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AD725472

DAVIDSON LABORATORY

Report SIT-DL-71-1533

June 1971

THE EFFECT ON DRAWBAR-PULL IN SAND OF THE LATERAL SPACING OF CLEATS

by

John Leroy Johnsen

prepared for
Department of Defense
under
Contract DAAE-07-69-0356
(Project THEMIS)

STEVENS INSTITUTE OF TECHNOLOGY
CASTLE POINT STATION
HOBOKEN, NEW JERSEY

68

R-1533

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Davidson Laboratory, Stevens Institute of Technology Hoboken, New Jersey 07030	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

THE EFFECT ON DRAWBAR-PULL IN SAND OF THE LATERAL SPACING OF CLEATS

4. DESCRIPTIVE NOTES *(Type of report and, inclusive dates)*

Final Report

5. AUTHOR(S) *(First name, middle initial, last name)*

John Leroy Johnsen

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1971	57	10

8a. CONTRACT OR GRANT NO. DAAE-07-69-0356 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited. [redacted]. Reproduction of the document in whole or in part is permitted for any purpose of the U.S. Government

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of Defense Washington, D. C. 20301

13. ABSTRACT

The primary objective of this work is to evaluate in relative terms the effect on drawbar-pull in sand of the lateral spacing of cleats with grousers. As a means of achieving this objective, a set of four varied cleat configurations is used as the basis for both a theoretical and an experimental evaluation of the effect.

A secondary objective of this work was to prepare for and place into operation Davidson Laboratory's newly acquired soil-bin dynamometer. Consequently, considerable information pertaining to the dynamometer is included.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
CLEAT						
DRAWBAR-PULL						
GROUSER						
LAND LOCOMOTION						
TRACTION						
TRACTIVE EFFORT						

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Approved

I. Robert Ehrlich, Manager
Transportation Research Group

ABSTRACT

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Author: LTC John L. Johnsen

Advisor: Dr. I. Robert Ehrlich

Date: 14 May 1971

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KEYWORDS

Cleat

Drawbar-Pull

Grouser

Land Locomotion

Traction

Tractive Effort

ACKNOWLEDGEMENTS

The author would like to express his sincere appreciation to all those who contributed to the accomplishment of this work. In particular, the author would like to thank Dr. I. Robert Ehrlich and Dr. Louis I. Leviticus for their guidance and assistance in all phases of the work; Mr. Karl Dannwolf and Lt. Samuel Shamay for their assistance in the dynamometer preparation and experimental phases of the work; and Miss Dolores Pambello for her help in the typing of the manuscript.

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c	Lateral flow proportionality constant
H	Tractive effort per unit width
H_T	Total tractive effort
h	Grouser height
ℓ	Rupture distance
m	Bearing capacity factor due to surcharge
n	Bearing capacity factor due to soil weight and friction
Q	Surcharge due to sinkage
s	Cleat length
V	Vertical load
W	Weight of soil involved in lateral flow
z	Cleat sinkage
δ	Angular limit of lateral soil involvement
φ	Soil angle of internal friction
γ	Soil density
θ	Angle between V and the resultant of H and V

CHAPTER I

INTRODUCTION

Objective

The primary objective of this work is to evaluate in relative terms the effect on drawbar-pull in sand of the lateral spacing of cleats with grousers. As a means of achieving this objective, a set of four varied cleat configurations will be used as the basis for both a theoretical and an experimental evaluation of the effect.

A theoretical analysis of the aforementioned effect, utilizing the unrefined relationships thus far developed, will usually predict the effect to be small. This leads one naturally to the conclusion that, from a purely practical point of view, whatever might be gained in terms of reduced weight or increased drawbar-pull by the lateral spacing of such devices would surely be offset by a corresponding loss in cleat structural strength. And, twenty years ago, this might have been an entirely valid conclusion. Today, however, in the light of an increasing requirement for improvements in cross-country mobility, an expanding program for the development of space exploration components, and an already highly developed materials technology, it is not. In the development today of any cross-country vehicle, weight and drawbar-pull are critical factors; structural strength can and must be achieved through the use of special materials, not at the unacceptable expense of weight or drawbar-pull.

The ability of soils to support various dynamic vehicle loads has been the subject of extensive investigation for some fifty years. Even so, this necessarily complex and often elusive phenomenon has yet to be described completely in manageable and readily applicable terms. In many instances, the soil-vehicle relationships which have been developed are only marginally capable of predicting performance. In others, the relationships are based solely on theoretical analyses and have never been subjected to experimental verification. The relationships, for example, which have been developed to describe the effect on tractive effort* of the lateral spacing of cleats have never been subjected to experimental evaluation.

As a final thought pertaining to the primary objective of this work, it must be emphasized that it calls for an evaluation in relative or qualitative terms. Such an evaluation not only meets the needs of a preliminary investigation of this sort, but also permits the use of existing Davidson Laboratory soil-bin test equipment. Only the design and construction of a wheel with provisions for the variable lateral spacing of cleats is required. An evaluation in absolute or quantitative terms would require either the design and construction of extensive soil-bin test equipment or the accomplishment of a highly complex theoretical analysis well beyond the scope

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*In a given situation, the tractive effort is equal to the drawbar-pull plus the soil's resistance to the motion.

of this work.

A secondary objective of this work was to prepare for and place into operation Davidson Laboratory's newly acquired soil-bin dynamometer. As of 1 January 1971, the dynamometer was, for all practical intentions and purposes, not operational. Many of the dynamometer's original components needed to be modified or adjusted, many accessory components needed to be designed, constructed, and installed and the rather awesome array of ten strain gauges needed to be calibrated. In short, a great deal of work needed to be done before the dynamometer could be ready for even limited operation.

By the end of April 1971, a great deal of work had been done and the dynamometer was ready for limited use. Although the required work had been accomplished by a number of individuals, the author's contribution to the effort was by no means the least substantial. As a matter of fact, the author devoted more than two months of full-time effort to the sole task of preparing the soil-bin dynamometer for operation.

Background

As early as 1926, J. W. Randolph had studied extensively the effect on drawbar-pull of the size and spacing of lugs on agricultural tractor wheels. Although the results of his work had application primarily in the improvement of agricultural tractor performance, at least one of his findings had application well beyond that realm of interest. His observation and analysis of the bridging or arching action of soils appears to have set the stage for the development of what is generally referred to today as the spaced-link track.[1]

It was not until 1943, however, that the effect on tractive effort of the longitudinal spacing of track links or cleats was actually investigated. During the last two years of World War II, a group of German engineers under the direction of W.I.E. Kamm conducted numerous tests in snow, soft earth, and bog, and among other things, demonstrated the above-mentioned effect. They found that, for the range of vertical loads being applied, a set of three cleats with proper spacing produced a higher tractive effort than the same set of three without spacing. Proper spacing, by the way, was found by the group to be roughly 1.5 times the cleat length.[2] Unfortunately, the accomplishment of related theoretical analyses was not a part of this purely experimental work. As a consequence, the application of its results in the general development of track design was virtually impossible.

M. G. Bekker appears to have been the first to approach the matter of cleat spacing from both a theoretical and an experimental viewpoint. During the years immediately following World War II, he did a great deal of work in this area and, by 1951, had developed a host of theoretical relationships, many of which he had also verified experimentally.[3] As a result of this impressive contribution to the field of soil-vehicle mechanics, Bekker is generally credited with having given birth to the spaced-link track. The spaced-link track, incidentally, is a track on which the links or cleats are spaced along the track in such a way as to prevent overlap of the areas of soil failure. Such an arrangement allows each cleat to act independently and, at moderate loads, to develop the maximum tractive effort. A section of conventional, closed-link track and its associated pattern of soil failure are shown schematically in Figure 1. A similar representation of a section of spaced-link track is shown in Figure 2.

Since Bekker's work, several further investigations of the spaced-link track concept and related phenomena have been made. During the period July 1952 through June 1954, C.J. Nuttall and J.P. Finelli carried out an extensive program of tests and theoretical analyses, with the overall objective of defining the relationship between soft terrain and the design controllable features of a tracked vehicle. One of their more significant conclusions was that the spacing at which individual cleats commence to act independently is considerably greater, namely 1.5 times greater, than that predicted by Bekker's spaced-link track theory.[4]

Then, in 1955-56, J.P. Finelli and C.W. Wilson conducted a large number of dynamic scale-model tests, with one of their objectives being to evaluate the relative performance of a conventional and a spaced-link track. The results of their particular tests indicated that, at low and moderate slips, the conventional closed-link track produced a higher drawbar-pull than the spaced-link track of the same length and width and that, even at high slips, performance of the spaced-link track was only modestly superior.[5]

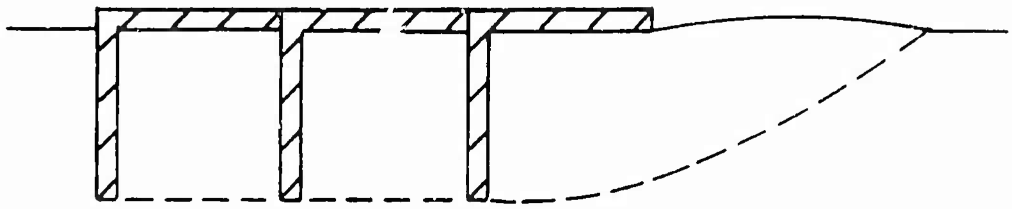

FIGURE 1. CLOSED-LINK TRACK

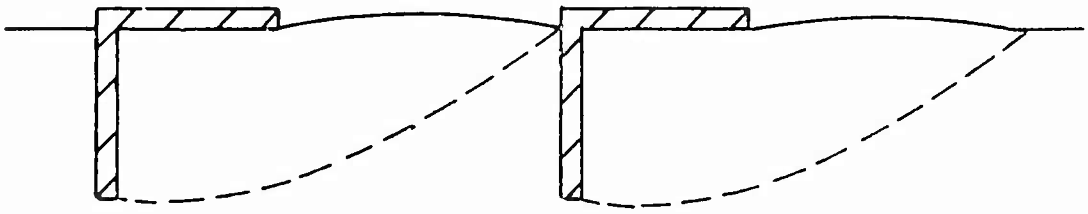

FIGURE 2. SPACED-LINK TRA'K

Finally, in 1969, Shun-Whi Cho, H. Schwanghard, and H. von Sybel published the results of an investigation of the effect on tractive effort of the spacing of track shoes or cleats. Their most significant finding was that, for a given number of cleats and a given longitudinal spacing, the "lengthened" track (where all the cleats were positioned in tandem) was invariably superior in the production of tractive effort to the "widened" track (where lateral groupings of cleats were positioned in tandem).[6]

With the exception of Bekker's, none of these investigations dealt with the effect on drawbar-pull of the lateral spacing of cleats, and even Bekker's treatment of the subject did not include an experimental verification. A logical next step, therefore, is an investigation which includes both theoretical and experimental evaluations of the effect.

CHAPTER II

THEORETICAL EVALUATION

Two-Dimensional Aspects

The four cleat configurations which were tested during the experimental portion of this work and for which the theoretical tractive effort must now be determined, are shown schematically in Figure 3. Since identical component cleats are used in all four configurations, this analysis will commence with the two-dimensional consideration of a single component cleat.

According to Bekker,[7] the tractive effort H per unit cleat width developed in frictional soil by the cleat shown in Figure 4 is given by the expression

$$H = (m\gamma s + n\gamma s^2)\sin\theta ,$$

where

θ = angle between the load V and the resultant of H and V

γ = density of the soil

s = length of the cleat

h = height of the grouser

z = sinkage of the cleat

m = bearing capacity factor due to surcharge

n = bearing capacity factor due to soil weight and friction

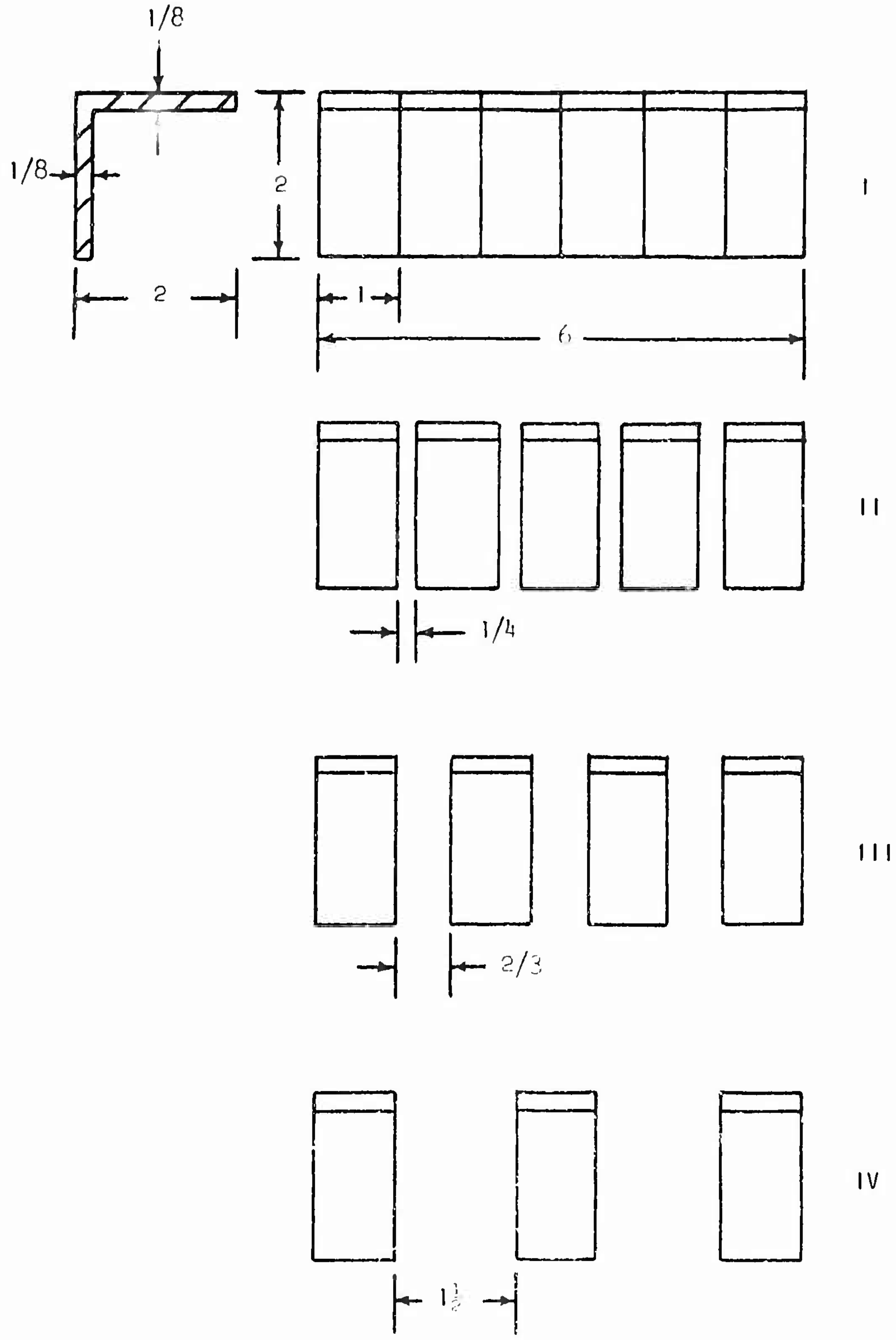

FIGURE 3. CLEAT CONFIGURATIONS

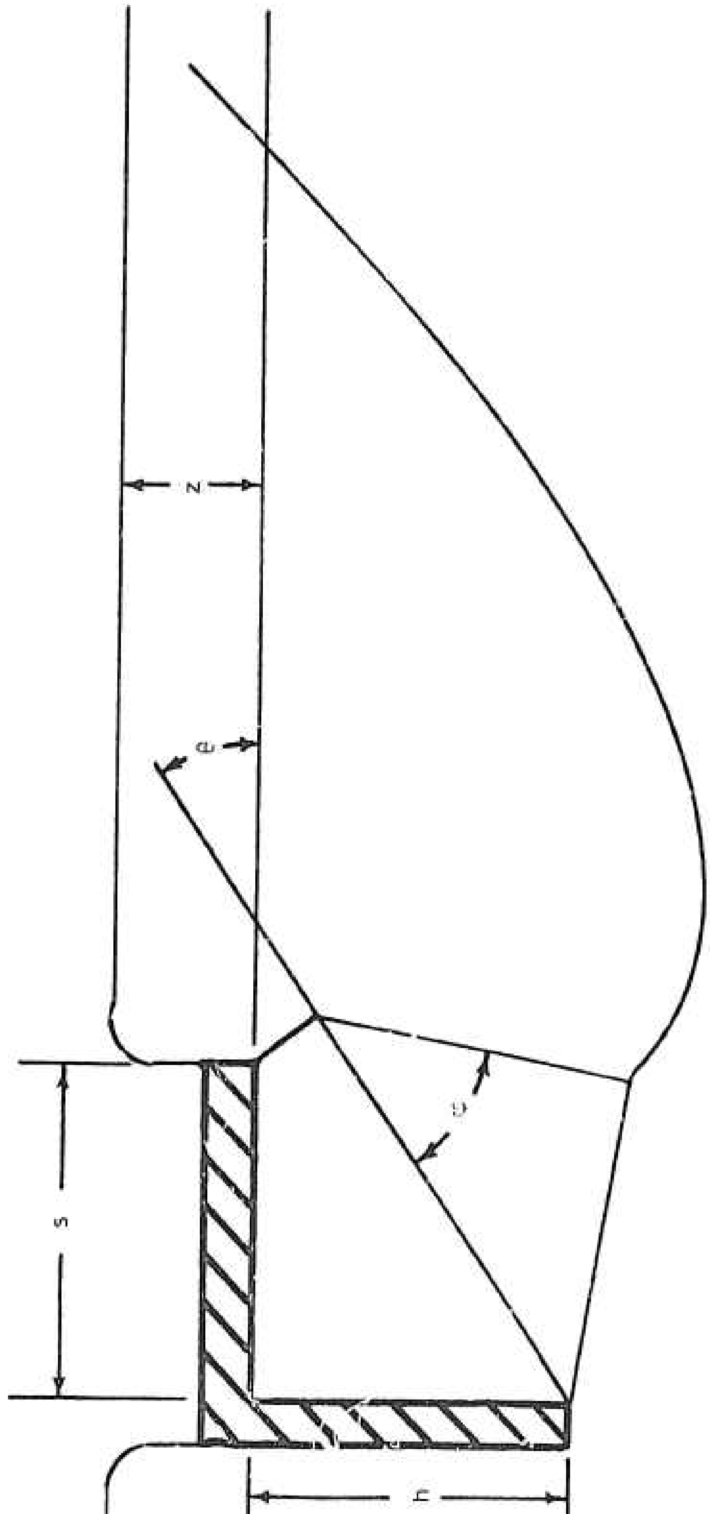

FIGURE 4. TWO-DIMENSIONAL CLEAT

For the aforementioned single component cleat, applicable values of these variables, with the exception of the functions m and n , are listed in Table I. Values of the functions m and n may be obtained directly from graphs developed by Bekker and reproduced in Appendix A.

Table 1

Applicable Values of Variables

	For a Component Cleat Used in Configuration			
	I	II	III	IV
s(in)	1.9	1.9	1.9	1.9
h(in)	1.9	1.9	1.9	1.9
γ(lb/in^3)	.052	.052	.052	.052
z(in)	.5	.6	.8	1.0
V(lb)	3.3	4.0	5.0	6.7
H(lb)	2.7	3.0	3.5	4.1

The foregoing expression for the tractive effort H does not constitute an explicit relationship, however, and cannot be solved directly. Hence, an iterative approach to its solution must be employed. Employment of such an approach yields the values of tractive effort H listed in Table I.

It should be noted here that a purely theoretical determination of the sinkage z is well beyond the scope of this work. Therefore, the sinkages shown in Table I are based on sinkages actually observed during the experimental portion of this work. It should also be noted here that the loads shown are based on an assumed uniform distribution of the 20 lb load to which all four configurations were subjected during the experimentation.

Three-Dimensional Aspects

The preceding consideration of the component cleat was based on the fundamental assumption that, for the range of loads involved, the development of tractive effort is accompanied by general or ground failure. Although to the two-dimensional aspects of this theoretical evaluation this assumption was not essential, to the three-dimensional aspects it is. Were grip failure only to occur, the lateral flow of soil would be negligible and the three-dimensional consideration of the component cleat meaningless. Fortunately, the author's experimental observations appear to support the validity of the assumption that general failure occurs.

According to Bekker,[8] the additional tractive effort ΔH as a result of lateral soil flow developed in frictional soil by one end of the cleat shown in Figure 5 is given by the expression

$$\Delta H = (W + Q)\tan(45 + \varphi/2) ,$$

where

$$W = \frac{\gamma \ell^3 \pi \delta}{1080} \tan(45 - \varphi/2)$$

and

$$Q = \frac{\gamma \ell^2 \delta \pi z}{360} .$$

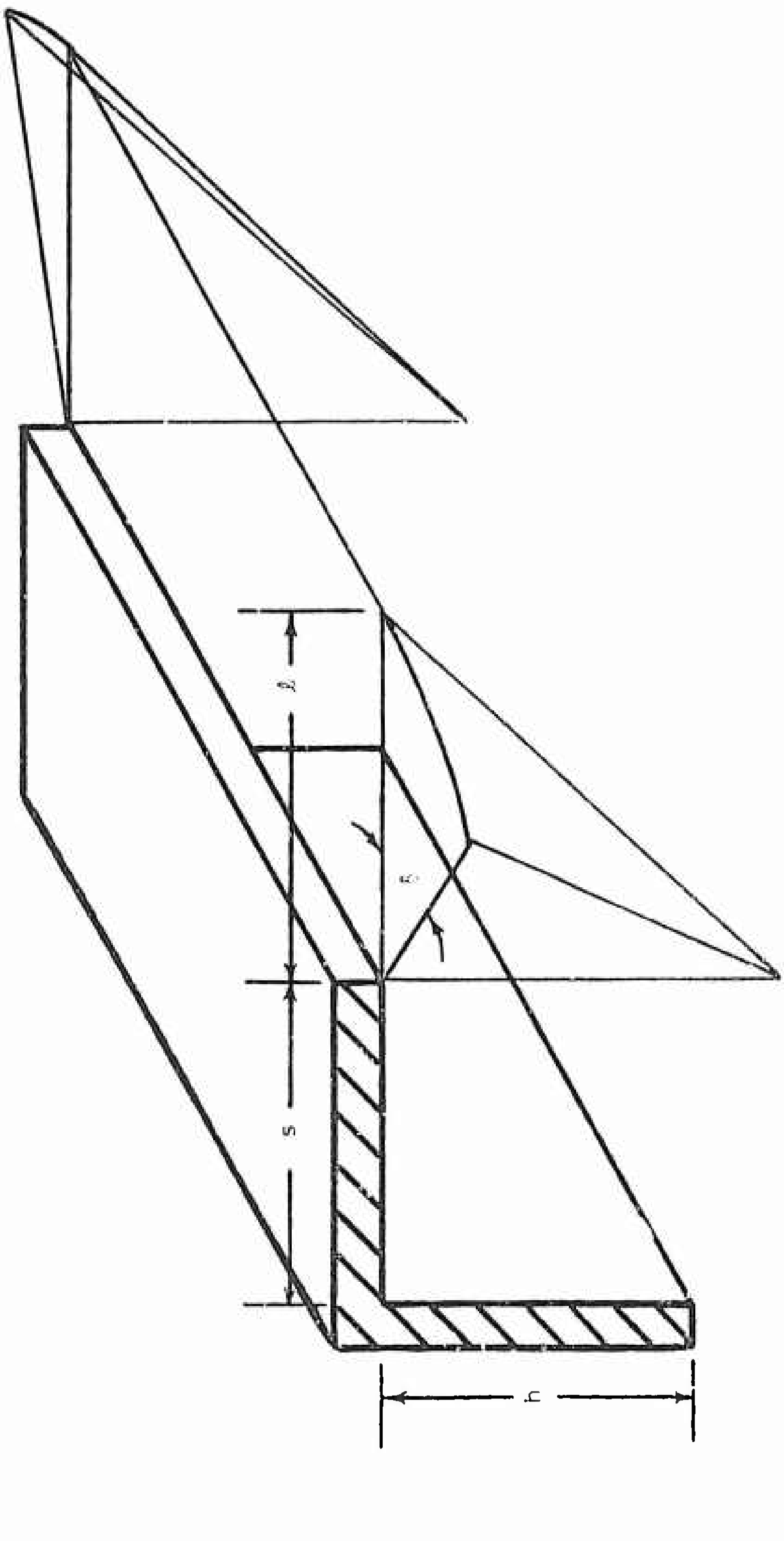

FIGURE 5. THREE-DIMENSIONAL CLEAT

In these relationships,

W = weight of the conical section of soil involved

Q = surcharge due to the sinkage z

φ = angle of internal friction of the soil

γ = density of the soil

ℓ = length of the soil failure pattern or rupture distance

δ = angular limit of lateral soil involvement

For the component cleat, then, with the length ℓ obtained directly from the graph developed by Bekker and included in Appendix A and δ taken as $45 - \varphi/2$, applicable values of Q, W, and ΔH are listed in Table II.

Table II

Applicable Values of Q, W, ΔH and HT

	For a Component Cleat* Used in Configuration			
	I	II	III	IV
Q(lb)	.22	.27	.37	.49
W(lb)	.44	.47	.49	.54
ΔH(lb)	1.25	1.41	1.63	1.95
HT(lb)	18.7	18.3	18.2	18.1

*Except in the case of the total tractive effort HT discussed below, where the value listed is for the entire configuration.

With H and ΔH thus calculated, the total tractive effort HT for each configuration may now be determined from the relationships:

$$HT_{I} = 6H_{I} + 2\Delta H_{I} ,$$

$$HT_{II} = 5H_{II} + (2 + 8c_2)\Delta H_{II} ,$$

$$HT_{III} = 4H_{III} + (2 + 6c_3)\Delta H_{III} ,$$

and

$$HT_{IV} = 3H_{IV} + (2 + 4c_4)\Delta H_{IV} ,$$

where the Roman numeral subscript indicates the configuration involved and the constants c_2, c_3, and c_4 represent that portion of the lateral flow pattern actually available for failure. In the case of configuration II, for example, the spacing between cleats is .25 in. Hence, only a .12-inch wide section of the lateral flow pattern is available for failure. This represents roughly 4% of the maximum lateral flow volume or $c_2 = .04$. Similar treatments of configurations III and IV yields $c_3 = .10$ and $c_4 = .22$. c_1, of course, is zero. Solving these relationships for the total tractive effort HT produces the results listed in Table II.

Results

The results of this theoretical evaluation are plotted in relative terms in Figure 6. This figure shows, for each of the three changes in cleat configuration, the actual decrease in contact surface area and the corresponding change in theoretical tractive effort. In changing from configuration I to configuration II, for example, a decrease of 17 percent in the contact surface area occurs, while a decrease of only 2 percent in the theoretical tractive effort takes place.

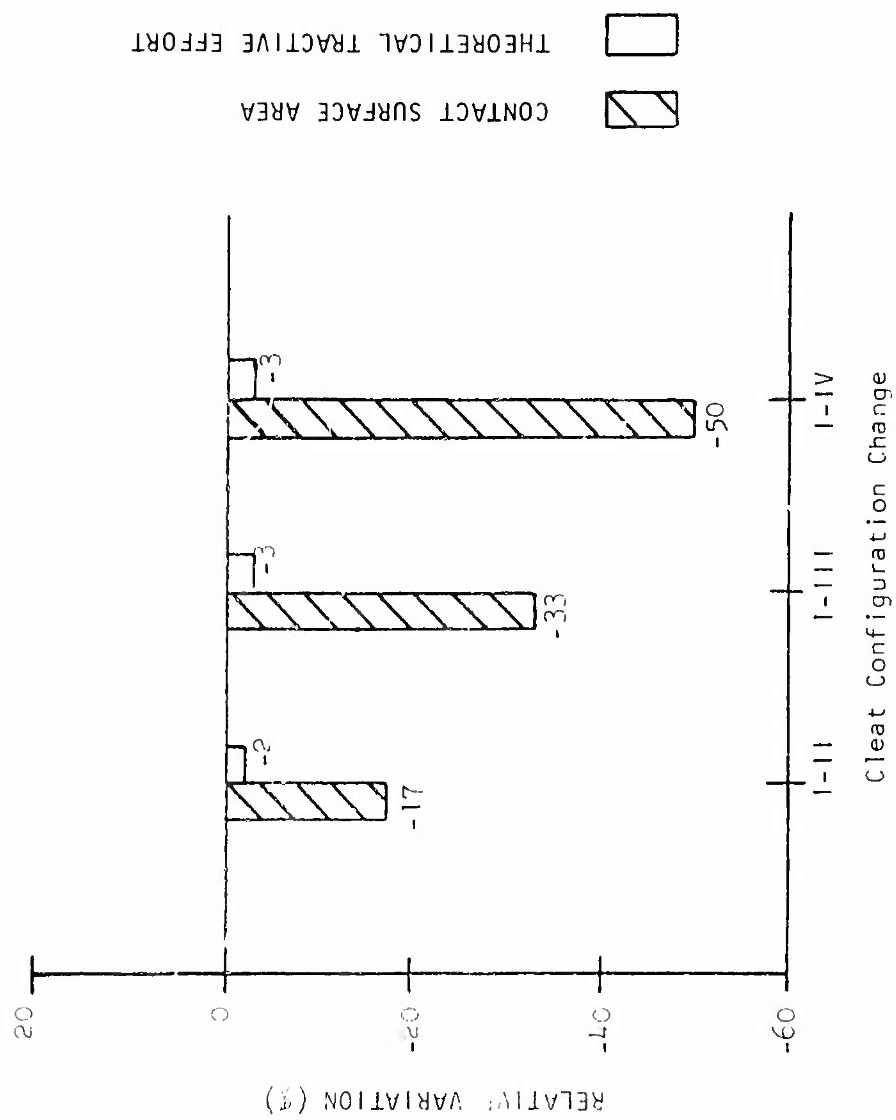

FIGURE 6. OVERALL THEORETICAL RESULTS

CHAPTER III

EXPERIMENTAL EVALUATION

Apparatus

The apparatus used in the experimental portion of this work consisted of four main components. These were a test wheel, a soil-bin dynamometer, a towing and soil-preparation carriage, and a set of data recording equipment.

The test wheel, which was designed and constructed by the author for the sole purpose of carrying out this work, is shown in Figures 7, 8 and 9. It was made up of a circular hub, sixteen cleat mounting brackets, and ninety-six removable cleats. The wheel was 27.0 inches in diameter, measured from grouser tip to grouser tip, and 6.0 inches wide, measured at maximum cleat width.

The test wheel hub consisted of two aluminum discs bolted together through six tubular stainless steel spacers. This arrangement afforded the wheel considerable structural stability while, at the same time, keeping the weight within reasonable limits. In addition, the hub was fitted with an adapter which permitted its mounting on the soil-bin dynamometer drive motor shaft.

The sixteen cleat mounting brackets were bolted along the periphery of the hub at a uniform interval of 24 degrees. Each of these aluminum brackets provided for the mounting of up to six cleats in a number of varied spacing configurations. It was

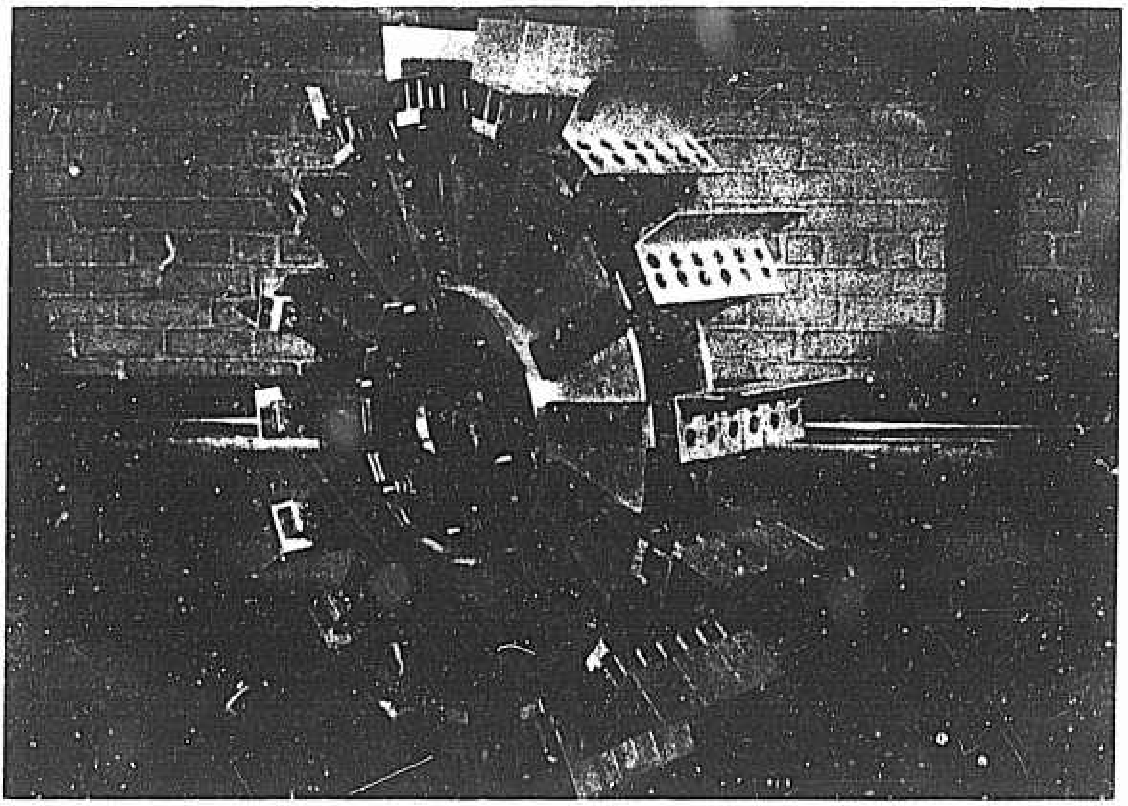

FIGURE 7. TEST WHEEL

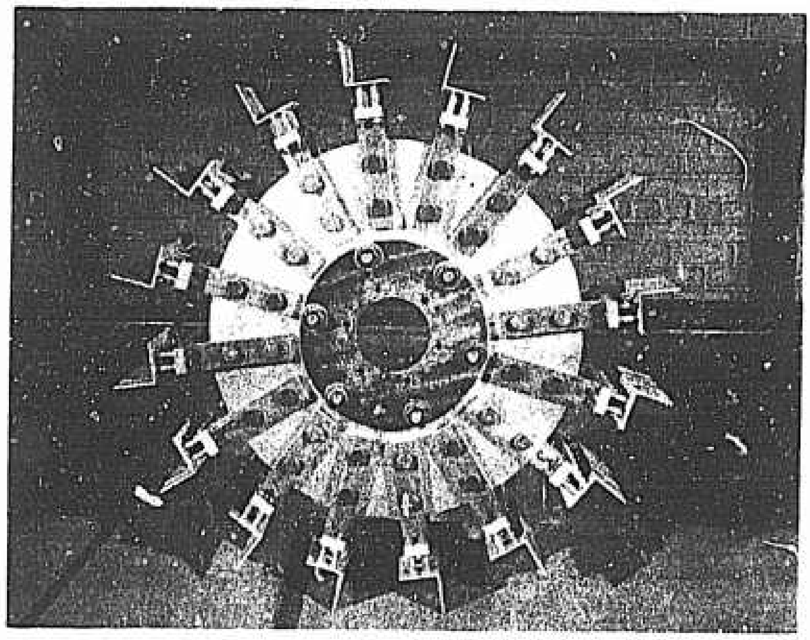

FIGURE 8. TEST WHEEL - SIDE VIEW

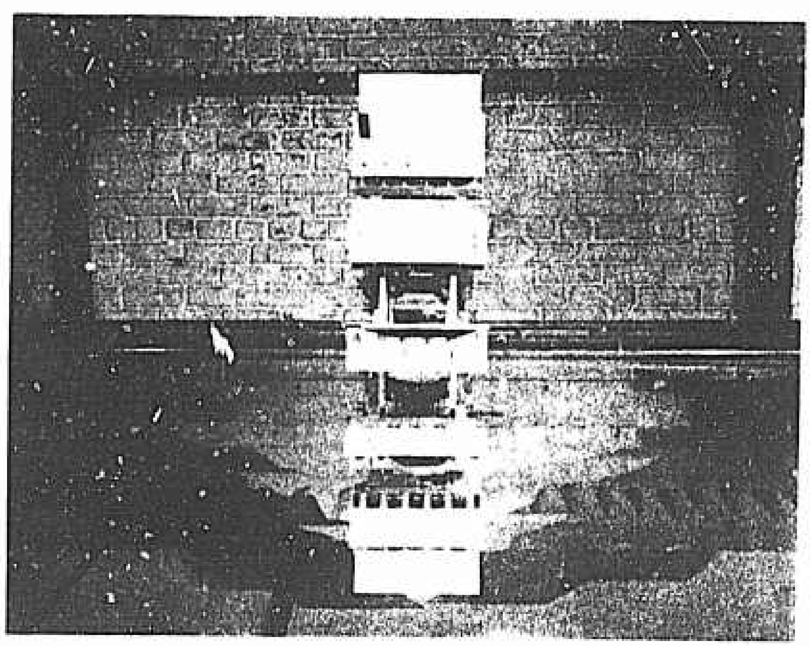

FIGURE 9. TEST WHEEL - FRONT VIEW

possible, for example, to remove one or more of the full complement of six cleats and to redistribute the remaining cleats evenly over the original 6 inches of width. A detailed graphic description of the mounting bracket is shown in Figure 10.

The ninety-six removable cleats were attached to the brackets in accordance with the particular configuration to be tested. Each aluminum cleat was bolted to the mounting bracket through two tubular aluminum spacers. These spacers were introduced for the purpose of insuring that the mounting bracket would not become involved in the shearing of soil and, hence, the production of drawbar-pull. A detailed graphic description of the removable cleat is also shown in Figure 10.

The soil-bin dynamometer with the test wheel previously described mounted, is shown in the general foreground of Figure 11. At the time this experimental work was conducted, the dynamometer was still not completely operational. In view of this, only those major components which were operational for and used in the conduct of this work will be discussed here. These were a sinkage gauge, a carriage position indicator, a load application system, a test wheel drive system, a drive motor tach-generator, and an array of ten temperature-compensated strain gauges.

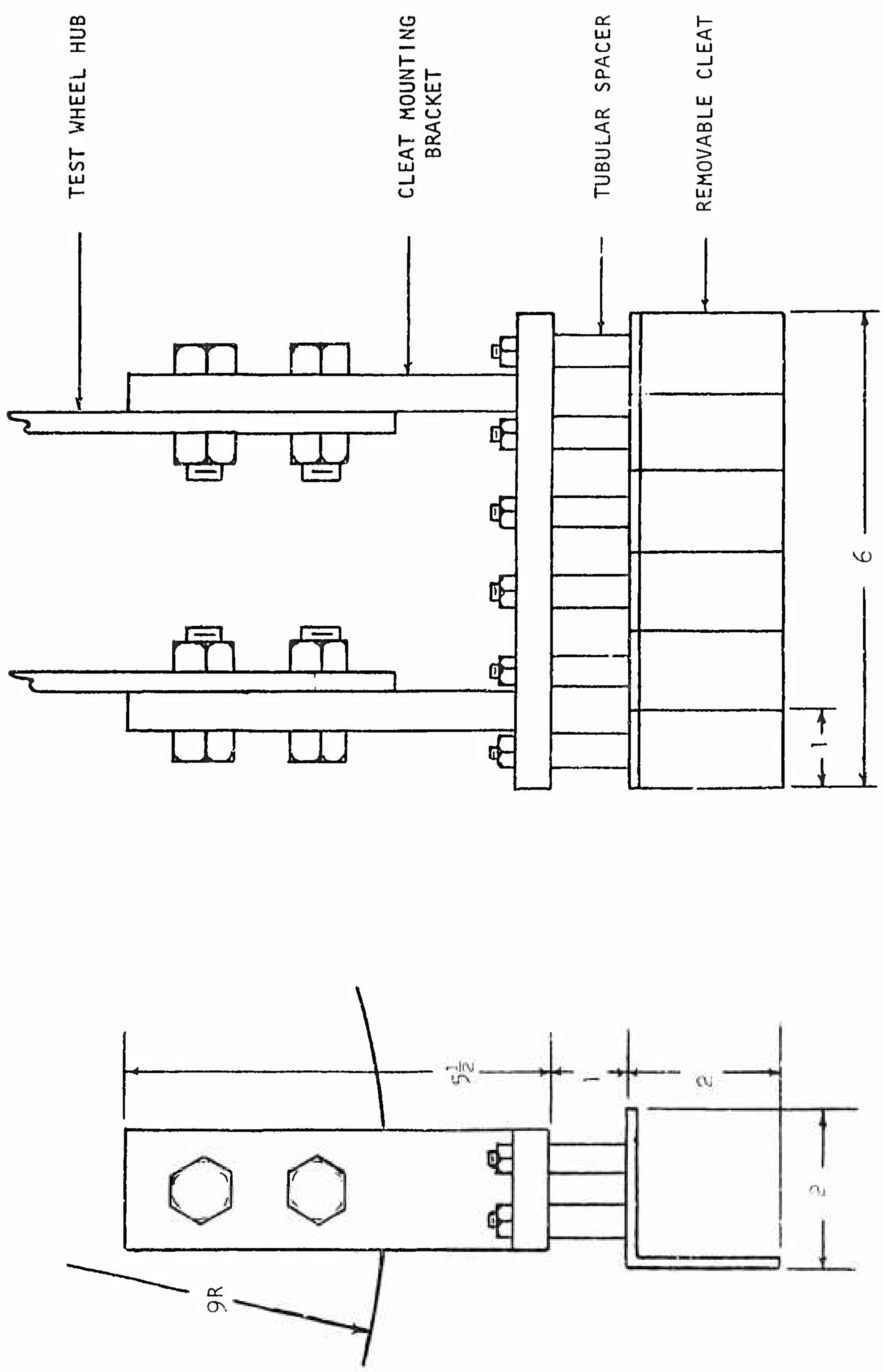

FIGURE 10. MOUNTING BRACKET AND REMOVABLE CLEATS

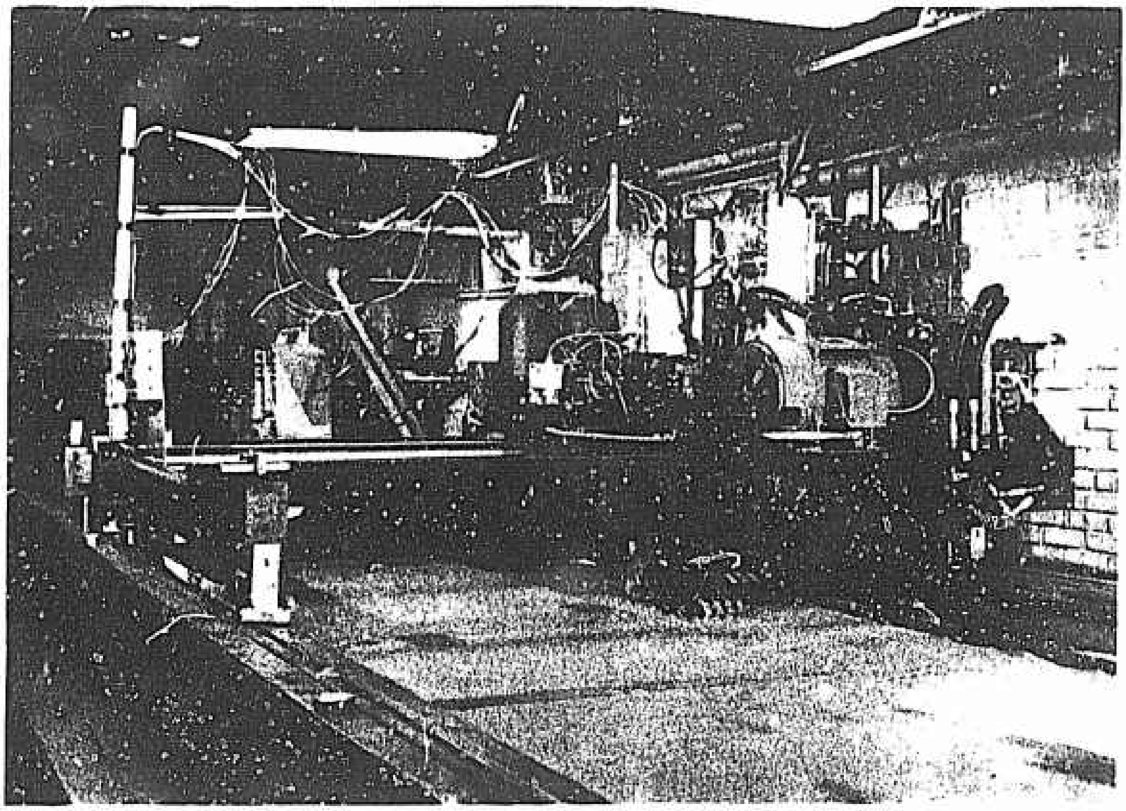

FIGURE 11. SOIL-BIN DYNAMOMETER

The soil-bin dynamometer sinkage gauge was a potentiometer mounted on a vertically fixed portion of the dynamometer chassis. The potentiometer was driven by a fine wire attached at one end to the vertically movable test wheel mounting framework and at the other end to a spring-loaded take-up drum on the potentiometer drive shaft.

The carriage position indicator consisted essentially of a microswitch, an actuation lever, a support wheel, and a number of round-head wood screws. The microswitch, actuation lever, and support wheel were mounted on the dynamometer chassis and the wood screws positioned at one-foot intervals along the soil-bin track. As the carriage proceeded along the soil bin, the actuation lever support wheel encountered the evenly-spaced wood screws, was raised, and through the lever to which it was attached actuated the microswitch. The leads from the normally open side of the microswitch were attached to a pair of leads from the sinkage potentiometer; hence, the output from the carriage position indicator appeared as a disturbance in the sinkage gauge output.

The load application system was a relatively complex hydraulic, pneumatic and electronic system, whose complete description would be unreasonably time-consuming and not particularly relevant. For purposes of this discussion, it suffices to point out that the load was determined pneumatically, applied hydraulically, and controlled electronically. At the time this experimental work was conducted, however, the electronic control equipment was not completely functional and a given load could not be maintained automatically for large variations in sinkage. It was necessary, therefore, that test loads be applied in the following manner:

First, the test wheel was raised clear of the soil and all system load removed by the establishment of an appropriate differential pressure between two air reservoirs. Next, the wheel was lowered to a point in the soil corresponding to the anticipated operational sinkage of the wheel. Finally, the wheel was raised slightly in order that no load would be indicated on the recorder and then the desired test load was applied by alteration of the differential pressure between the two air reservoirs. Where the actual sinkage of the wheel proved to be considerably greater than anticipated, the load would be lost and would have to be reapplied at a greater initial sinkage.

The test wheel drive system was a relatively simple system and consisted of only two major components. One of these components was a hydraulic motor on whose output shaft the test wheel was mounted; the other was an electrically driven hydraulic pump. The speed of the hydraulic drive motor was controlled manually through adjustment of the pump. This same hydraulic pump, incidentally, was used to charge the two accumulators which maintained the hydraulic pressure required for load application.

The drive motor tach-generator was a small direct-current generator mounted inside the hydraulic drive motor housing and gear-driven by the drive motor output shaft. Use of this small device permitted the accurate determination of the instantaneous angular velocity of the test wheel.

The ten temperature-compensated strain gauges were mounted directly on the drive motor housing in such a manner as to make possible the accurate measurement of any forces, moments, or combinations thereof to which the test wheel might be subjected. Of the eight tension/compression gauges, two were located on top of the housing, two on the bottom, and two on each side. One gauge from each of these pairs was located toward the front of the housing and the other toward the rear. Of the two twist gauges, one was located on the top of the housing and the other on the bottom. Both twist gauges were positioned toward the front or wheel end of the motor.

At the time this experimental work was carried out, the entire array of ten strain gauges had been calibrated; however, analysis of the calibration data had not been accomplished. As a result, an electronic device capable of resolving the outputs from these ten gauges into a set of basic component outputs had not been constructed and was not available for use. It was necessary, therefore, that a limited number of gauges be used and that gauge interaction adjustments be carried out manually. Two gauges were actually used (one horizontal and one vertical) and a small gauge interaction adjustment had to be made in the output of the horizontal (drawbar-pull) gauge.

The towing and soil-preparation carriage is shown in Figure 11 in its normal operating position behind the soil-bin dynamometer. The carriage was chain-driven (actually, towed) along the soil-bin by a stationary, variable-speed, electrically-powered drive system.

The carriage, in turn, imparted motion to the dynamometer carriage through a towing link situated between the two. The soil-preparation equipment mounted on the towing and soil-preparation carriage consisted of an electrically-driven soil tiller, a soil leveling blade, and an electrically operated soil compacting vibrator. All of these devices were capable of being raised and lowered hydraulically. The towing and soil-preparation carriage also provided electrical power to the dynamometer carriage.

The data recording equipment used consisted basically of the Sanborn 150 recorder shown in Figure 12. Three alternating-current and one direct-current preamplifiers were installed in the 150 for this work. Output from the vertical strain gauge (load) was recorded on one alternating current channel, output from the horizontal strain gauge (drawbar-pull) was recorded on a second, and outputs from the sinkage gauge and carriage position indicator were recorded on the third. Output from the drive motor tach-generator was recorded on the one direct-current channel. This arrangement, with the recorder's timer also in operation, permitted the recording of load, drawbar-pull, and those variables essential to the calculation of test wheel slip rate.

Procedure

Although the apparatus employed was relatively complex, the experimental procedure was quite straightforward. The original schedule of tests called for ten test runs at varied slip rates or each of the four cleat configurations. During the conduct of

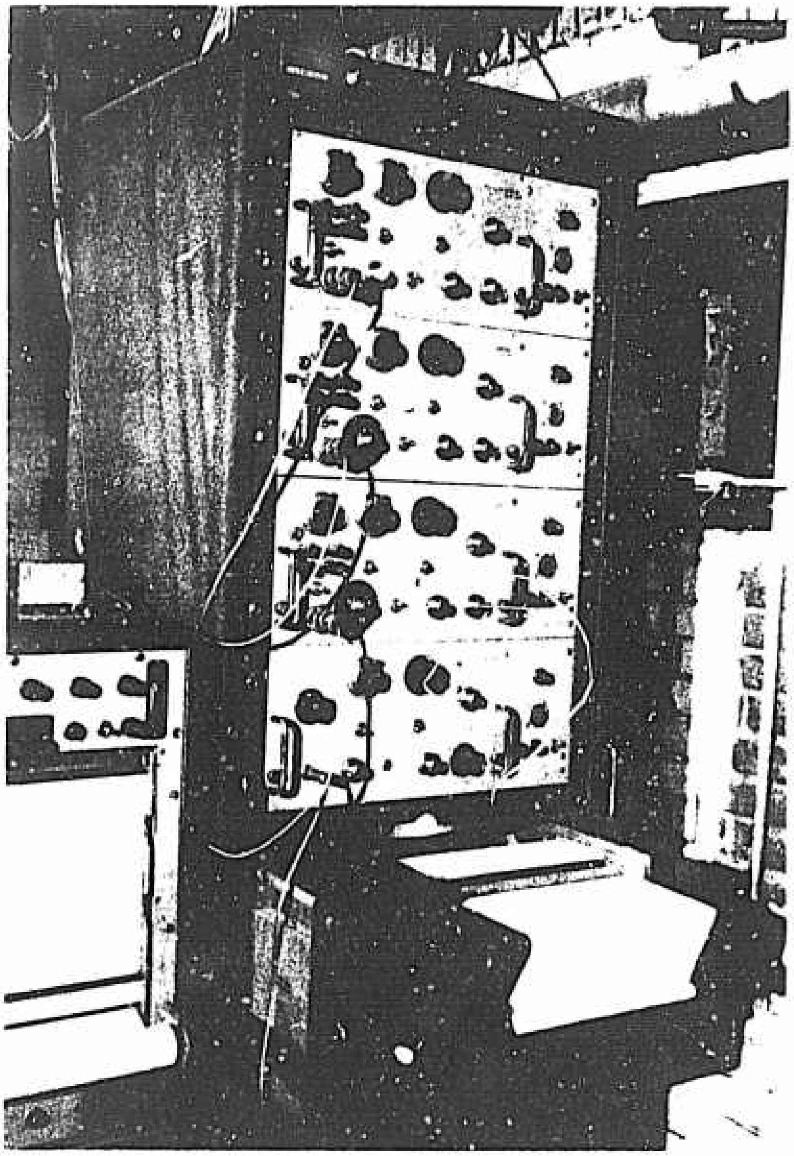

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FIGURE 12. DATA RECORDING EQUIPMENT

the tests, however, it was found that the slip rate could easily be varied twice over the course of a single test run. Hence, the total number of runs made was reduced substantially. The four cleat configurations as they actually appeared for testing are shown in Figures 13, 14, 15 and 16.

Prior to the commencement of each day's testing, all recording channels were balanced, all measuring devices were calibrated, and all components of the apparatus were checked for operational readiness. Then, prior to each test run, the air dry sand* was tilled to a depth of 17 inches and leveled, the tillage equipment was removed from the soil, the soil-bin dynamometer accumulator tanks were charged, the desired test load was applied to the wheel, and the desired carriage speed was preset.

Initiation of each test run consisted simply of activating the data recorder, test wheel, and dynamometer carriage drive systems. Termination of each run consisted of deactivating the data recorder and test wheel drive systems. The carriage drive was cut off automatically as the carriage reached the end of the soil-bin.

Two individuals were required for the conduct of the tests. One manned the data recorder and carriage speed control. The other manned the towing and soil-preparation carriage and the soil-bin dynamometer carriage. One individual could not have carried out these tests alone. Three would have gotten in each other's way.

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*Moisture content was consistently less than 1%. Grain size distribution data are contained in Appendix B.

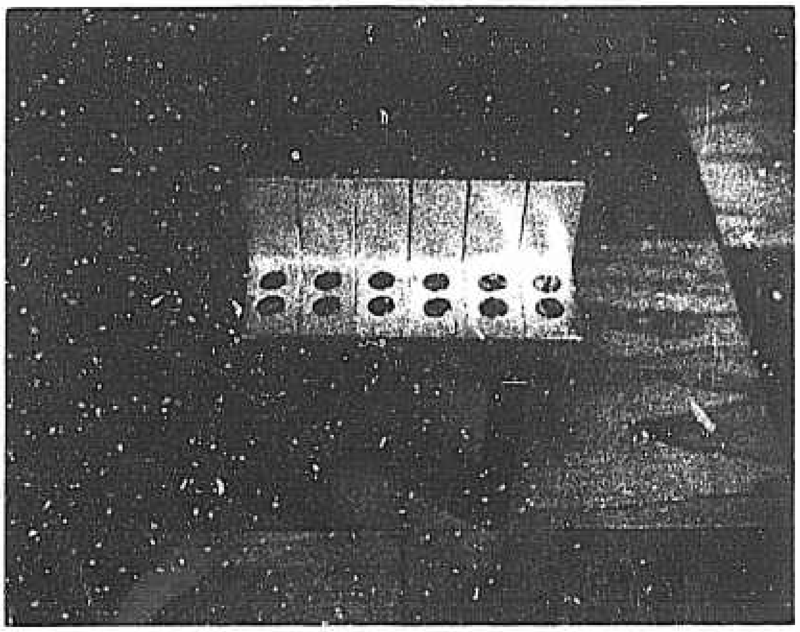

FIGURE 13. CLEAT/GROUSER - CONFIGURATION

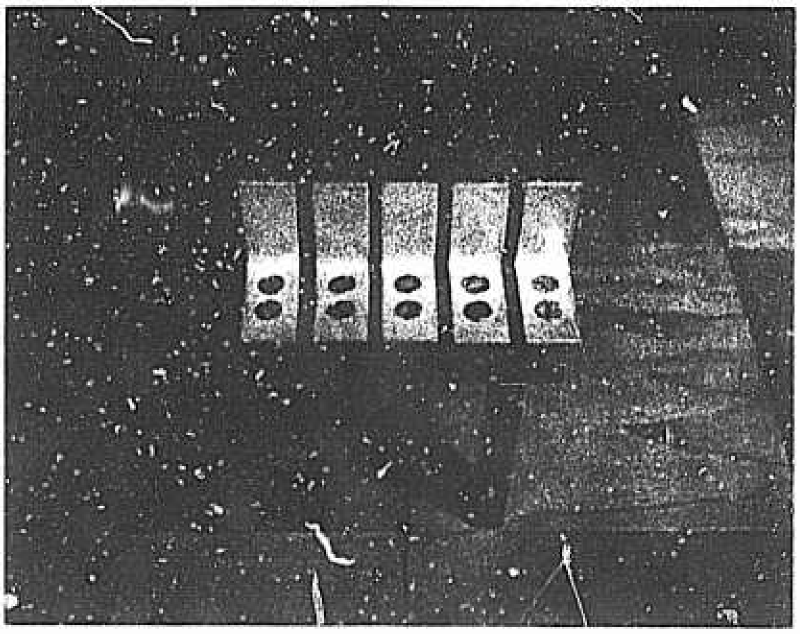

FIGURE 14. CLEAT/GROUSER - CONFIGURATION II

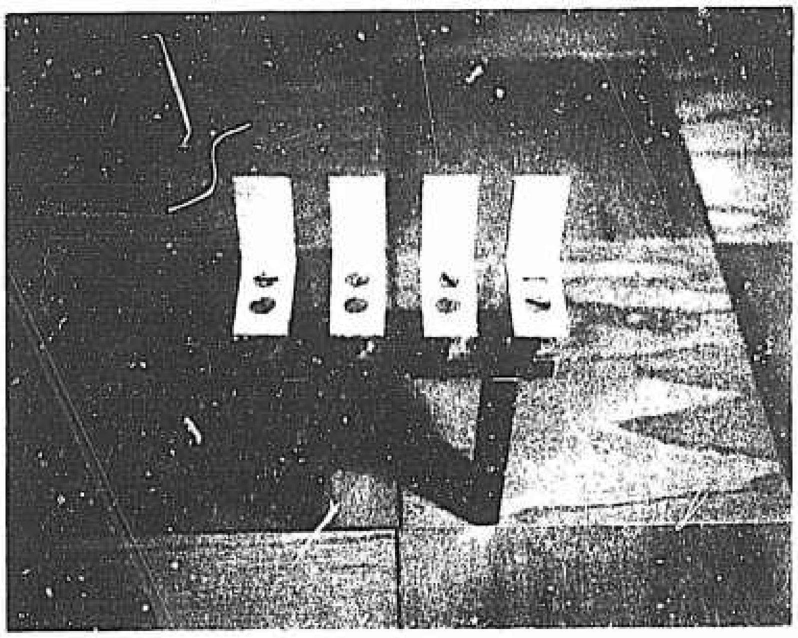

FIGURE 15. CLEAT/GROUSER - CONFIGURATION III

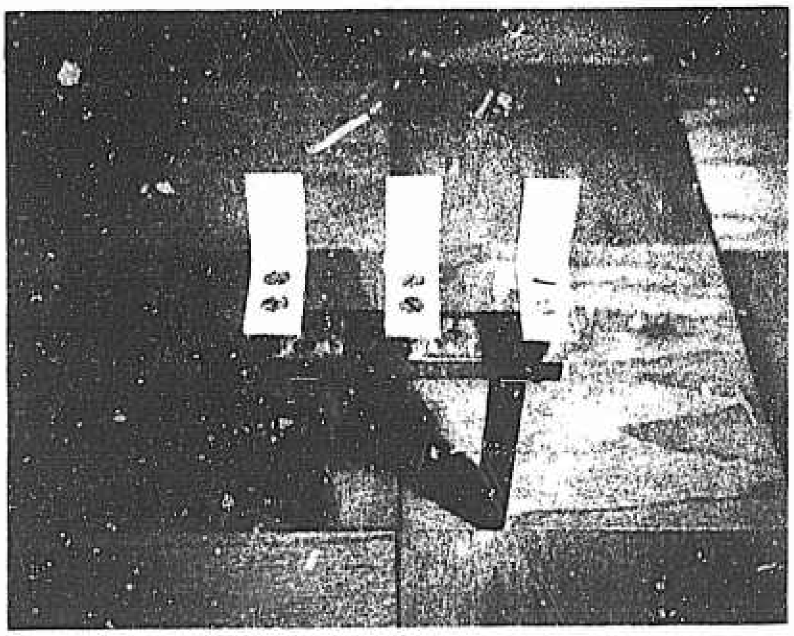

FIGURE 16. CLEAT/GROUSER - CONFIGURATION IV

Results

The results of this experimental evaluation expressed in absolute terms are listed in Tables III, IV, V and VI and plotted in Figures 17, 18, 19 and 20. The results expressed in relative terms are plotted in Figure 21. This latter figure indicates, for example, that in changing from configuration I to configuration II, a reduction of 17 percent in the contact surface area occurs, while an increase of 2 percent in the drawbar-pull takes place. The values of drawbar-pull from which Figure 21 was developed were obtained from the drawbar-pull versus slip rate curves, not from individual values of drawbar-pull observed.

Typical footprints of each of the four cleat configurations are shown in Figures 22, 23, 24 and 25. The variation in failure pattern visible in the center of each figure reflects a change at that point of slip rate.

TABLE III

Test Results - Configuration I

Drawbar Pull (lb)	Wheel Velocity (ft/sec)	Carriage Velocity (ft/sec)	Slip Rate (%)
-19.5	.82	.86	-5
- 2.5	.73	.69	5
16.0	.58	.48	17
18.0	.94	.71	24
17.5	.96	.71	26
20.5	.98	.59	40
18.5	.86	.47	45
17.3	1.20	.59	51
19.5	.96	.37	61
17.0	1.26	.47	63

TABLE IV

Test Results - Configuration II

Drawbar Pull (lb)	Wheel Velocity (ft/sec)	Carriage Velocity (ft/sec)	Slip Rate (%)
-10.0	.79	.86	-9
- 2.3	.66	.65	2
15.5	.91	.80	12
15.3	.53	.45	15
17.5	.58	.48	17
15.5	.55	.45	18
19.0	.78	.56	28
19.5	.74	.45	39
21.0	.79	.45	43
19.0	.84	.44	48

TABLE V

Test Results - Configuration III

Drawbar Pull (lb)	Wheel Velocity (ft/sec)	Carriage Velocity (ft/sec)	Slip Rate (%)
-4.0	.72	.67	7
7.5	.86	.77	10
9.5	.96	.79	18
10.0	1.03	.79	23
12.5	.67	.49	27
15.4	.98	.63	36
15.0	1.20	.77	36
13.0	1.27	.77	39
15.5	1.14	.59	48
15.0	.72	.37	49

TABLE VI

Test Results - Configuration IV

Drawbar Pull (lb)	Wheel Velocity (ft/sec)	Carriage Velocity (ft/sec)	Slip Rate (%)
-17.5	.72	.89	-24
- 6.0	.79	.77	3
6.5	.76	.67	12
14.0	.84	.67	20
13.0	.62	.48	23
14.5	.65	.47	28
14.5	.94	.67	29
15.0	.67	.47	30
14.5	.70	.48	31
14.5	.74	.48	35

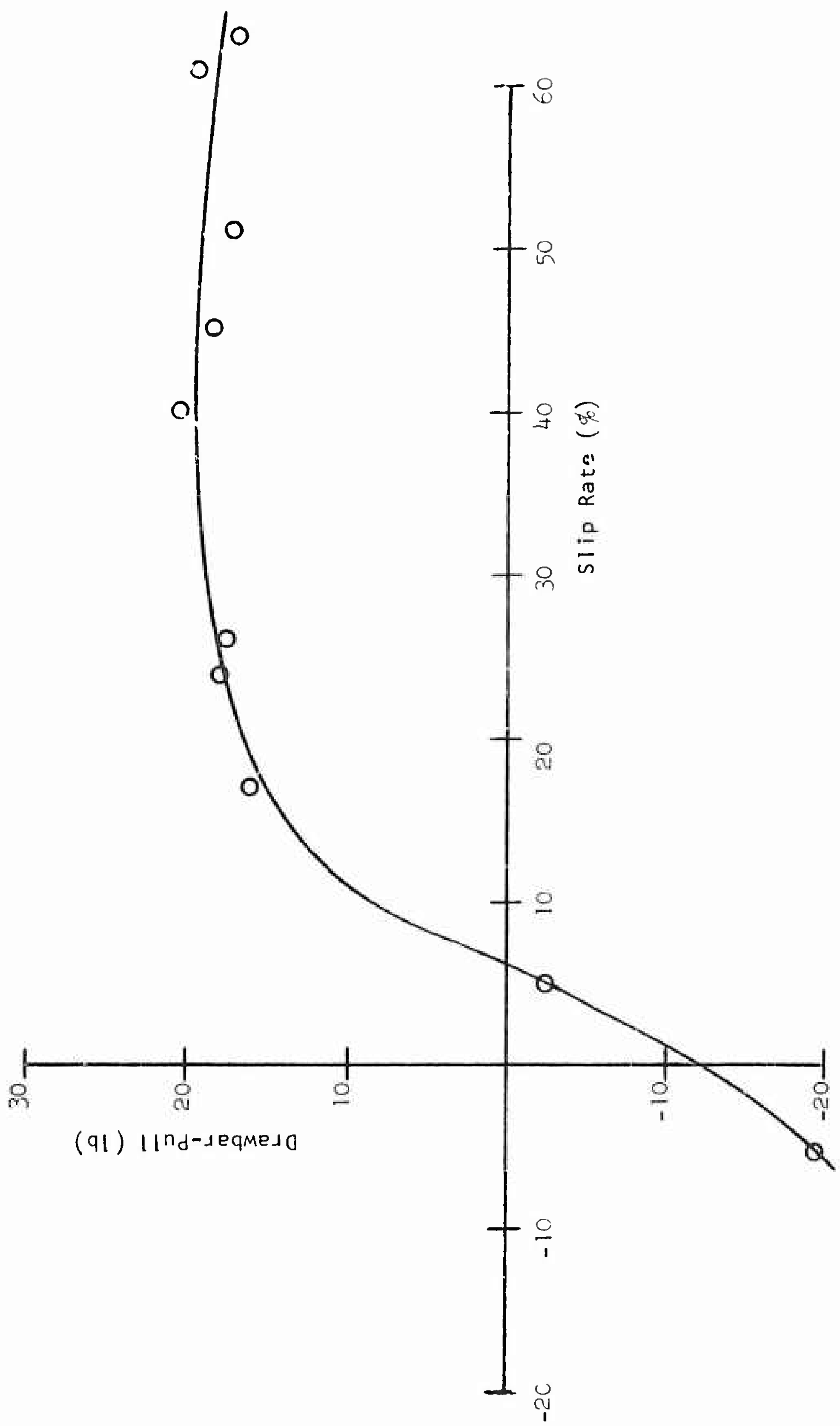

FIGURE 17. TEST RESULTS - CONFIGURATION I

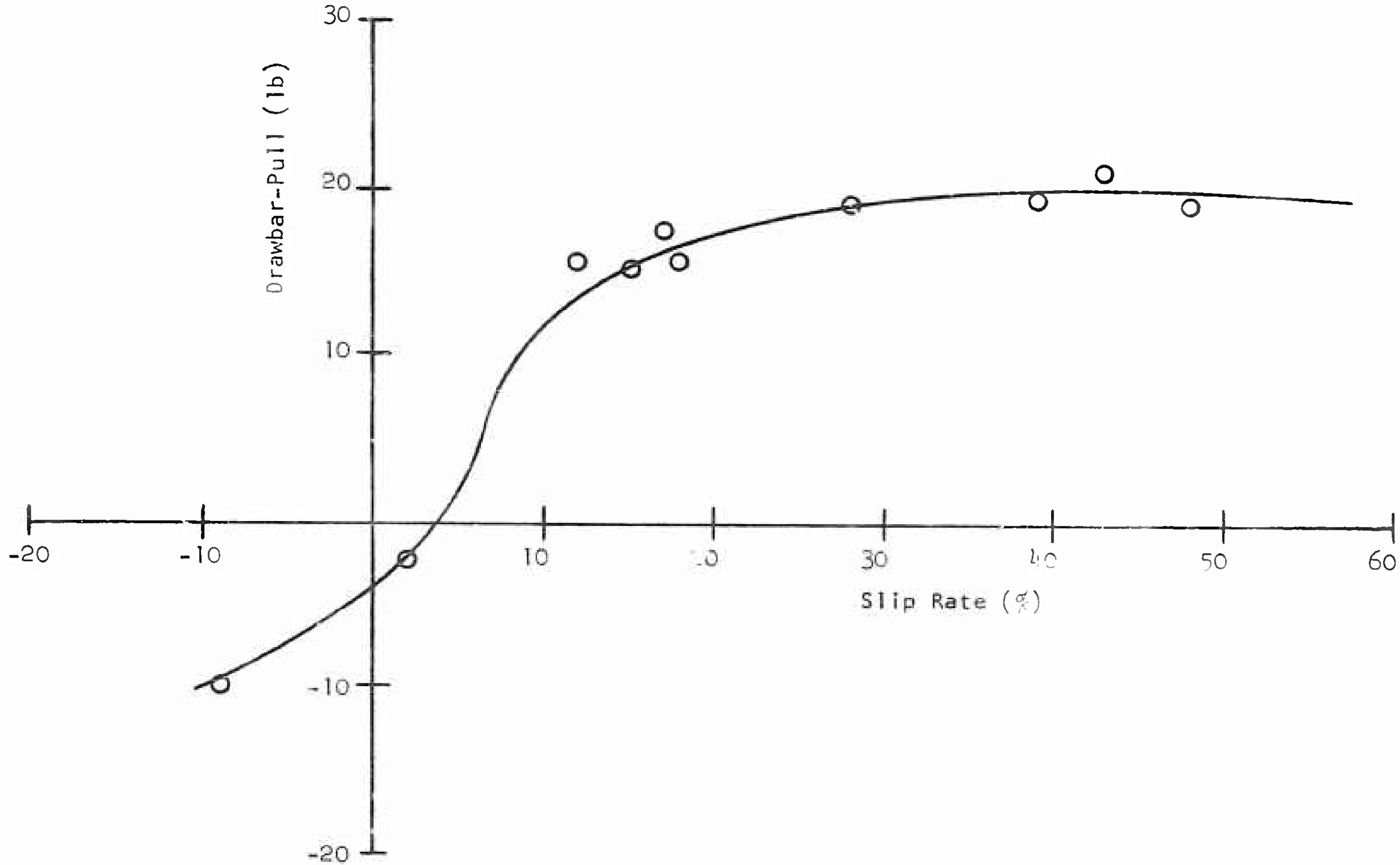

FIGURE 18. TEST RESULTS - CONFIGURATION II

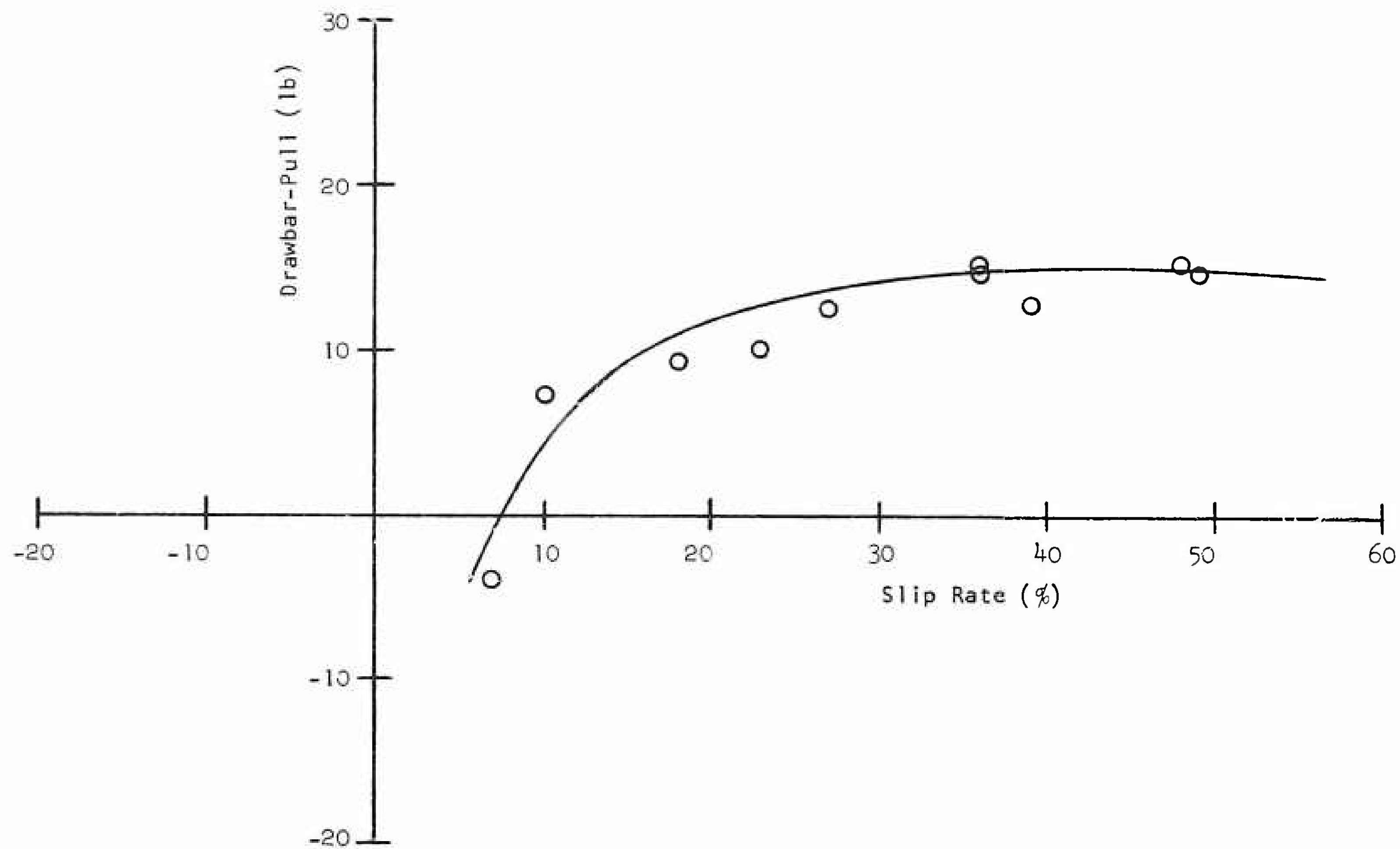

FIGURE 19. TEST RESULTS - CONFIGURATION III

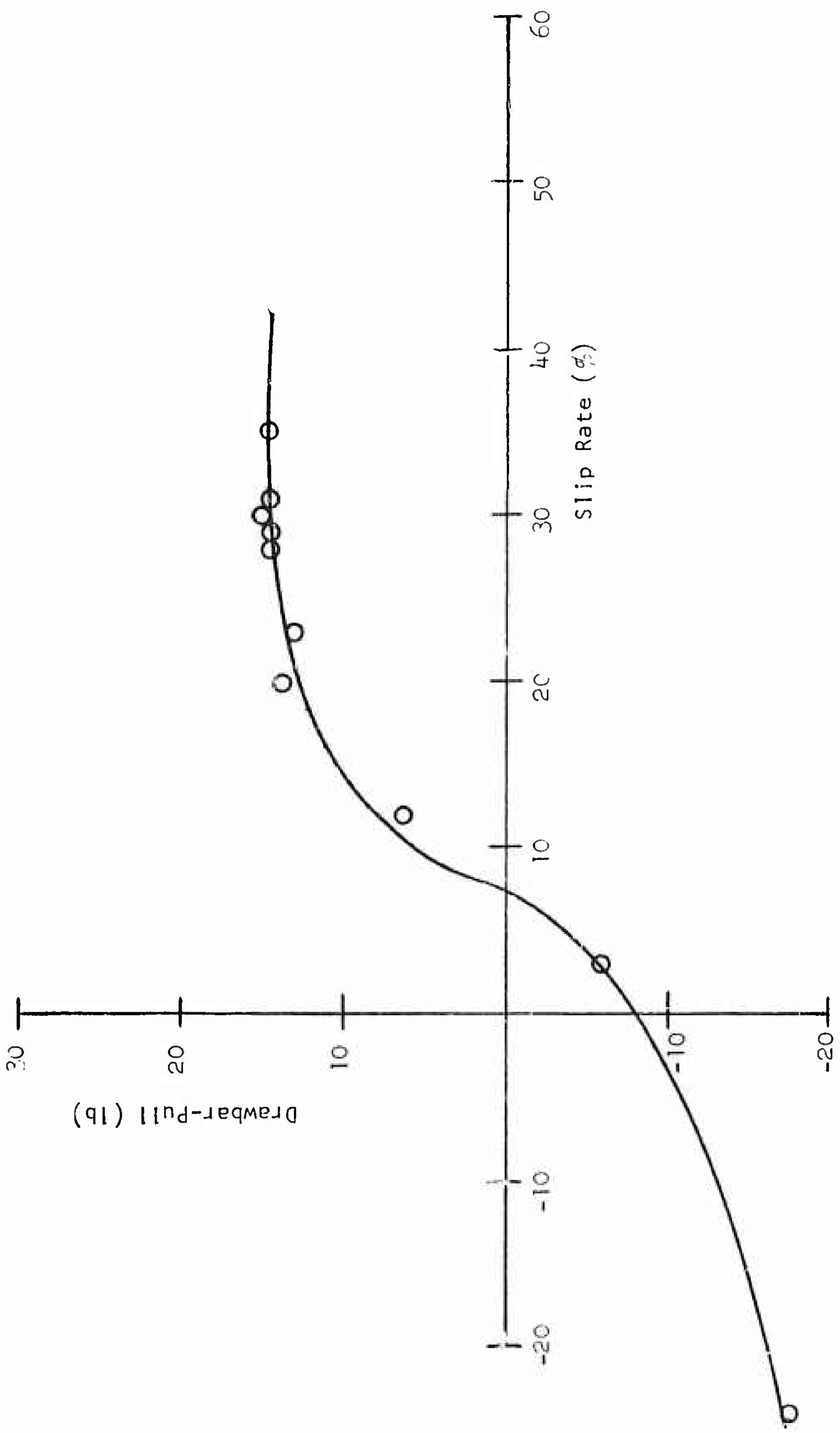

FIGURE 20. TEST RESULTS - CONFIGURATION IV

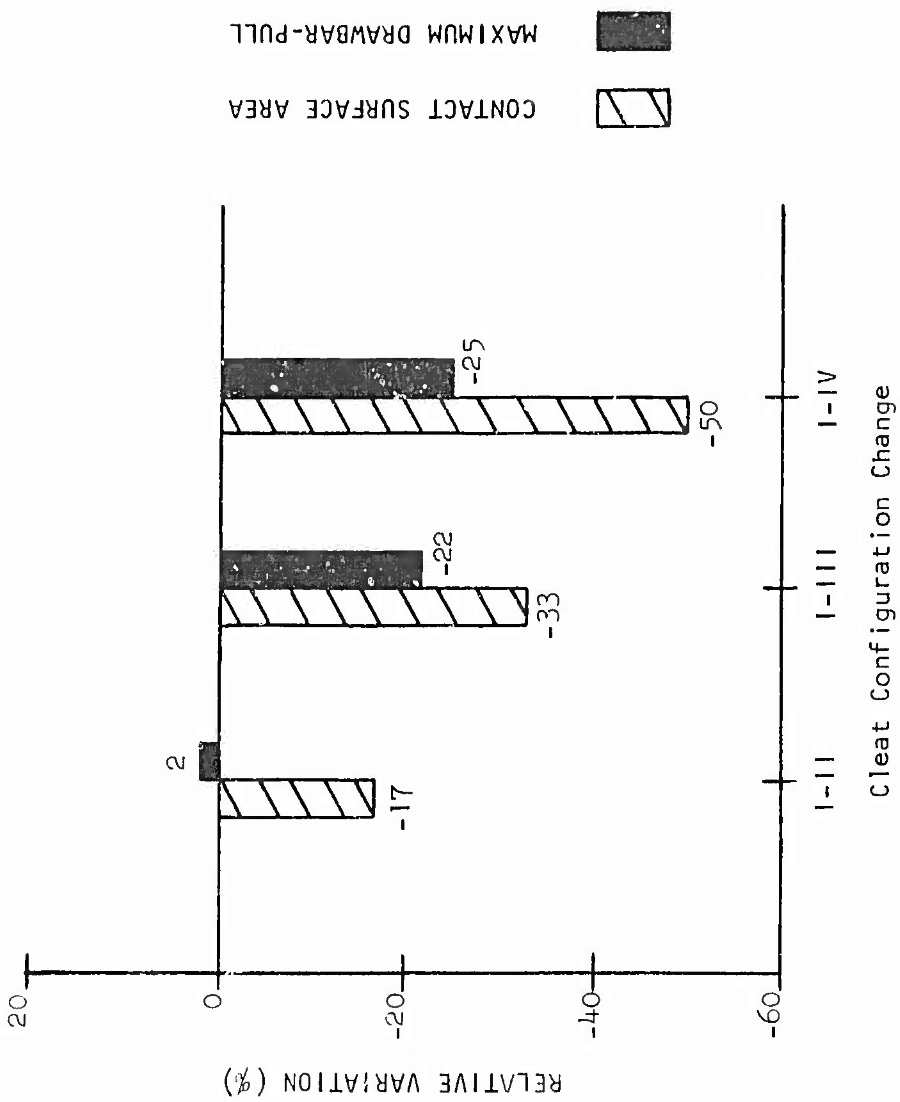

FIGURE 21. OVERALL EXPERIMENTAL RESULTS

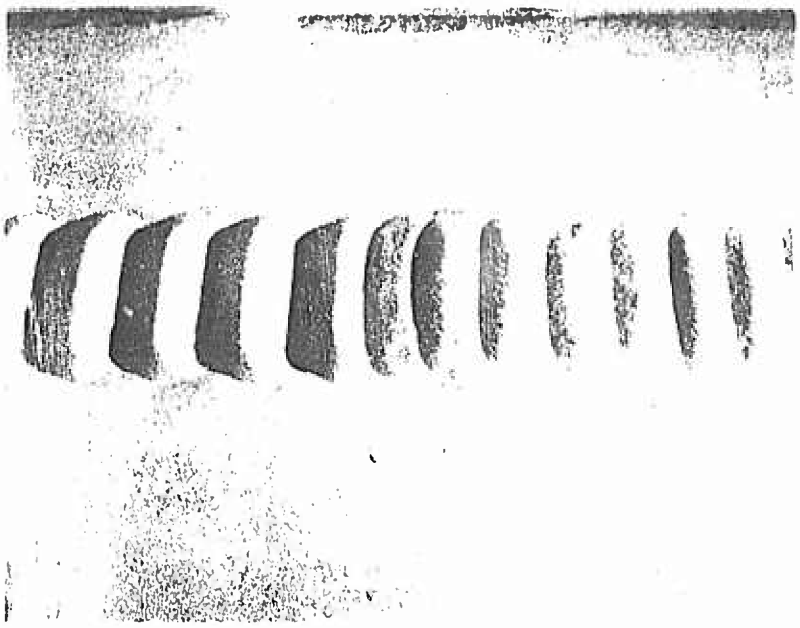

FIGURE 22. FOOTPRINT - CONFIGURATION I

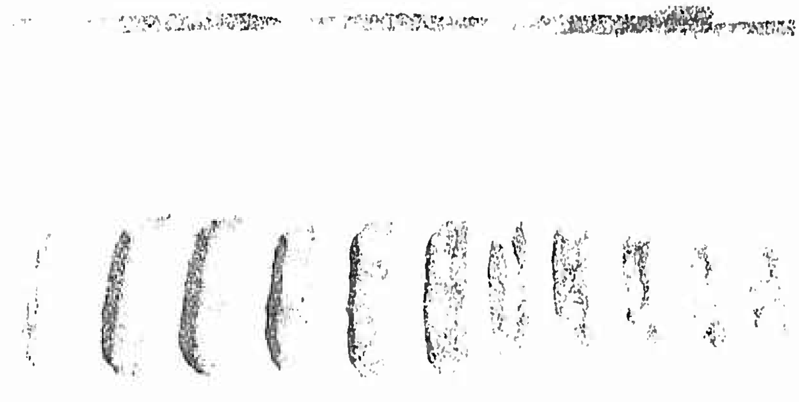

FIGURE 23. FOOTPRINT - CONFIGURATION II

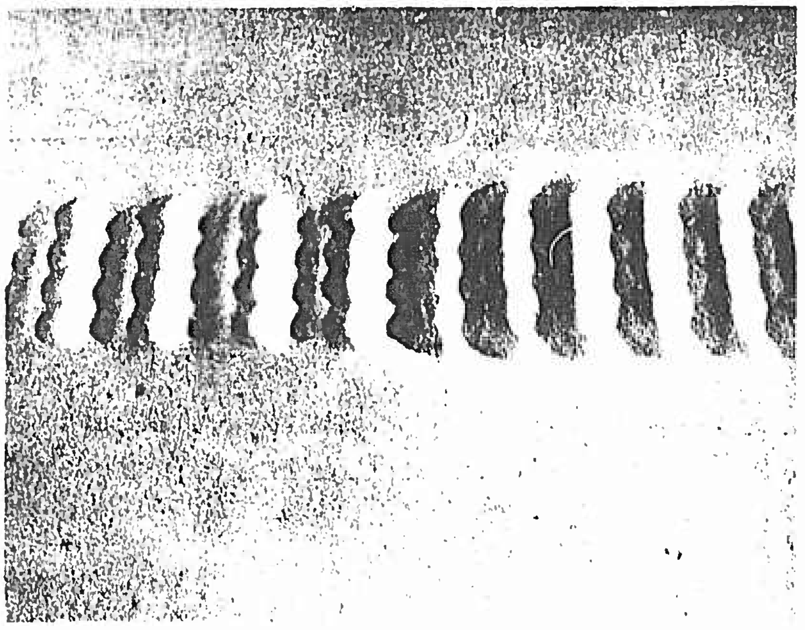

FIGURE 24. FOOTPRINT - CONFIGURATION III

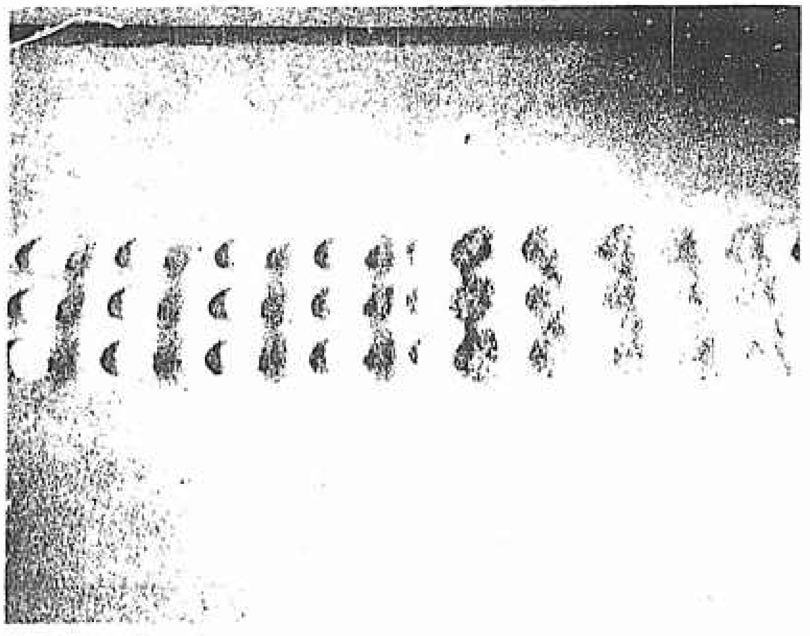

FIGURE 25. FOOTPRINT - CONFIGURATION IV

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The combined theoretical and experimental results of this work expressed in relative terms are shown in Figure 26. This figure indicates that, for each of the three changes in cleat configuration, the decrease in contact surface area is greater than the corresponding decrease in either theoretical tractive effort or experimental drawbar-pull. Before the theoretical and experimental results may be compared, however, it must be assumed that with changes in cleat configuration the relative changes in the rolling resistance of the test wheel are negligible. Inasmuch as the drawbar-pull at zero slip rate is fairly consistent for all four cleat configurations, this appears to be a reasonable assumption.

The discrepancy between the theoretical and experimental results is believed by the author to stem from inaccuracies in the theoretical determination of the length of the soil failure pattern or rupture distance, ℓ . From a theoretical standpoint, this is a highly influential factor, particularly as the cleat spacing becomes large. The values of ℓ obtained from Bekker's graph all fail in the vicinity of 6 inches. No failure pattern of that length was observed during the testing. Had somewhat smaller and perhaps more realistic rupture distances been utilized in the theoretical calculations, the theoretical and experimental results would undoubtedly have been more compatible.

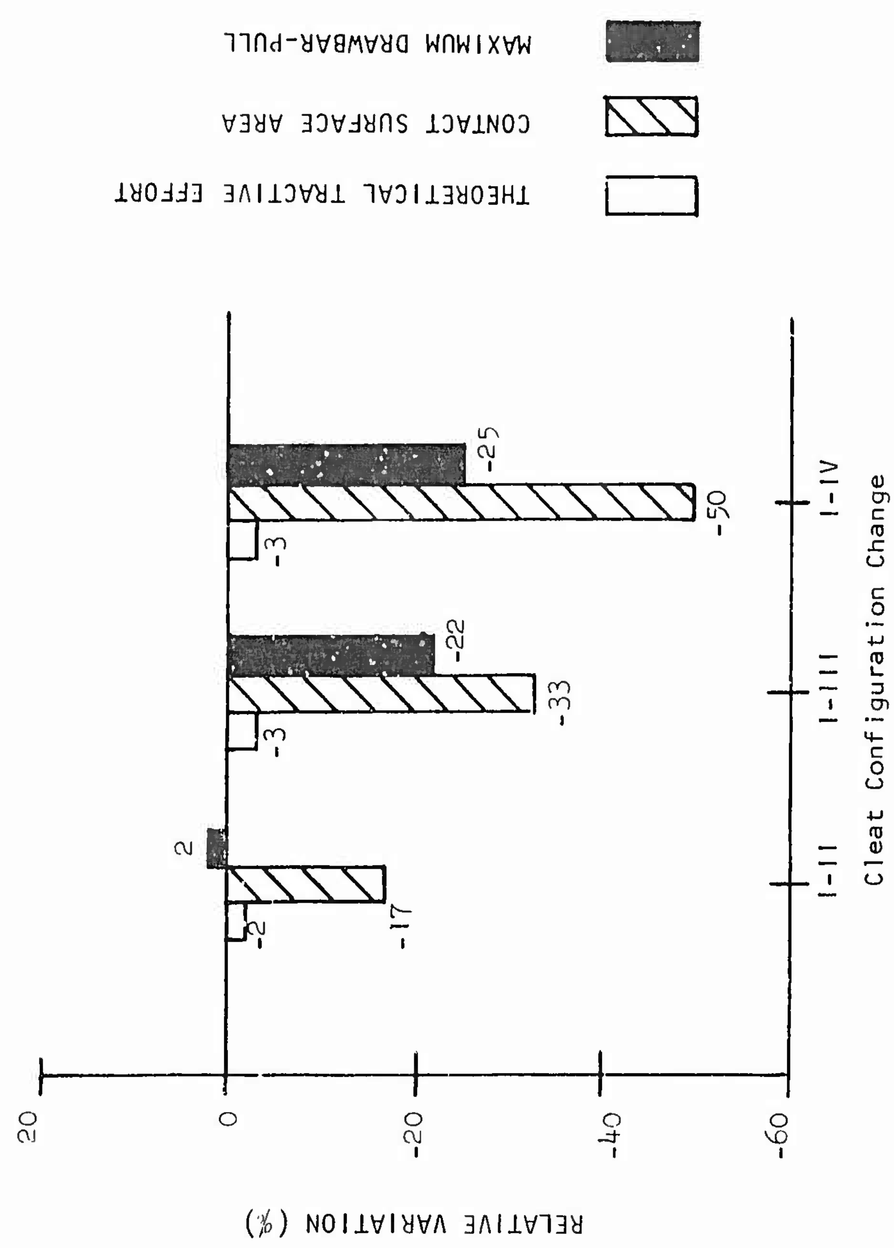

FIGURE 26. COMBINED THEORETICAL AND EXPERIMENTAL RESULTS

Because of their significance, the experimental results of this work, expressed in somewhat different terms than in Chapter III, are presented in Figures 27 and 28. Figure 27 suggests that the maximum drawbar-pull is achieved at some optimum contact surface area or optimum cleat spacing. Figure 28 indicates that the maximum efficiency of the contact surface area in the production of drawbar-pull is obtained at some other optimum contact surface area or cleat spacing. It must be emphasized, however, that there is no assurance that the paths of the curves depicted in Figures 27 and 28 are accurate. Except at those points determined experimentally, the paths of these curves are simply not known.

In view of the foregoing, it is concluded that distinct advantages related to the production of drawbar-pull may be realized by the lateral spacing of cleats. It is concluded also that these advantages may be realized to the fullest extent by the employment of optimum spacing. At the same time, it is recognized that such conclusions are valid only insofar as the load, soil, and cleat configurations used in this work are concerned. The task of ascertaining their general validity still remains to be accomplished.

The soil-bin dynamometer performed extremely well throughout the experimental portion of this work. It was easy to operate, produced consistent data, and suffered no malfunctions. As a result, it is concluded that, when fully operational, the soil-bin dynamometer will provide a highly effective means of conducting a wide variety of dynamic wheel tests.

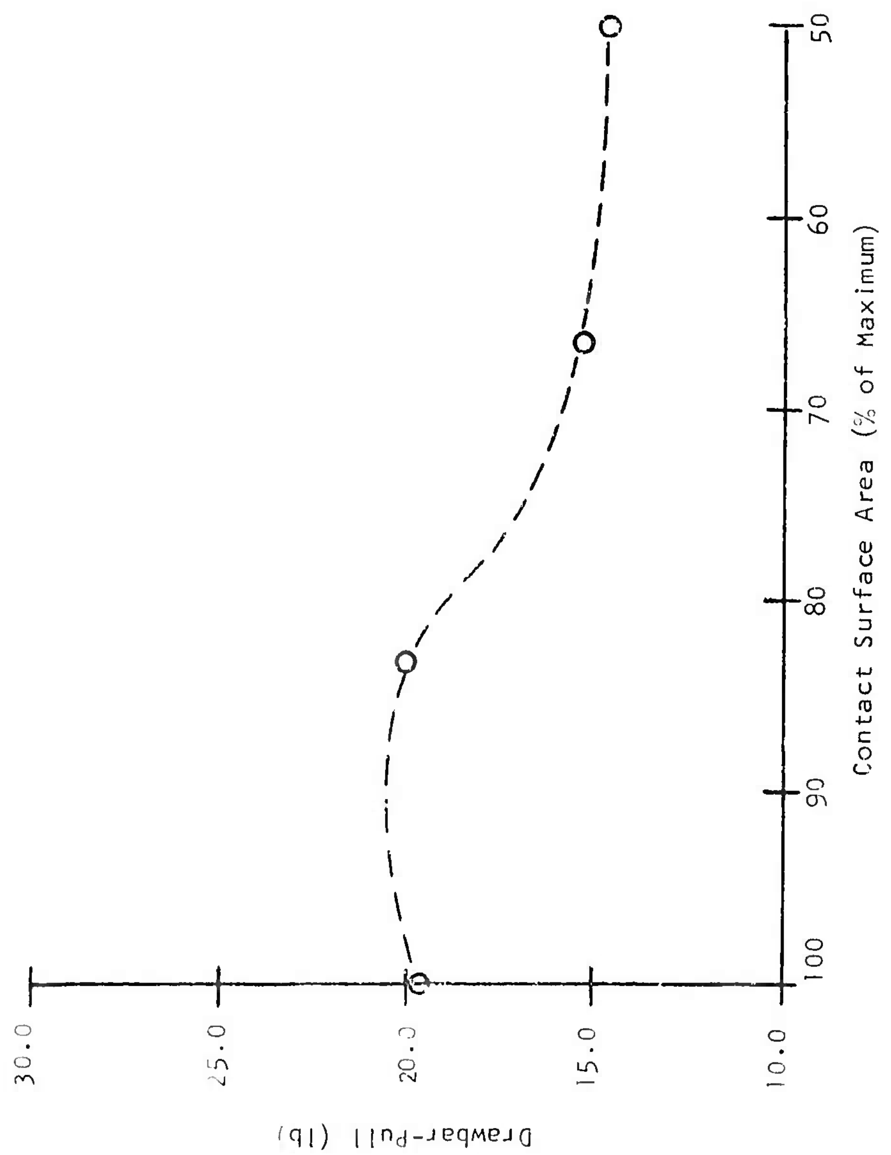

FIGURE 27. CONTACT SURFACE AREA IN PRODUCTION OF DRAWBAR-PULL

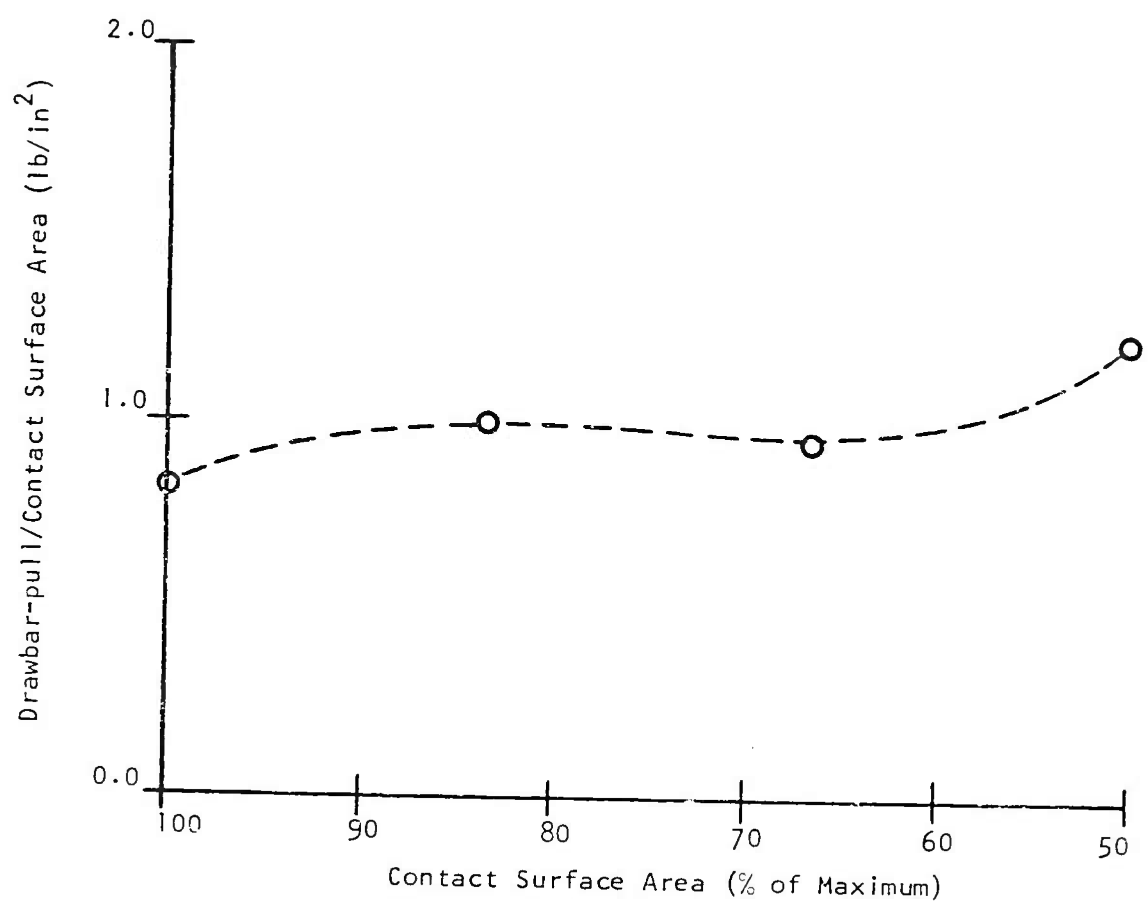

FIGURE 28. EFFICIENCY OF CONTACT SURFACE AREA IN PRODUCTION OF DRAWBAR-PULL

Recommendations

Based on the above conclusions pertaining to the production of drawbar-pull, it is recommended that additional preliminary investigations of this sort be conducted for different ranges of vertical load, for different sets of varied cleat configurations, and for both frictional and cohesive soils. At such time as the general validity of these conclusions has been established, the task of evaluating in absolute or quantitative terms the effect on drawbar-pull of the lateral spacing of cleats should be undertaken.

Further, based on the above conclusions pertaining to the soil-bin dynamometer, it is recommended that efforts to render the soil-bin dynamometer completely operational be continued. The installation of electronic control equipment for the load application system should be given first priority.

APPENDIX A

This appendix contains the graphs developed by M. G. Bekker and used in the theoretical portion of this work. The graphs of m and n versus θ are shown in Figure 29. The graph of i versus θ is shown in Figure 30.

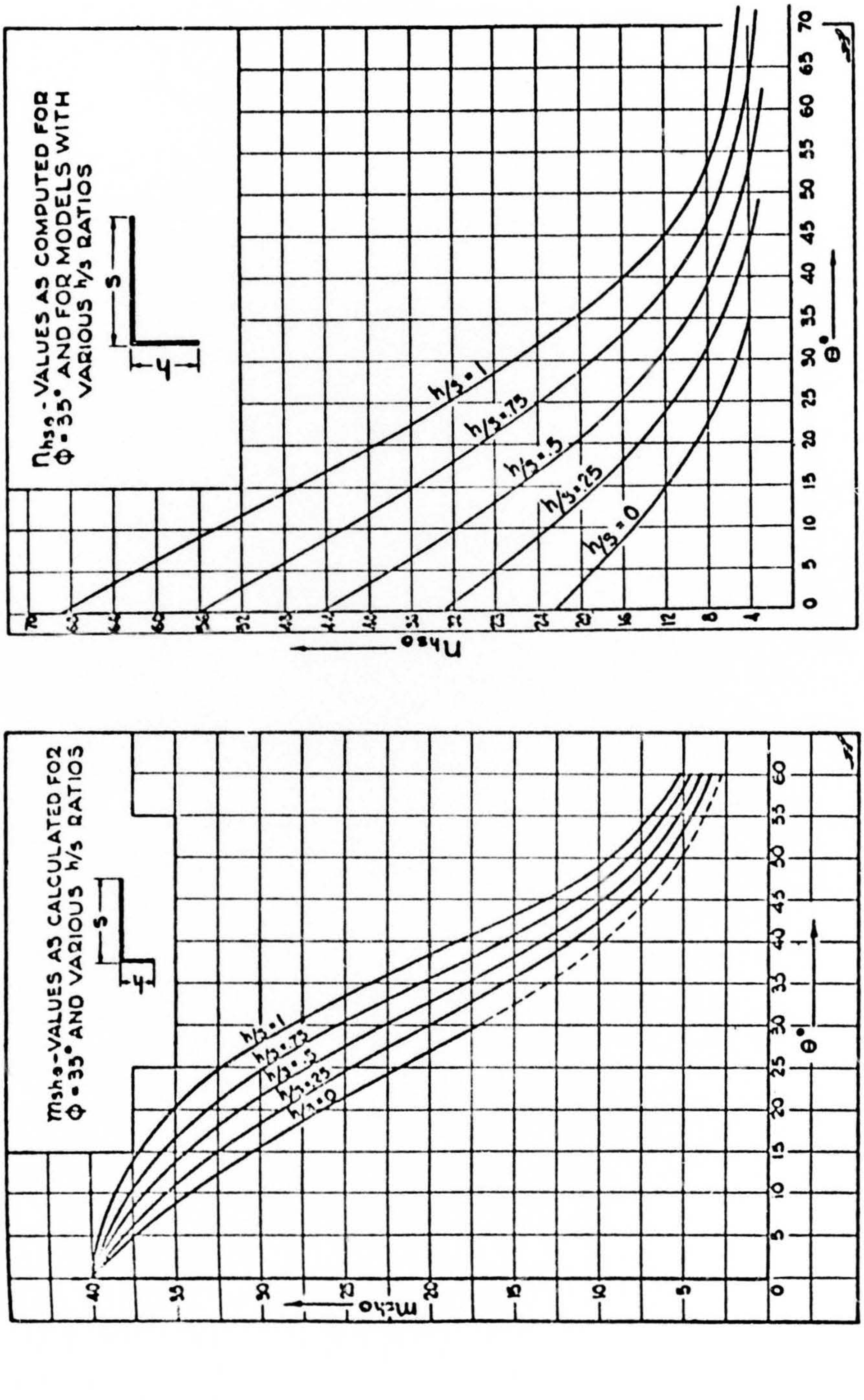

FIGURE 29. GRAPHS OF m AND n VERSUS θ 9

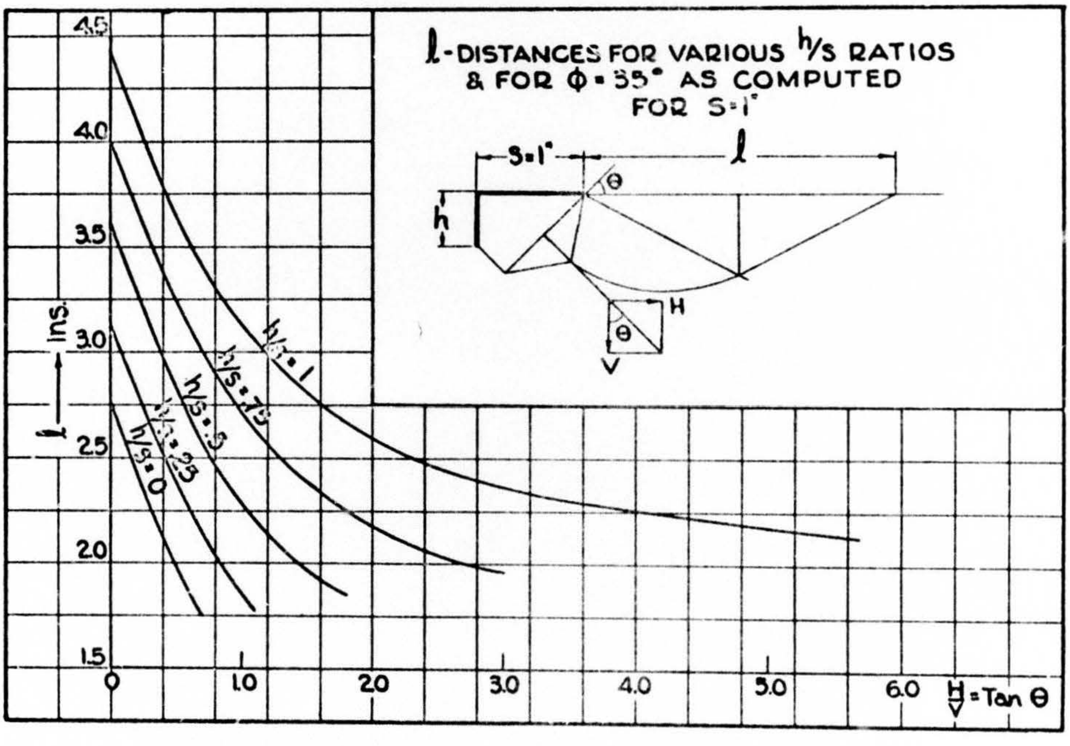

FIGURE 30. GRAPH OF ℓ VERSUS θ[10]

APPENDIX B

This appendix contains the grain size distribution data for the dry sand used in the experimental portion o' this work.

TABLE VII

GRAIN SIZE DISTRIBUTION DATA

TEST 1 - Sample Size: 504.018 gr.

RETAINED ON SIEVE No.	OPENING SIZE mm	in.	NEW WEIGHT (grams)	FREQUENCY ABSOLUTE	CUMULATIVE
14	1.41	.0555	6.539	1.30	1.30
30	.59	.0232	55.461	11.00	12.30
35	.50	.0147	54.151	10.77	23.07
45	.35	.0138	143.846	28.61	51.68
50	.297	.0117	72.165	14.35	66.03
60	.250	.0098	29.313	5.93	71.96
80	.177	.0070	101.249	20.15	92.11
100	.149	.0054	18.541	3.68	95.79
140	.105	.0041	15.507	3.09	98.88
PAN			5.690	1.13	100.01
			502.980		
Lost			1.038		

TEST 2 - Sample Size: 539.054 gr.

RETAINED ON SIEVE No.	OPENING SIZE mm	in.	NEW WEIGHT (grams)	FREQUENCY ABSOLUTE	CUMULATIVE
14	1.41	.0555	8.153	1.51	1.51
30	.59	.0232	59.880	11.12	12.63
35	.50	.0197	57.758	10.73	23.36
45	.35	.0138	152.449	28.32	51.68
50	.297	.0117	77.889	14.47	66.15
60	.250	.0098	48.161	8.95	75.10
80	.77	.0070	94.731	17.59	92.69
100	.149	.0054	18.731	3.48	96.17
140	.105	.0041	14.809	2.75	98.92
PAN			5.791	1.08	100.00
			538.352		
Lost			0.702		

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7. Bekker, p. 34.

8. *Ibid.*, p. 65.

9. *Ibid.*, p. 35.

10. Ibid., p. 56.

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