conducted in an effort to determine the coefficient of drag resistance which occurs during the yarding of partially suspended logs by cable logging systems. The results of this study are directly applicable to skyline logging configurations but should be useful in the study of other yarding systems as well. For the purpose of this study, yarding is defined as the process of moving a log from the stump to a landing with one end of the log lifted free of the ground. It can further be classified as cable or tractor yarding. Skidding differs from yarding in that no vertical lift is applied to the log which is being dragged. Examples of this would be animal or tractor (drawbar only) skidding. In the literature on drag resistance, arch[1] or sulky[2] yarding is often used in place of tractor yarding. This study is concerned with yarding only.

The coefficient of drag resistance is one of the most critical considerations in the analysis of the mechanics of a log being yarded. It is also one of the most difficult to determine since it is dependent on a great many variables (O'Leary, 1963). The value of μ is site-dependent and therefore it is impossible to determine a general value suitable for all cases.

In order to increase the confidence in a value for μ to be used on a specific site, it would be desirable to develop a technique to measure μ in the field. The techniques used to date have required a large amount of instrumentation and are not as adaptable to cable yarding systems. One researcher used two recording load cells in the choker line. These had to remain parallel and perpendicular to the slope at all times (Garlicki, 1967). This system as well as some others used are not feasible for cable systems. It is proposed in this study to use a photographic technique suggested by Carson (1976). The method uses angles measured from a photo of the dragging log to calculate μ. The method has the potential of being fast and economical while providing accurate results.

Another possibility would be to determine the relationship between soil conditions and the coefficient of drag resistance. A model could then be developed that could be used to predict the value of μ for a specific site prior to logging. This value could then be used for more accurate load capacity calculations for the partial suspension system being considered.

This study was conducted under both laboratory and field conditions. The laboratory portion was limited to analyzing the

1) An arch is a track mounted trailer pulled behind a tractor. Logs are snubbed up under the arch, front end free of the ground to make movement easier (McCulloch, 1958).

2) A sulky is a two-wheeled carrier used in yarding behind a tractor in place of an arch (McCulloch, 1958).

photographic measurement technique and its variability. Field work was conducted on the McDonald and Dunn State Forests (Figure 3). These 11,000-acre forests are located in the foothills of the Oregon Coast Range. The surface soils occurring there are typical of soils in the Pacific Northwest.

Results from the field work were for young growth Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco). This is the predominant species being logged in the Coast and Cascade Mountain Ranges where extensive cable logging is used.

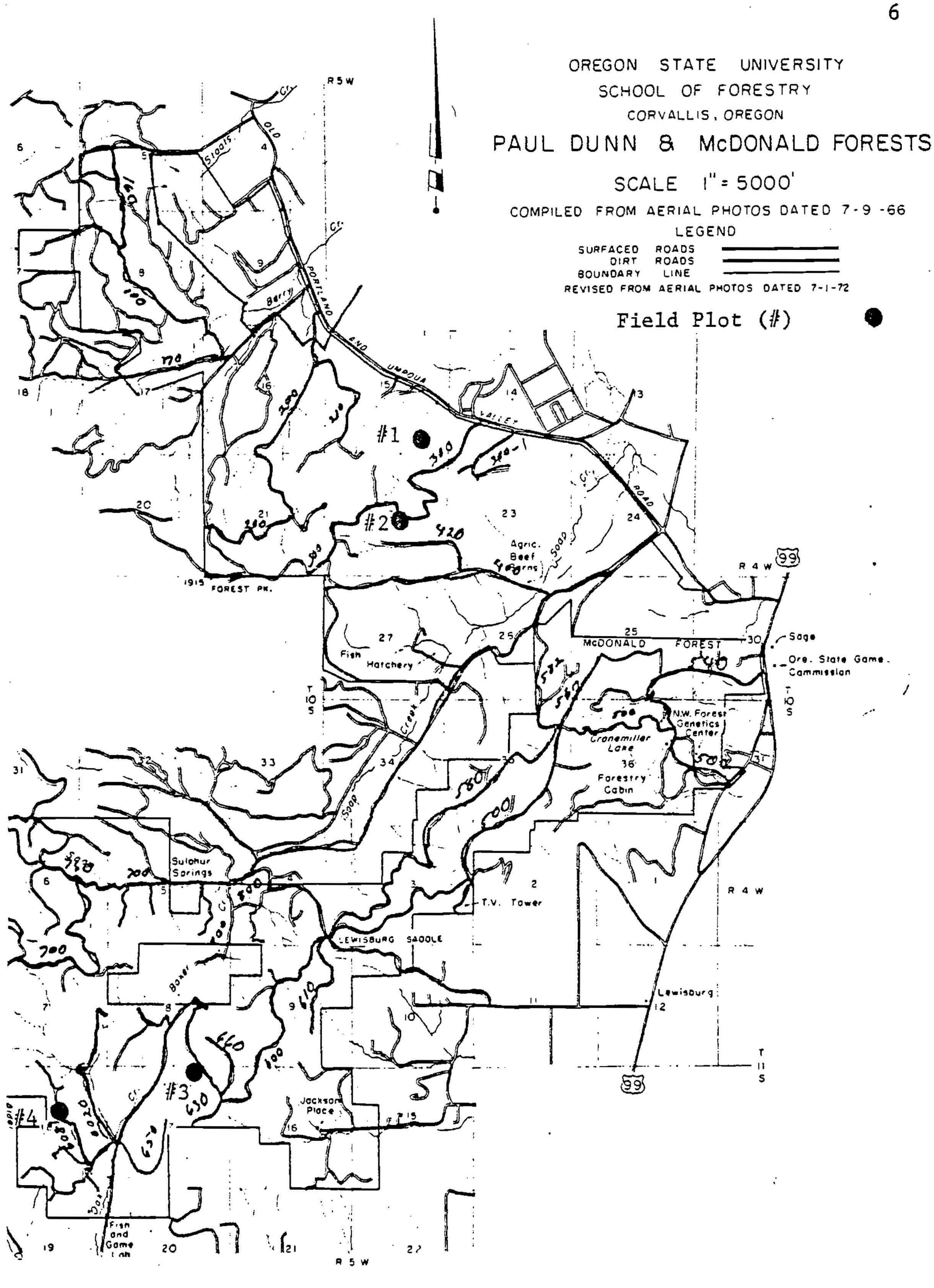


Figure 3. Map of Paul Dunn and McDonald State Forests.

STUDY OBJECTIVES

The primary objectives of this study were

1. To develop and test a photographic technique to measure the coefficient of drag resistance between a log and the soil during yarding that could be applied in the field to cable logging systems.
2. To investigate the static and dynamic coefficient of drag resistance on a limited number of soils with different characteristics.

LITERATURE REVIEW

The magnitude and variation of the resistance occurring during the dragging of logs has been under study since R.G. Forster of Vienna, published his first test results in 1885. His publication discussed the sliding of sawlogs both with and without bark on wooden slides and earth roads. Although his values are of little practical significance in the yarding of logs with cable systems today, his publication does show the early interest in determining the resistance occurring in logging.

Since Forster's work, there have been many efforts to determine the amount of resistance and the tractive effort required to skid whole trees and logs with ground based systems. Although these studies dealt mainly with little or no slope and observations were limited to ground skidding with tractors or skidders over specially prepared surfaces, they are useful in identifying possible influencing factors. This is especially true in cases where logs were skidded with a sulky which produces a partially suspended condition similar to that found in cable logging. The following discussion is organized according to those factors that have been found to influence the amount of resistance in skidding logs.

Surface

Most studies of skidding resistance have been done on specially prepared surfaces of mineral soil and grass turf. Because ground conditions are so heterogenous many authors have attempted to remove some of the variation by grouping the ground conditions by certain factors such as slope, soil moisture, the composition of soil, and the nature of the vegetation.

The influence of particle size and form was found to be an important factor of the friction function by Lunzmann (1964). He found that the coefficient of drag resistance between ground skidded logs and bare mineral soil is about equal to the internal friction in the soil itself, which in turn is strongly dependent on particle shape.

Bennett (1962) found very little correlation between soil texture and the horizontal pull required to move a log. He also tried to correlate soil compaction to the horizontal pull, again with little success. Soil compaction was measured with a cone penetrometer and the cone index was used in the regression equation. His study did show a strong relationship between horizontal pull and soil moisture. Logically, it may be assumed that soil texture and the degree of compaction do affect the moisture retention and drainage characteristics of the soil and therefore indirectly influence horizontal pull. As horizontal pull is directly influenced by the coefficient of drag resistance, soil compaction and texture may have an indirect influence on the coefficient.

Bjorklund (1968) found the variation among different surface types to be generally less than the variation due to moisture for any one surface. A difference of 30% in the coefficient of drag resistance between "wet" and "dry" conditions was reported by Kamiizaka and Shishiuchi (1962). Studies by Garlicki and Calvert (1969) also showed soil moisture to be highly significant in determining the coefficient of drag resistance. In general most researchers who measured the soil moisture in their studies found evidence of μ decreasing with increasing soil moisture content.

The only reported results which suggested that μ is increased with increasing moisture content in the soil are those of Darwin (1965). His investigation was done on clay, with large logs (19 inches (48.3 cm.) diameter) and underground skidding. When the clay held maximum moisture (61%) the logs acted as deep plows, whereas they reached a more shallow depth on the dryer hard clay.

Table 1 is a comparison of investigations of the skidding resistance for different soil types. Variations among the results in Table 1 for the same surface result from several causes. First, some authors used total weight rather than the portion of the weight supported by the ground when calculating the coefficient of drag resistance. This means the resistance force $\underline{D}$ would be calculated as $\underline{D} = \mu * \underline{W}$ rather than the more standard form $D = \mu * \underline{N}$ where $\underline{W}$ equals the weight of the

Table 1 - Summary of Coefficients of Drag Resistance for Logs by Surface Type

Surface	Drag Resistance Coefficient Reported by: (Mean ± Standard Deviation)								
	Bennet [(a]	Björklund	Calvert - Garlicki	Darwin [(a]	deMegill [(a]	Herrick	Kamiizaka - Shishiuchi	Lünzmann	Stajniak [(a]
Gravel	0.63	0.84 ± .19							
Snow	0.17								
Coarse Sand									
General			0.77 ± .21					0.63 ± 0.01	
Sand									
General	0.541		0.73 ± .18			0.92 ± 14		0.67 ± 0.05	
Dry							0.67 ± .06		
Wet							0.42 ± .08		
Fine Sand									
General		0.86 ± .18			0.73 - 0.80			0.53 ± 0.01	
Dry				0.82 - 0.88					
Wet				0.92 - 0.99	0.54 - 0.64				
Turf									
General	0.63	0.73 ± .20						0.78 ± 0.25	0.44 - 0.51
Dry									
Wet									0.63 - 0.73
Humus									
Dry	0.453								
Wet	0.343								

(a No standard deviations reported.

log and N equals the normal force of the ground in contact with the log. The study by Calvert and Garlicki (1970) was the only study using $D = \mu * W$ in which there was enough data so it was possible to convert μ to the standard form. Also different types of trees, dimensions, and lengths of logs were used on soils of different moisture contents. A conclusion which may be drawn from Table 1 is that the resistance on bare ground shows great variation due to differing conditions which make comparisons difficult.

Barked Versus Unbarked Logs

Unbarked logs have their natural bark in place, whereas barked logs have all of the bark removed. In Table 1 the values for μ reported by Bennett, Lunzmann, and Stajniak are for barked logs and clearly show lower values than the other studies. Darwin (1965) and Bjorkland (1968) studied both barked and unbarked logs and agree that the reduction is 15% to 25% of the resistance for unbarked logs. However for the present study this information is of marginal utility, because it is not common to debark logs prior to cable yarding.

Type of Trees

When comparing the dragging resistance of logs of different species the major contributing factor to the difference is the species' bark characteristics. This may be highly dependent on the age of the species, however none of the researchers found the exact age of the logs or trees they skidded.

The variation due to bark types would theoretically not be larger than the variation between barked and unbarked. (15% to 25%.)

Bennett (1962) found no significant difference in drag resistance for tree length log skidding of four eastern Canadian species of trees (white spruce, black spruce, jack pine, and balsam fir) because of similar bark characteristics. Darwin (1965) used southern hardwoods with considerable differences in bark characteristics, but found no significant difference in skidding resistance at the five percent level. Bjorklund (1968) found a non-significant difference of four percent between Norway spruce and Scotch pine.

The type of tree is of more importance when one considers whole trees due to differences in crown size. This was shown to make a significant difference in skidding resistance by both Bennett (1962) and Calvert and Garlicki (1967). However, Bjorklund (1968) found that if the crowns are of equal size one cannot expect any significant differences between species.

With increased thinning and smallwood logging in the Pacific Northwest, this information on log versus whole tree yarding may become more important. It will not be considered in this study, however, because of budgetary and physical contraints.

Dimensions

Lunzmann (1962) found that resistance was reduced from 67% to 55% when log diameter increased from 9.45 in. (24 cm.) to 14.57 in. (37 cm.). The hypothetical cause of this result was one of soil mechanical conditions. The increased diameter caused a lower normal pressure and thus a reduction in inner friction in the surface, particularly for sands. However, Lunzmann's results were obtained in ground skidding of short (6.56 ft. (2 m.) and 19.69 ft. (6 m.)). barked logs and his coefficient of drag resistance included a larger effect of soil gouging because a ground lead system was used.

Herrick (1955) found no significant difference between diameters of 12 inch (30.48 cm.) and 18 inch (45.72 cm.) in skidding eastern hardwoods.

The values for μ given deMegill (1956) were listed by diameter but there was no discussion on significance of the differences. The regression equation to predict the tractive power required to skid a turn of stems by Calvert and Garlicki (1970) includes the effect of diameter by using the sum of the midpoint diameters for a turn of logs as an independent variable.

Number of Logs Per Turn

Bjorklund (1968) found no significant effect related to the number of stems being skidded on grass turf. However, Calvert and Garlicki (1967) show a difference for individual stems with a resistance of 80% as compared to 74% and 72% for bunches of 6 and 12 stems, respectively. Their results were obtained on loosely packed sand and gravel which may explain the differences. A later study by Calvert and Garlicki (1970) produced regression equations to predict the power required to skid bunches of stems in which piece number was not included as an independent variable. It is generally considered that the number of logs has very little influence on resistance coefficients in skidding (Bjorklund, 1968).

Skidding Weight or Normal Force

Skidding weight is defined by Bjorklund (1968) to be that part of the weight of the log or tree which is directly supported by the ground. In engineering mechanics this is referred to as the normal force (Meriam, 1975). Normal force (N) multiplied by the coefficient of drag resistance (μ) is equal to the resistance force (D). This force plus the component of the weight along the slope will determine the total force required to move the load.

The normal force is equal to the total weight of the log in ground skidding on horizontal surfaces. When slopes are considered, the skidding weight is modified by the cosine of the slope angle. (Figure 4.)

The normal force is affected by the slope, the elasticity of the log, and the center of gravity of the log. Although the coefficient of drag resistance is independent of the normal force, the product of the two determines total resistance. The normal force was found in most of the studies by weighing the whole log or tree and then measuring the force required to suspend the end of the log (e.g. Calvert and Garlicki, 1968). The difference between the two forces is the normal force on level ground.

Angle of the Log

When using a static analysis to calculate the coefficient of drag resistance for partially suspended logs, it is necessary to determine the angle of the log. Kamiizaka and Shishiuchi (1962) used this technique in their calculations of μ. They did not show their results as a function of the angle of the log but indicated the angle of the log was necessary in the calculations. This will be discussed further under measuring techniques.

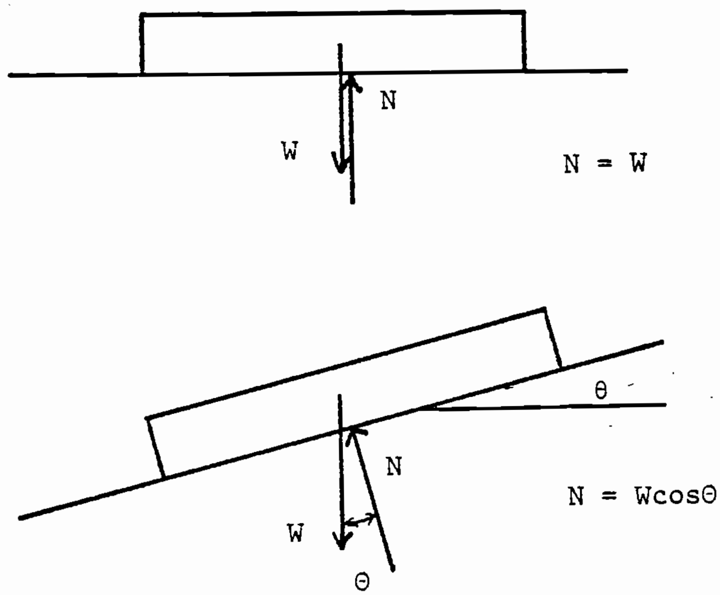


Figure 4. Comparison of normal force on horizontal versus inclined terrain.

Bjorklund (1968) found that the resistance coefficient was reduced with higher log angles. This could be due to less rubbing surface as the log angle increases.

Although none of the other authors directly measured the angle of the log, several investigated it indirectly by studying the effect of the height of the hoisted end of the log during skidding. Calvert and Garlicki (1969) found that with increasing the height of suspension there was a decrease in the ground contact and a decrease in the skidding weight. This directly influenced drag resistance but the difference was not proportional to the height of suspension. They found the higher the hoisted end the higher μ, but this was not significant at the 5 percent level.

Direction of Pull

Bjorklund (1968) reported that all of his studies with stems or parts of stems indicated that pulling the top end is preferable. Stajniak (1965) found that pulling in the top end caused a reduction of resistance of 11%. Lunzmann (1964) found a reduction to be about 8%. Herrick (1955) reported that a previous study by Steinlin and Zehnter (1953) showed that ground skidding small end first was definitely advantagous. It should be noted that all these studies were with ground skidding only. In studies by Calvert and Garlicki (1967, 1968, 1970) it was found that with partial suspension, substantial reductions in power requirements may be achieved by skidding logs butt foremost because the heavy butt end is lifted off the ground.

The direction of pull is more important in full-tree skidding since pulling in the top means that a larger part of the crown is lifted off the ground. Bennett (1962) and Bjorklund (1968) found on firm, solid soil the pull direction should influence the coefficient of drag resistance approximately 5%. In both ground skidding and partial suspension skidding with a sulky, Kamiizaka and Shishiuchi (1962) found the coefficient of drag resistance to be less by pulling the small end of the tree. A summary of resistance coefficients for both stems and trees is shown in Table 2.

Speed of Travel

The speed of travel was not analyzed in any of the research work found on the coefficient of drag resistance. However, it is a well-known principle of physics that the coefficient of resistance is independent of the rubbing speed (Meriam, 1965).

Log Weight

In all of the reports analyzing the total resistance during skidding of timber, the weight of the log was found to be the most significant factor. This would be expected since the resistance is a product of the skidding weight and the coefficient of drag resistance. None of the previous work found a relationship between

Table 2 - Summary of Results of Tests with Logs and Trees to Determine the Coefficient of Drag Resistance (a

	Method Direction of Pull	Surface B - bare S - snow	Drag Resistance Coefficients Reported by: Bennet	Björklund	Calvert - Garlicki	Darwin	Herrick	Wiesik	Kamiizaka - Shishiuchi	Lünzmann
Logs or Tree-length Logs	ground skidding butt first	B			0.83			(0.68-0.87)	1.16	0.64
	ground skidding top first	B			0.81	0.91	0.92		0.65	0.59
	tractor yarding butt first	B	(0.28-0.48) (0.17)	0.71	0.84				1.22	
	tractor yarding top first	B		0.75	0.66				0.56	
Full-Tree	ground skidding butt first	B					1.0			0.7 0.5
	ground skidding top first	B								
	tractor yarding butt first	B S	(0.34-0.75) (0.17)	0.83			(0.70-0.80)			
	tractor yarding top first	B		0.69			(0.75-0.85)			

(a Values in parentheses indicate resistance as a proportion of total weight (W), other values are true μ in relation to the normal force (N).

log weight and the coefficient of drag resistance, which complies with the laws of engineering mechanics (e.i. that μ is independent of the normal force).

Measuring Techniques

All of the studies cited pertaining to ground skidding used the free body diagram in Figure 5a to derive:

$$\mu = \frac{H - W\sin\Theta}{W\cos\Theta}$$

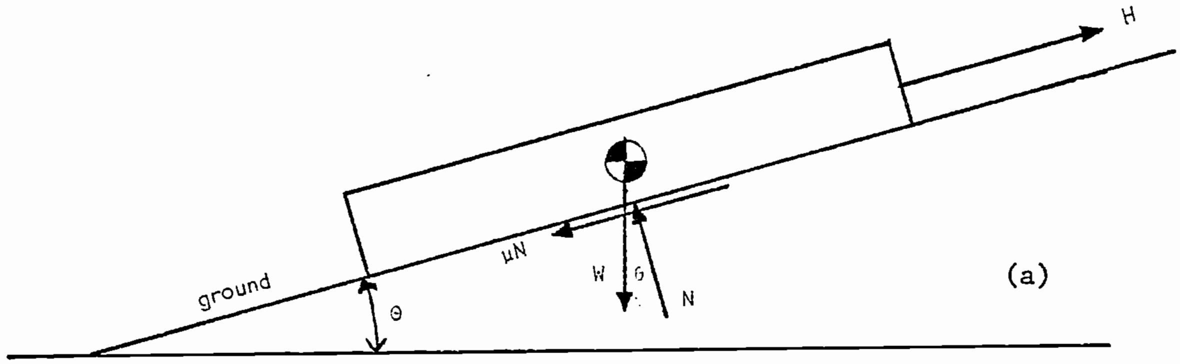
In the case of $\Theta = 0$, $\sin \Theta = 0$, and $\cos \Theta = 1$ so that:

$$\mu = \frac{H}{W} \qquad \text{(Figure 5b)}$$

It should be noted that it is very difficult to collect data to determine μ when the logs are being ground skidded. This is because there is a rapid build up of soil in front of the log that is gouging at a right angle to the direction the log is moving. Lunzmann (1964) and Herrick (1955) both commented on this difficulty and tried to reduce its influence by reducing the length the log was dragged. This reduced the amount of soil that built up in front of the log by reducing the time it was dragged. However, the shorter distance reduced the time that was needed to obtain a constant velocity which is necessary for the static equations used to calculate μ. This increase in the amount of acceleration of the logs in the experiments was the cause of many outliers in their data. Both researchers discussed this problem and eliminated the outliers from their data. Both researchers alluded that the criteria for omitting data was when the pull force, which equals the resistance force on level ground exceeded the weight of the log. This would correspond to a μ greater than one.

In the case where the log is in partial suspension the plowing or gouging of the log is reduced but not eliminated. However, the calculation of μ for the partially suspended case has other inherent problems which will be discussed later.

The methodology of studies involving skidding of partially suspended logs and stems with a high hoist or a sulky are not nearly



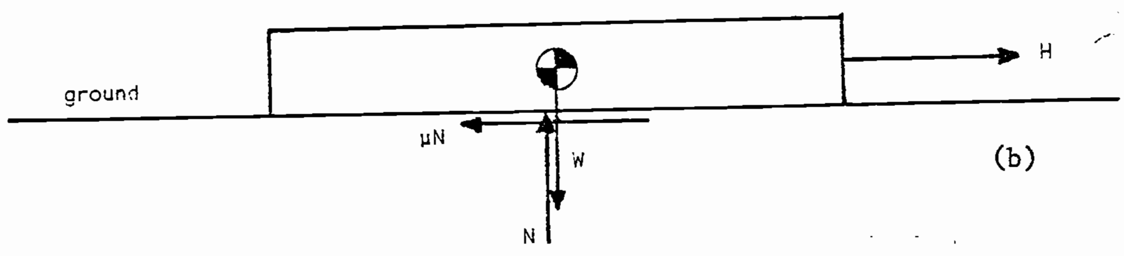
H = Pull required parallel to slope

N = Normal force

W = Weight of log

μ = Coefficient of drag resistance

Θ = Angle of slope to horizonal



H = Horizonal pull required

N = Normal force

W = Weight of log

μ = Coefficient of drag resistance

Figure 5. Geometry and free body diagram of a log being ground skidded on (a) an inclined surface and (b) a horizontal surface.

as clear. The most accurate means to facilitate the measurement was found by Garlicki (1967) and used in all of the tests made by Calvert and Garlicki. It was called a rectangular component transducer and is based on the law of mechanics dealing with the resolution of forces. The transducer simultaneously measures the components of the main line force, both normal and parallel to the skidding trail. This permits a solution for μ from the free body diagram (Figure 6):

$$\mu = \frac{R_{sp} - W\sin\beta}{W\cos\beta - R_{sn}}$$

In this case the weight of the log must be known. However, if the distance from the end of the log to the center of gravity is known, then the weight is not needed because a summation of moments can be taken.

Bennett and Bjorklund (1962) made the assumption that the vertical component of the force in the main line is the same before and during movement with partially suspended logs. Both these studies considered only skidding on horizontal surfaces. They attached a load cell gauge in the main line and lifted the load to the maximum possible safe height behind the sulky and then the sulky was jockeyed back and forth until the load cell hung vertically. A reading on the gauge was then recorded (V). During the skidding process a reading of the mainline force (MLF) was made at points along the track. Then the horizontal force (H) was calculated from:

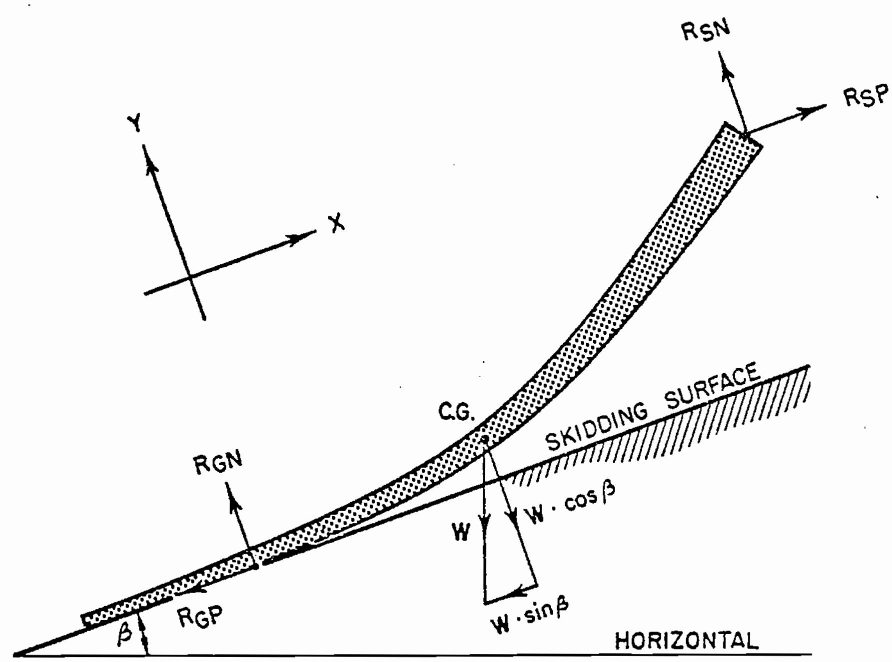
$$H = (MLF)^2 - (V)^2$$

The force (V) was determined before movement and the force (MLF) was determined during movement.

The coefficient of drag resistance could then be calculated from:

$$\mu = \frac{H}{N} = \frac{H}{W-V}$$

Herrick (1955) makes note of recording the vertical force in the mainline before skidding but does not discuss his procedure in calculating μ for sulky skidding.



FORCES WHEN SKIDDING TREE LENGTHS SUSPENDED ONE END.

W - Total weight of skidded tree length(s)
R_{GN} - Ground supported end reaction normal to skidding surface
R_{GP} - Ground supported end reaction parallel to skidding surface
R_{SN} - Suspended end reaction normal to skidding surface
R_{SP} - Suspended end reaction parallel to skidding surface
β - Angle between skidding surface and the horizontal

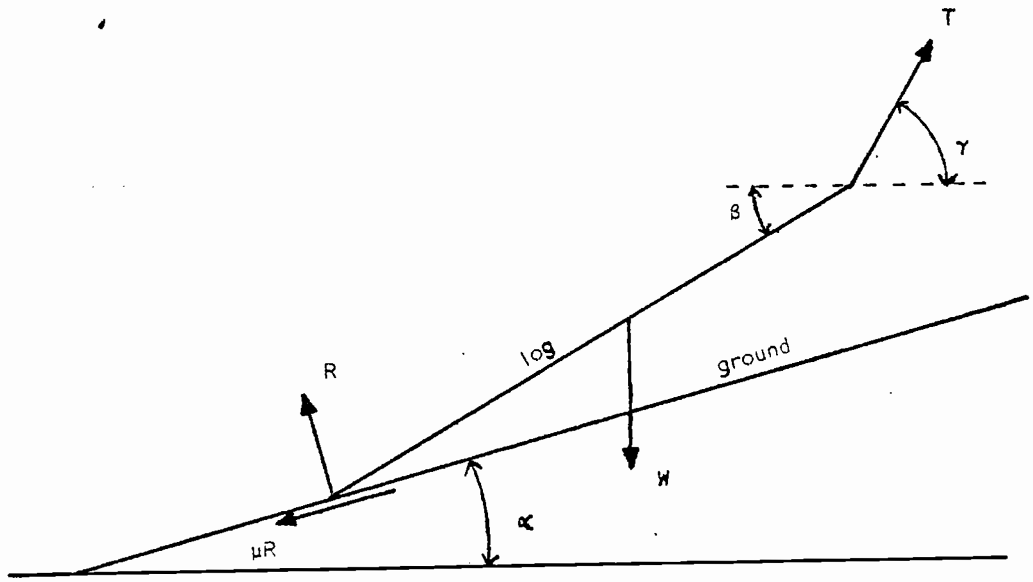
Figure 6. Geometry and free body diagram of a log being yarded on a slope with one end supported (source: Calvert and Garlicki, 1970).

The most complete discussion of the mechanics of skidding partially suspended logs is given in Kamiizaka and Shishiuchi (1962). Their free body diagram (Figure 7) and their approach for the calculations of the forces is similar to that which is used in this study and also the study by Carson (1975). They used the basic principle of summation of moments and forces to derive as many equations of motion as there are unknown forces. This requires that the angles of slope (α), log (β), and tagline (γ) be known (see methods for discussion). However, they assumed that the angles could be measured before movement at the point of impending motion. When the value of μ is determined at impending motion rather than at a constant velocity, it is called the static coefficient rather than dynamic. In engineering mechanics it is known that the static coefficient is always higher than the dynamic for the same contact surface. However, they did not report their results as being for the static coefficient because they measured the force in the choker line during motion. This may have introduced an error in their results. Also, they measured these angles with a clinometer which, because of the instrument's low precision, might have introduced error.

Summary of Literature Review

Tables 1 and 2 give some idea of the amount of variation which has been encountered in previous studies of the coefficient of drag resistance in log skidding. The studies in Table 1 which reported the standard deviation of their μ values indicate that this variation may be as much as 32% of the mean. The lowest variation reported was by Lunzmann (1964) for coarse sand, sand, and fine sand. In his tests, all natural soil was removed to a depth of 45 cm. and replaced by a homogeneously sized sand. In the one test Lunzmann did run on natural soil covered with turf, the coefficient of variation was 32%. In all the studies the indication is that a fair amount of variability can be expected in the coefficient of drag resistance data for natural soils.

When comparing the values in Tables 1 and 2, it should be remembered that many of these studies were concerned with the power requirements for tractors and skidders rather than the coefficient



α = ground slope

γ = angle of choker line to horizontal

R = ground surface reaction

W = weight of log

T = tractive force

μ = coefficient of drag resistance

Figure 7. Free body diagram of a log being yarded on a slope (source: Kamiizaka and Shishiuchi,1962).

of drag resistance. In fact the results of both Bennett (1962) and Calvert and Garlicki (1970) had to be recalculated to determine μ. However, all of the studies seem to indicate the following effects on the coefficient of drag resistance between logs and the ground:

(1) That changes in soil moisture will cause larger variations in μ on the same surface than changes in surface texture.

(2) That log diameter seems to have an inverse effect on μ.

(3) That the range of μ on bare ground for logs with bark is between 0.5 to 1.0.

(4) That there is a reduction in μ with smaller soil particles.

(5) That lower values of μ are obtained with barked logs.

(6) For logs of different species, the variation is related to different types of bark.

(7) That as soil moisture content increases, μ decreases.

FORMULATION OF EQUATIONS

In the analysis of cable yarding it is necessary to identify the geometry and forces involved. Carson (1975) has employed a free body diagram to determine the load capacity of running skylines when logs are partially suspended (Figure 8). A modification of Carson's geometry (Figure 9) was used in this report to develop an analytical model to measure μ. Figure 9 implies the following:

1. The log is a rigid body. This means that any two points on the log are always an equal distance apart. This is a valid assumption so long as the diameter/length ratio is not too small. It would not be valid when considering whole trees or tree length logs because the deflection in the log or trees would not conform to the rigid body principle (Figure 6).
2. The log is considered to be a truncated circular cylindrical cone with diameter d_1 at the point of attachment of the choker and diameter d_2 at the aft end of the log in contact with the ground.
3. The center of gravity lies along the center axis of the log. This is reasonable due to the fairly symmetrical growth and uniform density of trees.
4. The log is moving at a constant velocity at the moment the angles are measured. This assumption allows us to apply equations of equilibrium.

In the analysis of the forces in Figure 9, it can be seen that from the summation of forces in the horizontal and vertical direction the following equations are formed:

$$\Sigma F_{horz.} \Rightarrow T\sin\alpha = N\sin\Theta + \mu N\cos\Theta \qquad (1)$$

$$\Sigma F_{vert.} \Rightarrow T\cos\alpha = W - N\cos\Theta + \mu N\sin\Theta \qquad (2)$$

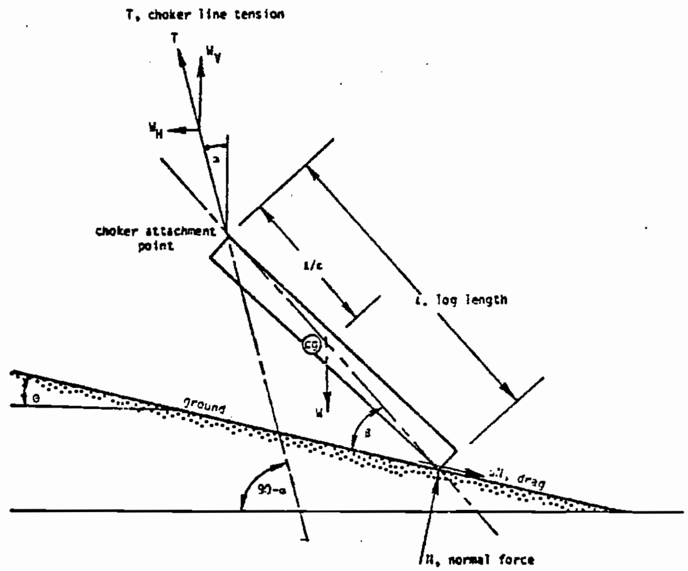


Figure 8 - Log yarding geometry and free body diagram used by Carson (1975).

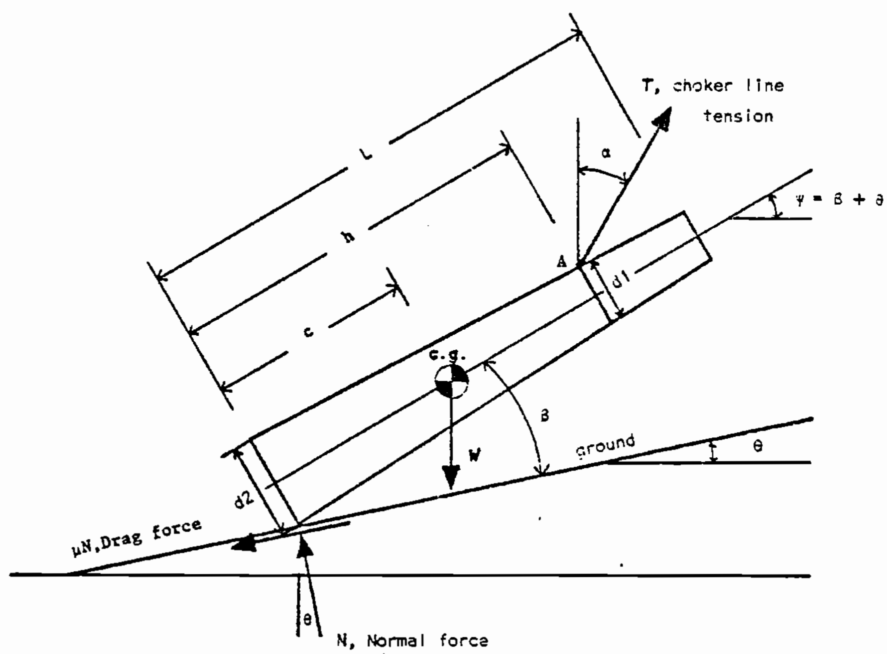


Figure 9 - Geometry and free body diagram of a log yarded with partial suspension.

By summing the moments about the point of attachment of the choker line to the log (Point A) and using the axes parallel and perpendicular to the long axis of the log:

$$\Sigma M \Rightarrow \quad W\{(h-c)\cos\psi - (d1/2)\sin\psi\} - N\{-((d1+d2)/2)\sin\beta + h\cos\beta\}$$
$$-\mu N\{h\sin\beta + ((d1+d2)/2)\cos\beta \quad = 0 \qquad (3)$$
$$\text{where } \psi=\Theta+\beta$$

Dividing equation 3 by L and letting D1=d1/2L, D2=d2/2L, H=h/L, and C=c/L, this result is modified to:

$$W\{(H-C)\cos\psi - D1\sin\psi\} - N\{-(D1+D2)\sin\beta + H\cos\beta\}$$
$$-\mu N\{H\sin\beta + (D1+D2)\cos\beta\} = 0 \qquad (3a)$$

Equation 1 divided by equation 2 eliminates the unknown force T and forms:

$$\tan\alpha = \frac{N\sin\Theta + \mu N\cos\Theta}{W - N\cos\Theta + \mu N\sin\Theta} \qquad (4)$$

Solving equation 4 for N obtains:

$$N = \frac{W\tan\alpha}{\mu(\cos\Theta - \sin\Theta\tan\alpha) + \sin\Theta + \tan\alpha\cos\Theta} \qquad (5)$$

Substituting N from equation 5 into equation 3a and solving for μ results in:

$$\mu = \frac{\{(H-C)\cos\psi - D1\sin\psi\}\{\sin\Theta + \tan\alpha\cos\Theta\} - \tan\alpha\{-(D1+D2)\sin\beta + H\cos\beta\}}{\tan\alpha\{H\sin\beta + (D1+D2)\cos\beta\} - \{(H-C)\cos\psi - D1\sin\psi\}\{\cos\Theta - \tan\alpha\sin\Theta\}} \qquad (6)$$

Thus by knowing the geometry of the log, the angles Θ, β, α, and the values for H & C, equation 6 can be used to calculate μ for the surface in contact the the log.

It should be noted that the above calculation is nothing more than solving a system of three equations (ΣF_H, ΣF_V, and ΣM_A) and three unknown ratios (T/N, N/W, and D/N where $\mu = D/N$). The force D is the drag resistance force. If one of the four forces can be measured directly then the other three forces can be calculated. In making any sort of engineering measurements, it is desirable to have redundancy in order to allow a check on the values obtained. This could be done in this case by measuring two or more of the forces. The force for which measurements could be most easily and accurately obtained is W, because it can be measured directly before the log is yarded. The second possibility is T; however this would require some sort of load cell to be placed in the choker/line. It is too difficult to measure D or N directly. When W is known the other forces can be solved for by:

$$N = \frac{W\tan\alpha}{\mu(\cos\Theta - \sin\theta\tan\alpha) + \sin\Theta + \tan\alpha\cos\Theta} \quad (7)$$

$$T = \frac{N\sin\Theta + \mu N\cos\Theta}{\sin\alpha} = \frac{W - N\cos\Theta + \mu N\sin\Theta}{\cos\alpha} \quad (8)$$

$$D = \mu N \quad (9)$$

When T is known then the forces can be solved for with equations 9, 10, and 11, as:

$$N = \frac{T\sin\alpha}{\sin\Theta + \mu\cos\Theta} \quad (10)$$

$$W = T\cos\alpha + N(\cos\Theta - \mu\sin\Theta) \quad (11)$$

The input of the weight of the log (W) or the tension in the choker line (T) also determines the units of all the forces. If they are input in newtons then all other forces will be in newtons, etc.

If both T and W are measured then μ can be calculated by another method using equations 9 and 1 to form:

$$\mu = \frac{T(\cos\alpha\sin\Theta + \cos\Theta\sin\alpha) - W\sin\Theta}{W\cos\Theta + T(\sin\Theta\sin\alpha - \cos\alpha\cos\Theta)} = \frac{T\sin(\alpha+\Theta) - W\sin\Theta}{-T\cos(\alpha+\Theta) + W\cos\Theta} \qquad (12)$$

It should be noted that although equations 6 and 11 both calculate μ, they are functions of a different set of parameters.

Equation 6 $\mu = f(H,C,D1,D2, \alpha, \beta, \text{and } \Theta)$

Equation 12 $\mu = f(W,T,\alpha,\Theta)$

When all the above parameters are known, it is possible to run a comparison test to check the results.

Numerical Example:

Let:	d1 = 7 inches	$\alpha = 21.66^{\circ}$
	d2 = 9 inches	$\beta = 19.41^{\circ}$
	h = 14 feet	$\Theta = 12.43$
	L = 16 feet	T = 186 pounds
	c = 7.5 feet	W = 233 pounds

Therefore:

$\mu = 0.7159$	(equation 6)
$\mu = 0.7360$	(equation 12)
N = 74.564	(equation 7)
T = 184.716	(equation 8)
D = 53.380	(equation 9)
N = 73.501	(equation 10)
W = 256.289	(equation 11)

PHOTOGRAPHIC TECHNIQUE

In order to apply equations 6 or 12 to calculate the coefficient of drag resistance between a log and the ground, certain angles must be known. The angles needed to calculate μ by the equations above are the slope of the ground (θ), the angle of the log to the ground (β), and the angle of the choker line to the vertical (α). Kamiizaka and Shishiuchi (1962) used a clinometer to measure the angle of the choker line. However, they were only able to take this measurement before the log was put into motion. This method was not desirable for the present study because of low precision associated with clinometer measurements and the fact that the procedure could not be used while the log was moving. O'Leary (1963) measured the angle of the tag line in yarding logs with a helicopter by taking motion pictures from a small helicopter flying beside the yarding helicopter. By projecting an individual frame of the film onto a screen, the angle of the tag could be measured with a large protractor. This work was done on horizontal ground and the picture frames always included the ground so that the angle could be referenced to the horizontal. The method used in the present study to measure the angles needed was similar to O'Leary's method.

The method uses a single photograph taken of the log in motion, or at impending motion, to record the angles α, β, and θ at the instant desired. Together with the log geometry these angles can be input into equation 6 to determine μ. Or, if the choker line force and the weight of the log are known, the angles can be used in equation 12 to find μ.

In order to reference the slope and the choker line angle with respect to the vertical and horizontal axes, it was necessary to hang a plumb line within the frame of the photograph. The angles were then measured directly from the photograph using an electronic digitizer in combination with a Hewlett-Packard model 9830 programmable calculator. A basic program was written to perform the calculation for μ from the coordinates read by the digitizer. Appendix II has the program description, listing, and an example of its application. Figure 10

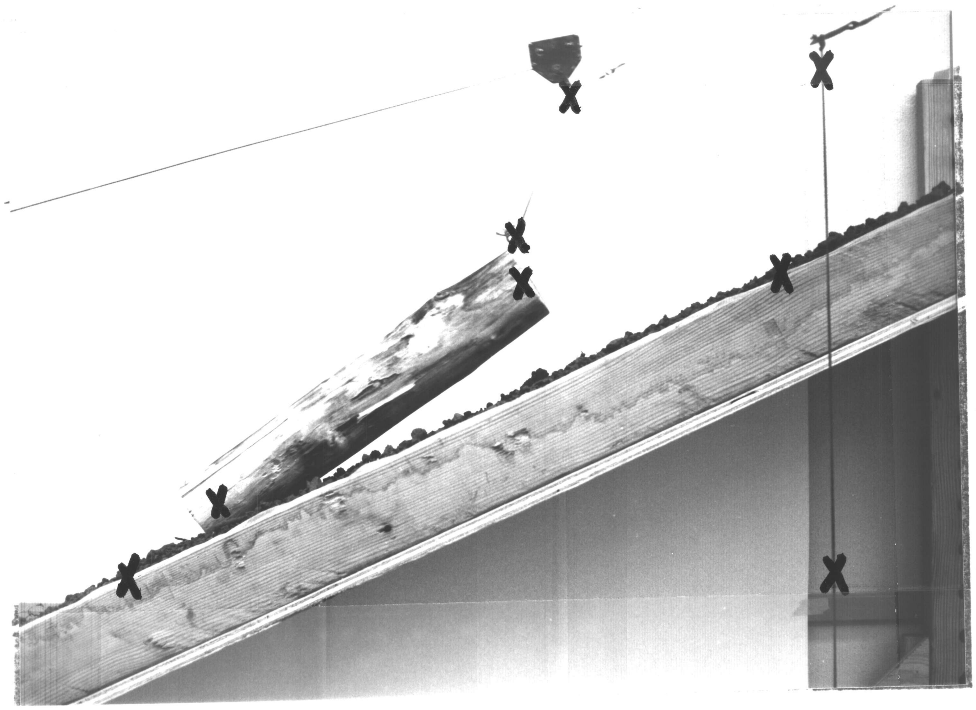


Figure 10. Photograph of a log yarded on the terrain model.

shows a photograph of a log being yarded. The points to be digitized are indicated with an "X". Note the plumb line on the right side of the photograph.

Basic photogrammetry was used to analyze the possible errors introduced by measuring angles from a photograph. The two major factors which might have introduced measurement errors in this procedure were:

1. A parallax error resulting if all the points that were digitized did not lie in the same plane.
2. A tilt error if the axis of the camera was not perpendicular to the plane described above.

In order to minimize the possibility of introducing either of the above errors, a surveying transit was used to lay out each camera station. With these errors eliminated or reduced to a minimum, the measurement of the angles by the digitizer reduced to a simple coordinate transformation problem.

TERRAIN MODEL SECTION

This portion of the study was conducted under controlled laboratory conditions to determine if the photographic technique would be feasible for determining the dynamic coefficient of drag resistance for a yarded log. The major concern was whether or not a log in motion would remain at a constant velocity while being yarded. This is necessary in order to apply the equations derived based on the equilibrium assumption. This experiment was also used to determine the amount of variability to be expected in μ when determined by the photographic technique. The effects of yarding direction (uphill versus downhill), slope, and the angle of the log on the coefficient of drag resistance were also examined to some extent.

Data Collection

Data collected were obtained with the aid of a small-scale ground terrain model and a miniature log (Figure 11). The terrain model was used in conjunction with an electric, scale-model yarder owned by the Forest Engineering Department at Oregon State University. The terrain model consisted of an eight foot (243.8 cm.), by one foot (30.5 cm.), by four inch (10.2 cm.) box of soil that was adjustable to several different slope angles.

The terrain model was oriented along a wall in the laboratory so that a white paper cover could be placed on the wall as a background for the log when the photo was taken (Figure 10). The model yarder was located at the end of the terrain model so that the skyline was centered over the length of the soil box (Figure 11). A 35-mm Nikkormat camera mounted on a leveled tripod was used to take the photographs. The camera station was located 8 feet (244 cm.) from the terrain model and perpendicular to the center line of the soil bed (Figure 12). The log was manually positioned at the opposite end of the soil bed from the yarder. The yarder was rigged in a slackline

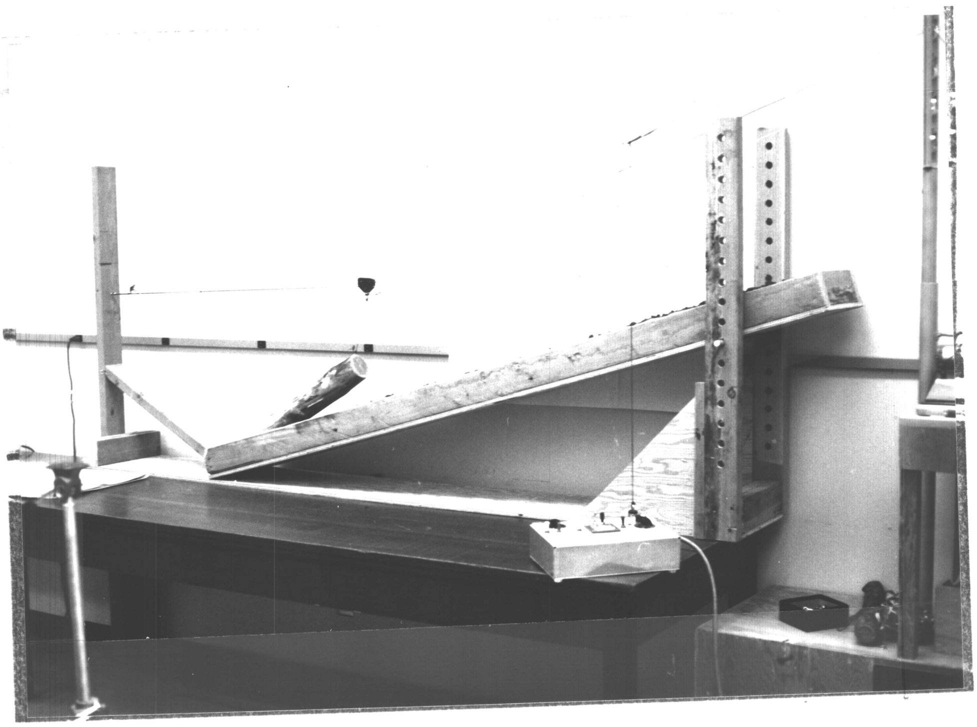


Figure 11. Terrain model used to simulate partial suspension of logs with cable systems.

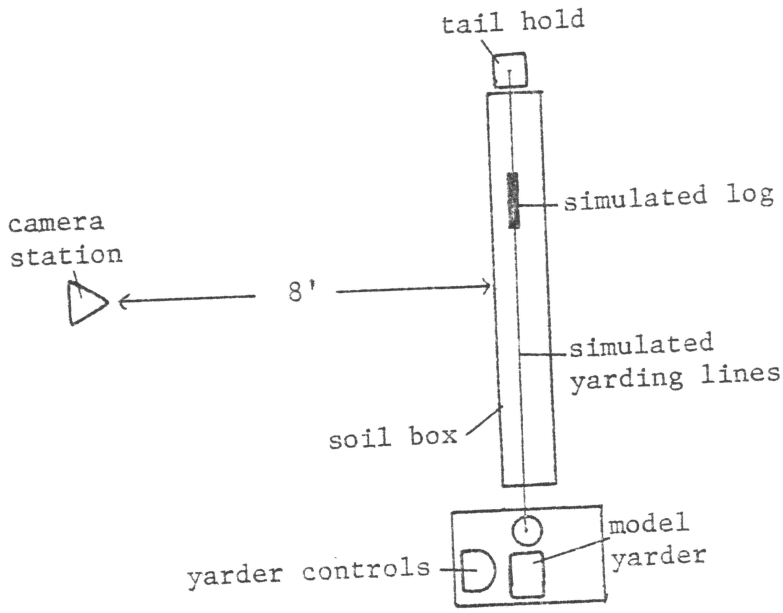


Figure 12. Schematic of camera station layout for terrain model section.

configuration with the skyline adjusted to provide adequate lift on all the miniature log. The height of the skyline was not changed after it was set, so for all experiments it was in the same position. The yarder mainline was then switched on to a constant speed which moved the log across the terrain model. As the log passed a point marked on the soil bed which was perpendicular to the camera station, the photo was taken. The mainline was then slacked, the log returned to the end of the soil bed, and the procedure repeated.

Ten such samples were taken under each of the conditions listed in Table 3.

Table 3. Configuration of Terrain Model for Each Experiment

Experiment #	Yarding Direction	Slope of Soil Bed (percent)
1	uphill	15.0
2	downhill	15.0
3	uphill	26.5
4	downhill	26.5
5	uphill	39.0
6	downhill	39.0

The soil in the terrain model was a clay loam and was air-dried at room temperature. The log was a barked piece of alder 3.1 inches (7.9 cm.) in diameter and 1.48 feet (45.1 cm.) long. It weighed 2.5 pounds (35.25 g.). The soil-log relationship was not intended to simulate the actual log-soil relationship in the field, however, the amount of variability determined in the method and any general relationships that were found gave an indication of what should be expected.

Results

Figure 13 shows a histogram of the results from all experiments with the terrain model. The mean value of μ was 0.8461 with a standard deviation of 0.3763 or 44.4% of the mean. A summary of results for the individual experiments is listed in Table 4.

Table 4. Results of the Data Collected on the Coefficient of Drag Resistance for the Terrain Model.

Experiment #	Direction of Yarding	Slope (Percent)	Sample Size n	Mean $\bar{x}$	Variance S^2
1	uphill	15.0	10	0.805	0.102
2	downhill	15.0	10	0.978	0.063
3	uphill	26.5	11	0.653	0.077
4	downhill	26.5	10	1.086	0.054
5	uphill	37.0	10	0.505	0.038
6	downhill	37.0	10	1.067	0.287

Analysis of variance (ANOVA) was used to determine that there was a significant difference between yarding uphill and downhill on all slopes. The coefficient of drag resistance was always greater for yarding downhill versus uphill on the same slope. When all the data were combined and divided between uphill and downhill yarding, the mean μ for downhill yarding was 59.5% greater than for uphill yarding. ANOVA was also used to determine that the effect of slope on μ was non-significant for both uphill and downhill yarding. Appendix III shows a summary of all ANOVA calculations with all tests for significance being compared at the $\alpha = 0.05$ level.

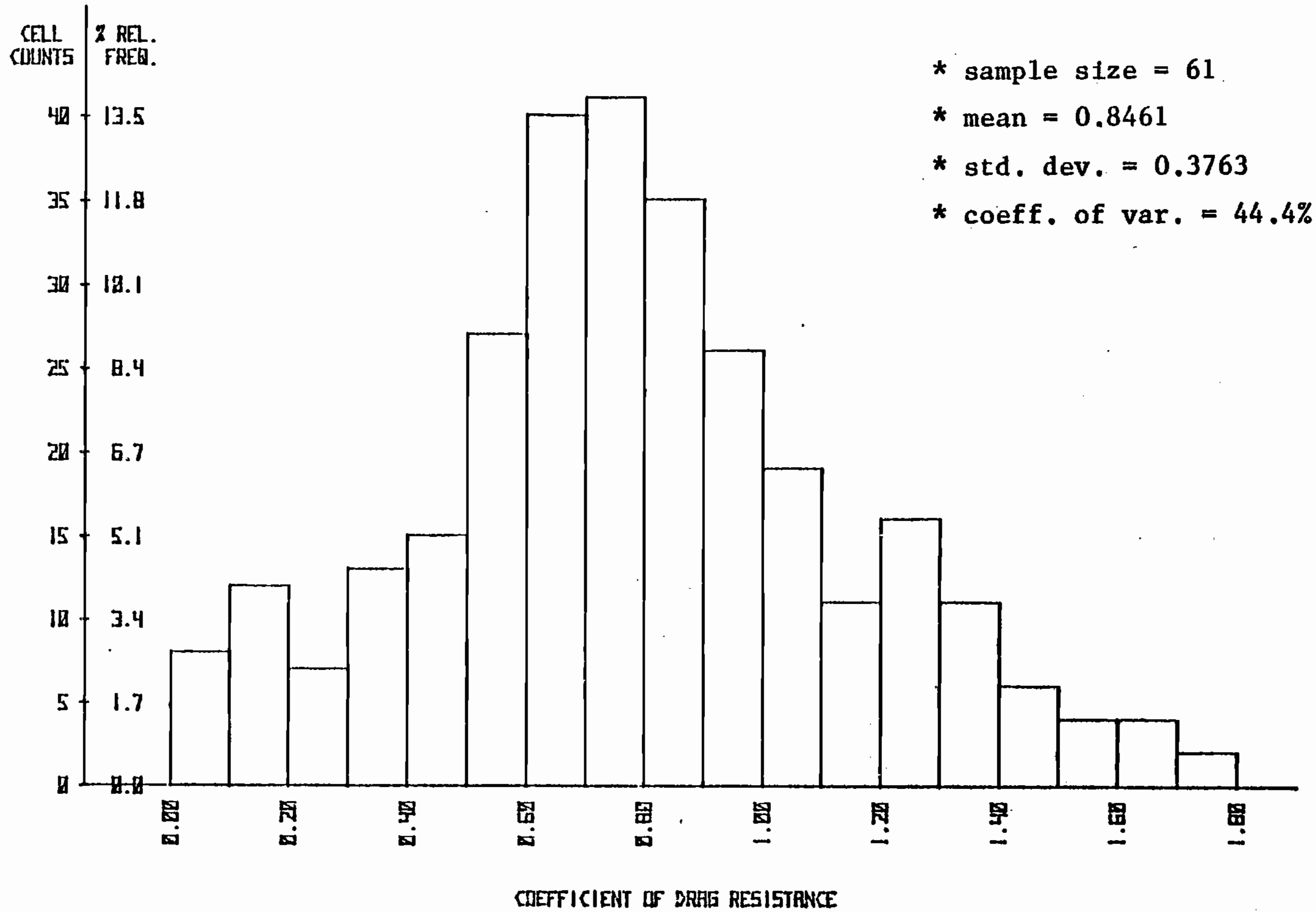


Figure 13. Histogram of all data from terrain model section.

The following regression equation was developed and explains 42.2% of the variation measured for the coefficient of drag resistance in the terrain model data.

$$\mu = 0.5643 + 0.03075(\beta) - 0.02289(\Theta) - 0.01702(\Delta)$$

where:

μ = coefficient of drag resistance

β = angle between the log and the soil $\qquad r^2 = .422$

Θ = slope angle

Δ = 1 for uphill yarding and 0 for downhill yarding

The above regression equation and all variables was found to be significant at the $\alpha = 0.05$ level (Appendix III).

Discussion

The actual values for the coefficient of drag resistance obtained in this section are not of practical use for field applications because the soil-log interaction is that of a laboratory model rather than a field situation. However, the results are useful in suggesting the amount of variability to be expected in measuring μ by the photographic technique. The trends observed in the data were also helpful in determining what was to be expected from the field experiments.

When examining the results for this section in Table 4, it should be remembered that all data were taken for the same log on the same soil. Therefore, the only factors producing the variation were: (1) the slope (Θ), which was controlled by adjusting the terrain model soil surface to three different angles; (2) the direction of yarding, which was divided equally between uphill and downhill for each slope; (3) the angle of the log with the soil (β), which was fairly continuous throughout the experiment; and (4) the inherent experimental variation resulting from the photographic technique.

It is not likely that the regression equation developed in this section will represent the variation in μ under field logging conditions, but it does suggest that values of μ can be estimated by a regression model. It is interesting to note that the slope angle was a significant variable in the regression equation after being found non-significant by ANOVA. The reason for this might have been the fairly high correlation ($r=0.374$) between the slope angle and the angle between the log and the soil (β). Interactions between these two independent variables might permit them both to enter the regression model when one of them would otherwise have been excluded.

In analyzing the results of this section, two non-significant trends were observed. First, for downhill yarding the values of μ are directly related to slope: as the slope increases so does μ. However this relationship was not significant at the $\alpha = 0.05$ level (Appendix III). Just the reverse situation occurred on the uphill yarding: as the slope increased, the value of μ decreased. The reason for these relationships can be partially explained by the angle of the log to the soil. In developing the regression equation with a stepwise procedure, the log angle (β) was the first variable to enter the model and explained 33.6% of the variation in μ. Recall that during the experiment the height of the skyline remained fixed. Under these conditions the log angle would tend to decrease as slope increased in uphill yarding and the log angle would tend to increase for greater slopes in downhill yarding. A greater log to soil angle would seem to produce greater gouging and therefore increase the value of μ. However the depth of gouging was not measured.

FIELD SECTION

This portion of the study was an attempt to analyze and model a limited number of physical factors influencing the coefficient of drag resistance between a log being yarded and bare forest soil. The data collected were divided between tests for static and dynamic values of μ. All data were collected by using the photographic technique tested in the terrain model section. Regression analysis was used to relate soil texture, soil moisture, log geometry, slope, soil density, and the angle of the log with the ground to the coefficient of drag resistance.

Data Collection

The data in this section were collected on McDonald and Dunn State Forests. Figure 3 indicates the location of the 4 test plots used for this study. The criteria for establishing the location of the test plots were:

1. That the plots were on different uniform slopes;
2. That an equal number of plots were selected with fine grain soils and granular soils. Fine grain soils are composed of 50% or more of the individual particles smaller than 0.00291 inch (0.074 mm.). Granular soils are defined as those soils composed of 50% or more of the individual particles smaller than 3 inches (76.2 mm.) and larger than 0.00291 inch (No. 200 U.S. Standard Sieve);[3]
3. That there were two trees, one at each end of the plot, that were of adequate size to support the skyline used to yard the test logs across the plots. It was necessary for the trees to be approximately 50 to 60 feet (15.24 to 18.29 m.) apart to provide enough distance for the test runs.

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3. Numerous soil identification systems are in existance. The particular one used for this study is based on the Unified Classification System.

4. That the tree on the upper end of the plot was near a road. This was required because the power system used to yard the test logs was based on the road and only 150 feet (45.72 m.) of yarding line was available.

Soil samples were collected for laboratory analysis just prior to data collection. The procedure for soil analysis consisted of:

1. Grain size analysis using U.S. Standard Sieves with oven dried soil samples;
2. Grain size analysis using the Boyucus hydrometer method on air dried soil samples of material smaller than U.S. Standard Sieve No. 10 (0.0787 inch, 2 mm.);
3. Atterberg limits using the standard procedures for liquid and plastic limits.
4. Determination of the soil class in the Unified Soil Classification System.

In procedures 1 and 2, the soil was pulverized mechanically by hand before the soil was passed through a sieve. Table 5 shows the results of the laboratory soil analysis for each plot. The soils of the 4 plots were identified into only 2 unified soil classes, MH and SM. The symbol MH represents inorganic elastic silts, and SM represents silty sands or silty sand mixtures. Although data were taken only on these 2 soil classes, the particular soils used in this study should represent soils on which cable yarding is commonly used. This is true because the soil classification system used in this study was based on the engineering properties of the top 6 inches (15.24 cm.) of the soil which should exhibit less variability than the standard vegetative soil classifications commonly used on forested terrain.

Two other soil characteristics were determined for the plots during data collection. The moisture content of the soil was taken 3 times a day during each test and averaged. Soil density was determined using a neutron portaprobe once prior and once after all static data on a plot were taken. During the collection of the dynamic data, soil density was determined after each log was tested (Figure 14).

Table 5. Results of Laboratory Analysis of the Soil on the Test Plots.

SOIL CHARACTERISTICS		Plot # 1	2	3	4
Slope		31%	10%	56%	24%
GRAIN SIZE ANALYSIS					
Percent passing					
SIEVE #	MM				
4	5.20	99.2	99.7	79.7	99.0
10	2.00	80.0	69.2	60.1	79.8
40	0.42	69.3	58.8	40.3	64.0
200	0.07	57.0	42.1	25.6	55.3
FINE GRAIN/GRANULAR		FINE	GRANULAR	GRANULAR	FINE
HYDROMETER ANALYSIS					
OF MATERIAL PASSING SIEVE #10					
% sand		32.26	37.11	41.83	24.18
% silt		32.24	36.07	30.83	38.27
% clay		35.50	26.82	27.34	37.55
SOIL TEXTURE		CLAY-LOAM	LOAM	LOAM	CLAY-LOAM
MATERIAL PASSING #200 SIEVE					
liquid limit		65.61	51.20	48.50	56.40
plastic limit		39.21	39.00	39.22	36.60
plasticity index		26.40	12.20	9.28	19.80
UNIFIED SOIL CLASS		MH	SM	SM	MH

Figure 14. The neutron portaprobe being used to determine soil density during test runs to determine the dynamic coefficient of drag resistance.

The preparation of a plot for data collection was:

1. A transit was used to sight in the camera station which was set 30 feet (9.14 m.) from the center of the plot (halfway between the trees and at a right angle to the line between the trees) (Figure 15);
2. The two trees on each end of the plot were climbed and the limbs removed to a height of 35 feet (10.67 m.);
3. A 3/8 inch (9.53 mm.) skyline was chokered off at 30 feet (9.14 m.) in the tree at the lower end of the plot (tail-spar). The skyline was then run through a 7 inch (17.78 cm.) rigging block strapped in the tree at the upper end of the plot (headspar) at 30 feet (9.14 m.) and hitched to the rear bumper of a pickup on the road (Figure 16);
4. The yarding line (mainline) was run from the power source through a 7 inch (17.78 cm.) rigging block strapped at a

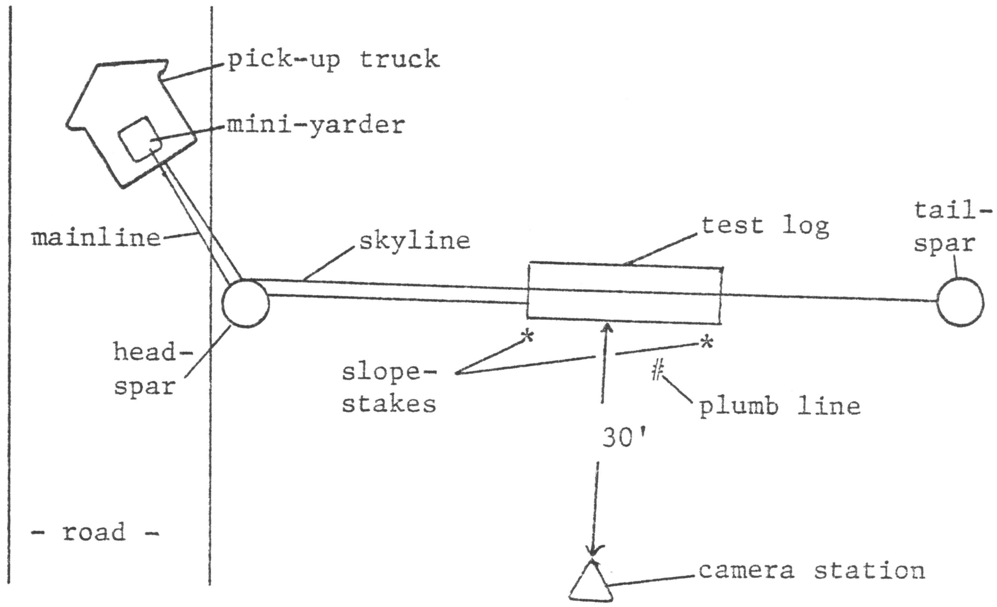

Figure 15. Schematic of test plot layout for the field data section.

Figure 16. Pickup truck and mini-yarder used to power the skyline and mainline on the test plots.

height of 29 feet (8.84 m.) in the headspar and then to the block simulating the carriage.

5. A 6 inch (15.24 cm.) rigging block was used to simulate a carriage on the skyline. This block was shackled to the skyline with the chokerline to the log hanging from it. The mainline was then attached to the block to provide power to yard the log across the plot (Figure 17).
6. Two stakes 4 feet (1.22 m.) long were driven into the ground 1 foot (30.48 cm.) at a distance of 3 feet (91.44 cm.) from the skyline on the side toward the camera station, and plumbed. The stakes were located 6 feet (1.83 m.) apart parallel to the skyline and perpendicular and centered on the line running between the camera station and the skyline (Figure 15). The stakes had marks 30 inches (76.20 cm.) above the ground which were digitized during data reduction to determine the slope of the plot.
7. The camera station consisted of a Nikkormat 35 mm. camera on a 4 foot (1.22 m.) leveled tripod. The axis of the camera was pointed toward a stake marking the center of the plot.
8. In order to determine the vertical, a plumb line was hung from a Peavy handle with a weight on the end of the line. Figure 14 shows the plumb line.
9. A rake was used to remove all vegetation from the plot directly under the skyline where the logs would travel during logging.
10. A blackboard was set in front of the skyline on which a numerical code was recorded for each sample taken.

Three logs were used in this portion of the study. They were obtained by falling a 15 inch (38.10 cm.) D.B.H. young growth Douglas-fir tree. The butt swell was cut off the butt end of the tree and the remainder was bucked into the three logs used. Table 6 lists the dimensional characteristics of these three logs. These three logs were used for all the initial field data collection on the plots in

Figure 17. Typical photograph sample for determining the static coefficient of drag resistance.

Table 6. Geometry of the Douglas-fir Logs Used for the Initial Field Data Collection.

Characteristic	Log Number		
	1	2	3
Top diameter (inches)	6.75	8.25	10.50
Butt diameter (inches)	8.50	10.50	15.00
Length (feet)	17.10	17.10	17.00
Weight (pounds)	294.00	530.00	777.00
Distance from butt to center of gravity (feet)	7.93	8.05	7.50

this study. They were moved from plot to plot by a flat bed trailer pulled behind a pickup (Figure 18). In order to verify the results from the initial field data, three different logs were obtained from a tree located near plot 4 using the same procedure. Table 7 lists the dimensions of these three logs.

The weight of each log and the distance to its center of gravity (c.g.) from the butt end was determined by hanging the log from the skyline with a short strap and a set of tongs. The tongs were moved back and forth until the log was balanced on its c.g. At this point, a dynamometer in the strap line was read and the length from the butt of the log to the tongs was measured (Figure 19). This procedure was repeated for each of the logs used in the study once prior and once after all the data were obtained. The average value was then used in the data reduction.

Figure 18. Flat bed trailer used to move the logs between plots.

Table 7. Geometry of the Douglas-fir Logs Used for the Verification Data.

Characteristic	Log Number		
	1	2	3
Top diameter (inches)	6.50	9.00	11.25
Butt diameter (inches)	8.75	11.00	12.75
Length (feet)	13.25	13.25	13.25
Weight (pounds)	233.00	380.00	530.00
Distance from butt to center of gravity (feet)	6.00	6.25	6.30

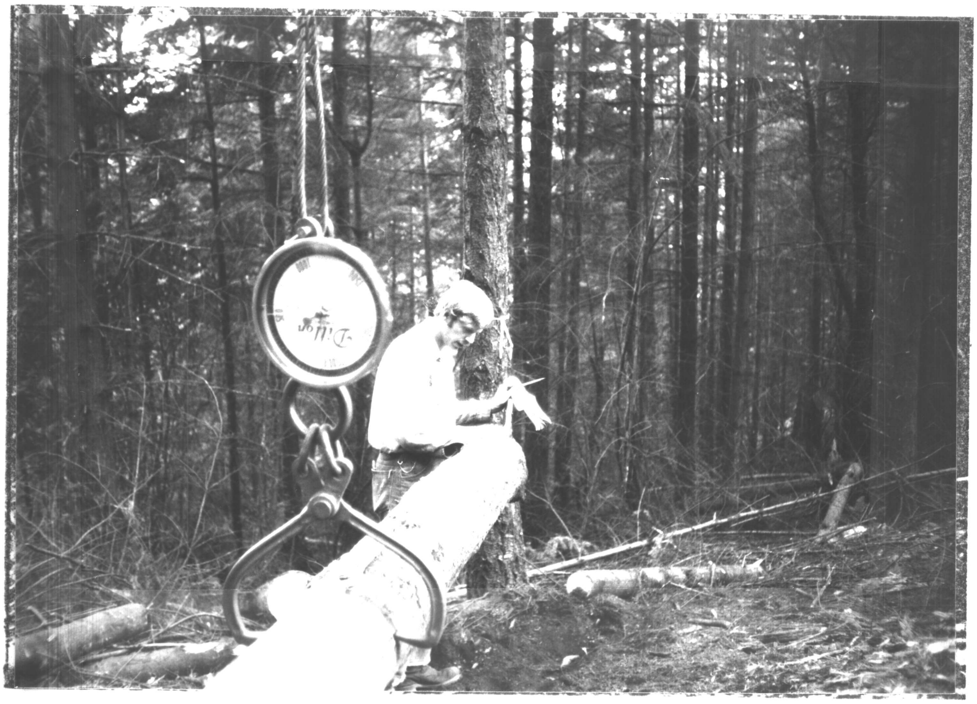

Figure 19. Weight and center of gravity (c.g.) of log being determined by hanging log at c.g.

Two different power sources were used to yard the logs across the plots. In the first portion of the field work, a mini-yarder mounted in the bed of a pickup truck was used to power the mainline (Figure 16). In this configuration the skyline was hitched to the rear bumper of the pickup truck so the truck was moved forward or backward to lower or raise the skyline. This system was used for data collection on plots 1, 2, and halfway through plot 3. On plot 3 the mini-yarder broke down. In order to continue data collection, another pickup truck was employed to power the mainline. This system was used for the rest of the initial field data collection on plots 3 and 4. During the collection of the verification data only the static μ case was considered. Therefore it was not necessary to have a powerful yarding system because the logs were not being dragged across the plot. Instead they were moved into impending motion which only required power enough to move the logs into position. In this portion of the study a winch mounted on a Toyota Land Cruiser was used to power the mainline (Figure 20).

Static Coefficient of Drag Resistance

In order to determine the value of the static μ for each plot, the following procedure was used:

1. The first log was rolled into position under the skyline. The skyline was then lowered so that a set of tongs on a strap from the carriage block could be attached near the top end of the log. The tongs were used instead of a choker for easier hooking and because they allowed the dynamometer in the strap line to be closer to the ground. This made for easier reading of the meter (Figure 17);
2. The skyline was then raised to obtain the desired log to ground angle. Each experiment set had a different log angle. No exact angles were used, but angles were classified as low, medium, and high;
3. The log was then moved near the center of the plot with the mainline;

Figure 20. Power winch mounted on a Toyota Land Cruiser used to power the mainline during verification data collection.

4. Tension was applied to the mainline until the log started to move. Then tension was manually applied by hanging on the mainline to bring the log into impending motion. At that point a photograph was taken and at the same time the meter in the strap line was read (Figures 17, 21 and 22).
5. The procedure in step 4 was repeated five times;
6. The skyline was adjusted to the two other log angles and the procedures in steps 3, 4, and 5 were repeated.
7. The skyline was then lowered and the log was rolled off to the side of the plot. The other two logs were tested using the same procedure, 1-6.

To summarize the above procedures, five sample photographs were taken of three logs at three different angles, for a total of 45 samples per plot. The only major exception to this procedure was on plot 3 where it was so steep that only two different log angles could be taken.

The data reduction to determine the value of μ for each photograph consisted of using the coefficient of drag resistance program on the

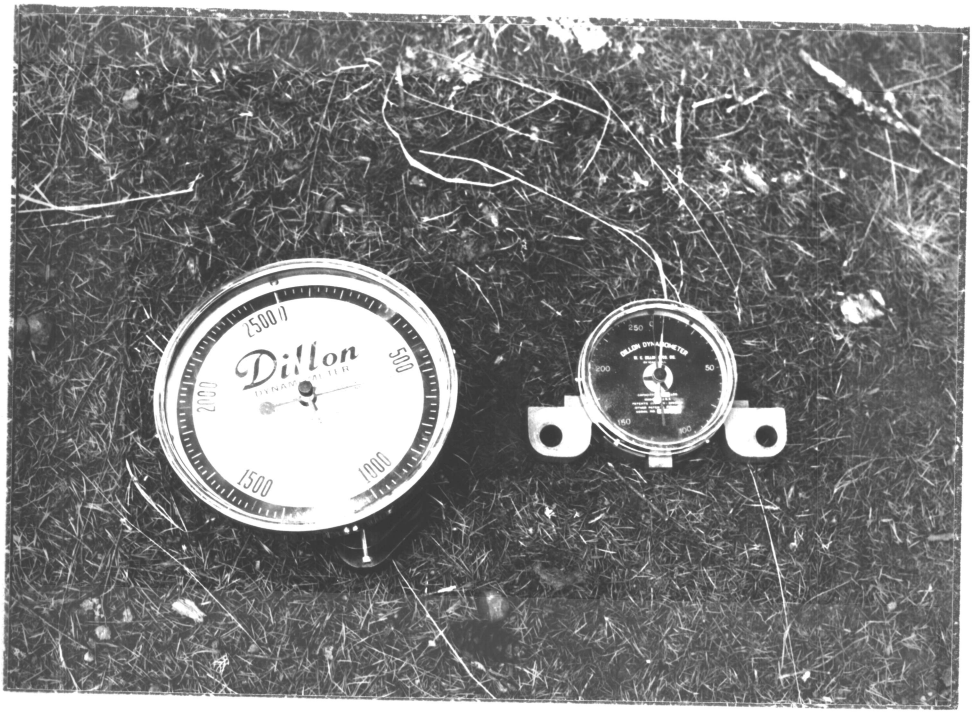

Figure 21. Dynamometers used to measure the tension in the chokerline. The meter on the right was used for log #1 and has a least reading of 5 pounds. The one on the left was used for logs #2 and #3 and has a least reading of 25 pounds. Both meters were calibrated before and after the tests.

Figure 22. Manual tension being applied to bring the log into impending motion for a static μ sample.

Hewlett-Packard 9830 desk top calculator/digitizer system (Appendix II). Each photograph was digitized five times and the mean value of μ was determined by two methods. The first method (1) was based on equation 6 and the second method (2) on equation 12. This allowed redundancy in the value of μ for this section of the study. It also offered a chance to verify the photographic method based on equation 6 which is suggested by the author for use in the field. A paired t-test was used to compare the two methods.

A hypothesis was formed that the coefficient of drag resistance was influenced by the following variables: soil moisture, soil density, soil texture, log to ground angle, log diameter, log weight, and ground slope. The stepwise procedure in the SIPS (Statistical Interactive Programming System) computer programs at Oregon State University was used to test the hypothesis and to determine regression coefficients.

Dynamic Coefficient of Drag Resistance

In order to determine the value of the dynamic μ for each plot the following procedure was used:

1. The first log was rolled under the skyline. The skyline was lowered and a choker was attached near the top end of the log;
2. The skyline was raised to the first desired log to ground angle. Again as in the static data three angle groups were used (low, medium, and high);
3. The mainline was slacked and the butt of the log was manually lifted and moved to the rear of the plot.
4. The mainline was then engaged at a constant speed and a photograph was taken as the log crossed the center of the plot.
5. Steps 3 and 4 were repeated five times.
6. The skyline was raised for the next two groups of log angles and procedure steps 3 and 4 were repeated.
7. Steps 1 - 4 were repeated for the other two logs.

This procedure was used on each of the four plots with the exception of plot 3 where only two log angles were used. Figure 23 is a sample photograph from this section on the dynamic μ.

Again the coefficient of drag resistance program was used to determine μ from each photograph. The analysis of the total was by basic statistics. Multiple regression analysis was attempted.

Verification Data

All data collected to verify the results of the initial field data were collected on plot 4. Only the static value of μ was determined in this section. Three new logs were cut to see if the results would hold for different logs. The procedures listed for static μ were used with only 2 log angles for each log and 20 rather than 5 samples for each log angle. The data were collected on a single day with 3 samples for soil moisture. Soil density was not determined.

Approximately three weeks after the above data were collected, another test was made with log number 6. This test was again on plot number 4, but it was just after a rain shower and the soil moisture

Figure 23. Typical photograph sample for determining the dynamic coefficient of drag resistance.

content was much higher than it had been during the previous tests. Two log to ground angles were taken and all data were collected for the static μ.

In order to verify the regression model developed in the initial field data section, a chi-squared test for goodness of fit was used to compare the verification data with results predicted by the regression equation.

Results

All results were obtained with the aid of Oregon State University's Control Data Corporation 3300 computer or the Forest Engineering Department's Hewlett-Packard 9830 system.

Static Coefficient of Drag Resistance

Figures 24 and 25 are histograms showing the results of all the data taken in the initial field trials to determine static μ using the two different measuring methods. The data in Figure 24 were collected by method 1 which utilizes the angles α, β, and Θ from the photograph and the log geometry to calculate μ. Each sample photograph was also analyzed using method 2 whereby the tension in the choker line and the weight of the log are used in combination with the angles α and Θ taken from the photograph to calculate μ (Figure 25). A paired t-test was conducted which indicated there is no significant difference in the mean value of μ for the two methods (Table 8).

Table 9 shows a summary of the results from the data collected to determine the static coefficient of drag resistance. Appendix IV has the histograms of the data summarized by plot number and log number. When combining all data on the static tests it was determined that an overall mean of 0.616 was obtained for μ. The standard deviation as a percent of the mean was 41%.

The following regression equations were developed using the stepwise

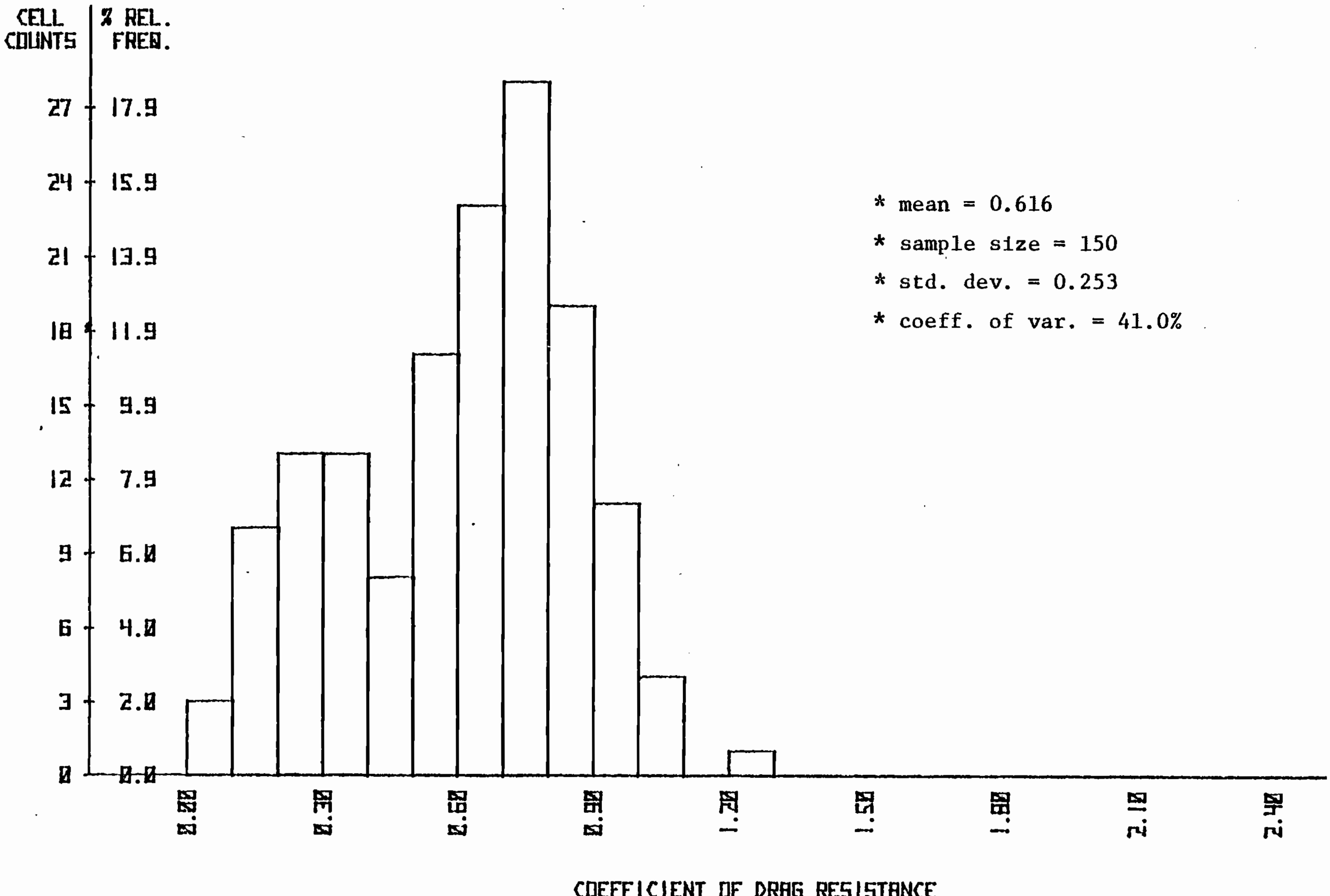

Figure 24. Histogram of initial field data for the static coefficient of drag resistance using method 1.

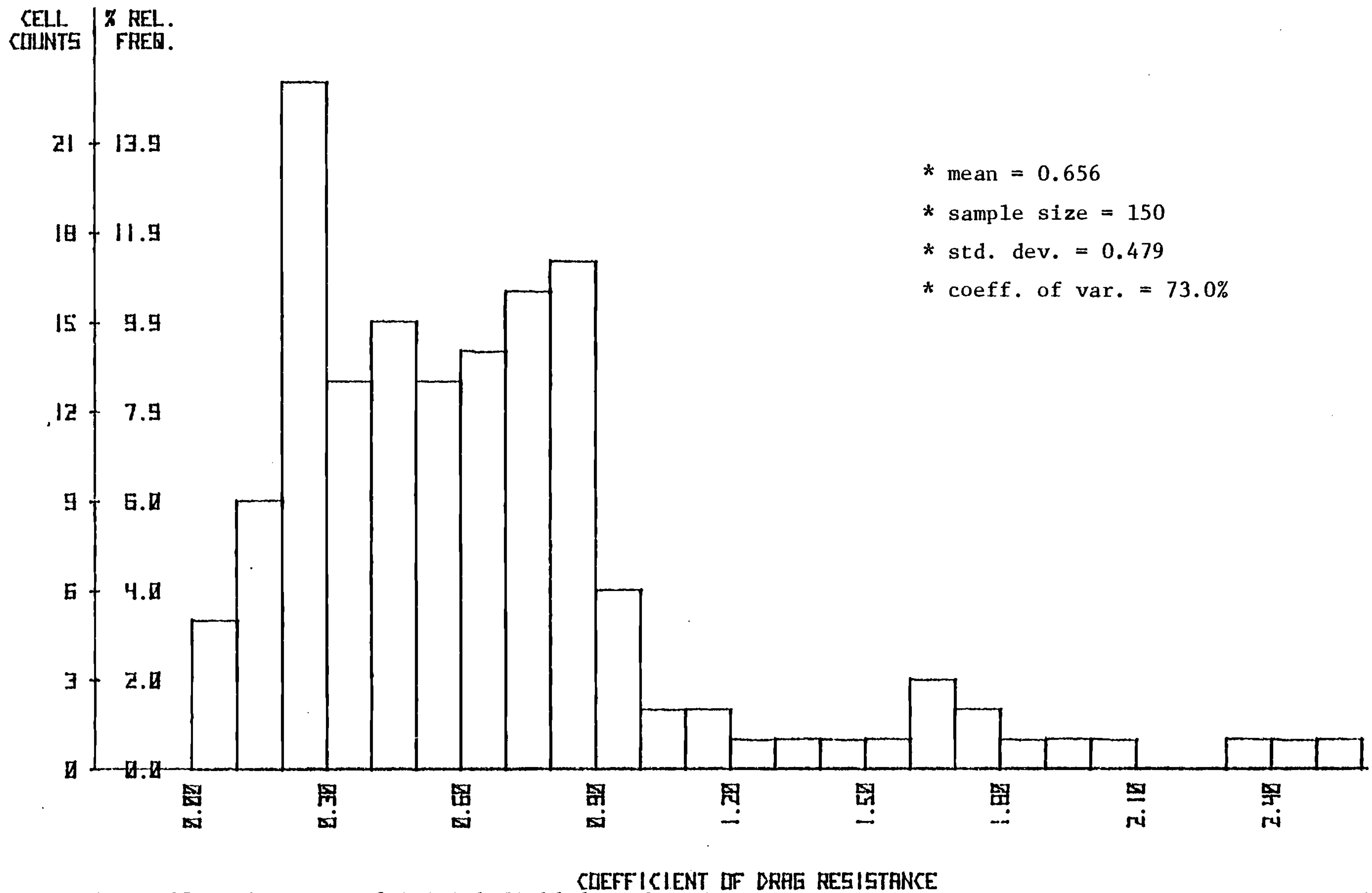

Figure 25. Histogram of initial field data for the static coefficient of drag resistance using method 2.

Table 8. Results From a Paired T-test for Comparison of the Two Measuring Methods Used for the Static Data From the Initial Field Data Section.

	Method 1 μ		Method 2 μ
Sample Size	150.000		150.000
Mean	0.616		0.656
Std. Err. of the Mean	0.021		0.039
Variance	0.064		0.229
Standard Deviation	0.253		0.479
Range	1.170		2.510
Mean Difference		-0.054	
Std. Err. of Difference		0.031	
T-Value		-1.707	
Degrees of Freedom		149.000	
T-Table Value at (.95)		1.960	
T-Table Value at (.99)		2.575	

Ho: $\mu_d = 0$

Ha: $\mu_d = 0$

Since t-value < t-table value at $\alpha = 0.01$, df = 149

Therefore: Fail to reject Ho

Table 9. Summary of Results for the Static Coefficient of Drag Resistance on Forest Soils.

Plot #	Exp. #	Log #	Avg. β (deg.)	% Slope	Coefficient of Drag Resistance Mean	Sample Size	Standard Dev.
1	1	1	10.01	31%	0.126	5	0.064
1	2	1	16.13	31%	0.108	5	0.085
1	3	1	23.60	31%	0.291	5	0.174
1	*	1	—	31%	0.199	15	0.130
1	4	2	12.26	31%	0.300	5	0.134
1	5	2	14.95	31%	0.327	5	0.132
1	6	2	21.83	31%	0.322	5	0.045
1	*	2	—	31%	0.367	15	0.134
1	7	3	13.03	31%	0.532	5	0.537
1	8	3	14.20	31%	0.324	5	0.058
1	9	3	21.83	31%	0.322	5	0.045
1	*	3	—	31%	0.406	15	0.314
1	**	—	—	31%	0.324	45	0.227
2	10	1	11.68	10%	0.627	5	0.065
2	11	1	15.62	10%	0.765	5	0.055
2	12	1	31.84	10%	0.764	5	0.277
2	*	1	—	10%	0.719	15	0.168
2	13	3	9.78	10%	0.816	5	0.124
2	14	3	21.84	10%	0.822	5	0.118
2	15	3	29.62	10%	0.623	5	0.139
2	*	3	—	10%	0.750	15	0.150
2	**	—	—	10%	0.724	30	0.158
3	16	1	7.56	56%	0.716	5	0.267
3	17	1	21.30	56%	0.404	5	0.070
3	*	1	—	56%	0.560	10	0.247
3	18	2	10.71	56%	0.878	5	0.196
3	19	2	17.20	56%	0.893	5	0.142
3	*	2	—	56%	0.885	10	0.162
3	20	3	11.47	56%	0.717	5	0.050
3	21	3	16.08	56%	0.777	5	0.170
3	*	3	—	56%	0.747	10	0.122
3	**	—	—	56%	0.731	30	0.224
4	22	1	13.63	24%	0.786	5	0.008
4	23	1	21.00	24%	0.595	5	0.047
4	24	1	32.97	24%	0.669	5	0.040
4	*	—	—	24%	0.673	15	0.088
4	25	2	14.66	24%	0.721	5	0.025
4	26	2	23.40	24%	0.716	5	0.095
4	27	2	40.32	24%	0.912	5	0.038
4	*	—	—	24%	0.773	15	0.110
4	28	3	14.88	24%	0.735	5	0.072
4	29	3	23.05	24%	0.089	5	0.127
4	30	3	38.18	24%	0.914	5	0.118
4	*	—	—	24%	0.819	15	0.109
4	**	—	—	24%	0.760	45	0.116
—	***		—	—	0.616	150	0.253

* Summary of results by log

** Summary of results by plot

*** Summary of all results

procedure from the static μ field data.[4]

In the regression equations that follow:

SOIL*MC = percent soil moisture content (%).

SLOPEQNG = ground slope (degrees).

L-DIA*WT = log aft diameter multiplied by log weight (in. - lbs.)

SOILTYPE = 0/1 variable, 0 for granular soils, 1 for fine-grained soils.

LOGANGLE = angle of the log to the soil (degrees).

SOIL*DEN = soil density of top 6 inches (15.24 cm.) (g/cc).

MU*DRAG = static coefficient of drag resistance.

STEPWISE PROCEDURE

$$\text{MU*DRAG} = 0.98510 - 0.013229\ (\text{SOIL*MC})^{*} \qquad (13)$$

$$r^2 = 0.466$$

$$s = 0.185$$

Figure 26 has a plot of this relationship for the sample data.

$$\text{MU*DRAG} = 1.204 - 0.012756\ (\text{SLOPEANG})^{*} - 0.013870\ (\text{SOIL*MC})^{*} \qquad (14)$$

$$r^2 = 0.592$$

$$s = 0.162$$

$$\text{MU*DRAG} = 1.1432 - 0.012617\ (\text{SLOPEANG})^{*} - 0.013507\ (\text{SOIL*MC})^{*} \qquad (15)$$

---

4. In the regression equations:

* indicates significance of a variable at the 0.01 probability level.

** indicates significance of a variable at the 0.05 probability level.

*** indicates significance of a variable at the 0.10 probability level.

**** indicates significance of a variable at the 0.20 probability level.

r^2 is the coefficient of determination.

s is the standard error of the regression equation.

Computer output is in Appendix IV.

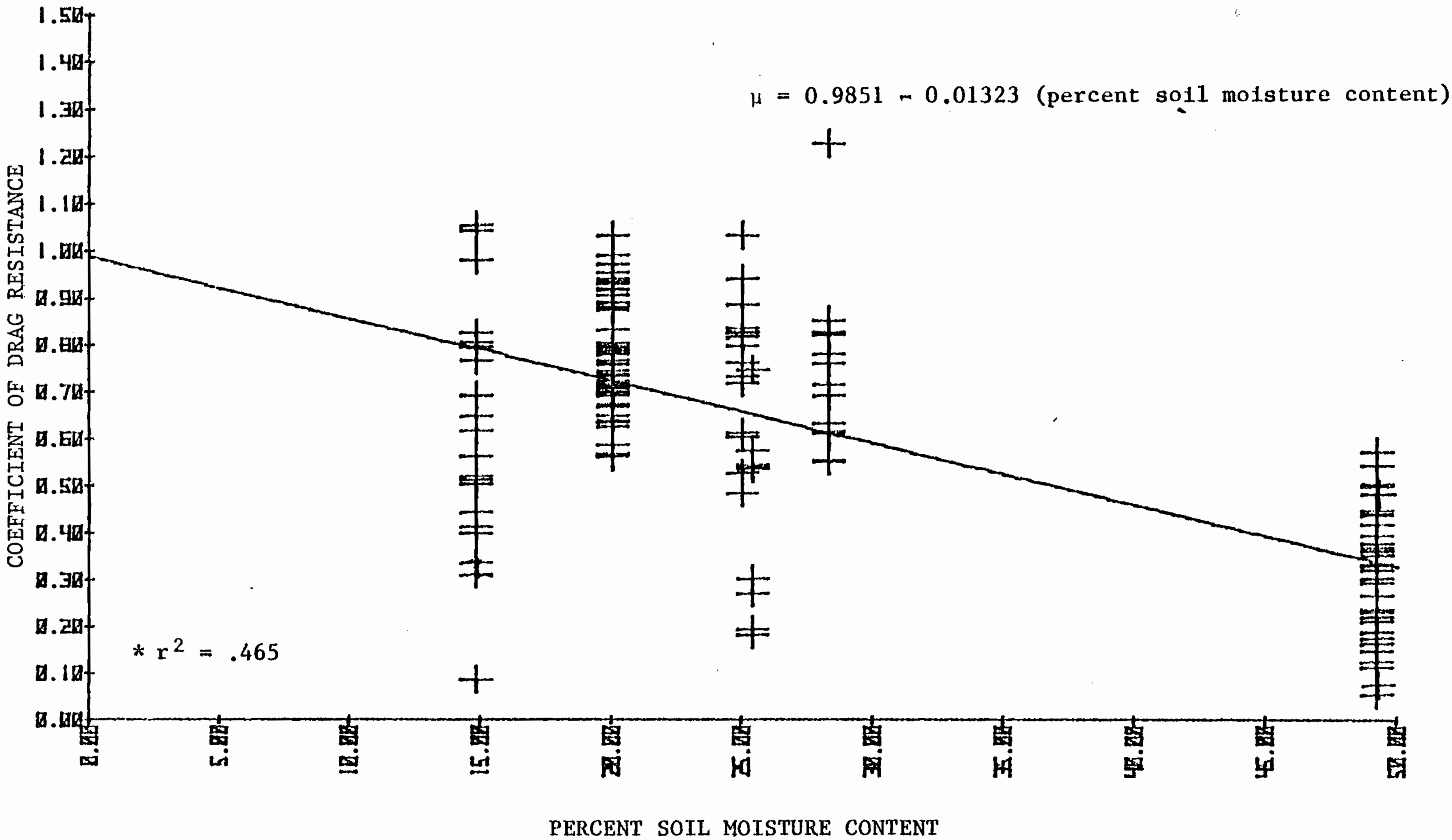

Figure 26. Relationship between percent soil moisture content and the static coefficient of drag resistance.

+ 0.000007014 (L-DIA*WT)**

r^2 = 0.616

s = 0.159

MU*DRAG = 1.1335 - 0.012592 (SLOPEANG)* (16)

- 0.014456 (SOIL*MC)*

+ 0.060552 (SOILTYPE)**

+ 0.0000070672 (L-DIA*WT)**

r^2 = 0.616

s = 0.159

MU*DRAG = 1.0812 + 0.0020483 (LOGANGLE)**** (17)

- 0.011935 (SLOPEANG)*

- 0.014093 (SLOPE*MC)*

+ 0.049307 (SOILTYPE)****

+ 0.0000066683 (L-DIA*WT)**

r^2 = 0.620

s = 0.158

MU*DRAG = 1.1852 + 0.0021653 (LOGANGLE)**** (18)

- 0.014811 (SLOPEANG)**

- 0.014292 (SOIL*MC)*

- 0.057473 (SOIL*DEN)*

+ 0.038409 (SOILTYPE)*

+ 0.0000074853 (L-DIA*WT)***

The log weight and diameter on the aft end of the log had to be entered as a product because of the high correlation between the two independent variables.

The second set of data collected on plot 4 was used in an effort to verify the regression equations. Figures 27 and 28 are histograms of the results of the verification data collected on plot 4 for two different moisture contents. In order to compare the observed values with what was expected from the regression equation, the following statistic was used:

$$\text{(chi-square)} \quad \chi^2 \quad \sum^{K} \frac{(f_i-F_i)^2}{F_i}$$

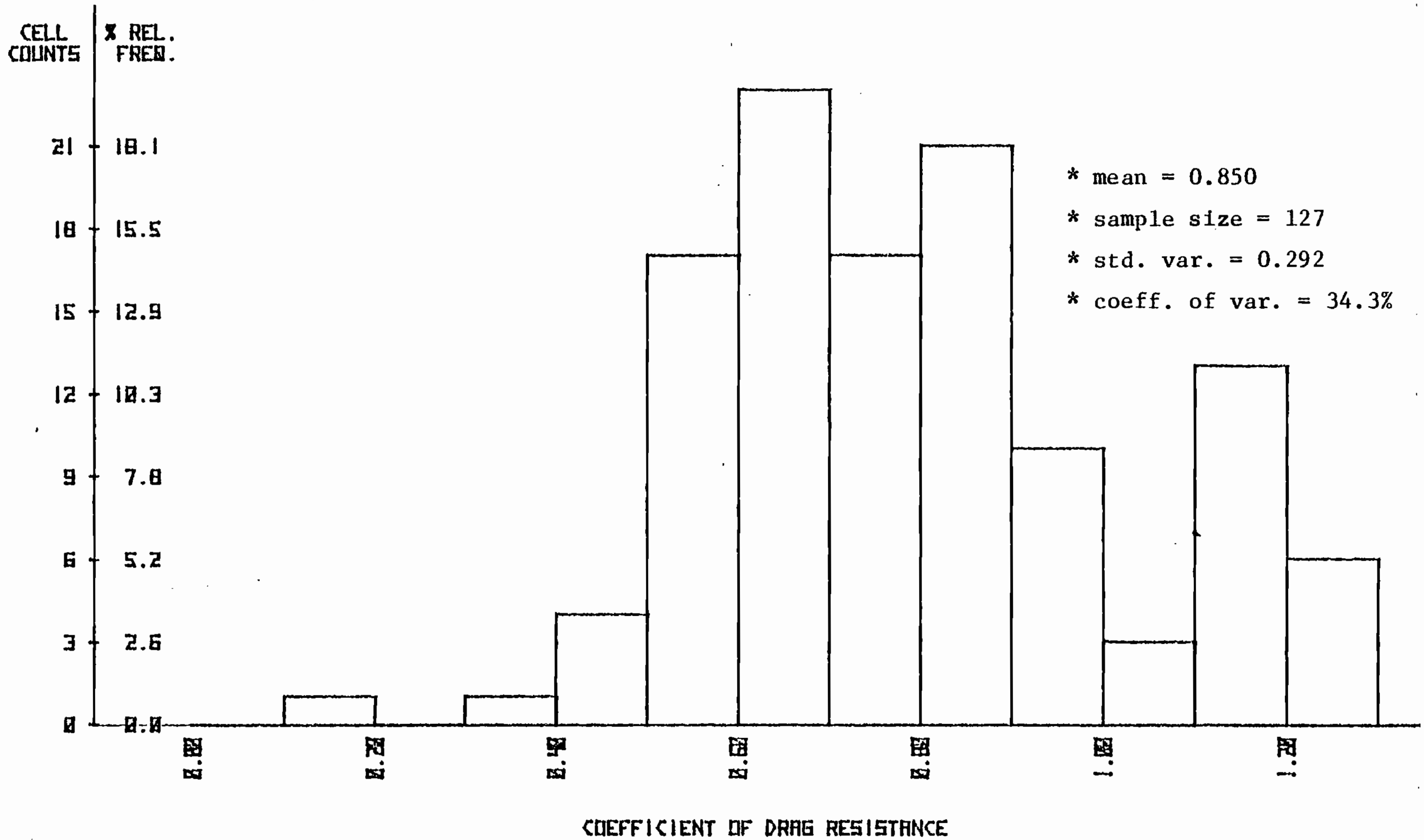

Figure 27. Histogram of the verification data collected on plot 4, 29% soil moisture content, log numbers 4, 5, and 6.

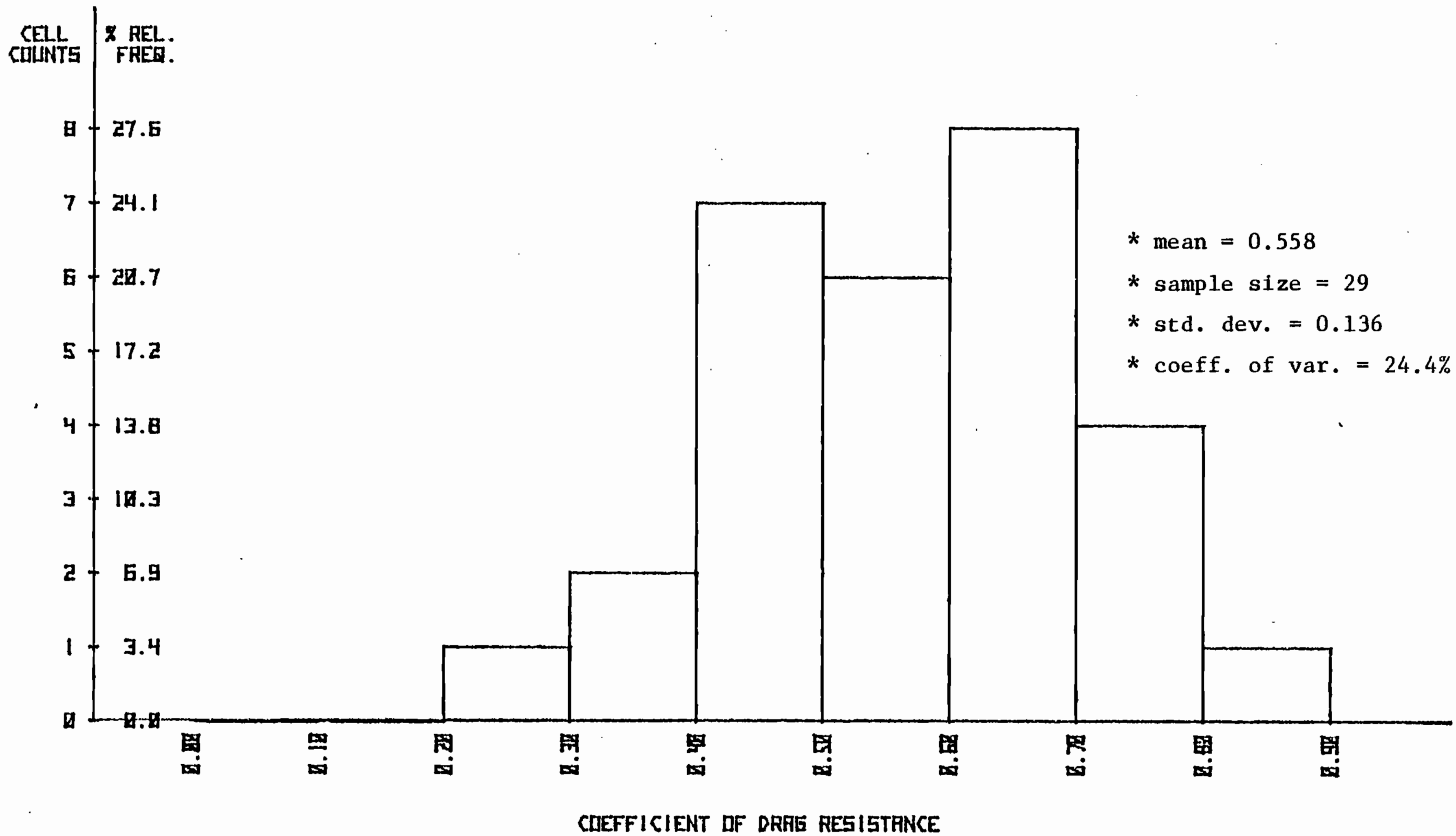

Figure 28. Histogram of the verification data collected on plot 4, 48.6% soil moisture content, log number 6.

Here f_i is the value of μ determined by measuring a sample in the verification data using method 1. F_i is the expected value of μ from a regression model formulated from the initial field data for static μ. The following null hypothesis was formulated to test each regression equation.

Ho: The sample data came from a population of μ that can be represented by the regression model.

Ha: The sample data came from a population of μ that is not represented by the regression model.

Regression equations (13) - (17) were found to represent the sample verification data at $\alpha = 0.05$ level. Equation (18) was not verified because the soil density was not taken for the verification runs.

Dynamic Coefficient of Drag Resistance

Figure 29 is a histogram of the results of all data for determining the dynamic coefficient of drag resistance on the test plots. The grand mean of a data was 1.233 with a standard deviation of 0.799. This represents a coefficient of variation of 64.8%. In an attempt to identify this large variation, the data were grouped by log to ground angles, log number, and plot number (Table 10). Table 10 indicates coefficients of variation up to 87%. Regression analysis was attempted with the highest $r^2 = 0.072$ and not significant at the $\alpha = 0.20$ level. Even the relationship of μ to the soil moisture content showed an unrealistic trend of μ decreasing as the soil moisture content increases (Figure 30).

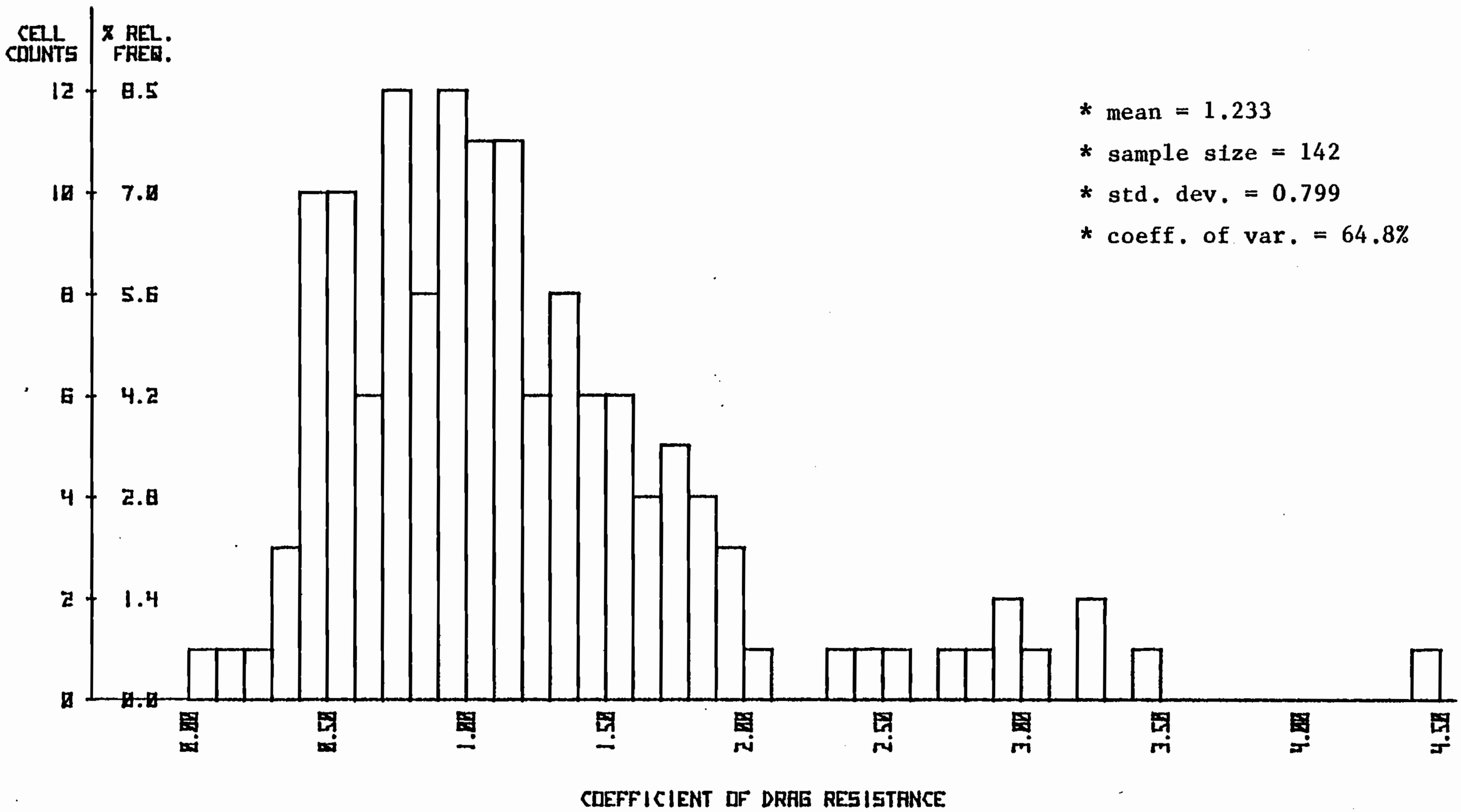

Figure 29. Histogram of all dynamic μ data collected on the field plots.

Table 10. Summary of Results for the Dynamic Coefficient of Drag Resistance on Forest Soils.

Plot #	Exp. #	Log #	Avg. β (deg.)	% Slope	Coefficient of Drag Resistance Mean	Sample Size	Standard Dev.
1	1	1	13.38	31%	0.502	2	0.104
1	2	1	21.08	31%	0.863	4	0.474
1	3	1	19.27	31%	2.664	2	0.479
1	*	1	—	31%	1.223	8	0.973
1	4	2	16.10	31%	1.479	5	1.096
1	5	2	20.11	31%	2.954	5	1.579
1	*	2	—	31%	2.216	10	1.493
1	6	3	12.07	31%	0.769	4	0.218
1	7	3	13.20	31%	1.316	5	0.418
1	8	3	27.81	31%	1.072	5	0.401
1	*	3	—	31%	1.072	14	0.406
1	**	—	—	31%	1.469	32	1.096
2	9	1	15.16	10%	1.151	5	0.215
2	10	1	25.58	10%	0.849	5	0.623
2	11	1	31.60	10%	0.858	5	0.753
2	*	1	—	10%	0.953	15	0.554
2	12	2	10.76	10%	1.047	5	0.089
2	13	2	19.28	10%	1.067	5	0.245
2	14	2	34.46	10%	1.849	5	1.604
2	*	—	—	10%	1.321	15	0.951
2	15	3	9.58	10%	1.321	5	0.951
2	16	3	22.09	10%	0.996	5	0.327
2	17	3	39.09	10%	1.052	5	0.972
2	*	3	—	10%	1.060	15	0.555
2	**	—	—	10%	1.111	45	0.713
3	18	1	13.73	56%	1.528	3	0.244
3	19	1	16.53	56%	1.051	3	0.634
3	*	1	—	56%	1.289	6	0.503
3	20	2	14.67	56%	1.221	5	0.831
3	21	2	18.04	56%	1.237	5	0.308
3	*	2	—	56%	1.229	10	0.591
3	22	3	12.93	56%	0.591	5	0.234
3	23	3	11.04	56%	0.805	5	0.349
3	*	3	—	56%	0.698	10	0.302
3	**	—	—	56%	1.034	26	0.534
4	24	1	11.12	24%	0.702	4	0.154
4	25	1	24.21	24%	0.988	5	0.625
4	26	1	40.74	24%	0.949	5	0.381
4	*	1	—	24%	0.892	14	0.432
4	27	2	16.43	24%	1.092	5	0.301
4	28	2	27.03	24%	1.449	5	0.437
4	29	2	41.21	24%	1.605	2	1.813
4	*	2	—	24%	1.326	12	0.669
4	30	3	13.20	24%	1.735	5	0.150
4	31	3	18.23	24%	1.595	5	0.923
4	32	3	34.61	24%	2.036	3	1.306
4	*	3	—	24%	1.751	13	0.779
4	**	—	—	24%	1.312	39	0.718
—	***	—	—	—	1.233	142	0.799

* Summary of results by log
** Summary of results by plot
*** Summary of all results

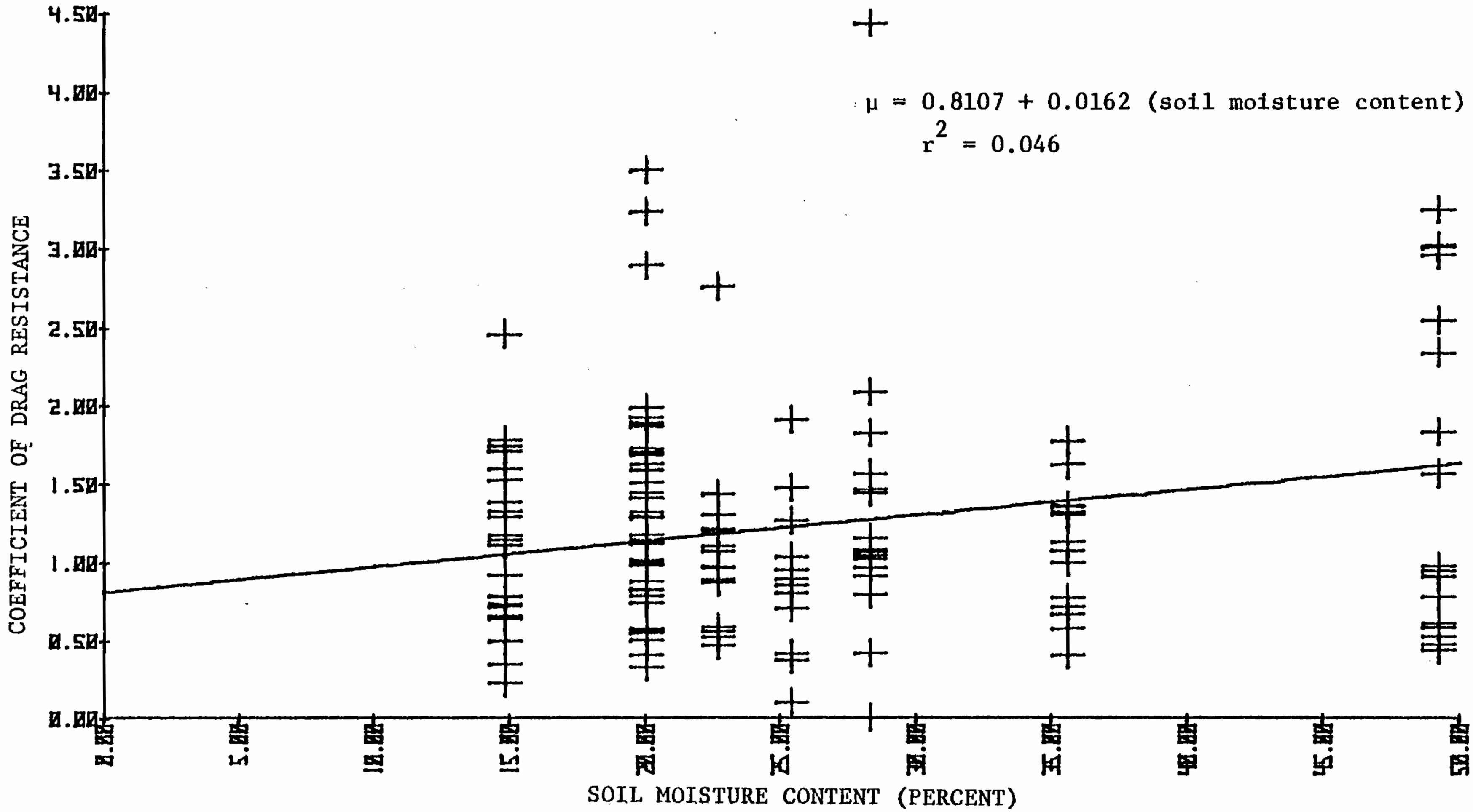

Figure 30. Relationship of the dynamic coefficient of drag resistance to percent soil moisture content.

Discussion

An analysis of the results of this study reveals that a large amount of variation can be expected when determining the coefficient of drag resistance, either static or dynamic. The amount of variation found in this study can be divided into three major sources. The first source of variation is due to the physical relationships occurring between the log and the soil. The understanding of the influence of these physical factors on the coefficient of drag resistance was the primary concern in this portion of the study. Certain factors were isolated and analyzed to determine whether their influence on μ could be modeled in order to permit predictions of μ for a given set of physical conditions.

The second and third sources of variation were unique to the determination of μ for this study. The method of determining μ consisted of two phases. The first phase of measurement was the recording of the log-ground geometry photographically. The variation occurring in this phase was attributed to the possibility that the log geometry recorded on the photograph did not represent the true geometry which would occur under equilibrium conditions for a particular value of μ. This would result if the log was under any sort of dynamic acceleration at the instant the photograph was taken. To be valid, the mathematical model for determining μ requires that dynamic acceleration be equal to zero. In the case of the static μ variation would arise if the photograph recorded the log-ground geometry under any condition other than impending motion. When a force is applied to a log through a chokerline, the magnitude of this force will vary continuously from zero to a value sufficient to move the log. If this force is increased, the log geometry will be changed continuously until the log begins to move. During the instant just prior to log movement the log is in a condition of impending motion. If the log geometry was not recorded at this instant, the value of μ determined from the photograph would be something other than the true static μ.

The second phase in the determination of μ was the data reduction of the photograph itself. The photograph had recorded the actual log-ground geometry at the instant it was taken. However, it was necessary to measure this geometry from the photograph, and this introduces the possibility of measurement error. In this study the angles were measured by digitizing the photograph to determine coordinates which represented the geometry (appendix II). In order to reduce the possibility of large errors, the photograph was digitized five times and the mean was used. These repeated measurements on the photograph represent the third source of variation in data reduction.

Table 11 shows a comparison of the variation in the data for μ between sets of photographs taken under static and dynamic conditions. The table shows the variation for a typical set of five sample photographs. In both the static and dynamic data sets the five photographs were taken on the same soil conditions with the same log and with the skyline at the same height, which in turn holds the log to ground angle fairly constant. On each photograph in table 11 the mean and standard deviation are shown. Just below each computed standard deviation there is a predicted standard deviation from the following equation.

$$s_\mu = \sqrt{\{\frac{\partial \mu}{\partial \alpha} s\alpha\}^2 + \{\frac{\partial \mu}{\partial \theta} s\theta\}^2 + \{\frac{\partial \mu}{\partial \beta} s\beta\}^2} \quad \text{(Holman,1971)}$$

where:

s_μ = expected standard deviation of μ for a photograph.

$\frac{\partial \mu}{\partial i}$ = partial derivatives of μ (equation 6) with respect to the $_i$th variable, $i = \alpha, \beta, \& \ \theta$.

s_i = the standard deviation computed for measurement of angle i from the photograph.

Table 11. Comparison of the variation in data for μ between static and dynamic.

STATIC				DYNAMIC			
	Photo #1				Photo #1		
Digitize #	α	β	μ	Digitize #	α	β	μ
1	14.23	20.82	0.601	1	18.79	27.19	1.481
2	13.31	20.82	0.458	2	20.02	27.44	1.832
3	15.16	20.94	0.765	3	18.85	27.31	1.488
4	12.99	20.94	0.358	4	19.08	27.31	1.558
5	13.03	20.94	0.332	5	19.63	27.60	1.710
$\bar{x}$	13.74	20.89	0.503	$\bar{x}$	19.27	27.37	1.614
s	0.94	0.06	0.181	s	0.53	0.16	0.153
		Predicted	(0.235)			Predicted	(0.181)
	Photo #2				Photo #2		
Digitize #	α	β	μ	Digitize #	α	β	μ
1	12.80	21.35	0.350	1	20.75	28.12	2.521
2	13.50	21.30	0.476	2	21.36	27.46	2.858
3	13.37	21.50	0.458	3	20.94	27.45	2.610
4	12.92	21.33	0.373	4	21.15	27.61	2.758
5	12.80	21.07	0.337	5	20.70	27.80	2.460
$\bar{x}$	13.08	21.37	0.399	$\bar{x}$	20.98	27.69	2.460
s	0.34	0.15	0.064	s	0.28	0.28	0.165
		Predicted	(0.071)			Predicted	(0.221)
	Photo #3				Photo #3		
Digitize #	α	β	μ	Digtize #	α	β	μ
1	12.67	21.64	0.355	1	18.10	25.89	1.121
2	13.34	21.38	0.428	2	17.95	26.14	1.065
3	13.34	21.50	0.435	3	17.80	26.03	1.067
4	13.34	21.27	0.422	4	17.54	26.52	1.038
5	14.29	21.50	0.573	5	17.80	25.99	1.063
$\bar{x}$	13.40	21.46	0.443	$\bar{x}$	17.84	26.11	1.071
s	0.58	0.14	0.080	s	0.21	0.24	0.030
		Predicted	(0.149)			Predicted	(0.059)
	Photo #4				Photo #4		
Digitize #	α	β	μ	Digitize #	α	β	μ
1	13.61	21.33	0.499	1	18.02	26.06	0.971
2	13.17	21.13	0.408	2	17.35	26.35	0.895
3	13.17	21.23	0.414	3	18.11	26.27	1.001
4	12.59	21.42	0.322	4	17.35	26.35	0.895
5	13.17	21.33	0.417	5	17.30	26.56	0.902
$\bar{x}$	13.14	21.29	0.412	$\bar{x}$	17.62	26.32	0.932
s	0.36	0.11	0.063	s	0.40	0.18	0.050
		Predicted	(0.076)			Predicted	(0.075)
	Photo #5				Photo #5		
Digitize #	α	β	μ	Digitize #	α	β	μ
1	12.05	21.47	0.254	1	19.79	27.82	1.760
2	12.97	21.52	0.374	2	20.20	28.06	1.974
3	12.02	21.57	0.254	3	19.96	28.27	1.888
4	13.11	21.53	0.399	4	19.96	28.17	1.898
5	12.16	21.53	0.072	5	20.16	28.30	1.978
$\bar{x}$	12.46	21.53	0.311	$\bar{x}$	20.02	28.12	1.900
s	0.53	0.03	0.070	s	0.17	0.20	0.089
		Predicted	(0.114)			Predicted	(0.074)

SUMMARY OF THE MEANS FOR EACH PHOTO

	$\bar{x}$	s		$\bar{x}$	s
α	13.16	0.47	α	19.15	1.43
β	21.30	0.26	β	27.12	0.87
μ	0.404	0.101	μ	1.595	0.624

In comparing the predicted and computed standard deviations for each photograph it is evident that the actual variation is generally less than what was predicted. In other words, the variation obtained in digitizing a photograph is within what would be expected under random conditions. Therefore it can be assumed that the errors associated with reducing the photograph data are random in nature. In general it can be stated that the variation in reducing the photograph data is a small component of the large variation found in the study.

Table 11 can also be used to analyze the component of variation associated with the photograph recording the true log-ground geometry for a specific value of μ. The summary for the means of each photograph shows that there is greater variation between sample photographs for dynamic μ than for static μ. In general this was the case for all data in the study. This is seen in a comparison of the distributions between the static data and the dynamic data for the field plot study (figure 24 and 29). The major reason for this higher variation in the dynamic data is that the probability that a dynamic log was photographed under acceleration was greater than the probability that a static log was photographed at some instant other than the point of impending motion. This can be attributed in part to the field prodedures. During the study two different power sources were used to yard the logs over the plots. One of these was a mini-yarder which did not seem to have enough power to sustain the yarded log at a constant velocity while moving across the plot.

It was observed during the study that logs yarded by the mini-yarder oscillated up and down as they moved across the plot. This oscillation apparently resulted from some sort of dynamic response of the log. An analysis of the dynamics of a yarded log was not part of this study. It had been assumed that the power source would be able to yard a test log at a constant velocity. This assumption had been reinforced by the favorable results from the terrain model section of the study. Although the actual values for μ in that section were not useful, the amount of variation indicated that it was possible to use the photographic method to measure the dynamic μ. It is possible that the ratio of yarder power to log weight was greater than that on the field plots, but this factor was not measured. In any case, the results were very reasonable using the method.

The second power system used to yard the test logs on the plots was a pickup truck with the mainline hitched to the rear bumper. This system was used for experiments number 22 through 32 in Table 10. The truck had more than enough power to yard the logs, but it was difficult to maintain a constant speed on the mainline. The truck would accelerate for half the length of the plot and then it would have to rapidly decelerate to keep from running the log into the headspar. This caused the log to oscillate heavily.

It was observed for both power systems that the test logs seldomly moved smoothly across the plots. This violated an important assumption on which the measurement method was based. Because of this, the results on the dynamic μ were not valid. This was also evident from a comparison of the static versus dynamic results. The dynamic μ for a given set of conditions was always higher than the static μ for the same conditions. When dealing with Coulomb friction, the dynamic coefficient of friction is always lower than the static coefficient of friction (Meriam, 1975). This should also hold true for the coefficient of drag resistance.

The above discussion does not mean that all of the data collected for the dynamic μ are invalid. However, because there is no means for determining whether an individual sample log run experienced acceleration at the time the photograph was taken, it must be concluded that the total collection of data obtained for the dynamic case cannot be used.

The experimental method developed here may have applicability in field conditions where small logs are yarded with large equipment. Visual indicators that the method may be successful are non-oscillating yarded logs and relatively constant log angles and chokerline angle over at least a short distance.

Tables 9 and 10 summarize the results of all the field data collected. In analyzing the sample size in the tables for each experiment, it is observed that some of the experiments do not record the five samples taken in the field. The missing data was attributed to two sources. First, some photographs were destroyed in developing the film, and second, on some photographs there was too much glare to read the blackboard code. The code was the link between the photograph sample and the conditions occurring when the sample was taken. The missing samples were not retaken because by the time the missing data was discovered, it was impossible to recreate the exact situation that occurred for the missing data. Fortunately the losses were small.

When analyzing the validity of the data collected for determining static μ, there was a check on the measurement method because the tension in the chokerline was measured for each sample. This allowed independent calculations of the static μ. In a comparison test it was determined that there was no significant difference between the means of the paired static μ data by the two measurement methods (Table 8). This not only suggests that the static data is valid, but also increases confidence that the photographic technique would work for determining the dynamic μ if the true log-ground geometry was recorded at the instant the photographic sample was taken. Due to this non-significant difference between the measurement methods, all further analysis was performed on the data collected using the results of Method 1 which was a function of log geometry and the angles α, β, and θ.

The regression equations developed were an attempt to relate the variability in μ to certain physical factors. As expected, it was impossible to develop a significant regression equation for the dynamic μ data even at the highest probability level allowed ($\alpha = 0.020$).

A stepwise procedure was used to develop several useful equations for the static μ data. The major portion of the variation in the data was explained by soil moisture, which was the first variable to enter the regression mode. The high influence of soil moisture on the value of μ had been identified by previous researchers and also follows what would be expected from soil mechanics (Bennett, 1962.)

APPLICATION OF RESULTS

The major practical use for the value of μ is in the calculation of the log load capacity of a yarding system. The value used is usually for the dynamic μ. The variability in the results of the dynamic μ for this study and the high probability that they are invalid suggests that they should not be used. As the value of μ increases, the load capacity of a yarding system decreases (Figure 1). When the static μ is used in the load capacity calculations rather than the dynamic μ, the log load capacity obtained will be conservative because the static value of μ should be higher than the dynamic value. The results for the static μ in this study show considerable variation. However, 45.6% of this variation was explained by soil moisture (Figure 26). For practical purposes it is suggested that at least the moisture content of the soil be considered when predicting a value of μ. Equation 13 was used in determining μ for Figures 31, 32, and 33 which show the load factor for typical logging. Geometricies under wet, moderate, and dry soil moisture conditions (50%, 35% and 20% moisture contents respectively). The logging engineer can use these figures to determine the amount of increase in net log load capacity that can be obtained by dragging the logs versus flying them with a skyline logging system.

The second equation developed (equation 14) includes the effect of ground slope as well as soil moisture.[5] This equation should only be applied for the case of uphill yarding because it was developed under uphill yarding conditions only. This equation could have been used in place of equation 13 in developing Figures 31, 32, and 33 but it would have only been valid for the uphill yarding side of the graphs. This equation could be integrated into some of the skyline analysis programs available (Carson, 1975). Many of the programs work from a profile of the ground stores in memory as coordinates. Any set of two profile coordinates could be used to calculate the slope

5) This equation accounted for 59.2% of the variation in the data for μ.

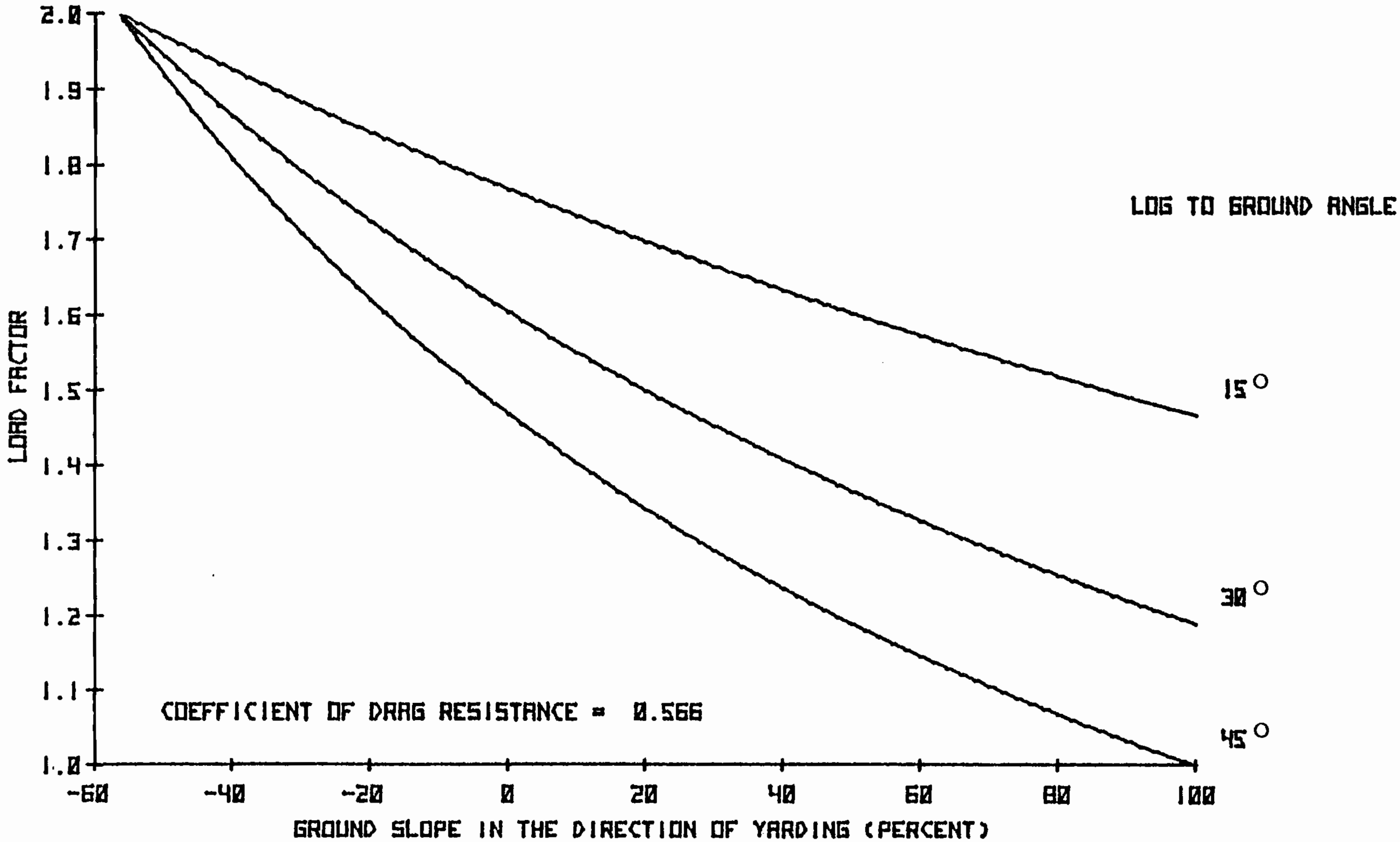

Figure 31. Load increase factor for skyline yarding under wet soil moisture conditions (50%).

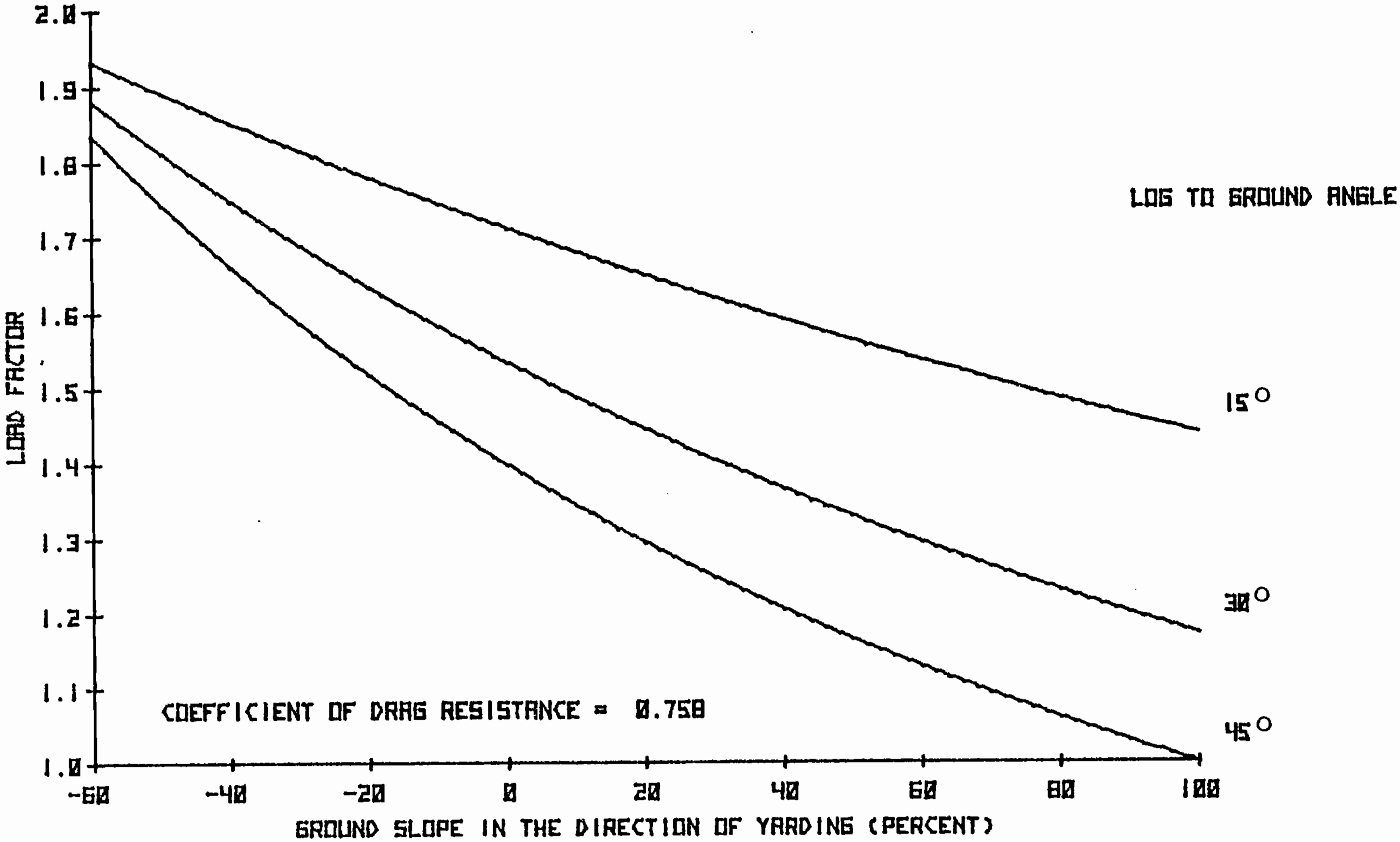

Figure 32. Load increase factor for skyline yarding under moderate soil moisture conditions (35%).

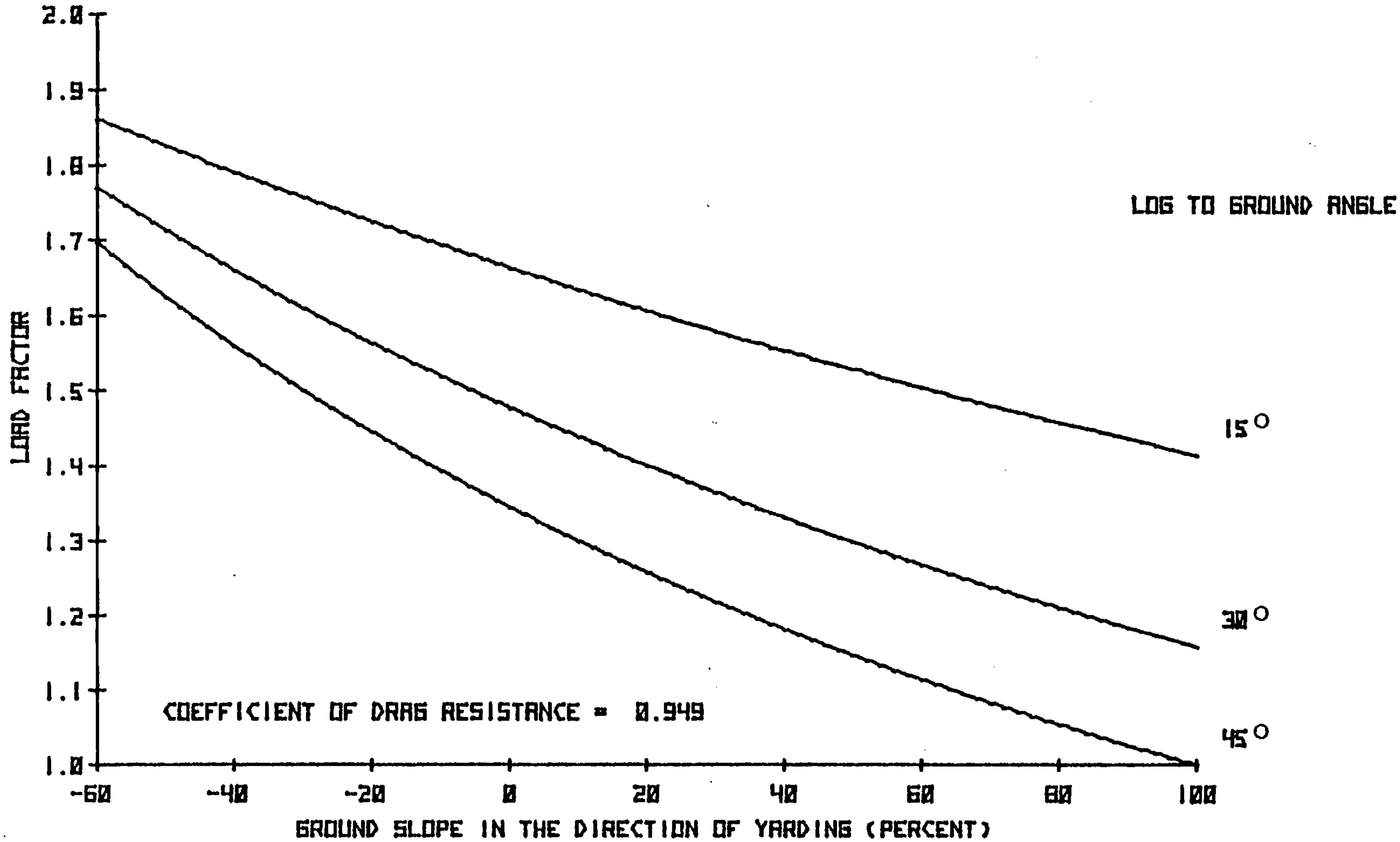

Figure 33. Load increase factor for skyline yarding under dry soil moisture conditions (20%).

of the ground for the section of terrain between the coordinate sets. This slope and the soil moisture content could be used to calculate the load factor for that section of the profile. The load capacity printout from the program could then list the log load capacity for both partial suspension and full suspension of the log load. Again this equation would only be valid for uphill yarding.

The other equations developed (equations 15 through 18) could possibly be used for situations where a more accurate value for μ is required. However, the additional explanation in the variability of μ is small for each variable added to the regression equation. Also the confidence level in the extra variables added in the equation are not as high.

If it is desired to use the photographic technique developed in this study to measure the value of the dynamic μ for a specific logging show, it is suggested that the yarding system be observed first to determine if there is an excessive amount of oscillation during yarding. If a log is moving at a constant velocity, the log geometry (angles α and β) should remain fairly constant. For the method to work, a photograph has to be taken at right angles to the direction of movement of the log. It is also necessary that some sort of plumb line be established so that it is included in the photograph. If too much oscillation is observed, it is suggested that the static value of μ be determined rather than the dynamic value. To do this the same setup could be used except the yarding system would be temporarily stopped so that the log could be photographed. On determining the static μ the log should be slowly moved into impending motion at the instant the photograph is taken. In using either of these methods it is necessary to obtain the log geometry (h, c, d1, and d2). These quantities could either be measured on the site or approximated knowing just the diameter of the log and applying Figures 34 and 35. Both these figures are based on the assumption that the log is a truncated cone of uniform density. This, of course, is an approximation but should produce adequate results when it is impossible or uneconomical to obtain all the log geometry measurements.

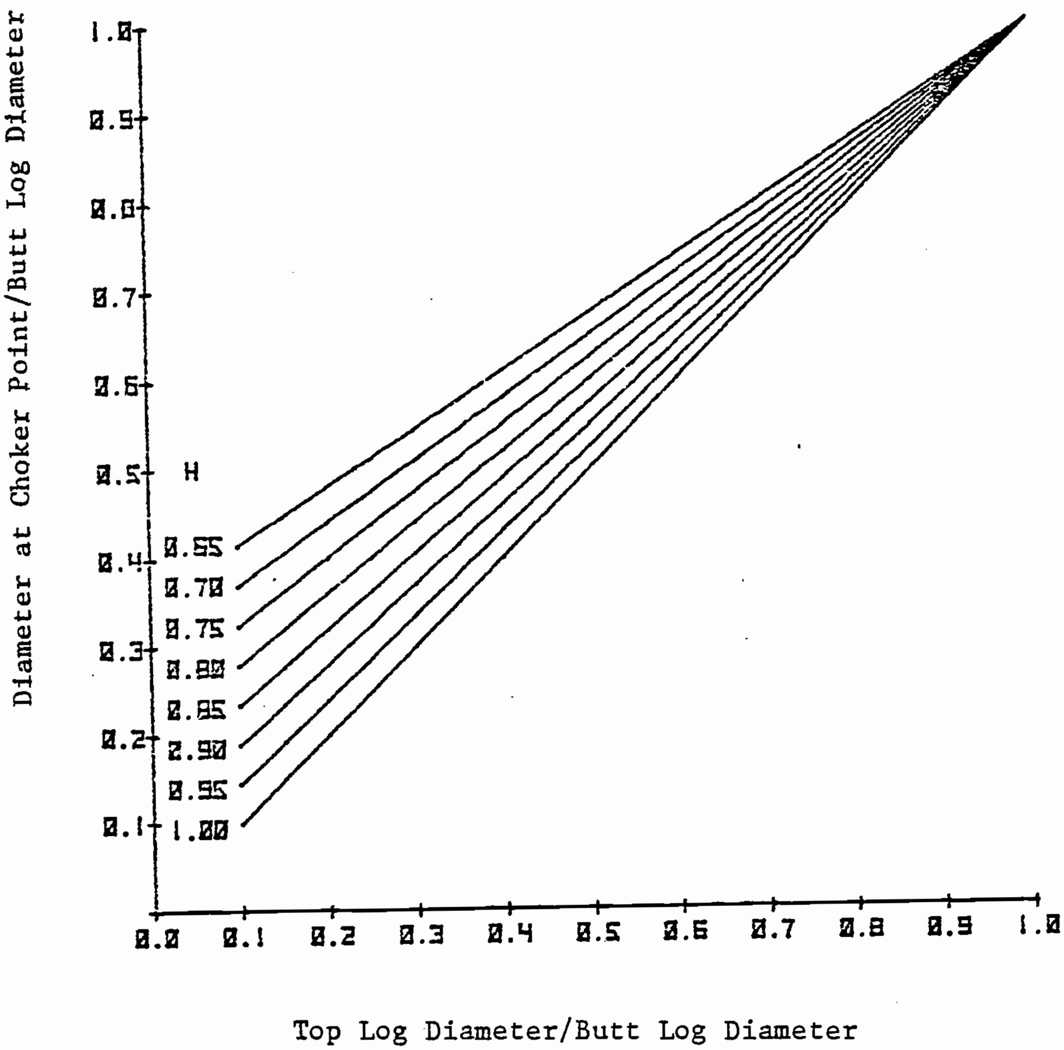

Figure 34. Approximation method to determine the diameter of a log at the choker point knowing the ratio top log diameter to butt log diameter for different hook points.

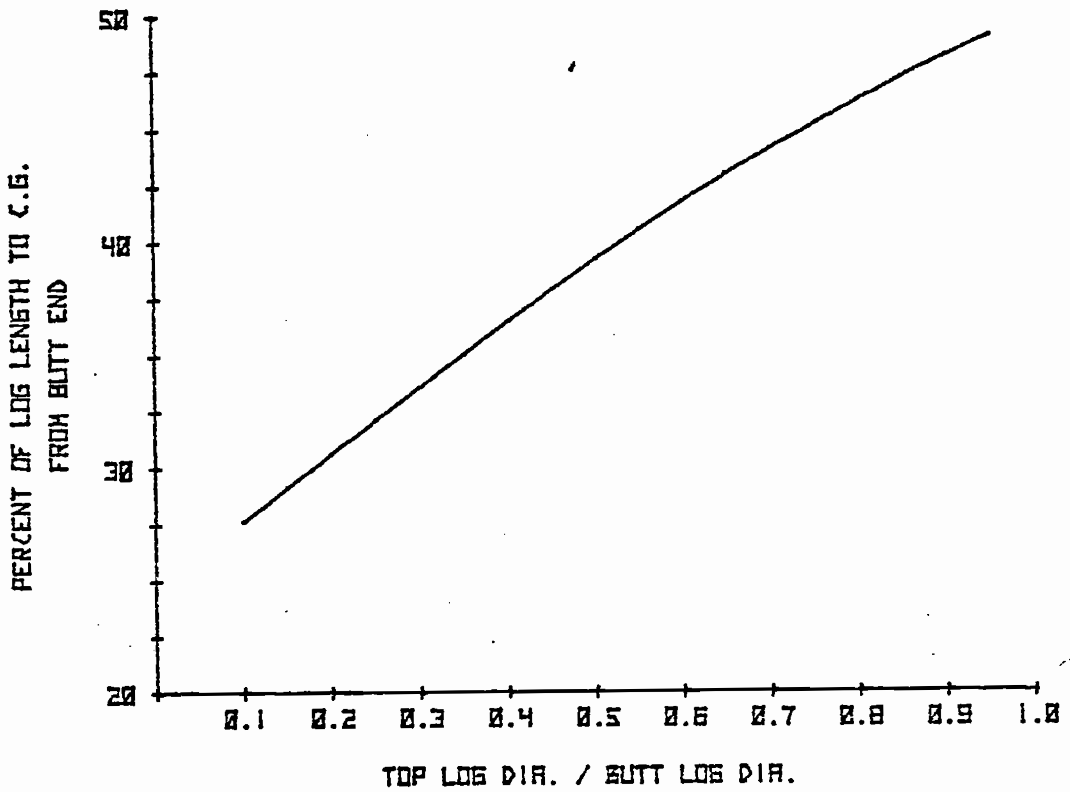

Figure 35. Approximation method to determine the percent of log length from the butt end of a log to the center of gravity of the log.

Comments on the Load Factor

The position of the center of gravity of the log (C) and the distance from the aft end of the log to the hook point are required to calculate the load factor (Appendix I). In Figures 31, 32, and 33 the center of gravity of the log is assumed to be at half the length and the hook point is assumed to be at the end of the log. In the general case this is a reasonable assumption because the values of the load factor should be used only to get an idea of the increase in log load from dragging rather than flying the log. However as Figures 3 and 3 suggest, the load factor is sensitive to the values of H and C The figures also suggest that as the center of gravity move closer to the aft end of the log and the hook point approaches the end of the log, the log factor increases.

From Figures 31, 32, and 33 it can be seen that the load factor is greater for lower log to ground angles. Combining these observations, the following general recommendation can be made to the logging engineer. If a large log which approaches the maximum capacity limit of a skyline is to be yarded, the log should be choked as close as possible to its small end. Then as the log is yarded to the landing, the log to ground angle should be kept as low as possible. This should produce the largest possible load factor and therefore minimize the strain on the cable system.

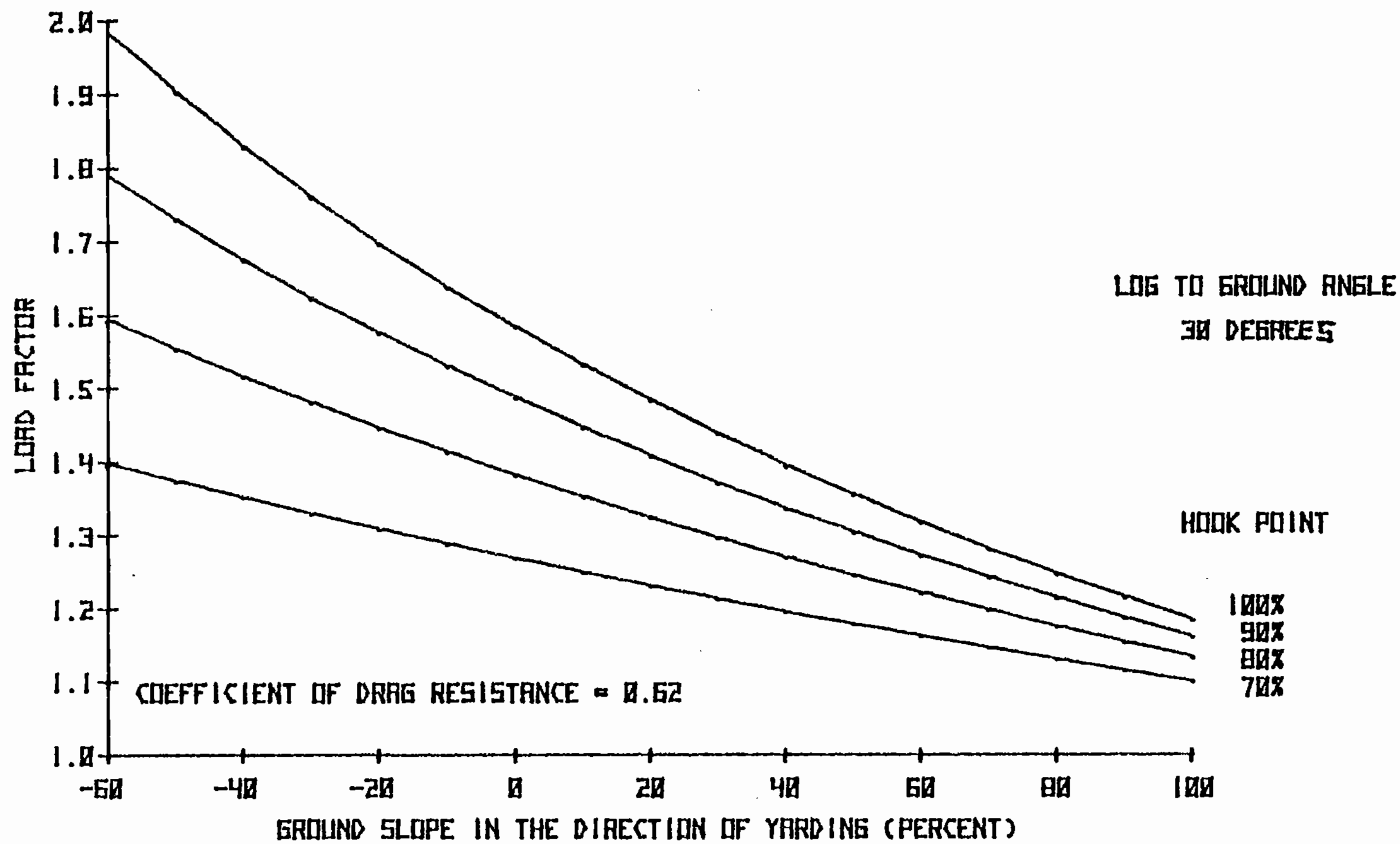

Figure 36. The sensitivity of the load factor to the position of the hook point.

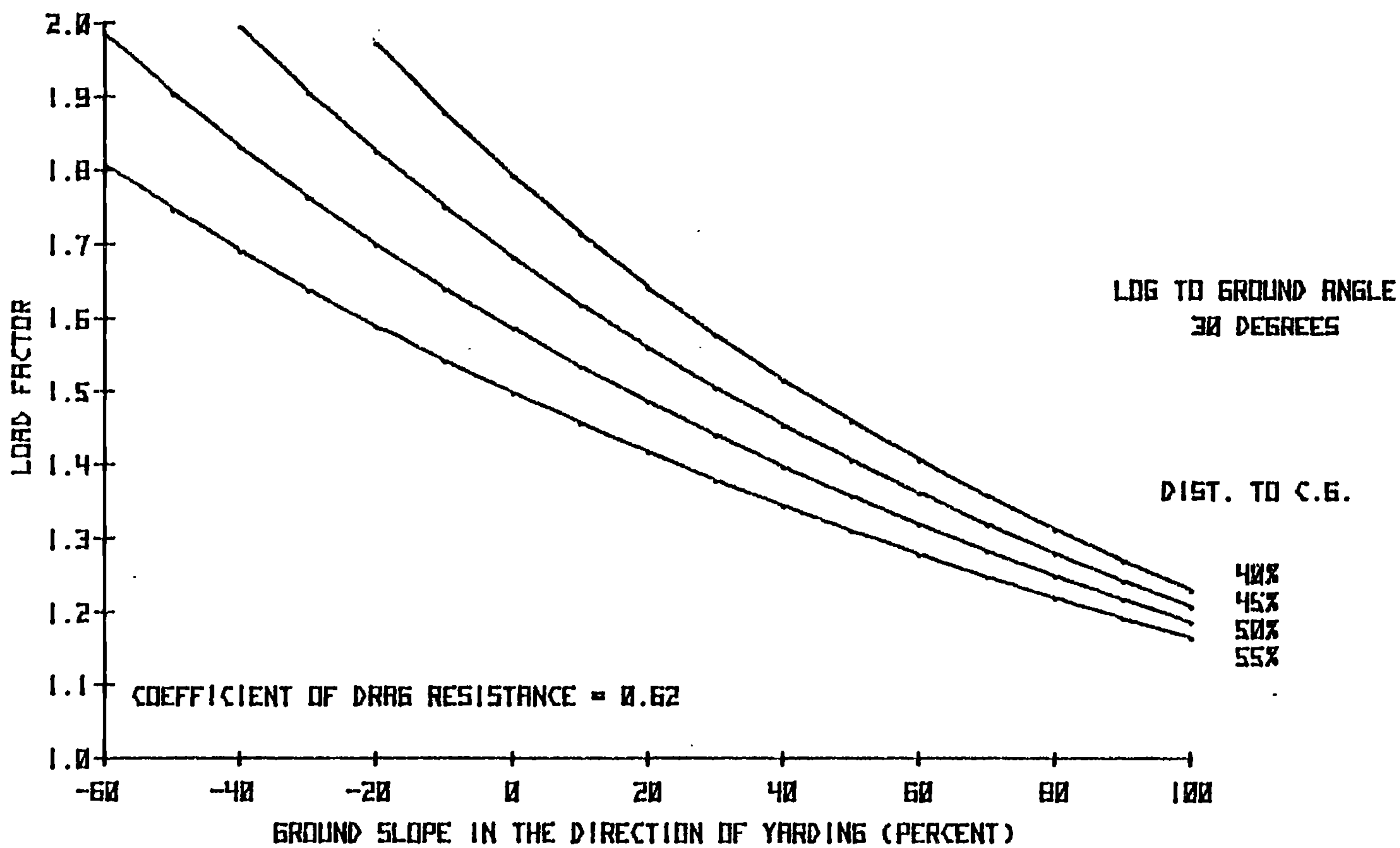

Figure 37. The sensitivity of the load factor to the position of the center of gravity of the log.

SUGGESTIONS FOR FURTHER RESEARCH

The next step suggested for research on the coefficient of drag resistance is to perform an analysis of the dynamics of a yarded log by a cable system. A first approximation of this could be made by assuming that the carriage is a frictionless slider running parallel to the slope and that the choker line is a weightless rigid link with the rigid log pinned to the chokerline. The model developed could be verified by taking motion pictures of a yarded log. With the film speed known, it would be possible to study the actual accelerations to which the log is subjected. It is possible that a study of this sort would be able to define the oscillation of a yarded log in terms of simple harmonic motion. This would be a real contribution to the knowledge of the mechanics of yarding logs.

Another area that could be studied is the effect of yarding uphill verses downhill on forest soils. The results of the first section of this study suggested that μ for downhill yarding is greater than μ for uphill yarding on the same slope. This could be investigated using a procedure similar to the one used in this study, but with longer plots and a more powerful yarder.

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APPENDICES

APPENDIX I

FORMULATION OF THE LOAD FACTOR EQUATION

The load factor is multiplied by the full suspension net log load capacity to determine the net log load capacity under partial suspension (yarding). The load factor is the ratio W/W_s where W is the weight of the maximum sized log a skyline can support in yarding, while W_s is the vertical force on the skyline while yarding that maximum sized log. The value W_s is equal to the log weight when the log is under full suspension. Therefore the load factor is also the ratio of the maximum log load a skyline can drag to the maximum log load that the system can fly.

Figure 38 was used to develop the equation for the load factor. The analysis upon which the figure is based assumes the following:

1. The lift force provided by the skyline will be the same whether the log is flown or dragged. This is equivalent to assuming that the skyline and mainline are parallel to the slope (Θ);
2. The log is a rigid body;
3. The log is a truncated circular cylindrical cone with d_1 at the point of attachment of the choker and d_2 at the aft end of the log in contact with the ground;
4. The center of gravity lies along the center axis of the log;
5. All cables are weightless and form rigid links.

In the analysis of the forces on the dragging log in Figure , it can be seen that from the summation of forces in the horizontal and vertical directions the following equations are formed:

$$\Sigma F_{vert} \Rightarrow V = W - N\cos\Theta + \mu N\sin\Theta \qquad \text{(I-1)}$$

$$\Sigma F_{horz} \Rightarrow H = N(\sin\Theta + \mu\cos\Theta) \qquad \text{(I-2)}$$

By summing the moments about the point of attachment of the choker line to the log (point A) and using the axis parallel and perpendicular

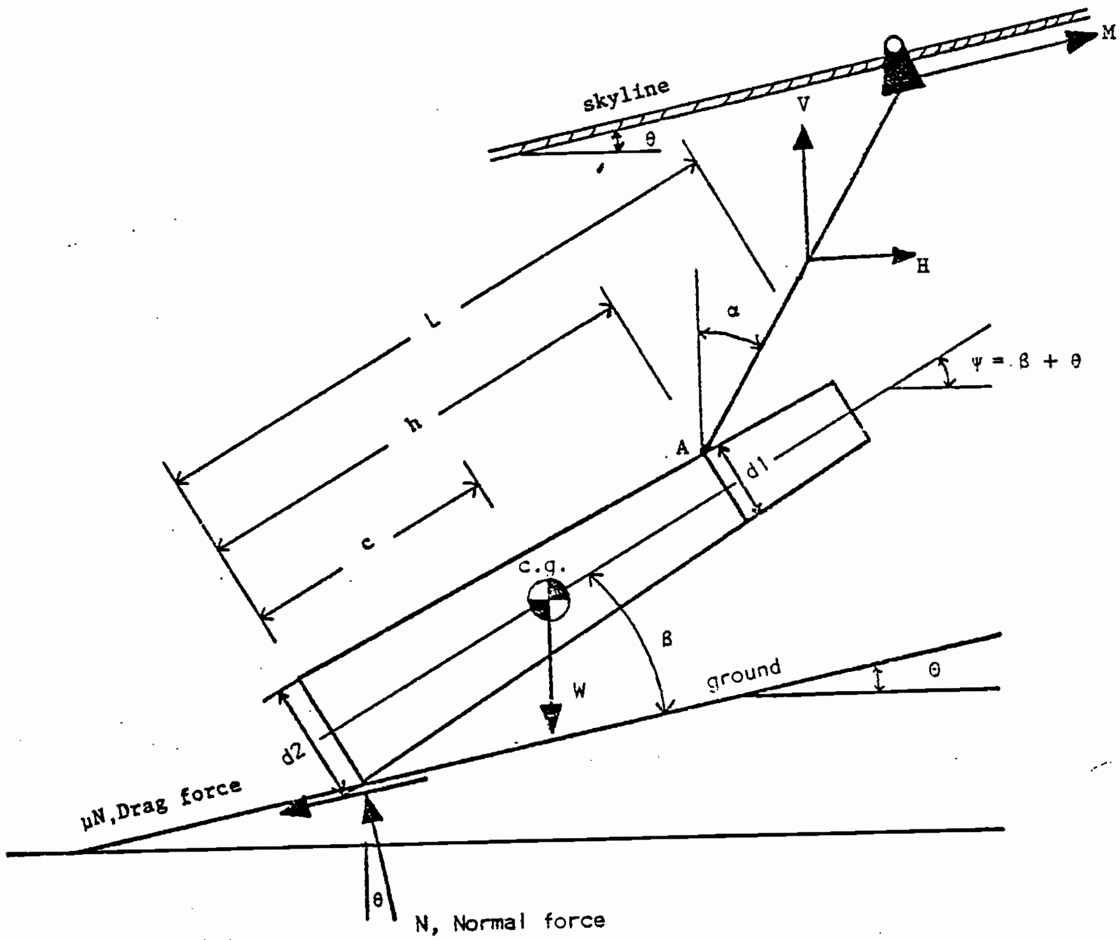


Figure 38. Free body diagram and geometry used in forming the load factor equation.

to the long axis of the log:

$$\Sigma M \Rightarrow W\{(h-c)\cos\psi - (d1/2)\sin\psi\} \\ -N\{-((d1+d2)/2)\sin\beta + h\cos\beta\} \\ -\mu N\{h\sin\beta + ((d1+d2)/2)\cos\beta\} = 0 \tag{I-3}$$

where $\psi = \Theta + \beta$

Dividing equation I-3 by L and letting $D1 = d1/2L$, $D2 = d2/2L$, $H = h/L$, and $C = c/L$, this result is modified to:

$$W\{(H-C)\cos\psi - D1\sin\psi \\ -N\{-(D1+D2)\sin\beta + H\cos\beta\} \\ -\mu N\{H\sin\beta + (D1+D2)\cos\beta\} = 0 \tag{I-4}$$

Solving equation I-4 for N obtains:

$$N = \frac{W\{(H-C)\cos\psi - D1\sin\psi\}}{\{-(D1+D2)\sin\beta + H\cos\beta\} + \mu\{H\sin\beta + (D1+D2)\cos\beta\}} \tag{I-5}$$

letting:

$$G1 = \{(H-C)\cos\psi - D1\sin\psi\}$$

$$G2 = \{-(D1+D2)\sin\beta + H\cos\beta\}$$

and $G3 = \mu\{H\sin\beta + (D1+D2)\cos\beta\}$

therefore:

$$N = \frac{WG1}{G2 + G3} \tag{I-6}$$

Substituting N from equation I-6 into equations I-1 and I-2 yields:

$$V = W[1- \frac{G1}{G2+G3}\cos\Theta + \mu\frac{G1}{G2+G3}\sin\Theta] \tag{I-7}$$

$$H = \frac{WG1}{G2+G3}(\sin\Theta + \mu\cos\Theta) \tag{I-8}$$

The vertical force on the skyline is:

$$W_s = V - \text{(mainline vertical force component)} \quad \text{(I-9)}$$

$$= V - H \tan\Theta$$

Therefore the load factor is:

$$\text{load factor} = \frac{W}{V - H\tan\Theta}$$

$$= \frac{1}{(1 - G4(\cos\Theta + \mu\sin\Theta)) - G4\tan\Theta(\sin\Theta + \mu\cos\Theta)} \quad \text{(I-10)}$$

Numerical Example:

Let Θ = 30% = 16.70°

μ = 0.6

β = 30°

L = 32 feet

h = 30 feet

D1 = 12 inches

D2 = 20 inches

c = 14.4 feet

Therefore:

G1 = 0.323

G2 = 0.791

G3 = 0.505

G4 = 0.295

V = 0.768

H = 0.254

and Load Factor = 1.44

Thus, for the conditions in this example a log can be yarded in partial suspension which is 1.44 times heavier than the largest log that can be flown fully suspended above the ground.

APPENDIX II

COEFFICIENT OF DRAG RESISTANCE PROGRAM

DESCRIPTION

This program is written in the American Standard Code for Information Interchange (ASCII) BASIC language common to many computer systems. It was developed on a Hewlett-Packard 9830 desk-top calculator/digitizer system at the Forest Engineering Department at Oregon State University, Corvallis, Oregon. This computer system and program were used to analyze the photographic data collected in this study.

A photograph of a log being yarded was placed on the digitizer and secured with tape. Information on the log geometry, weight, and tension in the choker line was entered into the calculator. The photo was then digitized in the following order: (1) the plumb line; (2) the slope; (3) the log; and (4) the choker line. For each entry, two points are digitized. This enters two sets of coordinates into the calculator. The angles α, β, and θ are calculated from these coordinates. This procedure was repeated five times on each photo to reduce errors in digitizing. Figure 39 is an example of the computer printout from a sample photograph. In this example the sample was for the static μ so both calculation methods were used. The first set of values are calculated using equation 6. The second set uses equation 12.

If a photograph was for determining the dynamic coefficient of drag resistance the same procedure in digitizing would be used but μ would only be calculated by equation 6 because it was impractical to measure the tension in the chokerline while the log was moving.

COEFFICIENT OF DRAG RESISTANCE MODEL

LOG IDENTIFICATION	6,2,17
WEIGHT OF LOG (#) :	540.00
LENGTH OF LOG (FEET) :	13.25
DIAMETER AT CHOKER POINT (INCHES) :	11.90
DIAMETER AT AFT END (INCHES) :	12.75
PERCENT OF LENGTH TO HOOK PT. :	85.50
PERCENT OF LENGTH TO C.G. :	49.70

STATIC CASE

CALCULATIONS BY ANGLES ONLY

RUN	ANGLES(DEGREES)				FORCE		COEFF.
#	ALPHA	BETA	THETA	T	N	F	MU
1	15.09	27.67	12.78	444.58	133.60	88.34	0.66122
2	14.32	27.88	12.29	434.14	139.49	79.53	0.57015
3	13.73	27.79	13.26	430.76	141.75	71.62	0.50526
4	13.90	27.79	13.26	432.80	140.52	73.70	0.52445
5	13.73	27.63	13.26	430.04	142.39	71.29	0.50068
MEAN	14.15	27.75	12.97	434.46	139.55	76.90	0.55235
SD	0.58	0.10	0.43	5.88	3.51	7.20	0.06677

CALCULATIONS BY ANGLES AND MEASURED TAG LINE FORCE

RUN	ANGLES(DEGREES)				FORCE		COEFF.
#	ALPHA	BETA	THETA	T	N	F	MU
1	15.09	27.67	12.78	457.50	122.18	94.38	0.77244
2	14.32	27.88	12.29	457.50	118.60	90.00	0.75881
3	13.73	27.79	13.26	457.50	117.92	83.75	0.71024
4	13.90	27.79	13.26	457.50	118.54	84.97	0.71679
5	13.73	27.63	13.26	457.50	117.92	83.75	0.71024
MEAN	14.15	27.75	12.97	457.50	119.03	87.37	0.73370
SD	0.58	0.10	0.43	0.00	1.79	4.69	0.02965

CONTACT AREA = 20.81 PRESURE = 6.71 OR 5.72 PSI

DATA OF LOG 6,2,17 STORED IN FILE # 155 TAPE JOHN 6

Figure 39. Printed output from the coefficient of drag resistance program.

LISTING OF THE COEFFICIENT OF DRAG RESISTACE PROGRAM

```
10 DIM A$[10],AS[7,11],B$[15]
20 DEG
30 DISP "WEIGHT OF LOG";
40 INPUT W
50 DISP "LOG LENGTH IN FEET";
60 INPUT L5
70 L=L5*12
80 DISP "DIA. AT CHOKER POINT IN INCHES";
90 INPUT D3
100 D1=D3/(L*2)
110 DISP "DIA. AT AFT END IN INCHES";
120 INPUT D4
130 D2=D4/(2*L)
140 DISP "% OF L TO C.G. (C)";
150 INPUT C
160 C=C/100
170 DISP "% OF L TO HOOK POINT";
180 INPUT H
190 H=H/100
200 DISP "STATIC OR DYNAMIC (1 OR 2)";
210 INPUT Z5
220 IF Z5=1 THEN 250
230 B$="DYNAMIC"
240 GOTO 260
250 B$="STATIC"
260 IF B$="DYNAMIC" THEN 300
270 DISP "TENSION IN TAG LINE";
280 INPUT T8
290 GOTO 310
300 T8=0
310 DISP "LOG IDENTIFICATION";
320 INPUT A$
330 IF Z5=2 THEN 380
340 DISP "TENSION IN TAG LINE";
350 INPUT T8
360 DISP "DISTANCE ON BUTT TO SOIL";
370 INPUT Z6
380 PRINT TAB13"***COEFFICIENT OF DRAG RESISTANCE MODEL***
390 PRINT
400 FIXED 2
410 PRINT "LOG IDENTIFICATION
420 PRINT "WEIGHT OF LOG (#) :
430 PRINT "LENGTH OF LOG (FEET) :
440 PRINT "DIAMETER AT CHOKER POINT (INCHES) :
450 PRINT "DIAMETER AT AFT END (INCHES) :
460 PRINT "PERCENT OF LENGTH TO HOOK PT. :
470 PRINT "PERCENT OF LENGTH TO C.G. :
480 PRINT
490 PRINT B$" CASE"
500 PRINT
```

```
510 FOR P=1 TO 5
520 DISP "DIGITIZE PERPENDICULAR"
530 WAIT 1000
540 WRITE (9,*)
550 ENTER (9,*)X1,Y1
560 WRITE (9,*)
570 ENTER (9,*)X2,Y2
580 R=(ATN((X2-X1)/(Y1-Y2)))
590 DISP "DIGITIZE SLOPE"
600 WAIT 1000
610 WRITE (9,*)
620 ENTER (9,*)X3,Y3
630 WRITE (9,*)
640 ENTER (9,*)X4,Y4
650 G=(ATN((Y3-Y4)/(X4-X3)))
660 T=G+R
670 DISP "DIGITIZE LEAD OF LOG "
680 WAIT 1000
690 WRITE (9,*)
700 ENTER (9,*)X5,Y5
710 WRITE (9,*)
720 ENTER (9,*)X6,Y6
730 L1=(ATN((Y5-Y6)/(X6-X5)))
740 B=L1+R-T
750 DISP "DIGITIZE TAG LINE"
760 WAIT 1000
770 WRITE (9,*)
780 ENTER (9,*)X7,Y7
790 WRITE (9,*)
800 ENTER (9,*)X8,Y8
810 G1=(ATN((X8-X7)/(Y7-Y8)))
820 A=(G1-R)
830 A[P,1]=A
840 A[P,2]=B
850 A[P,3]=T
860 Y=B+T
870 T1=SINT
880 T2=COST
890 B1=SINB
900 B2=COSB
910 A1=TANA
920 Y1=SINY
930 Y2=COSY
940 U1=((H-C)*Y2-D1*Y1)*(T1+A1*T2)-A1*(-(D1+D2)*B1+H*B2
950 U2=A1*(H*B1+(D1+D2)*B2)-((H-C)*Y2-D1*Y1)*(T2-A1*T1)
960 A[P,7]=U1/U2
970 A[P,5]=(W*A1)/(A[P,7]*(T2-T1*A1)+T1+A1*T2)
980 A[P,6]=A[P,7]*A[P,5]
990 A[P,4]=(A[P,5]*(T1+A[P,7]*T2)/SINA)
1000 IF B$="DYNAMIC" THEN 1000
```

```
1010 M1=T8*(COSA*T1+T2*SINA)-W*T1
1020 M2=W*T2+T8*(T1*SINA-T2*COSA)
1030 A[P,11]=M1/M2
1040 A[P,8]=T8
1050 A[P,9]=(W*A1)/(A[P,11]*(T2-T1*A1)+T1+A1*T2
1060 A[P,10]=A[P,11]*A[P,9]
1070 GOTO 1090
1080 A[P,8]=A[P,9]=A[P,10]=A[P,11]=0
1090 NEXT P
1100 P1=P2=P3=P4=P5=P6=P7=P9=0
1110 J1=J2=J3=J4=J5=J6=J7=J9=0
1120 K1=K2=K5=K6=0
1130 FOR P=1 TO 5
1140 P1=P1+A[P,1]
1150 P2=P2+A[P,2]
1160 P3=P3+A[P,3]
1170 P4=P4+A[P,4]
1180 P5=P5+A[P,5]
1190 P6=P6+A[P,6]
1200 P7=P7+A[P,7]
1210 P9=P9+A[P,9]
1220 K1=K1+A[P,10]
1230 K2=K2+A[P,11]
1240 J1=J1+A[P,1]↑2
1250 J2=J2+A[P,2]↑2
1260 J3=J3+A[P,3]↑2
1270 J4=J4+A[P,4]↑2
1280 J5=J5+A[P,5]↑2
1290 J6=J6+A[P,6]↑2
1300 J7=J7+A[P,7]↑2
1310 J9=J9+A[P,9]↑2
1320 K5=K5+A[P,10]↑2
1330 K6=K6+A[P,11]↑2
1340 NEXT P
1350 A[6,1]=P1/5
1360 A[6,2]=P2/5
1370 A[6,3]=P3/5
1380 A[6,4]=P4/5
1390 A[6,5]=P5/5
1400 A[6,6]=P6/5
1410 A[6,7]=P7/5
1420 A[6,8]=T8
1430 A[6,9]=P9/5
1440 A[6,10]=K1/5
1450 A[6,11]=K2/5
1460 A[7,1]=SQR((J1-(P1↑2/5))/4)
1470 A[7,2]=SQR((J2-(P2↑2/5))/4)
1480 A[7,3]=SQR((J3-(P3↑2/5))/4)
1490 A[7,4]=SQR((J4-(P4↑2/5))/4)
1500 A[7,5]=SQR((J5-(P5↑2/5))/4)
```

```
1510 A[7,6]=SQR((J6-(P6↑2/5))/4)
1520 A[7,7]=SQR((J7-(P7↑2/5))/4)
1530 A[7,8]=0
1540 A[7,9]=SQR((J9-(P9↑2/5))/4)
1550 A[7,10]=SQR((K5-(K1↑2/5))/4)
1560 A[7,11]=SQR((K6-(K2↑2/5))/4)
1570 PRINT "CALCULATIONS BY ANGLES ONLY"
1580 PRINT
1590 WRITE (15,1610)
1600 WRITE (15,1620)
1610 FORMAT 2X,"RUN",2X,"ANGLES(DEGREES)",17X,"FORCE"
1620 FORMAT 3X,"#",3X,"ALPHA   BETA  THETA",6X,"T",7X
1630 FOR P=1 TO 5
1640 WRITE (15,1650)P,A[P,1],A[P,2],A[P,3],A[P,4],A[P.
1650 FORMAT 2X,F2.0,2X,F6.2,1X,F6.2,1X,F6.2,2X,F7.2,2)
1660 NEXT P
1670 P=6
1680 WRITE (15,1690)A[P,1],A[P,2],A[P,3],A[P,4],A[P,5]
1690 FORMAT 1X,"MEAN",1X,F6.2,1X,F6.2,1X,F6.2,2X,F7.2,
1700 P=7
1710 WRITE (15,1720)A[P,1],A[P,2],A[P,3],A[P,4],A[P,5]
1720 FORMAT 1X," SD ",1X,F6.2,1X,F6.2,1X,F6.2,2X,F7.2,
1730 PRINT
1740 IF B$="DYNAMIC" THEN 2040
1750 IF T8=0 THEN 2040
1760 PRINT "CALCULATIONS BY ANGLES AND MEASURED TAG LINE
1770 PRINT
1780 WRITE (15,1610)
1790 WRITE (15,1620)
1800 FOR P=1 TO 5
1810 WRITE (15,1650)P,A[P,1],A[P,2],A[P,3],T8,A[P,9]
1820 NEXT P
1830 P=6
1840 WRITE (15,1850)A[P,1],A[P,2],A[P,3],A[P,8],A[P,9]
1850 FORMAT 1X,"MEAN",1X,F6.2,1X,F6.2,1X,F6.2,2X,F7.2
1860 P=7
1870 WRITE (15,1880)A[P,1],A[P,2],A[P,3],A[P,8],A[P,9]
1880 FORMAT 1X," SD ",1X,F6.2,1X,F6.2,1X,F6.2,2X,F7.2
1890 PRINT
1900 IF Z5=2 THEN 2040
1910 RAD
1920 D8=(A[6,2]/360)*2*PI
1930 L8=(D4-Z6)/SIND8
1940 C9=SQR((D4↑2/4)-(Z6-(D4/2))↑2)
1950 A8=(D4/2)/SIND8
1960 X9=(L8-A8)/A8
1970 IF X9=1 THEN 1990
1980 U2=ATN(X9/SQR(1-X9↑2))
1990 U2=PI/2
2000 A9=A8*(D4/2)*((PI/2)+U2+0.5*SIN(2*U2))
```

```
2010 PRINT "CONTACT AREA ="A9"PRESURE ="A[6,5]/A9"
2020 PRINT
2030 DEG
2040 DISP "STORE IN FILE #";
2050 INPUT N
2060 IF N=1 OR N=0 THEN 2120
2070 FIXED 0
2080 PRINT "DATA OF LOG "A$" STORED IN FILE #"N
2090 PRINT
2100 PRINT
2110 STORE  DATA #5,N,A
2120 GOTO 310
2130 END
```

APPENDIX III

DATA ANALYSIS OF TERRAIN MODEL SECTION

Question: Is there a significant difference in the mean values obtained in the section one data between yarding uphill versus downhill?

Treatment #1 All values of μ for uphill yarding. Mean = 0.6545, Variance = 0.0831, for a sample size of 31.

Treatment #2 All values of μ for downhill yarding. Mean = 1.044, Variance = 0.1274, for a sample size of 30.

$$Ho: \mu_1 = \mu_2$$

$$Ha: \mu_1 \neq \mu_2$$

ANALYSIS OF VARIANCE TABLE

Source of variation	DF	SS	MS	F
Total	60	8.4982		
Treatments	1	2.3128	2.3128	22.06
Error	59	6.1854	0.1048	

$$F_{0.05(1),1,59} = 4.01$$

Therefore: Reject Ho

Question: Is there a significant difference in the mean values obtained in this section for yarding uphill on different slopes?

Treatment #1 All values of μ for uphill yarding on a 15% slope. Mean = 0.805, Variance = 0.102, for 10 samples.

Treatment #2 All values of μ for uphill yarding on a 26.5% slope. Mean = 0.653, Variance = 0.077, for 11 samples.

Treatment #3 All values of μ for uphill yarding on a 37.0% slope.

Mean = 0.505, Variance = 0.038, for 10 samples.

$$Ho: \mu_1 = \mu_2 = \mu_3$$

$$Ha: \mu_1 \neq \mu_2 \neq \mu_3$$

ANALYSIS OF VARIANCE TABLE

Source of variation	DF	SS	MS	F
Total	30	2.492		
Treatments	2	0.451	0.2256	3.096
Error	28	2.041	0.0729	

$$F_{0.05(1),2,28} = 3.34$$

Therefore: Fail to Reject Ho

Question: Is there a significant difference in the mean values obtained in this section for yarding downhill on different slopes?

Treatment #1 All values of μ for downhill yarding on a 15% slope.

Mean = 0.978, Variance = 0.063, for 10 samples.

Treatment #2 All values of μ for downhill yarding on a 26.5% slope.

Mean = 1.086, Variance = 0.054 for 10 samples.

Treatment #3 All values of μ for downhill yarding on a 37.0% slope.

Mean = 1.067, Variance = 0.287, for 10 samples.

$$Ho: \mu_1 = \mu_2 = \mu_3$$

$$Ha: \mu_1 \neq \mu_2 \neq \mu_3$$

ANALYSIS OF VARIANCE TABLE

Source of variation	DF	SS	MS	F
Total	29	3.6934		
Treatment	2	0.0663	0.0332	0.2468
Error	27	0.6271	0.1343	

$$F_{0.05,2,27} = 3.35$$

Therefore: Fail to Reject Ho

STEPWISE PROCEDURE

DRAG-MU = 8.4607E-01

STEPWISE

VARIABLE ENTERING: BETA

DRAG-MU = 3.1164E-01 +2.6025E-02 BETA

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	60	8.49820574E 00	1.41636762E-01
REGRESSION	1	2.85217511E 00	2.85217511E 00
RESIDUAL	59	5.64603063E 00	9.56954343E-02

R SQUARED = .33562086

VAR	S.E. OF REGR. COEF.	T
CONSTANT	1.05600999E-01	2.95109316E 00
BETA	4.76704904E-03	5.45936944E 00

VARIABLE ENTERING: THETA

DRAG-MU = 5.6641E-01 +2.9881E-02 BETA
-2.2405E-02 THETA

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	60	8.49820574E 00	1.41636762E-01
REGRESSION	2	3.58927416E 00	1.79463708E 00
RESIDUAL	58	4.90893157E 00	8.46367513E-02

R SQUARED = .42235670

VAR	S.E. OF REGR. COEF.	T
CONSTANT	1.31589360E-01	4.30435042E 00
BETA	4.66966089E-03	6.39893192E 00
THETA	7.59205478E-03	-2.95109665E 00

VARIABLE ENTERING: DELTA

DRAG-MU = 5.6430E-01 +3.0754E-02 BETA
-2.2886E-02 THETA -1.7020E-02 DELTA

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	60	8.49820574E 00	1.41636762E-01
REGRESSION	3	3.59072050E 00	1.19690683E 00
RESIDUAL	57	4.90748523E 00	8.60962322E-02

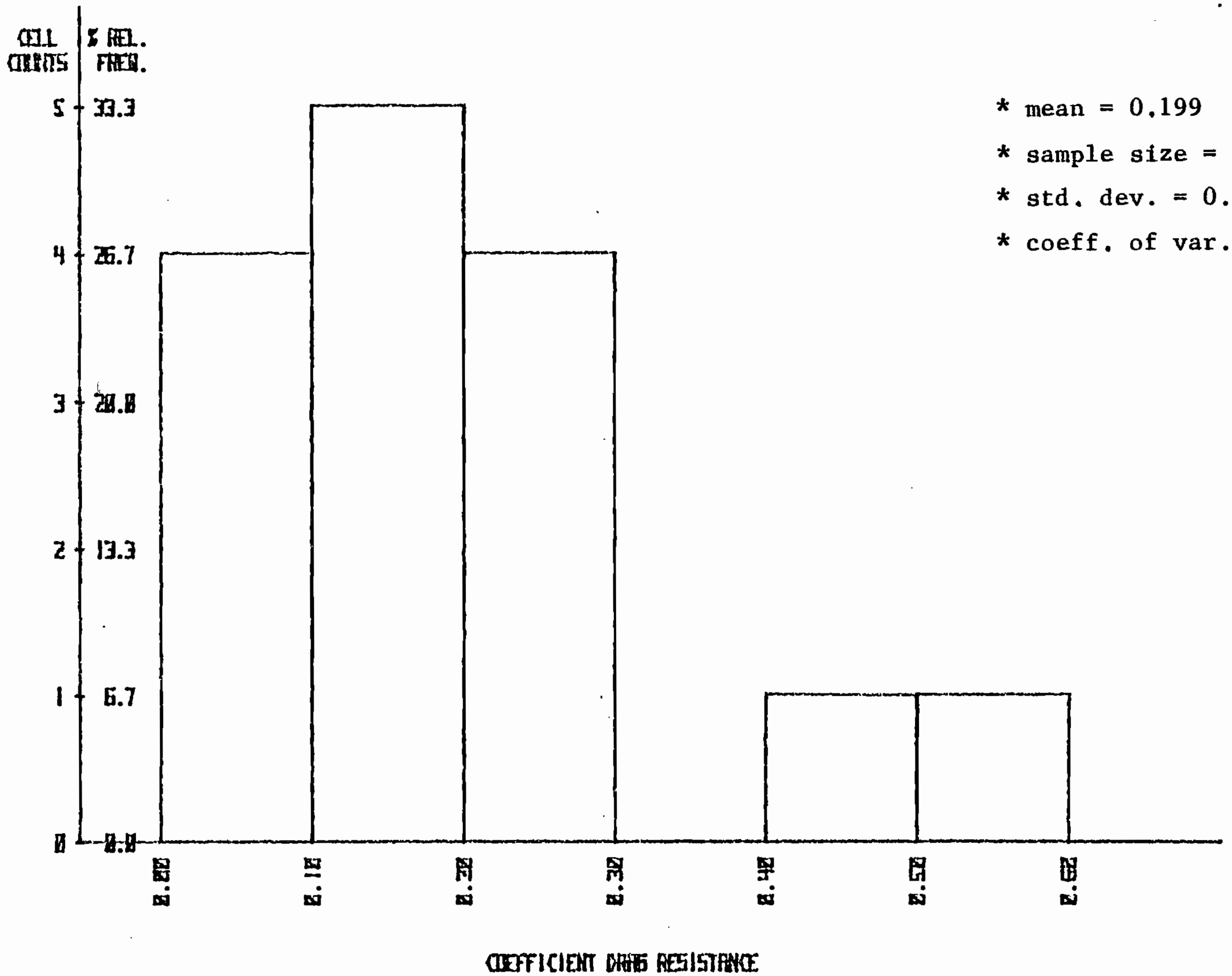
R SQUARED = .42252690

VAR	S.E. OF REGR. COEF.	T
CONSTANT	1.33711016E-01	4.22029294E 00
BETA	8.21950740E-03	3.74158085E 00
THETA	8.50991351E-03	-2.68934787E 00
DELTA	1.31315952E-01	-1.29611448E-01

APPENDIX IV

DATA ANALYSIS OF FIELD DATA

The following set of figures and computer output summarizes the data analysis of the initial field data collected for determining the static and dynamic μ on the four test plots. The histograms are divided by plot number and log number for the static μ data. The dynamic μ data is summaried in histograms by plot number only. The computer output is from the stepwise procedure used to form the regression equations for the static μ data.



* mean = 0.199
* sample size = 15
* std. dev. = 0.130
* coeff. of var. = 65.3%

Figure 40. Histogram of field data for log 1 collected on plot 1 (static μ).

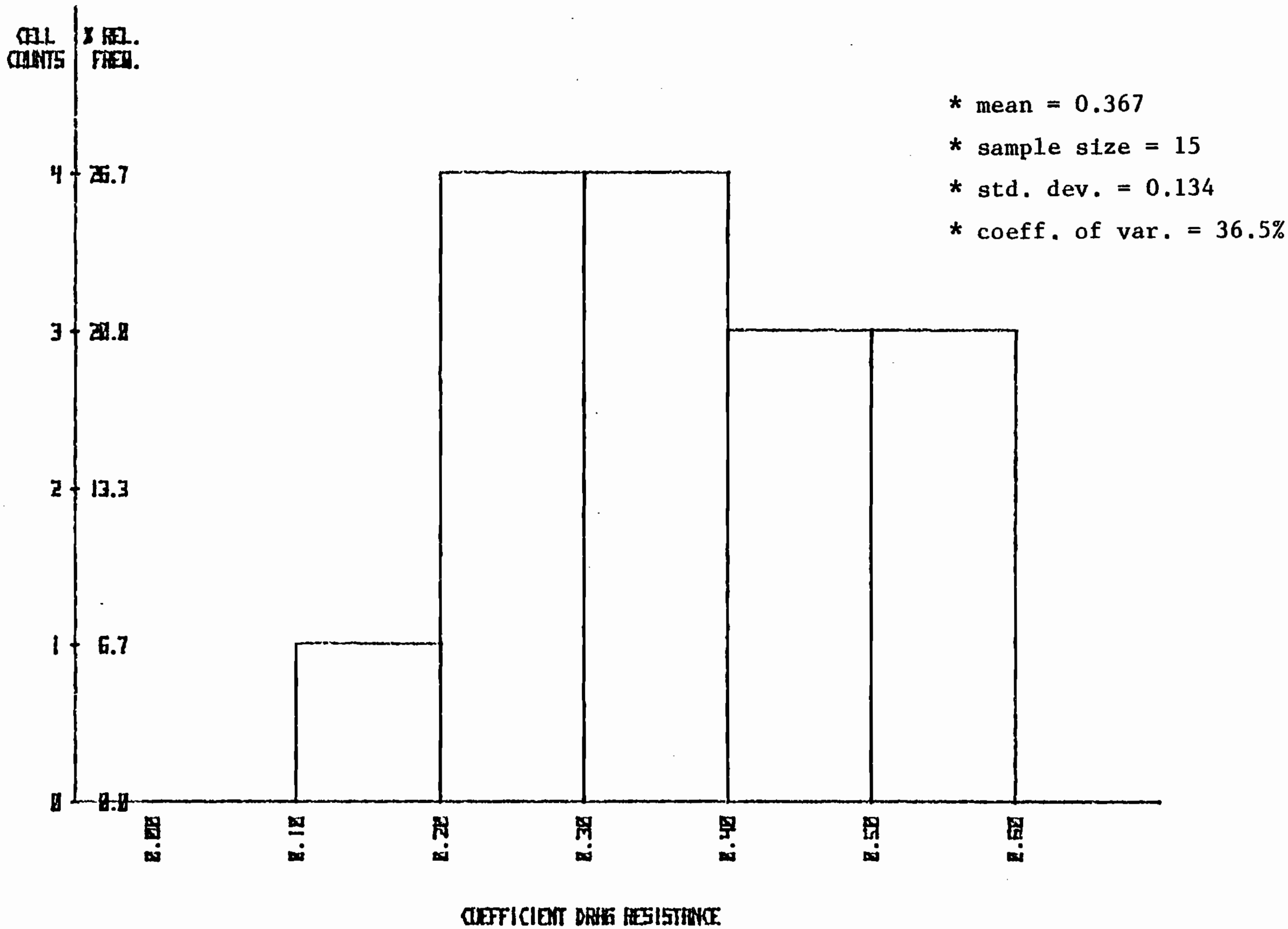


Figure 41. Histogram of field data for log 2 collected on plot 1 (static μ).

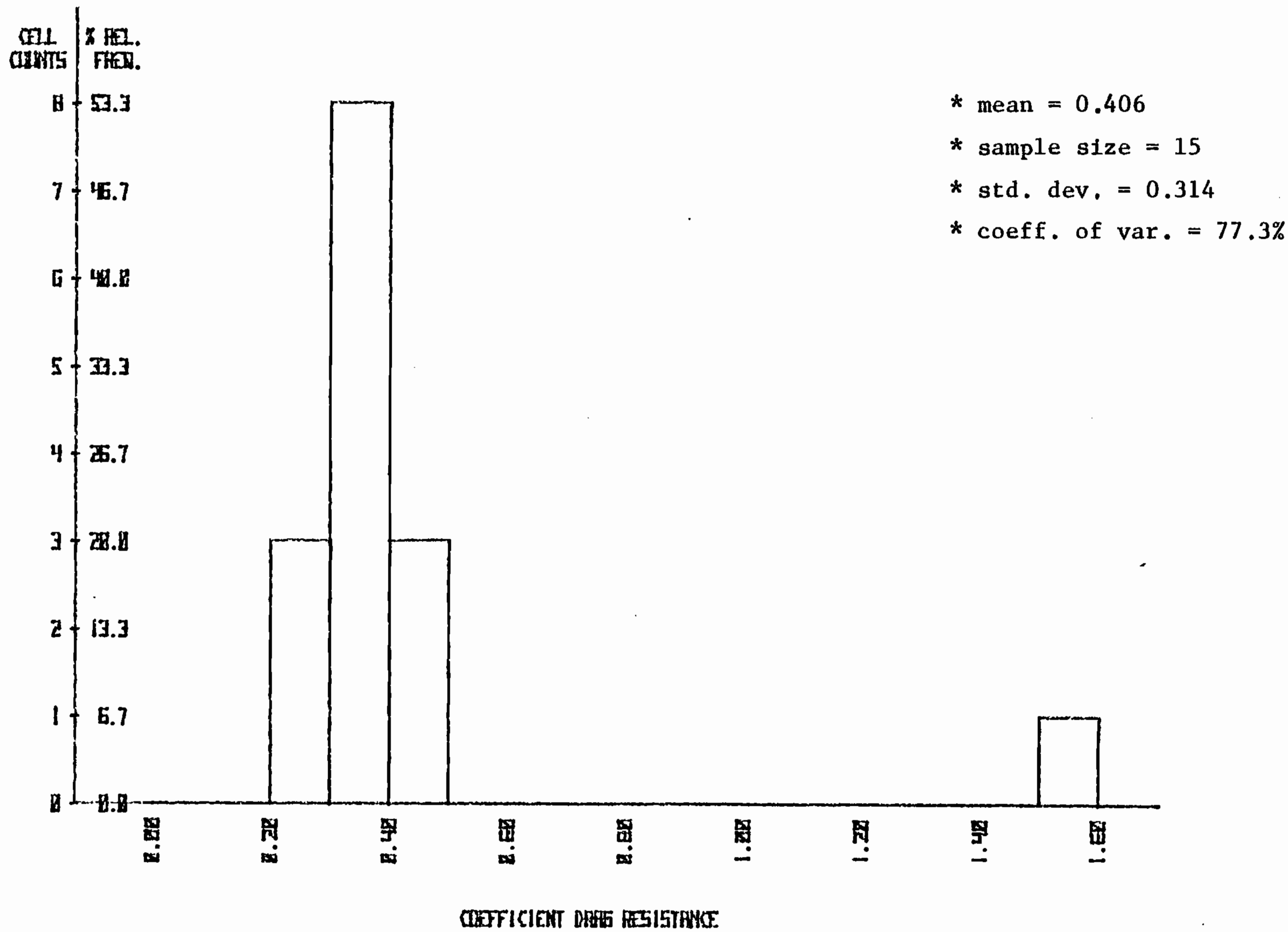
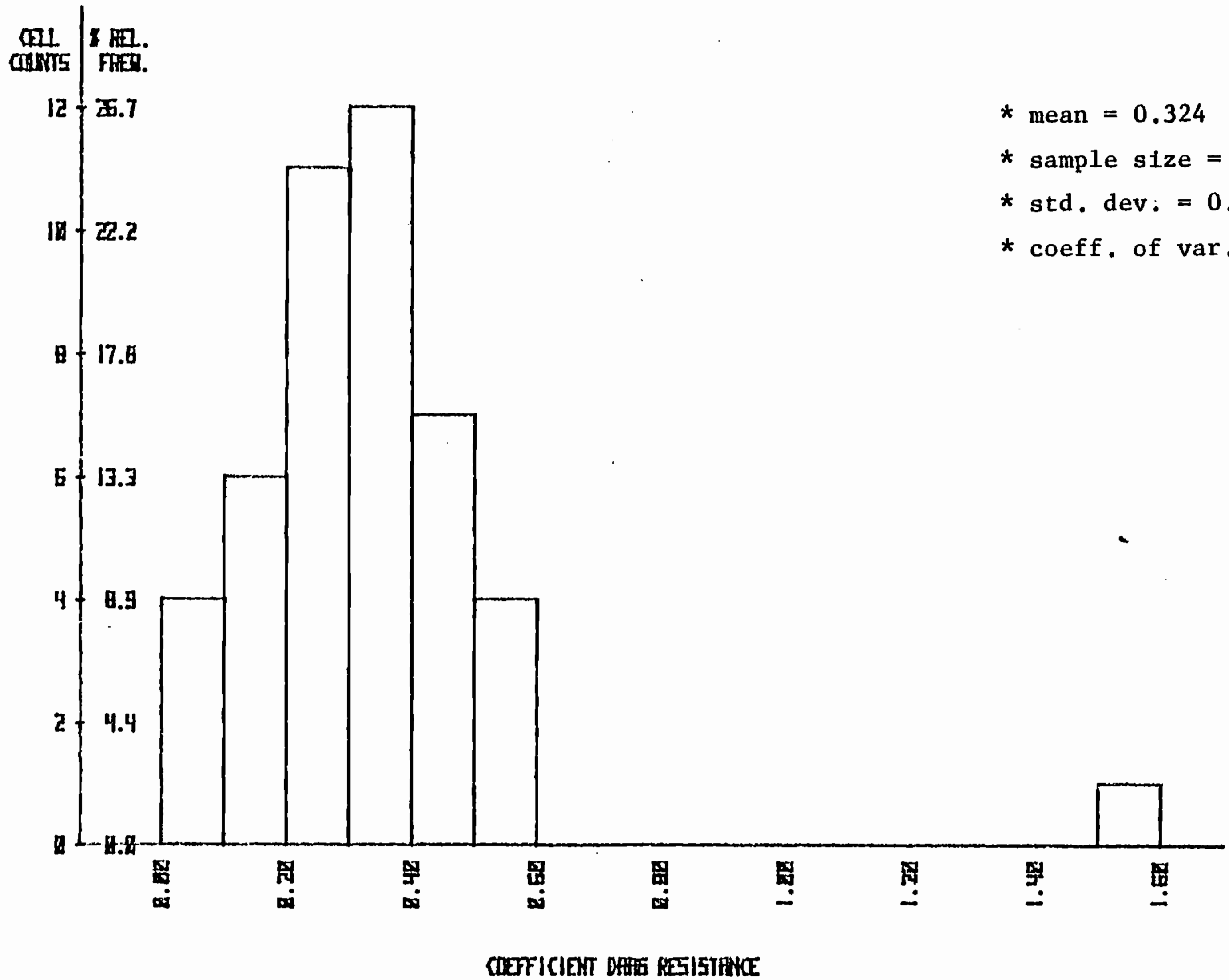


Figure 42. Histogram of field data for log 3 collected on plot 1 (static μ).



* mean = 0.324
* sample size = 45
* std. dev. = 0.227
* coeff. of var. = 70.1%

Figure 43. Histogram of all field data collected on plot 1 (static μ).

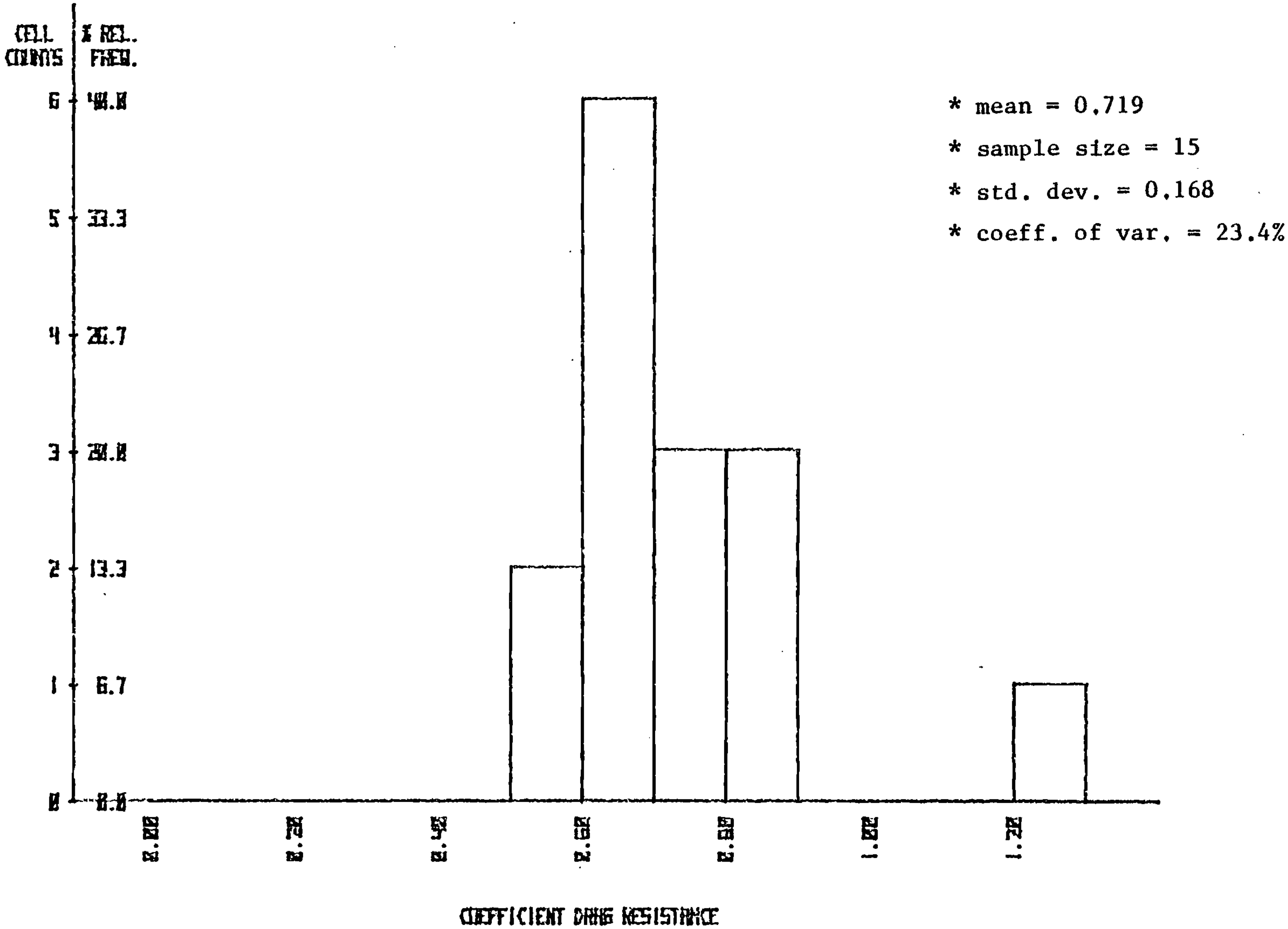


Figure 44. Histogram of field data for log 1 collected on plot 2 (static μ).

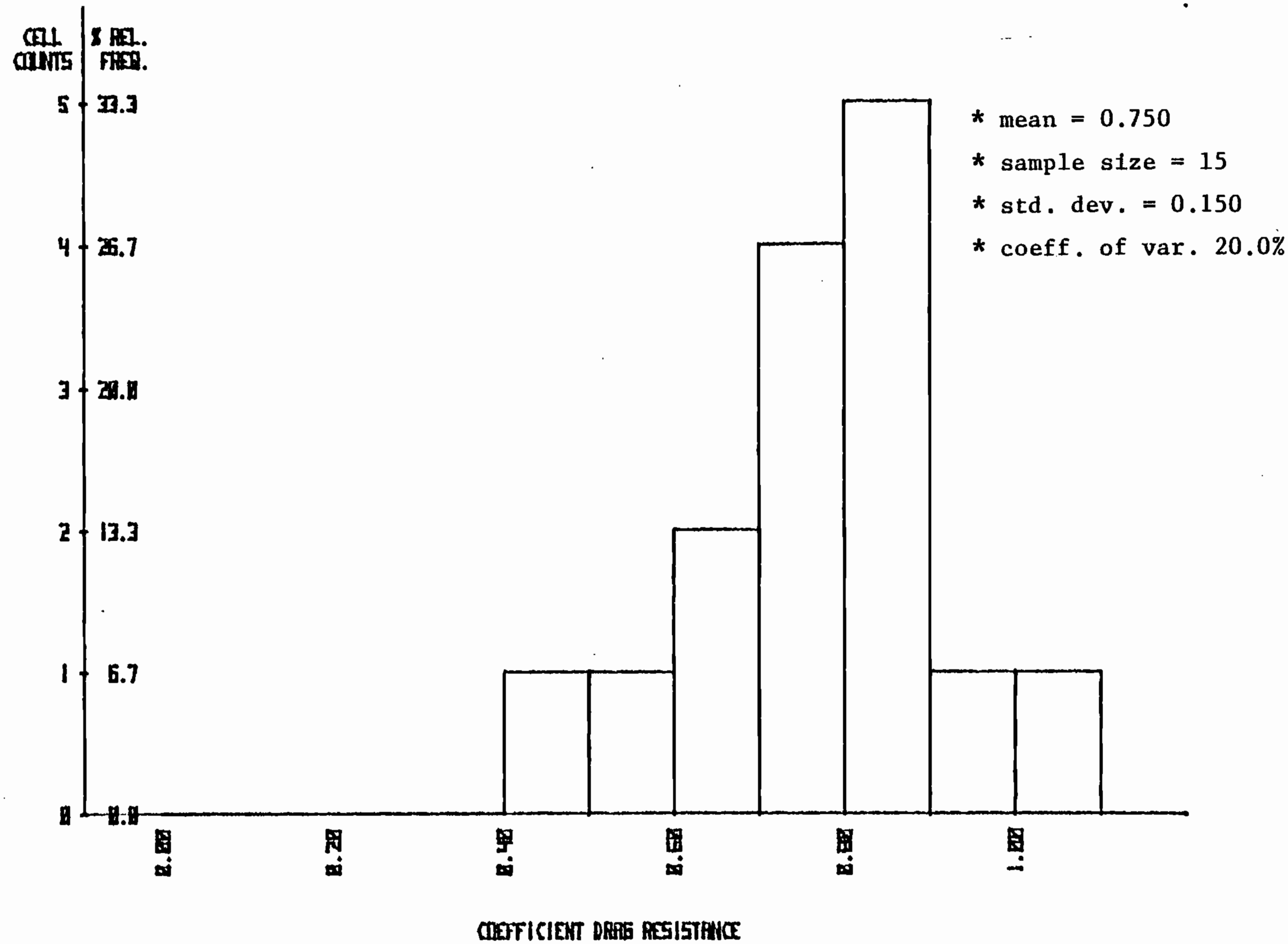
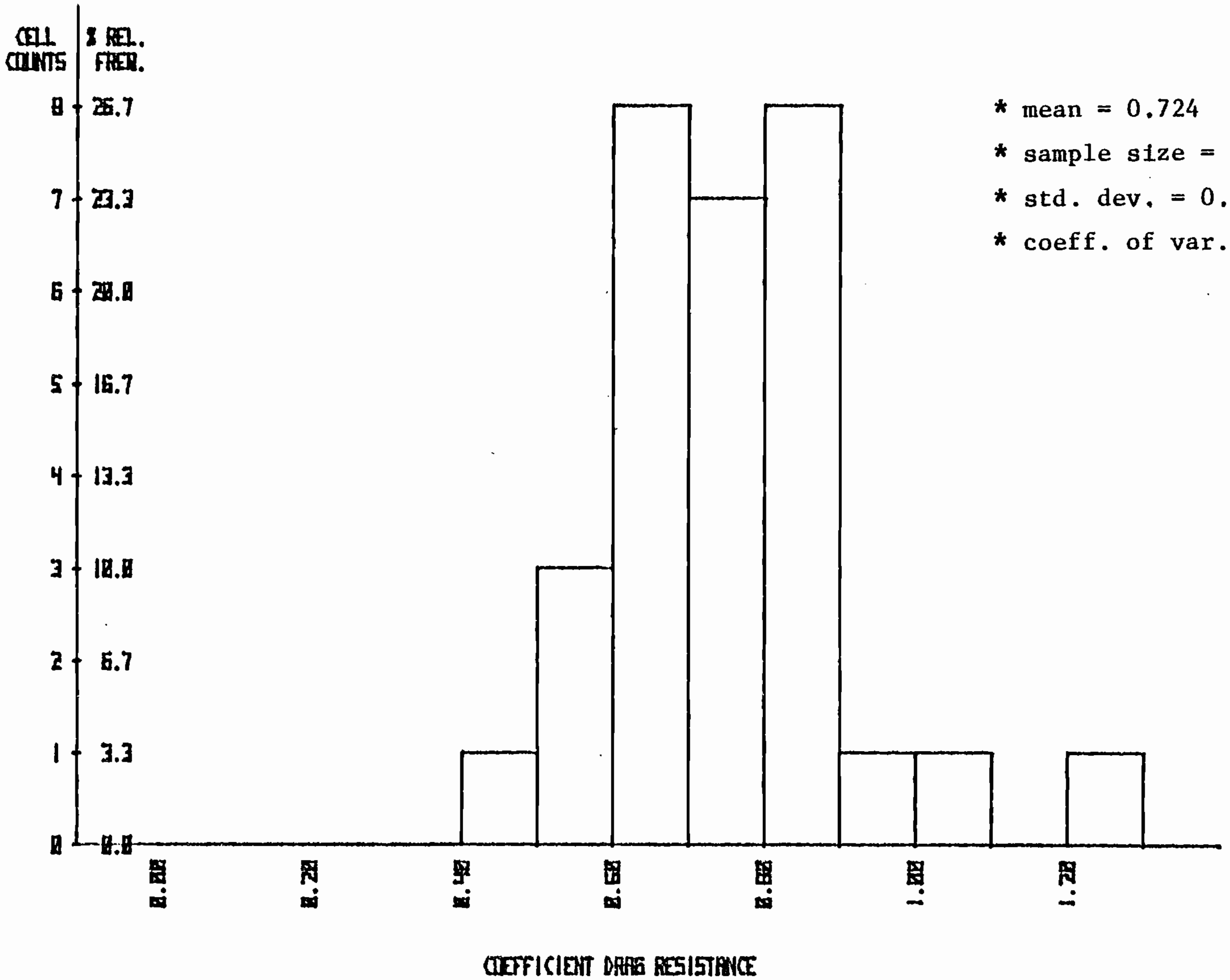


Figure 45. Histogram of field data for log 3 collected on plot 2 (static μ).



* mean = 0.724
* sample size = 30
* std. dev. = 0.158
* coeff. of var. = 21.8%

Figure 46. Histogram of all field data collected on plot 2 (static μ).

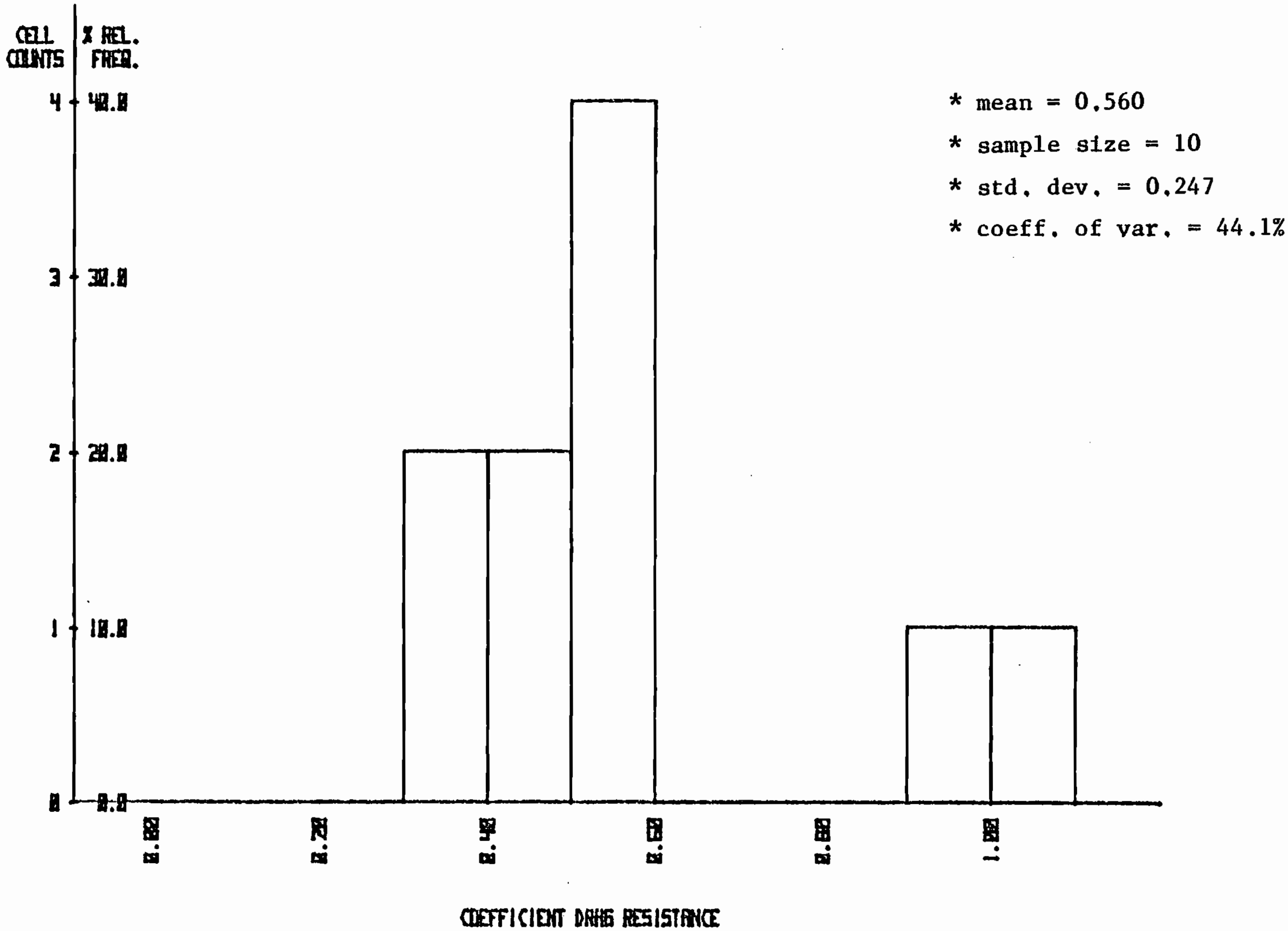


Figure 47. Histogram of field data for log 1 collected on plot 3 (static μ).

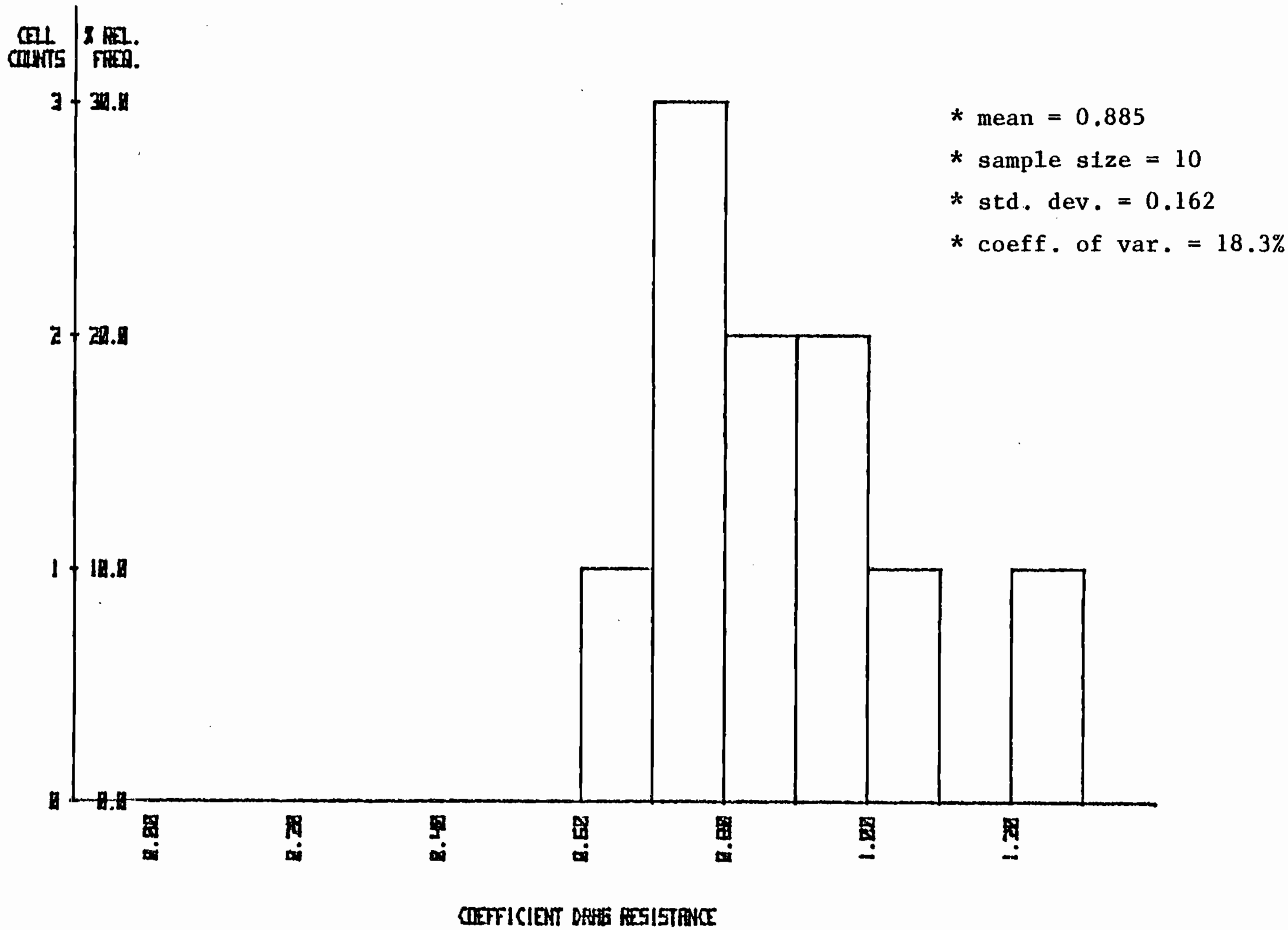


Figure 48. Histogram of field data for log 2 collected on plot 3 (static μ).

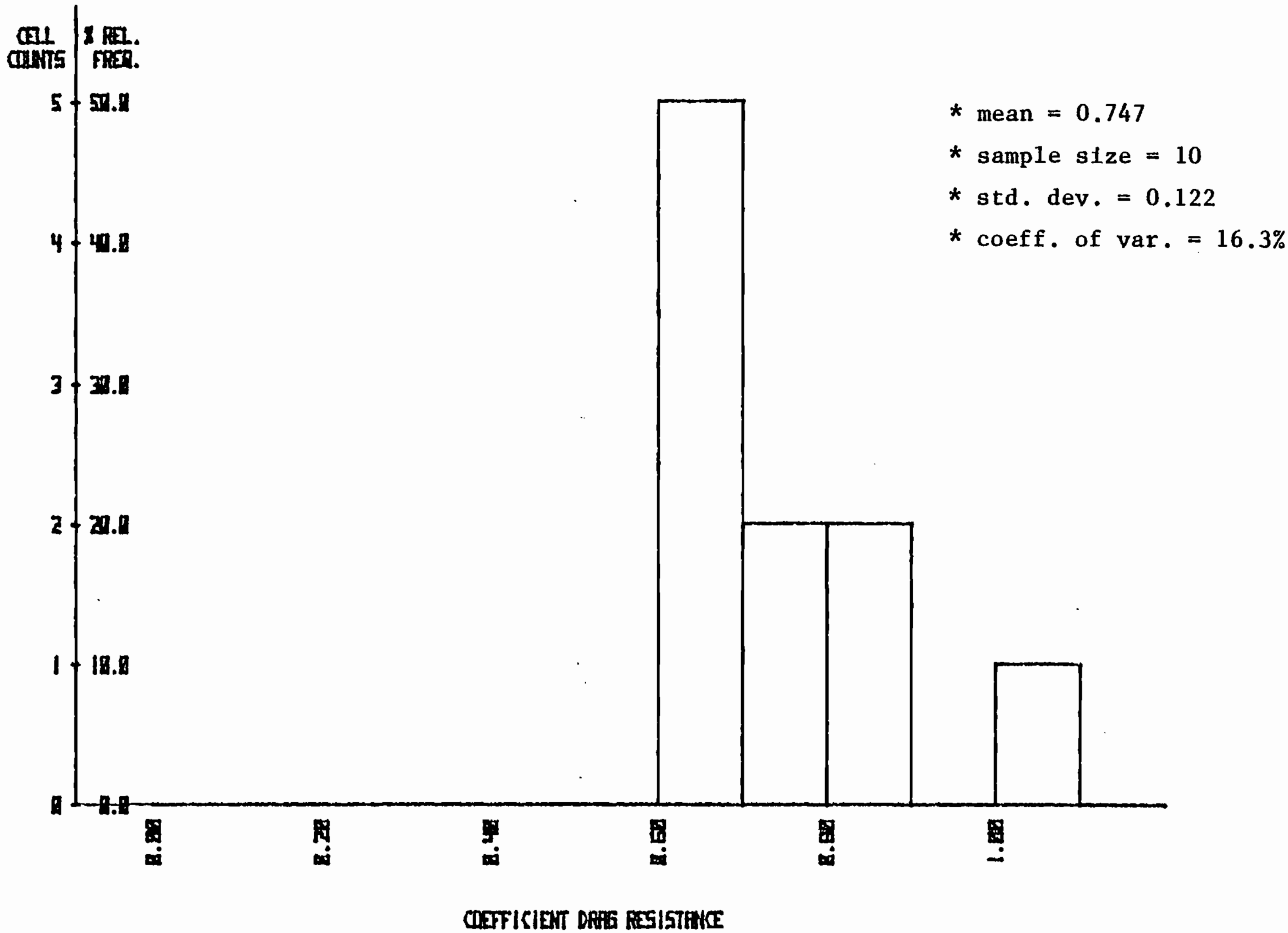


Figure 49. Histogram of field data for log 3 collected on plot 3 (static μ).

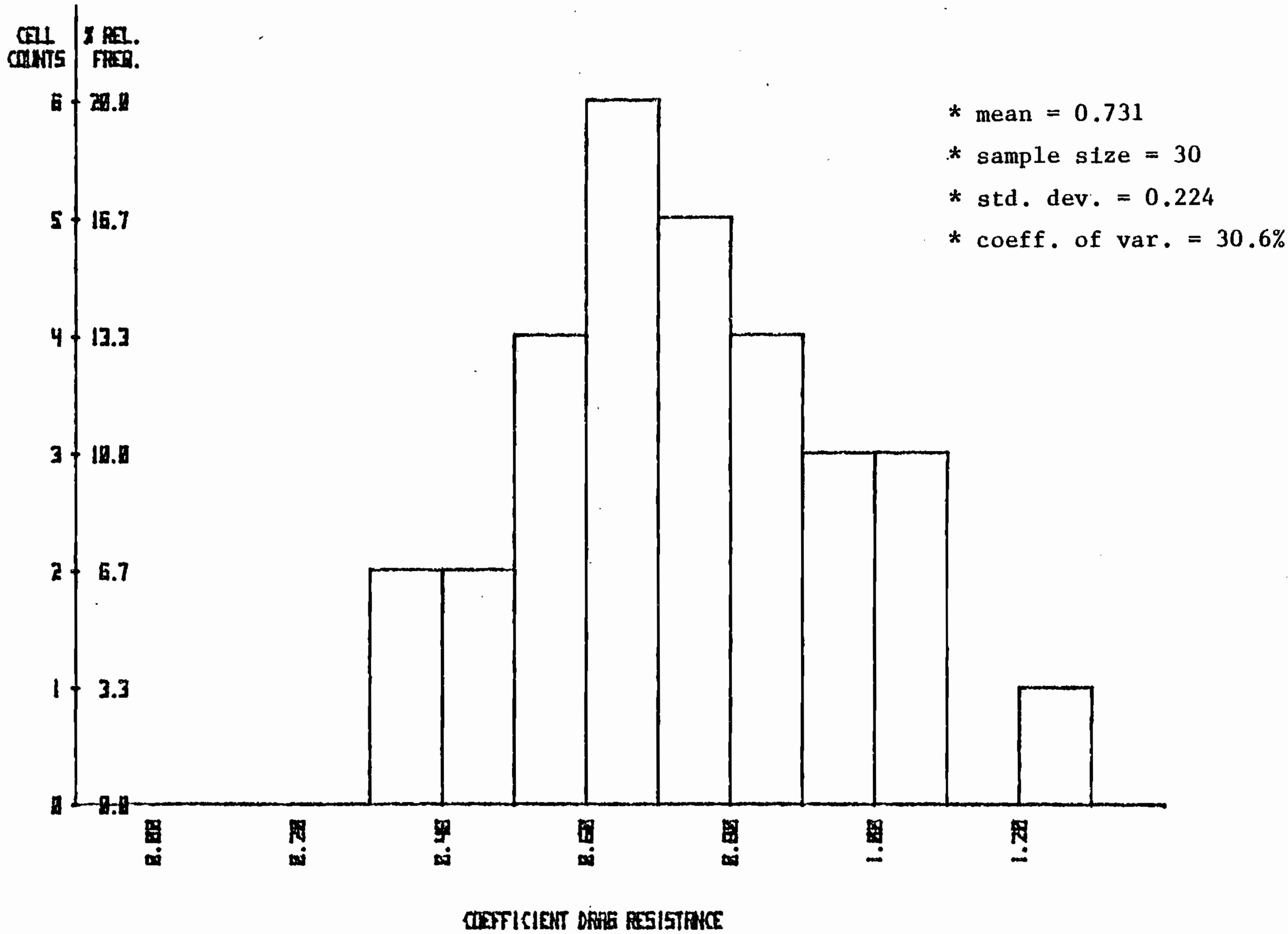


Figure 50. Histogram of all field data collected on plot 3 (static μ).

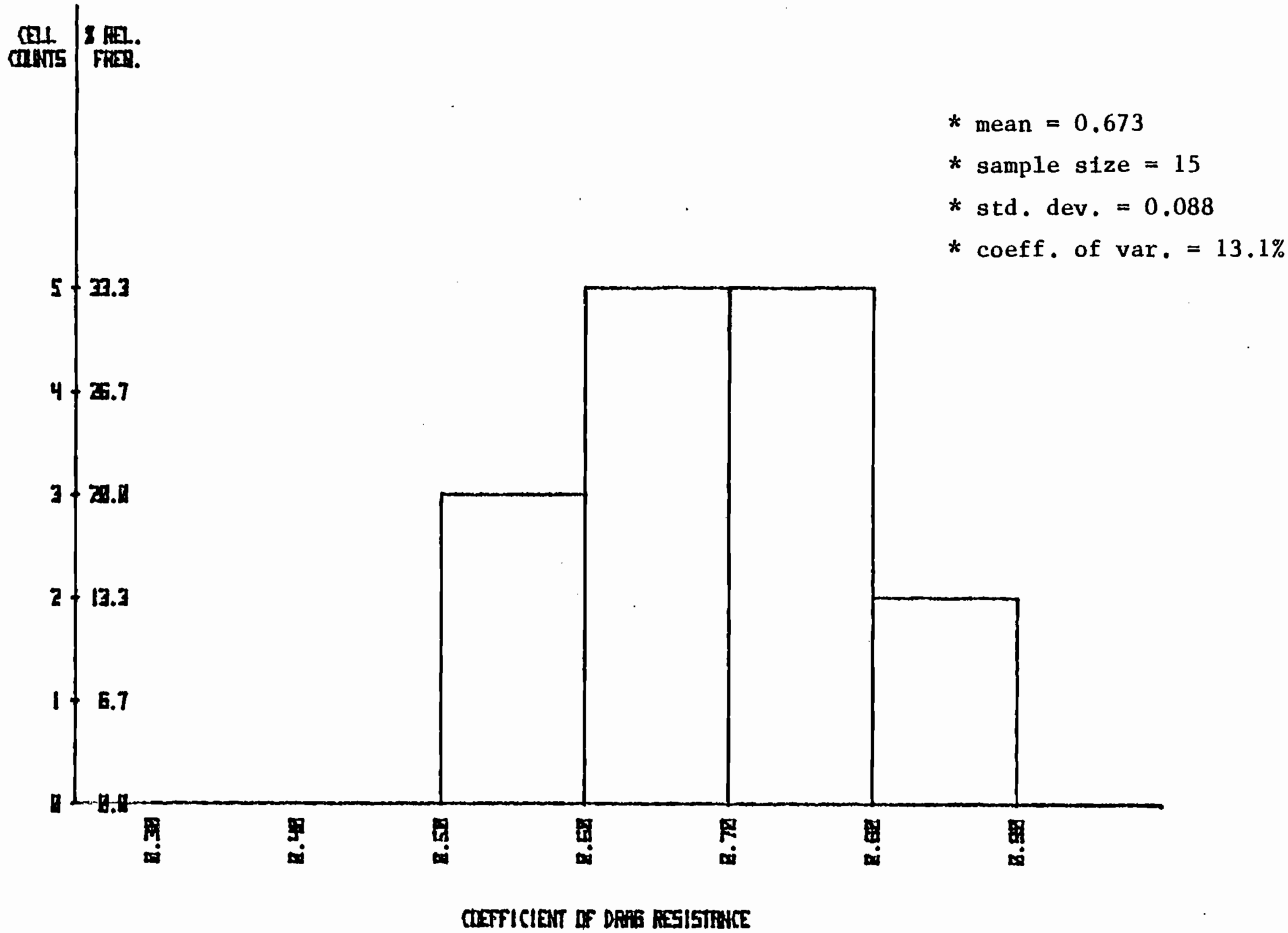


Figure 51. Histogram of field data for log 1 collected on plot 4 (static μ).

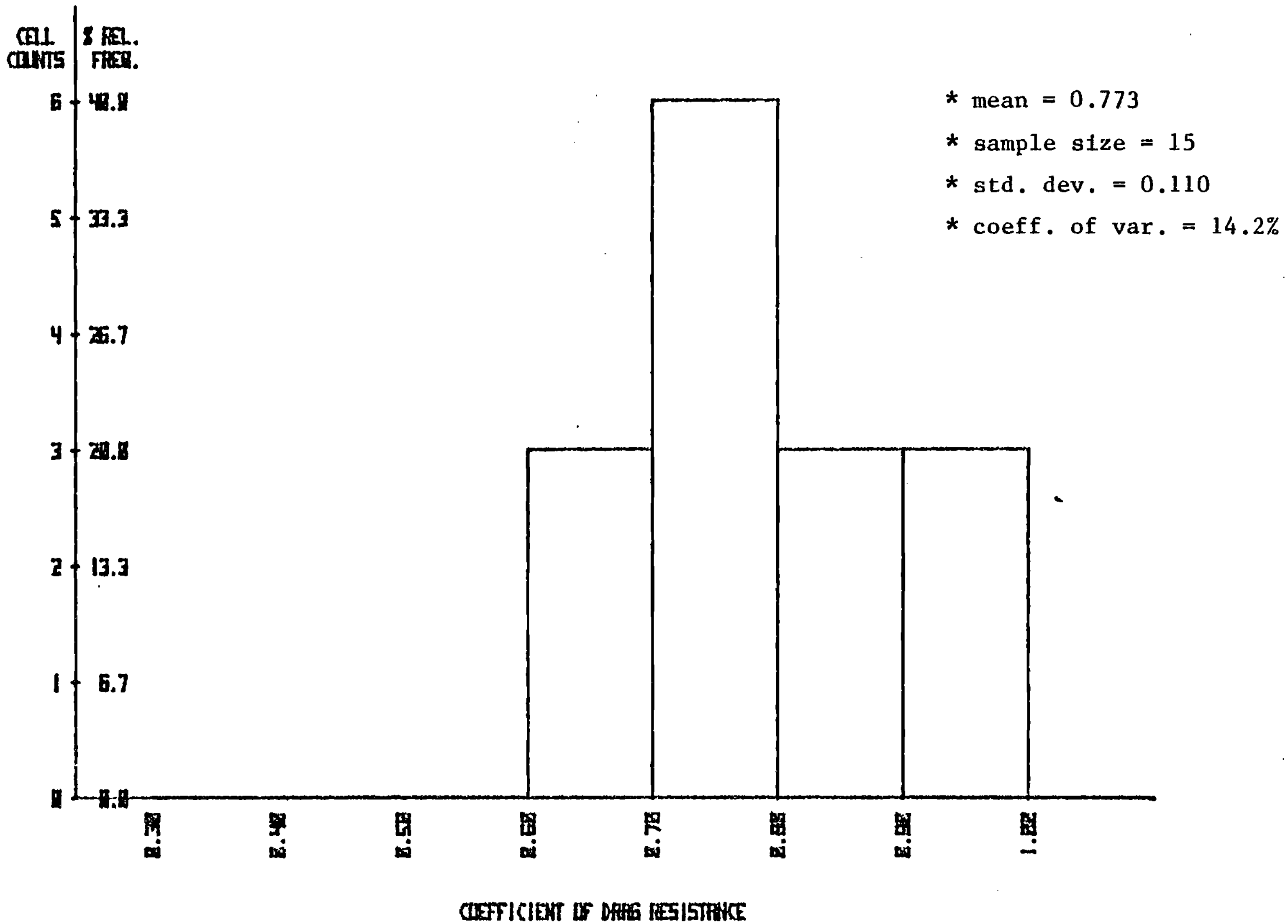


Figure 52. Histogram of field data for log 2 collected on plot 4 (static μ).

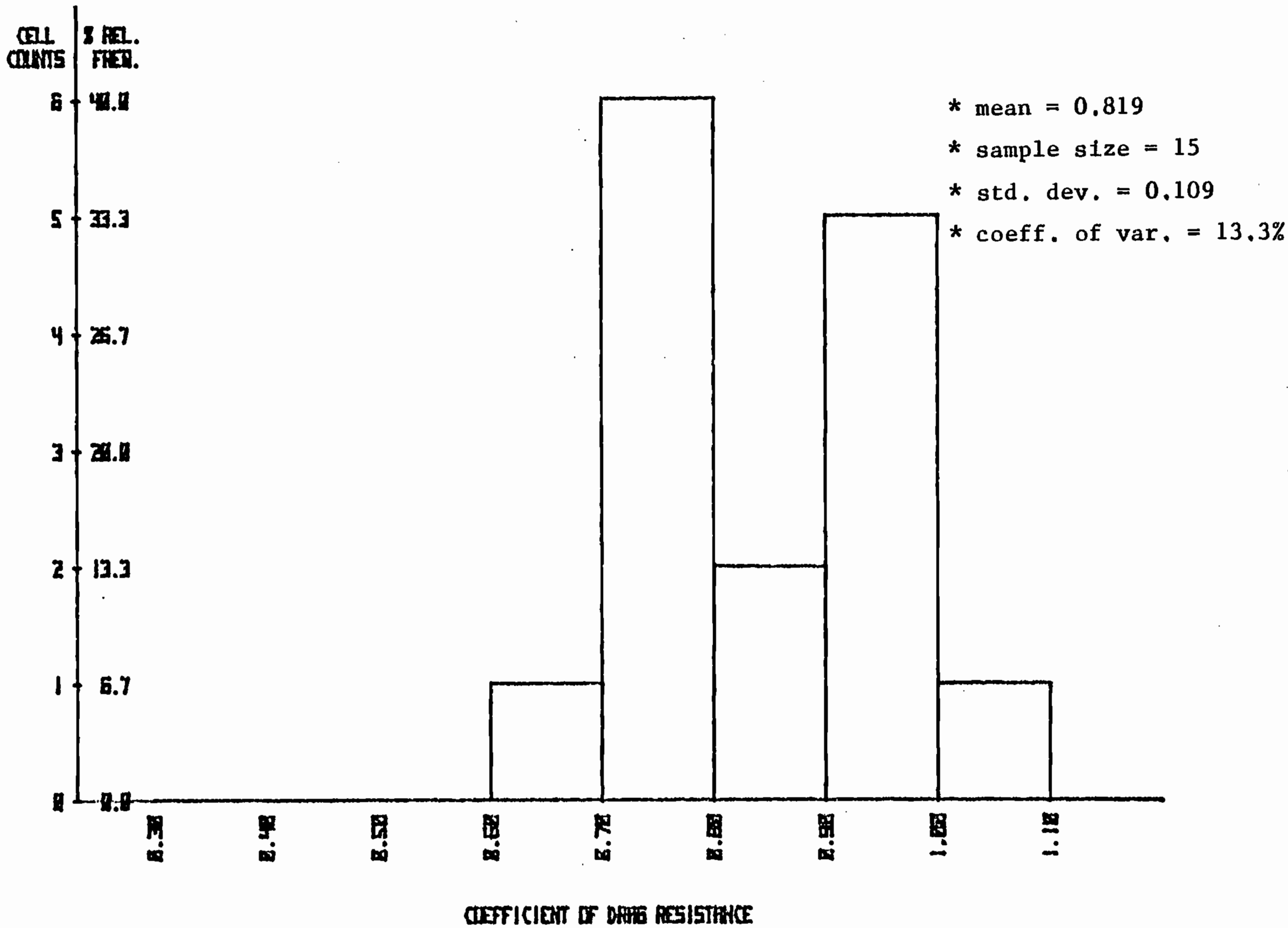


Figure 53. Histogram of field data for log 3 collected on plot 4 (static μ).

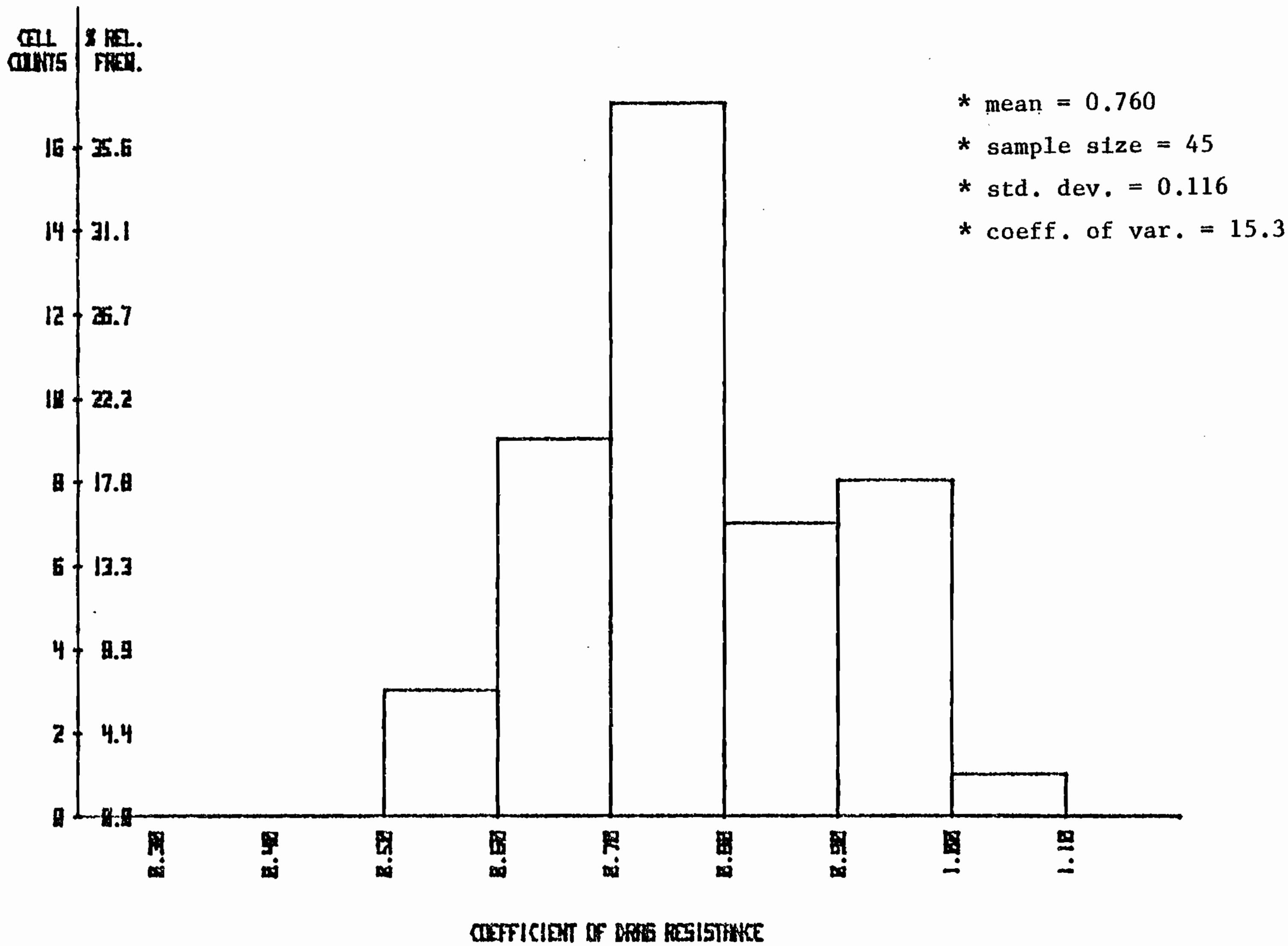


Figure 54. Histogram of all field data collected on plot 4 (static μ).

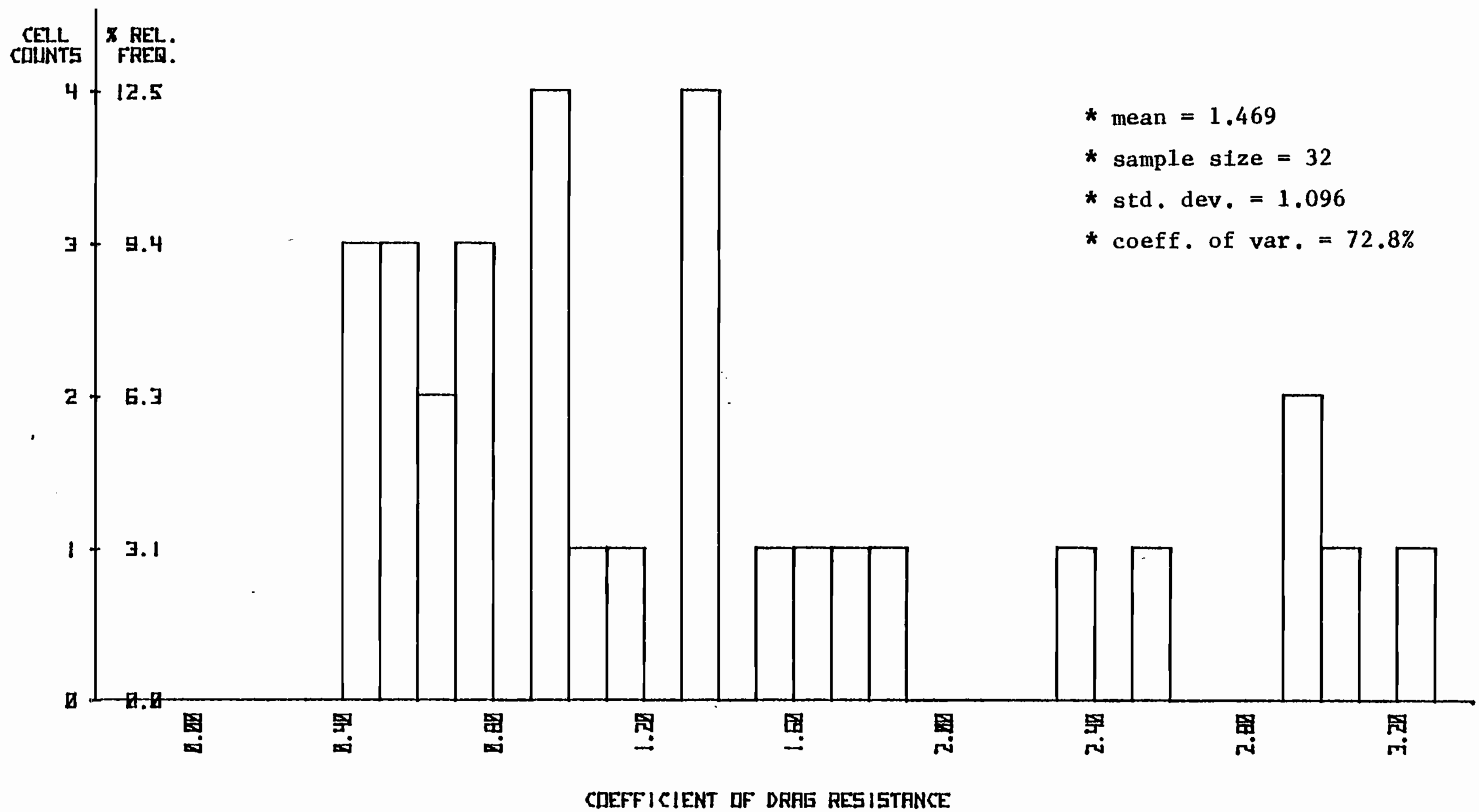


Figure 55. Histogram of all field data collected on plot 1 (dynamic μ).

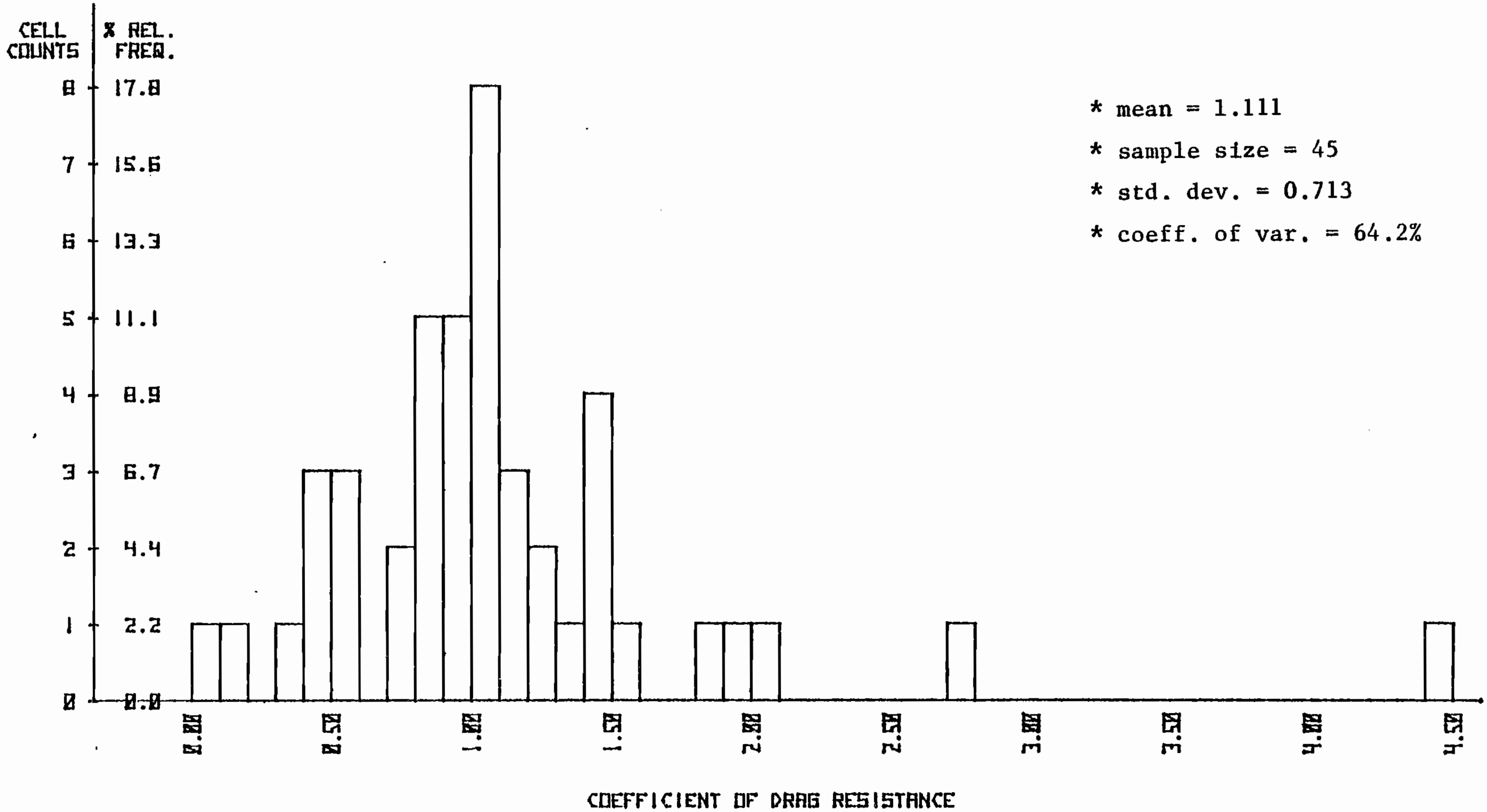


Figure 56. Histogram of all field data collected on plot 2 (dynamic μ).

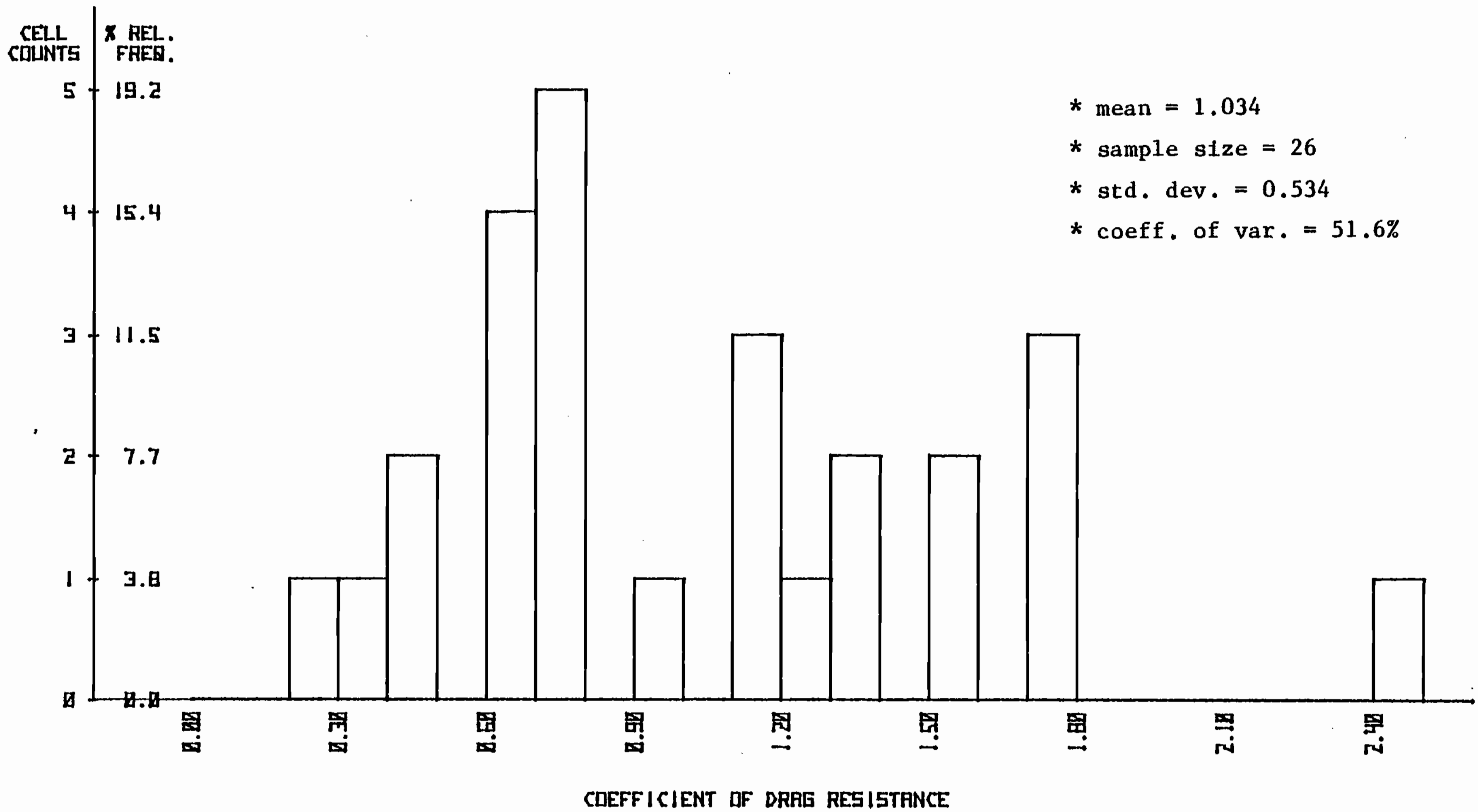


Figure 57. Histogram of all field data collected on plot 3 (dynamic μ).

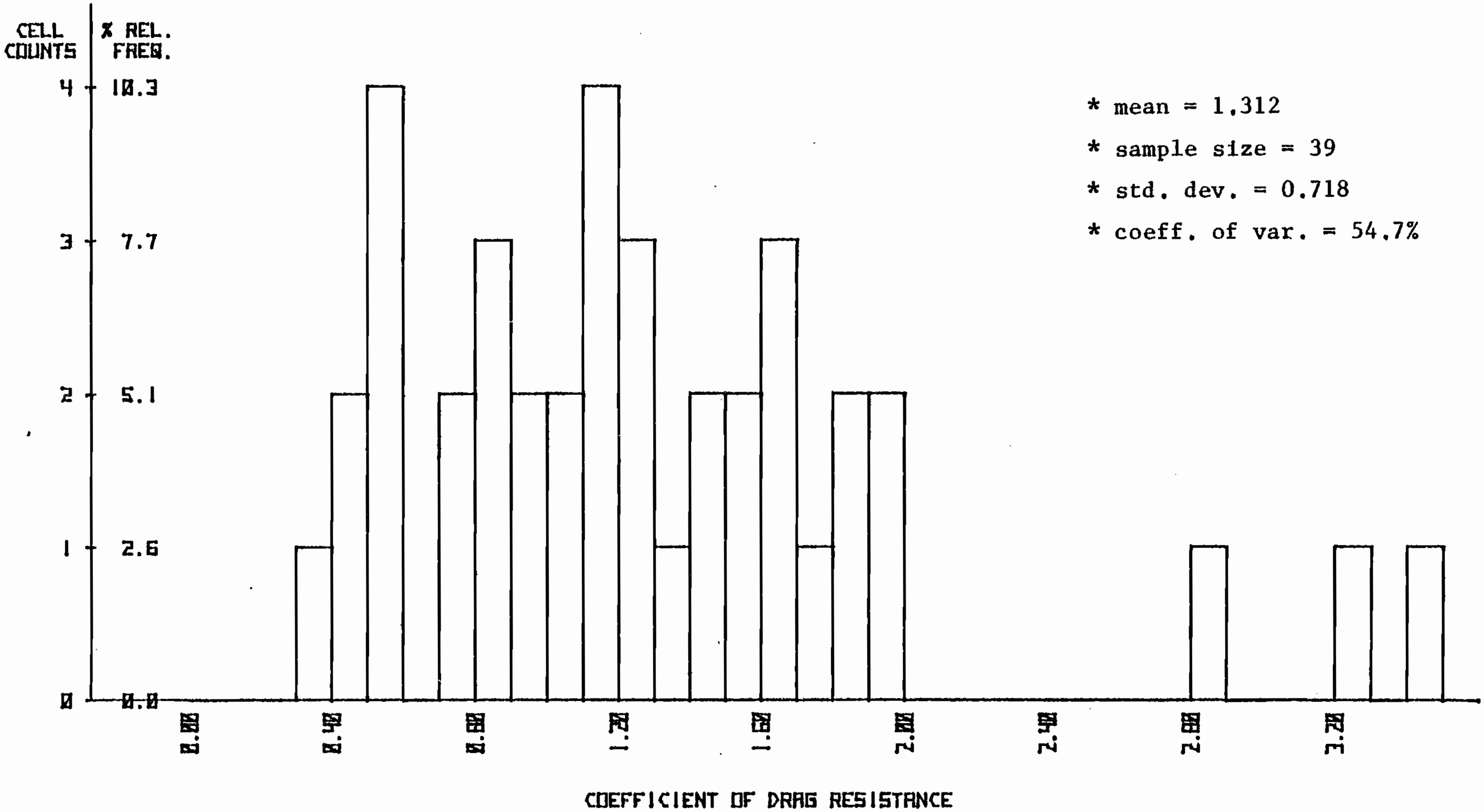


Figure 58. Histogram of all field data collected on plot 4 (dynamic μ).

Computer Printout of Regression Equations

:STEPWISE

VARIABLE ENTERING: SOIL*MC

MU*DRAG = 9.8510E-01 -1.3229E-02 SOIL*MC

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	149	9.51685917E 00	6.38715381E-02
REGRESSION	1	4.42495033E 00	4.42495033E 00
RESIDUAL	148	5.09190884E 00	3.44047895E-02

R SQUARED = .46495911

VAR	S.E. OF REGR. COEF.	T
CONSTANT	3.69836199E-02	2.66360834E 01
SOIL*MC	1.16647769E-03	-1.13408276E 01

VARIABLE ENTERING: SLOPEANG

MU*DRAG = 1.2040E+00 -1.2756E-02 SLOPEANG
-1.3870E-02 SOIL*MC

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	149	9.51685917E 00	6.38715381E-02
REGRESSION	2	5.63598817E 00	2.81799409E 00
RESIDUAL	147	3.88087100E 00	2.64004830E-02

R SQUARED = .59221095

VAR	S.E. OF REGR. COEF.	T
CONSTANT	4.57597622E-02	2.63108303E 01
SLOPEANG	1.88346517E-03	-6.77287281E 00
SOIL*MC	1.02619200E-03	-1.35159504E 01

VARIABLE ENTERING: L-DIA*WT

```
MU*DRAG = 1.1432E+00                 -1.2617E-02 SLOPEANG
          -1.3507E-02 SOIL*MC        +7.0140E-06 L-DIA*WT
```

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	149	9.51685917E 00	6.38715381E-02
REGRESSION	3	5.75314103E 00	1.91771368E 00
RESIDUAL	146	3.76371814E 00	2.57788914E-02

R SQUARED = .60452098

VAR	S.E. OF REGR. COEF.	T
CONSTANT	5.34614614E-02	2.13831713E 01
SLOPEANG	1.86231647E-03	-6.77467926E 00
SOIL*MC	1.02321547E-03	-1.31365799E 01
L-DIA*WT	3.29020278E-06	2.13178957E 00

VARIABLE ENTERING: SOILTYPE

```
MU*DRAG = 1.1335E+00                 -1.2592E-02 SLOPEANG
          -1.4456E-02 SOIL*MC        +6.0552E-02 SOILTYPE
          +7.0672E-06 L-DIA*WT
```

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	149	9.51685917E 00	6.38715381E-02
REGRESSION	4	5.86218980E 00	1.46554745E 00
RESIDUAL	145	3.65466937E 00	2.52046164E-02

R SQUARED = .61597946

VAR	S.E. OF REGR. COEF.	T
CONSTANT	5.30658177E-02	2.13607487E 01
SLOPEANG	1.84149477E-03	-6.83783268E 00
SOIL*MC	1.11427240E-03	-1.29732290E 01
SOILTYPE	2.91110922E-02	2.08003351E 00
L-DIA*WT	3.25344892E-06	2.17221238E 00

```
VARIABLE ENTERING: LOGANGLE

MU*DRAG = 1.0812E+00               +2.0403E-03 LOGANGLE
         -1.1935E-02 SLOPEANG -1.4093E-02 SOIL*MC
         +4.9307E-02 SOILTYPE +6.6633E-06 L-DIA*WT

                 ANALYSIS OF VARIANCE TABLE

SOURCE        DF    SUM OF SQUARES        MEAN SQUARE
TOTAL        149    9.51685917E 00      6.38715381E-02

REGRESSION     5    5.90362737E 00      1.18072547E 00

RESIDUAL     144    3.61323181E 00      2.50918876E-02

                 R SQUARED =    .62033358

VAR          S.E. OF REGR. COEF.             T
CONSTANT        6.67919732E-02      1.61876103E 01
LOGANGLE        1.58769481E-03      1.28908085E 00
SLOPEANG        1.90710535E-03     -6.25826186E 00


SOIL*MC         1.14712499E-03     -1.22851353E 01
SOILTYPE        3.03352859E-02      1.62541627E 00
L-DIA*WT        3.26096769E-06      2.04489828E 00

VARIABLE ENTERING: SOIL*DEN

MU*DRAG = 1.1852E+00               +2.1653E-03 LOGANGLE
         -1.4811E-02 SLOPEANG -1.4292E-02 SOIL*MC
         -5.7473E-02 SOIL*DEN +3.8409E-02 SOILTYPE
         +7.4853E-06 L-DIA*WT

                 ANALYSIS OF VARIANCE TABLE

SOURCE        DF    SUM OF SQUARES        MEAN SQUARE
TOTAL        149    9.51685917E 00      6.38715381E-02

REGRESSION     6    5.90813993E 00      9.84689989E-01

RESIDUAL     143    3.60871924E 00      2.52357989E-02

                 R SQUARED =    .62080775

VAR          S.E. OF REGR. COEF.             T
CONSTANT        2.54917368E-01      4.64939086E 00
LOGANGLE        1.61942982E-03      1.33705915E 00
SLOPEANG        7.06360119E-03     -2.09674202E 00
SOIL*MC         1.24347576E-03     -1.14937350E 01
SOIL*DEN        1.35912559E-01     -4.22866473E-01
SOILTYPE        3.98708835E-02      9.63346704E-01
L-DIA*WT        3.79828168E-06      1.97069686E 00
```