EVALUATION OF PLASTIC SOIL RESISTANCE TO DEFORMATION

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EVALUATION OF PLASTIC SOIL

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CHAPTER I

INTRODUCTION

General

Numerous criteria, both theoretical and empirical, have been developed by highway engineers for designing asphaltic concrete pavements. Most of them involve the stress-strain characteristics of the paving materials. One method which is employed by many states in flexible pavement design is the stabilometer method. Essential to this method is the employment of the stabilometer device for evaluating stress-deformation relations in the paving materials.

In 1948, the stabilometer method was introduced by Hveem and Carmany (1948) of the California Highway Department. Several physical characteristics of the pavement surface, base, and subgrade as well as the traffic load were considered as the factors governing the pavement thickness design. The design is based upon the principle that the particles in pavement layers tend to be displaced along the curved paths shown in Fig. 1, and thus develop an upward thrust against the underside of the pavement layers. Glossop, Vokac and Golder had also expressed this concept earlier (1943).

In pavement design theory, the required thickness varies directly as the tire pressure, the radius of loading and the logarithm of the load repetition. Applying the stabilometer method to pavement design, Hveem and Carmany added that the thickness also varies inversely as

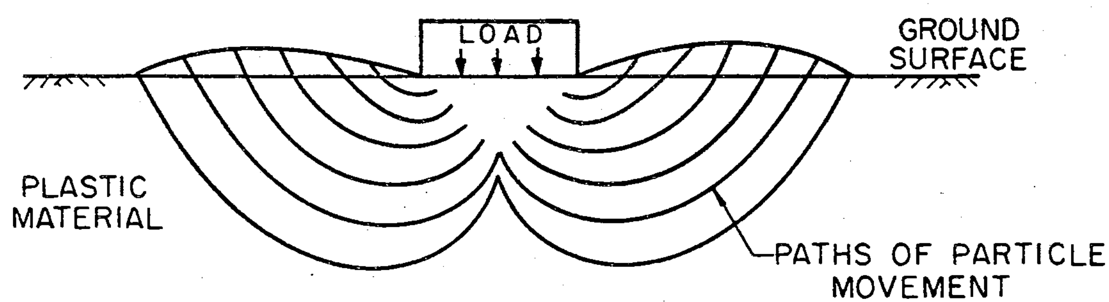

Figure 1. Paths of Particle Movement upon Deformation

the fifth root of the cohesion of the flexible layers. Furthermore, the pavement thickness has a linear relationship with the value of soil deformation resistance which has been expressed as the ratio between the transmitted horizontal pressure and the applied vertical pressure.

The ability of pavement material to resist displacement was designated as the "resistance value" or R-value. The stabilometer, shown in Fig. 2, designed by Hveem, furnishes a means for measuring the R-value directly. When a stabilometer is not available, the resistance value can be approximated by one of its various relationships with several soil classification systems and the California Bearing Ratio.

Methods for Evaluation of Resistance Value

The stabilometer has been devised to provide direct measurement of the lateral pressure transmitted by a plastic material upon which a vertical load is applied. As indicated in Fig. 3, a sample four inches in diameter and 2-1/2 inches in height is inserted into the stabilometer chamber. Vertical loads are applied to the sample, and the resulting laterally developed stresses are measured. The resistance value can be computed through the formula

$$R = 100 - \frac{100}{\frac{2.5}{D}\left(\frac{Pv}{Ph} - 1\right) + 1} \qquad (1)$$

where R = resistance value

Pv = applied vertical pressure, in psi

Ph = transmitted horizontal pressure, in psi

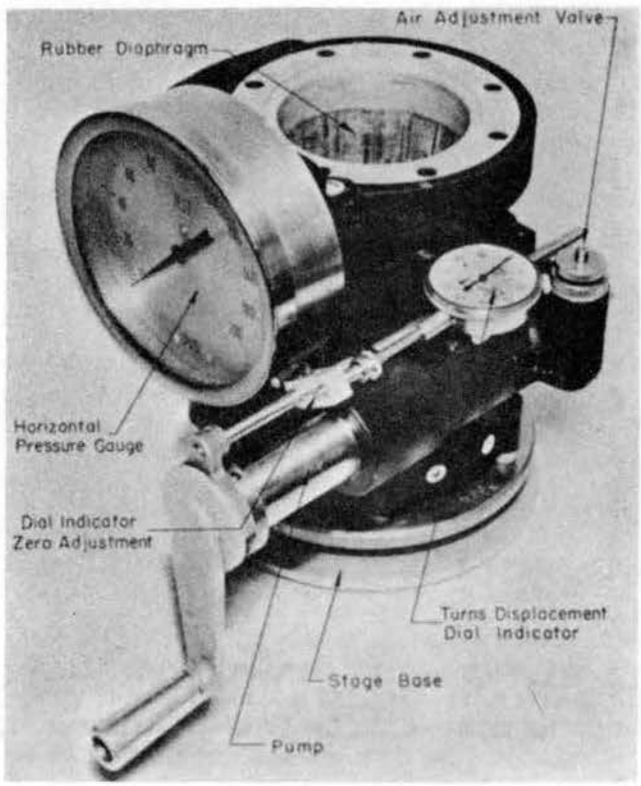

Figure 2. Stabilometer

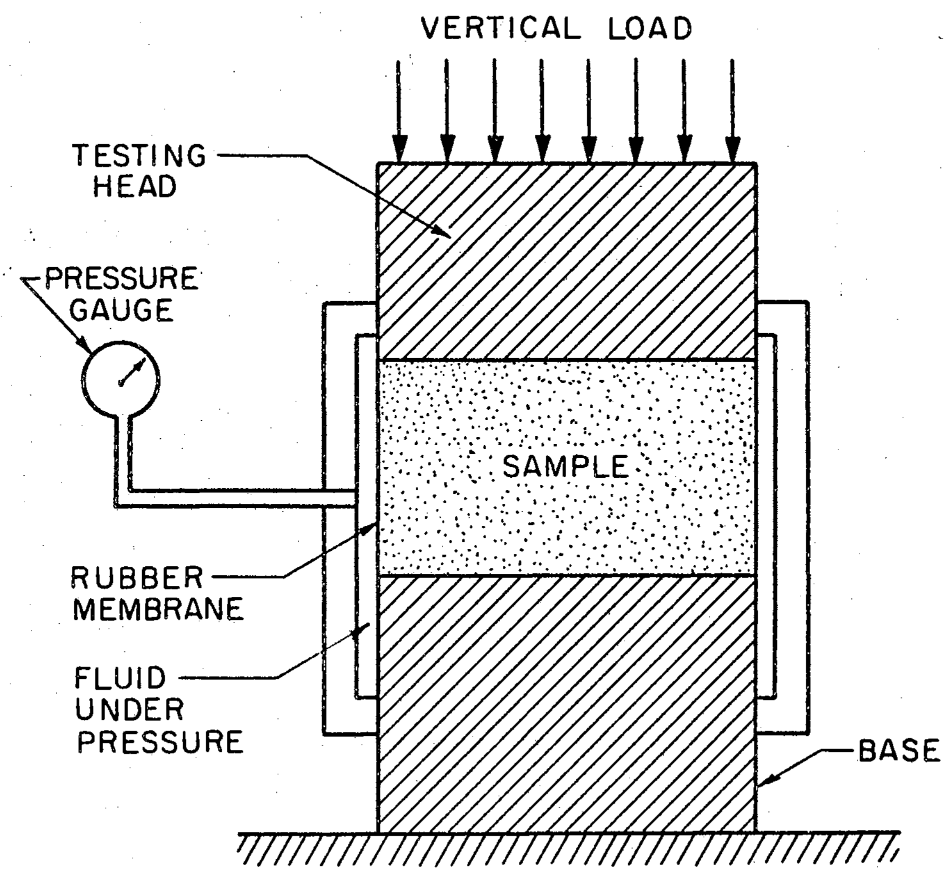

Figure 3. Schematic Diagram of Stabilometer.

D = displacement of stabilometer fluid, measured in revolutions of a calibrated pump handle

The Portland Cement Association has suggested a method to approximate the R-value without using the stabilometer (PCA, 1962). Figure 4 shows the relationships between R-value and various soil classifications. These relationships give the general limits of the R-value for soils ranging from poorest to best with regard to their supporting power.

Another alternate method, which makes use of the group index, was proposed by Hveem (1948). He indicated that the R-value is a linear function of the group index. The graphical representation of the relationship is shown in Fig. 5. Upon knowning the relationship, one can obtain the resistance value directly from this functional relation.

Hveem (1948) refers to an unpublished communication from D. J. Steele in which it is suggested that the California Bearing Ratio when combined with the grading analysis and measured expansion, has a definite relationship to the resistance value as derived from the stabilometer test. The relationship involved is indicated in the chart shown in Fig. 6. In using this chart, a straight line is drawn through the value of CBR at 0.1 inch penetration on Scale F and the ratio between percentages passing #200 and #4 sieves on Scale G. This line is extended to intersect the Scale H. From this point on Scale H a straight line is drawn through the CBR expansion value on Scale I and extended to intersect Scale J at the R-value. Hveem remarks that this chart should not be employed for any material which has the following properties:

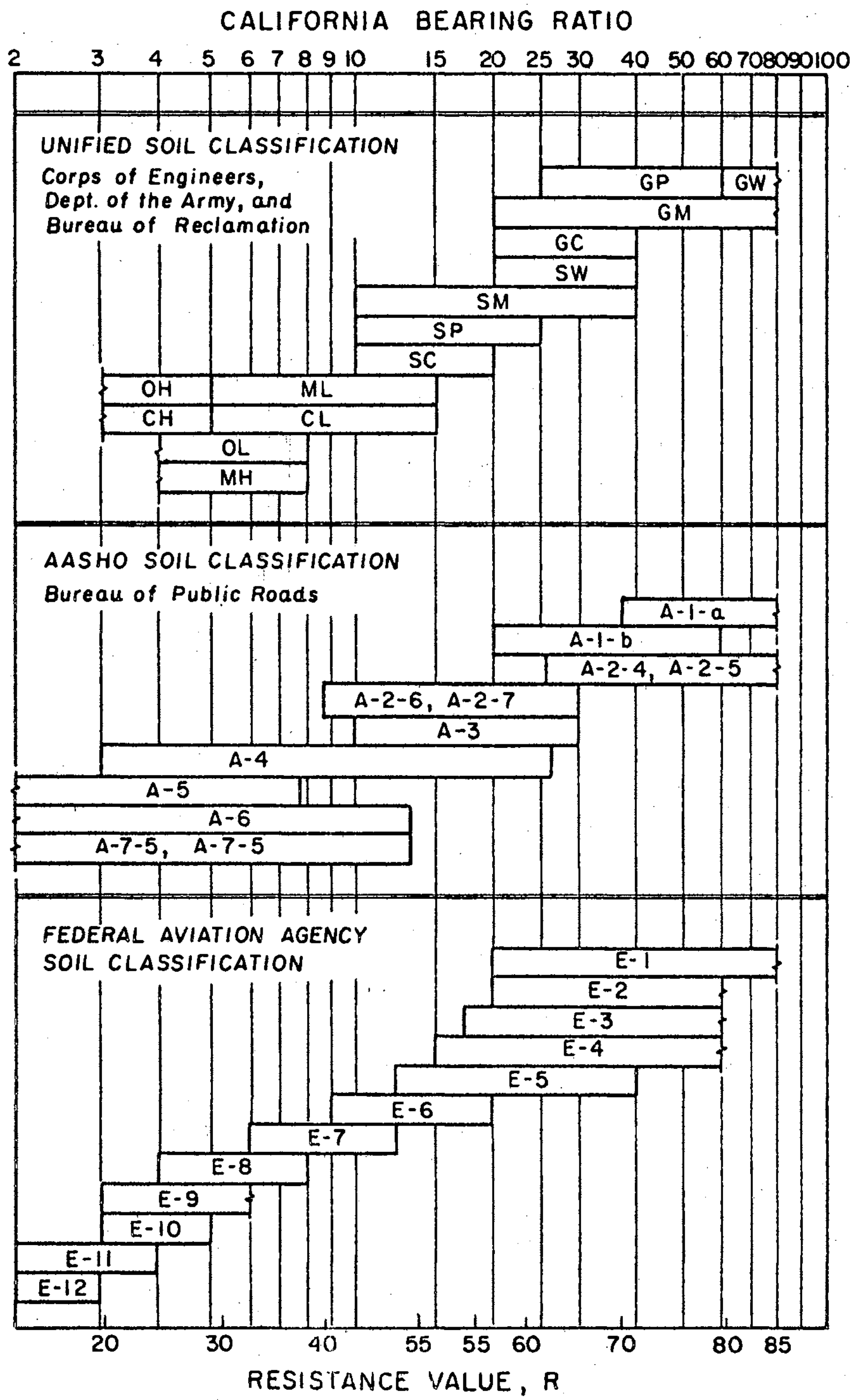

Figure 4. Relationships Between R-value and Soil Classification Systems (modified after PCA, 1962)

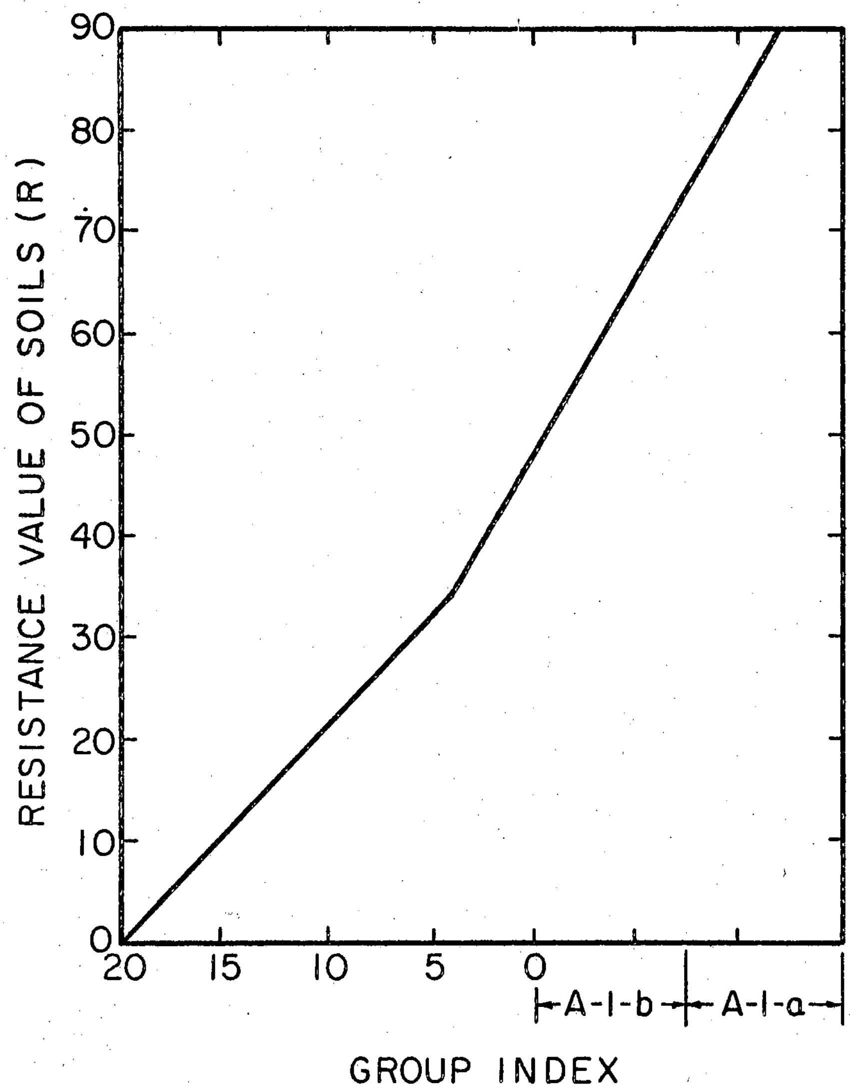

Figure 5. Soil Resistance Value vs. Group Index (after Hveem, 1948)

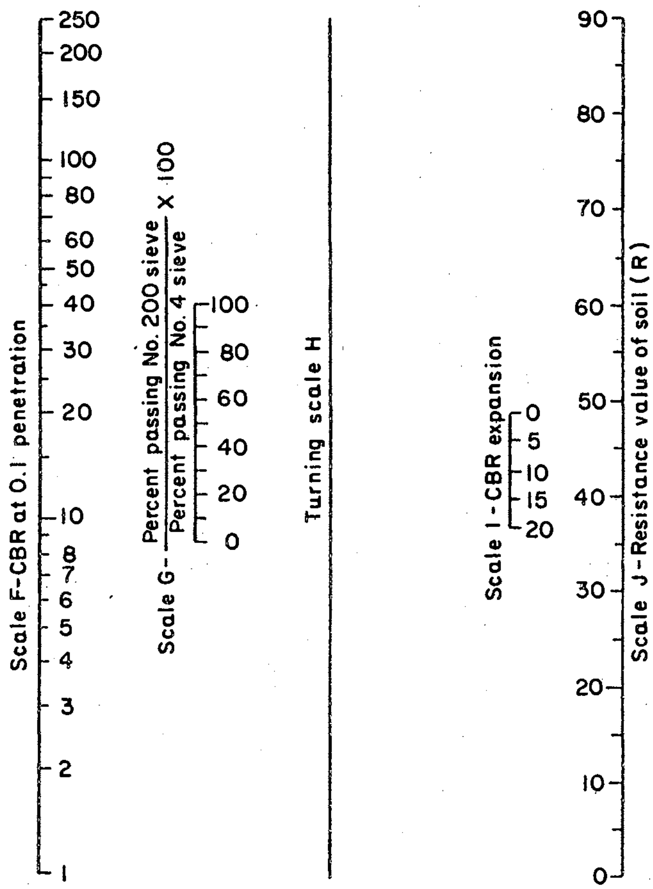

Figure 6. Resistance Value vs. California Bearing Ratio (modified after Hveem, 1948)

a. less than 75 percent passing #4 sieve,

b. more than 8 percent passing #200 sieve, and

c. the product of the plasticity index and percent passing #200 sieve greater than 72.

The Problem

The stabilometer method has been adopted by many states as a standard pavement design procedure. This procedure is presented in many publications which will be referred to in a later chapter of this paper. In order to evaluate the resistance value, one must utilize a stabilometer, a kneading compactor, an exudation pressure device and a compression testing machine. These devices are more delicate and expensive than those employed by other standard processes that are involved in highway design procedures. A complete stabilometer test run by an experienced technician usually takes more than 10 hours of work. Because of the laborious work, the tendency toward using other methods for R-value estimation has increased.

Other methods present certain disadvantages. Use of the approximate relationships (Fig. 4) between R-value and various soil classification systems leads to a wide range of possible R-values for any single soil type. Therefore, it is not feasible to use these relationships to evaluate the resistance value with satisfactory precision.

As far as the use of the group index as a measure of the R-value is concerned (Fig. 5), the author's research revealed that most of the observed R-values fall below the line and scatter over the right hand corner of the diagram without following a pattern. Based on this observation, the writer has little confidence in using this curve as a means to evaluate the resistance value.

When the California Bearing Ratio is used to evaluate the R-value, one has to be aware of certain limitations on the type of material being tested. Evaluation of the California Bearing Ratio involves laborious experimental work. In addition, the CBR Test does not appear to be any better than the Stabilometer Test in estimating soil strength.

To the present time, there is no method, other than the Stabilometer Test, which has been established for predicting soil resistance to deformation with satisfactory precision.

Objective and Scope

The objective of this study was to investigate the relationship between the deformation resistance of plastic highway subgrade soils and the soil moisture content. It was hoped that such an investigation would lead to useful predictive equations from which the deformation resistance of certain soils could be ascertained.

In this research, 63 samples of in-place plastic subgrade material obtained from the Oklahoma state highway system were subjected to laboratory testing, including liquid limit and plastic limit determinations, sieve analysis, standard compaction test, and Hveem stabilometer test. Study of the plotted test results led to the conclusion that a meaningful relationship could be demonstrated between the deformation resistance and the moisture content at 300 psi exudation pressure. Various statistical analyses were employed, leading to the establishment of the desired equations for three different groups of soils.

During the course of the investigation a useful relationship between soil moisture content at 300 psi exudation pressure and the optimum moisture content was discovered.

CHAPTER II

PRIOR STUDIES OF PLASTIC DEFORMATION AND INTERNAL RESISTANCE

General

Engineers have broadly referred to the resistance of soil to deformation as the supporting power or bearing capacity of soils. More precise terminology would be the expression "internal resistance to deformation". The resistance responds not only to different load conditions, but is also affected by the nature of the soil. Several attempts have been made to analyze soil resistance through mathematical treatments based on the theory of elasticity. However, the properties of soils may be more easily understood by extending the principles of hydrostatics. One of the characteristics of a liquid is the ability to transmit pressure equally in all directions. When combined with various amounts of water, a soil mass will transmit some pressure in all directions, but not in the uniform pattern like that of a liquid. The variation depends upon the soil characteristics and the amount of water in the soil mass. More specifically, when a vertical load is applied to a soil mass, the resulting lateral pressure varies inversely with the internal resistance of the soil. The plastic deformation of soil mass has been observed in both field and experimental simulation by many researchers. Both experimental observations and analytical determination of soil resistance to deformation under load will be discussed subsequently.

Experimental Results

Various researchers have conducted model studies of the plastic failure of a soil mass under ultimate load, by applying the theory of similitude (Jumikis, 1956; Jumikis, 1961; Housel, 1935). These investigators presented photographs of sand and clay masses being deformed under vertical load. The photographs showed that both materials produced similar deformation patterns. The potential paths of individual particle movement are shown in Fig. 1. The rupture surface curves had the shape of a logarithmic spiral.

It is obvious that if the load exceeds the resistance of the soil particles underneath the load and a general shear failure occurs, lateral movement will take place. If the material in the surrounding area provides adequate resistance the movement will stop. Otherwise, the surrounding mass yields in the path which has the least resistance.

The soil resistance could be predicted by the analytical methods which were developed from the above experimental observations. These methods are presented in the following section.

Analytical Results

In 1920, Prandtl published his study on the penetration of a statically loaded hard body into another softer, homogeneous, isotropic material. He studied the phenomenon from the viewpoint of plastic equilibrium. Figure 7 shows the system in his study and

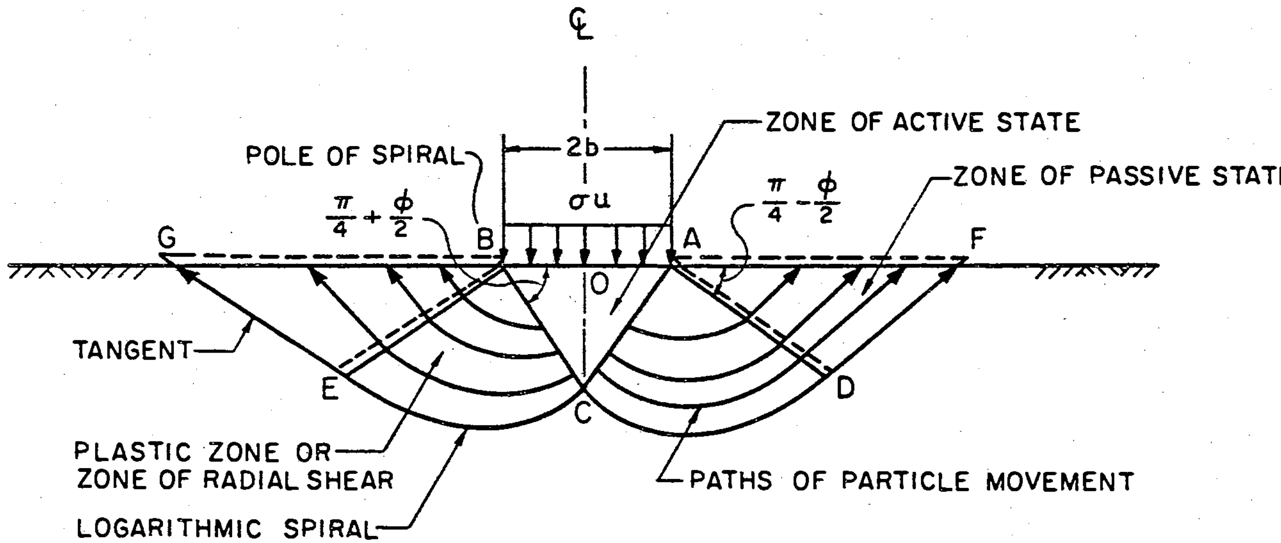

Figure 7. Prandtl's System of Study (modified after Prandtl, 1920)

modified later by Krynine (1947). Upon application of the vertical stress (σ_u) on the ground surface, the soil wedge (Δ) ABC was pushed downward into the soil mass. The pressures from Δ AOC and Δ BOC were transmitted to Δ ADF and Δ BEG through Δ ACD and Δ BCE respectively. The location of Δ ADF and Δ BEG, being deformed, are indicated in Fig. 7 with dotted lines. The paths of particle movement are also shown in the same figure.

The stress σ_u acting on Δ ABC, the active zone, was considered to be of a hydrostatic nature and therefore had the same intensity on the face AC and BC. Due to force equilibrium, the forces acting on faces AD and BE were the same as those acting on faces AC and BC.

Prandtl's (1920, 1921) final equation for estimating the ultimate bearing capacity was

$$\sigma_u = \frac{c}{\tan \phi} \left[\tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2}\right) e^{\pi \tan\phi} - 1\right] \qquad (2)$$

where, c = cohesion

ϕ = internal friction

The formula was later modified by Terzaghi (1943) to include the effect of surcharge and became

$$\sigma_u = \frac{c + c'}{\tan \phi} \left[\tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2}\right) e^{\pi \tan\phi} - 1\right] \qquad (3)$$

where, $c' = \gamma t(\tan \phi)$, and

t = equivalent height of surcharge of soil material

γ = unit weight of soil

An alternative modification of Prandtl's equation was developed by Taylor (1948):

$$\sigma_u = [c \cot \phi + \gamma b \tan (\frac{\pi}{4} + \frac{\phi}{2})] \{[\tan^2(\frac{\pi}{4} + \frac{\phi}{2})] e^{\pi \tan\phi} - 1\} \quad (4)$$

where b = half of the loading width.

It is not the purpose of this paper to explain all the details concerning the derivations of the above equations since they are outside the scope of this study. Nevertheless, the reader should be aware of the principles upon which the calculations of the above equations were based.

CHAPTER III

SAMPLING AND TESTING

Introduction

The experiments which were performed in this research evolved from a satellite study of the road test equations resulting from the American Association of Highway Officials (AASHO) National Road Test. The purpose of the satellite study was to investigate the applicability of the equations to Oklahoma conditions. One of the Oklahoma conditions which was not present in the AASHO test involved the subgrade. In the AASHO tests only one subgrade type was present, whereas the existing Oklahoma subgrades display considerable variation in soil characteristics. The author was responsible for monitoring the field sampling of in-place subgrades by the Oklahoma Department of Highways, and for performing tests on these samples in the Civil Engineering laboratories at Oklahoma State University.

The method selected for soil strength measurement was the determination of resistance value, or R-value, using the Hveem stabilometer. This method was developed for use by the California Division of Highways. The R-value ranges from zero to 100. R-value of steel should give a value approaching 100, whereas water would give a value of zero. Most plastic soil materials would range from zero to 90. Materials having an R-value in excess of 90 would be capable of sustaining traffic without pavement cover except that they would probably be brittle enough to fail in tension under skidding loads.

In addition to soil strength determinations, classification tests were also performed on each of the subgrade samples collected on the satellite study. Several classification systems for soils are in common usage; however, all of them make use in some manner of the basic soil tests, including liquid limit, plastic limit, and sieve analysis.

In order to insure maximum stability of subgrades in fill sections, it is desirable to place the soil and compact it at a moisture content that will provide the greatest density obtainable with the compaction equipment used. To determine this optimum moisture content, several compaction procedures are available. The one selected for use in the satellite study was the Standard Proctor Test. This test was performed on each of the subgrade soil samples obtained.

Sampling

The soil sampling method used in the satellite project was developed jointly by the Research Division, Oklahoma State Highway Department and personnel of the O.S.U. AASHO Satellite Research Project. The author participated in the field work; however, the sampling was conducted by the highway department personnel. Simpler or even better methods might have been used had the sole purpose of the sampling been to collect subgrade samples. However, it must be noted that the procedures were designed to best accomodate the entire field experimentation of which the subgrade sampling was only a portion.

It is not intended in this paper to discuss the entire field work but to present only the embankment soil sampling procedure. Readers are again reminded that the materials that were used in this study were the subgrades of the flexible pavements in the State of Oklahoma.

Before excavating the material from the embankment of the roadway, several holes were drilled using a core drill attached at the rear of a pick-up truck as shown in Fig. 8. The diamond drill was 6 inches in diameter and 12 inches in length. Except for the pavements with aggregate base, cores were cut to the subbase level. After removing the pavement core, the subbase material was excavated down to the top of the subgrade soil. The embankment soil was then scooped out to a depth of approximately 6 inches and collected in a sample bag. On pavements having an aggregate base the depth of drilling was limited to the top of the base. Having removed the core, base and subbase materials, the subgrade material was collected.

On each test site or loaction of the roadway, a bulk subgrade sample of about 30 lbs was collected, labelled, and transported to the O.S.U. Civil Engineering laboratories for further tests.

Preparation of Soil Sample for Experiments

The samples received from the field were immediately placed in large trays and air-dried for at least 24 hours to facilitate subsequent pulverizing of the material. Aggregations were broken up in a mortar using a rubber-covered pestle. For samples containing large amounts of friable material a power driven pulverizer, shown in Fig. 9, was used. It consisted of a ceramic jar containing three hard rubber rollers which served the same purpose as the mortar and pestle. Rubber-covered pestle and rubber rollers were used rather than hard-surfaced implements, to prevent reduction of the natural size of

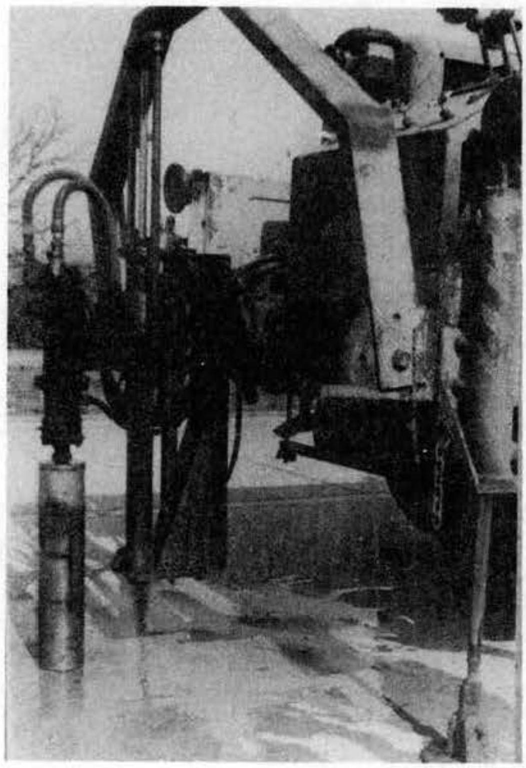

Figure 8. Core Drill

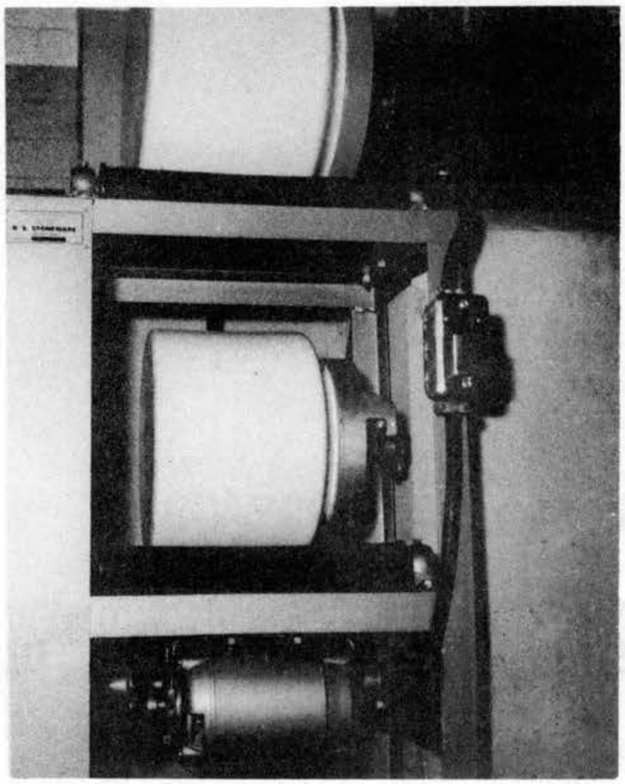

Figure 9. Soil Pulverizer

individual soil particles.

The representative sample for each of the laboratory tests was selected by quartering. This method was used in preference to a soil-splitter because it minimized the possibility of losing the fine particles of the pulverized material during the selecting process. The required amount of sample for each individual test was then obtained and stored in plastic containers. Procedures for quantitative preparations of the samples are given in the Procedures for Testing Soils (ASTM, 1964) under the designation of D 421-58.

Laboratory Tests

A. Identification Tests

These tests included liquid limit determination, plastic limit determination, and sieve analysis. The standard procedures, D 423-61T, D 424-59, and D 422-63 in the Procedures for Testing Soils by American Society for Testing and Materials, 1964, were followed.

Presentation and application of results obtained from these tests are discussed in subsequent chapters.

B. Resistance Value Determination

This experiment was conducted in three stages (The Asphalt Institute, 1964). The first stage was test sample preparation, principally blending and soaking of the embankment materials. The blending was done for the purpose of duplicating the field material gradation and the soil was soaked to represent the worst condition which the subgrade would encounter in the field during the wet season. This was followed by compaction, for which a hydro-electric kneading compactor was used. This type of compaction effort simulates the action of a sheep's-foot roller in compacting plastic soils. The third stage involved the exudation test which assured the complete saturation of the molded specimens. Complete saturation was necessary to represent the field condition in which the pavement foundation is subject to a high water-table. The determination of R-value was the final stage of this experiment. The adoption of the stabilometer for estimating the horizontal pressure, transmitted from the vertical pressure through the plastic soil medium, provided a relatively fast measurement of the soil resistance strength.

Repetitions of this test were made for several samples to provide data for the evaluation of the technical error. The data are presented in a later chapter of this paper.

C. Density - Moisture Relation Determination

Standard Proctor Test is used for estimating the optimum moisture which is required in the compaction of embankment soils in order to obtain the desirable density. This method has been widely accepted as a routine operation in engineering practice. The method is described in the Procedures for Testing Soils (ASTM, 1964), under the designation D 698-64T. The presentation of the test results are given in the following chapter.

TABLE I

SOIL PROPERTIES

SAMPLE NUMBER	LL	PL	PI	PERCENTAGE PASSING SIEVE 10	40	100	GI	OPT. M.C.	M.C.	RV
1	29	21	8	100	94	36	0	13.7	13.7	11
2	44	20	24	97	96	17	0	21.0	24.4	5
3	34	18	16	85	83	19	0	14.0	15.0	10
4	27	16	11	100	100	37	0	12.5	12.0	36
5	21	17	3	100	83	35	0	12.0	12.0	21
6	32	21	10	62	44	30	0	16.0	17.2	7
7	26	21	5	100	98	28	0	13.5	13.2	20
8	20	16	4	100	99	32	0	11.5	10.0	57
9A	25	17	8	100	98	28	0	12.5	12.0	24
9B	25	17	8	100	98	28	0	12.5	12.0	20
10	20	7	13	96	86	4	0	11.5	10.8	31
11A	20	16	4	100	100	33	0	*	10.0	60
11B	20	16	4	100	100	33	0	*	10.0	63
11C	20	16	4	100	100	33	0	*	10.0	59
12	26	18	8	100	99	34	0	*	13.5	22
13	38	22	17	96	76	36	2	19.0	21.8	7
14	23	14	9	99	97	47	2	12.9	12.8	32
15	22	15	7	100	98	48	3	14.5	14.5	8
16	20	14	6	97	95	48	3	14.5	13.3	18
17	25	15	10	100	98	48	3	13.3	12.7	27
18	19	12	7	100	98	51	3	12.3	12.3	34
19A	19	17	2	100	93	48	3	11.5	11.0	30
19B	19	17	2	100	93	48	3	11.5	11.0	35
20A	23	19	4	100	100	53	4	12.5	13.0	12
20B	23	19	4	100	100	53	4	12.5	13.0	18
21	34	27	7	92	83	55	4	18.0	21.5	5
22	26	15	11	100	99	54	4	*	13.5	18

TABLE I (CONT'D)

SOIL PROPERTIES

SAMPLE NUMBER	LL	PL	PI	PERCENTAGE PASSING SIEVE 10	40	100	GI	OPT. M.C.	M.C.	RV
23A	21	14	7	100	98	60	5	10.0	10.3	56
23B	21	14	7	100	98	60	5	10.0	10.3	59
24	22	15	8	99	98	60	5	12.0	12.1	35
25	21	15	6	96	93	62	5	12.9	11.5	60
26A	24	18	6	100	99	63	6	13.5	13.0	30
26B	24	18	6	100	99	63	6	13.5	13.0	35
27A	29	22	7	100	100	64	6	13.4	15.0	26
27B	29	22	7	100	100	64	6	13.4	15.0	23
28A	27	14	13	63	57	57	6	15.5	16.0	18
28B	27	14	13	63	57	57	6	15.5	16.0	16
29	28	24	4	91	85	65	6	13.7	13.8	33
30	30	19	12	100	99	63	6	16.5	22.2	5
31	28	16	12	100	99	64	7	13.5	14.7	20
32	33	20	13	98	89	63	7	16.5	17.4	7
33	37	20	17	98	95	56	7	18.9	19.3	5
34	25	19	6	98	97	70	7	14.0	12.6	34
35	23	13	10	100	100	72	8	15.5	15.7	15
36	49	37	12	97	89	65	8	21.8	26.5	5
37	31	22	9	100	100	100	8	19.0	21.0	6
38	36	18	19	100	98	58	8	15.5	16.6	12
39	32	13	19	100	96	58	8	18.5	22.1	5
40	24	13	11	100	100	100	9	15.5	14.7	18
41A	23	12	11	100	100	84	9	13.0	11.5	50
41B	23	12	11	100	100	84	9	13.0	11.5	54
42	34	22	12	99	89	74	9	21.0	26.0	6
43	27	16	11	100	98	82	8	*	16.2	11
44	42	27	15	100	97	66	9	*	24.0	5
45	36	24	12	100	99	82	9	*	14.9	30
46	32	20	12	100	100	100	9	*	23.0	5
47	29	16	13	100	100	77	9	14.5	15.0	16
48	40	18	22	98	87	58	9	17.5	20.2	5

TABLE I (CONT'D)

SOIL PROPERTIES

SAMPLE NUMBER	LL	PL	PI	PERCENTAGE PASSING SIEVE 10	40	100	GI	OPT. M.C.	M.C.	RV
49	34	12	22	66	66	66	11	14.5	16.5	5
50	33	16	17	100	96	76	11	16.5	22.4	5
51	38	21	17	100	93	78	11	18.0	24.6	5
52	46	22	24	98	83	58	11	17.5	22.5	6
53	39	20	18	97	96	69	10	*	24.0	5
54	32	14	18	100	98	77	11	16.5	21.7	5
55	34	15	19	99	97	87	12	18.5	26.0	5
56	36	13	23	100	92	70	12	18.5	25.0	5
57	40	19	22	100	99	82	13	15.5	16.9	8
58	36	13	23	100	99	75	13	16.1	19.8	7
59	43	22	22	100	98	92	13	*	24.0	5
60	41	17	24	100	98	77	14	*	24.0	5
61	45	22	24	99	97	74	14	16.0	21.0	5
62	41	11	30	99	95	68	15	15.9	17.5	5
63	60	19	41	100	100	86	20	17.5	24.0	5

* MISSING DATA (INSUFFICIENT MATERIAL FOR TESTING)

NOTATION -

LL = LIQUID LIMIT, IN PERCENT
PL = PLASTIC LIMIT, IN PERCENT
GI = GROUP INDEX
OPT. M.C.= OPTIMUM MOISTURE CONTENT, IN PERCENT
M.C. = MOISTURE CONTENT AT 300 PSI EXUDATION PRESSURE, IN PERCENT
RV = R-VALUE AT 300 PSI EXUDATION PRESSURE

CHAPTER IV

PRESENTATION OF LABORATORY RESULTS

Introduction

The results obtained from the laboratory tests are presented in tabular form. In the data presented, the sample number has no special significance other than to identify the individual materials. The table includes not only directly measured values, but, also quantities derived from these measured values. The computational procedures used are given in the testing manuals that were previously referred to in Chapter III. Most of these computations were performed by utilizing the IBM 1620 computer.

Group Index Determination

In order to classify the subgrade material according to the AASHO Soil Classification system, three tests were performed to determine the liquid limit, plastic limit and grain size distribution. Table I shows the results of the tests performed for each sample. Also listed in the same table are the difference between liquid limit and plastic limit (plasticity index) for each sample.

Group Index (Steele, 1946) was selected in this research to identify the soil samples. Its value can be obtained by the equation shown below:

$$G.I. = 0.2a + 0.005ac + 0.01bd \quad (5)$$

where a = that portion of percentage passing No. 200 sieve greater than 35% and not exceeding 75%, expressed as a positive whole number (1 to 40)

b = that portion of percentage passing No. 200 sieve greater than 15% and not exceeding 55%, expressed as a positive whole number (1 to 40)

c = that portion of the numerical liquid limit greater than 40 and not exceeding 60, expressed as a positive whole number (1 to 20)

d = that portion of the numerical plasticity index greater than 10 and not exceeding 30, expressed as a positive whole number (1 to 20)

The results of the computation are tabulated in Table I.

Resistance Value Determination

The R-values and the soil moisture contents at 300 psi exudation pressure are given in Table I. This particular exudation pressure was selected in the satellite research project so as to simulate the field compaction effort. The density of the soil specimen having an exudation pressure of 300 psi is assumed to be similar to that of the same soil compacted by sheep's-foot roller. Note in the table that certain samples were subjected to replicate tests. These are indicated by a letter following the sample number, e.g., 11B.

Density - Moisture Relation Determination

The performance of this test resulted in values being obtained for maximum dry density and optimum moisture content. Since the maximum dry density is not used in the analysis of this study, only the values of the optimum moisture content are presented in Table I.

CHAPTER V

ANALYSIS AND RESULTS

Introduction

The soil samples tested in the laboratory as described in the previous chapter, were divided into three groups on the basis of the group index value according to their supporting power. Group indices from 0 through 4, 5 through 9, and 10 through 20 were selected, since these divisions are widely recognized by engineers to correspond to "good", "fair" and "poor" soils respectively. Regression analyses were then performed on each of the three groups of R-value data plotted against the moisture content at 300 psi exudation pressure, to establish functional relationships.

Similarly, regression analyses were carried out to establish the relationship between moisture content at 300 psi exudation pressure and optimum moisture content in each of the three soil quality groups.

Graphical Method

For each soil group a scatter diagram was constructed by the computer plotter. The moisture content (at 300 psi exudation pressure) and R-value were considered as the X variable and Y variable respectively. Each dot represents one pair of observation from the Stabilometer Test.

The diagrams are shown in Figures 10 through 12. The trends shown on Figures 10 and 11 appear to be the types which can be described by asymptotic equations. It was decided therefore to run an asymptotic regression analysis on the data.

Figure 12 reveals that for a group index above 10, a linear relationship exists between the two variables. Furthermore, it is noted that the moisture content affects very little the strength of the soil resistance. This is shown by a linear regression analysis which is presented subsequently.

The optimum moisture content data obtained from the standard compaction test was plotted against the moisture content at 300 psi exudation pressure in the scatter diagrams shown in Figures 13 through 15. The linear relationships between the two variables suggested that straight lines could be used to fit the data on these diagrams.

In the following sections these relationships are further examined through linear regression analyses.

Analytical Method

A. Relationship Between R-value and Moisture Content at 300 psi Exudation Pressure

It was concluded, after examining the scatter diagrams in Figures 10 and 11, that the plotted points in each of these two figures could be fitted by a mathematical model having the form of an exponential curve,

$$Y = \alpha + \beta\rho^{X} + \varepsilon \qquad (6)$$

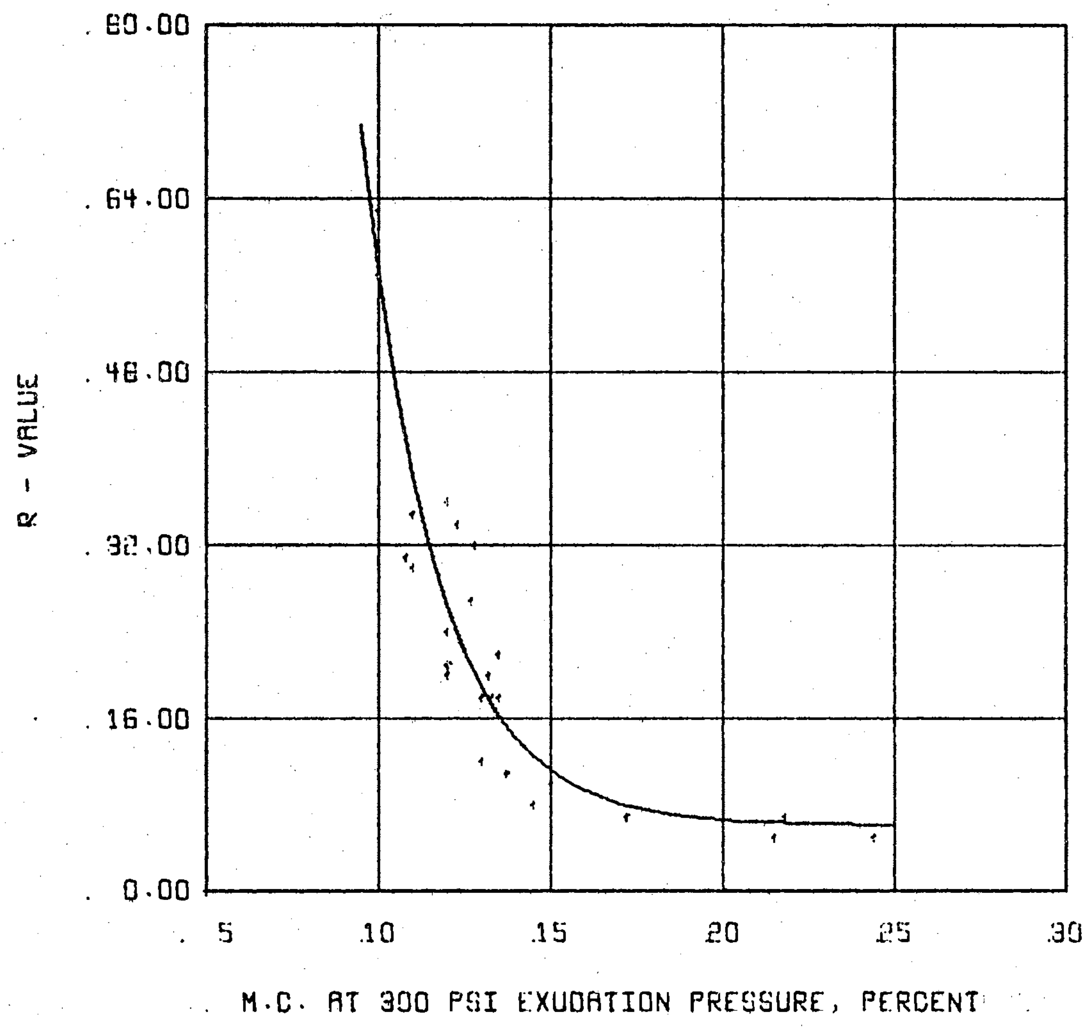

Figure 10. R-value vs. Moisture Content at 300 psi Exudation Pressure; for Soils with Group Indices Ranging from 0 to 4.

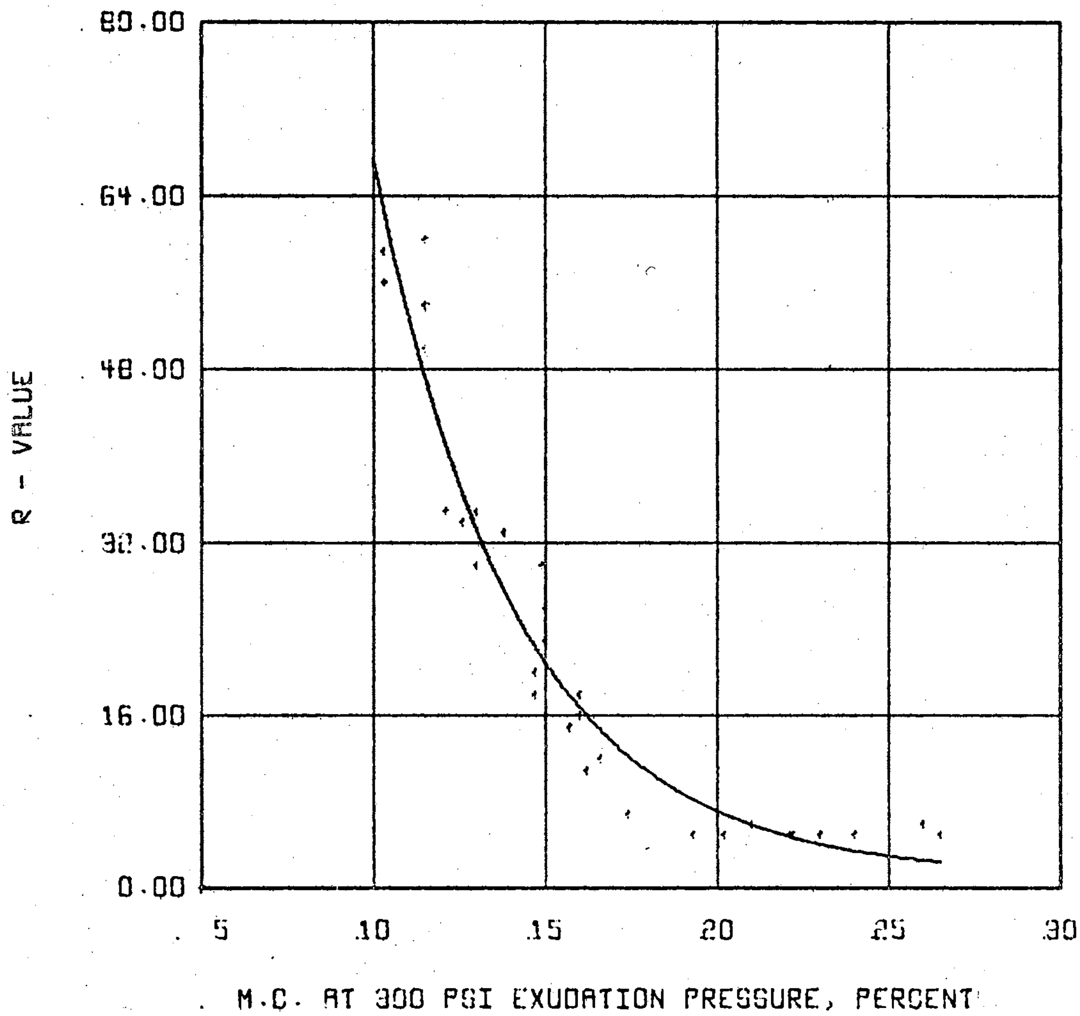

Figure 11. R-value vs. Moisture Content at 300 psi Exudation Pressure; for Soils with Group Indices Ranging from 5 to 9.

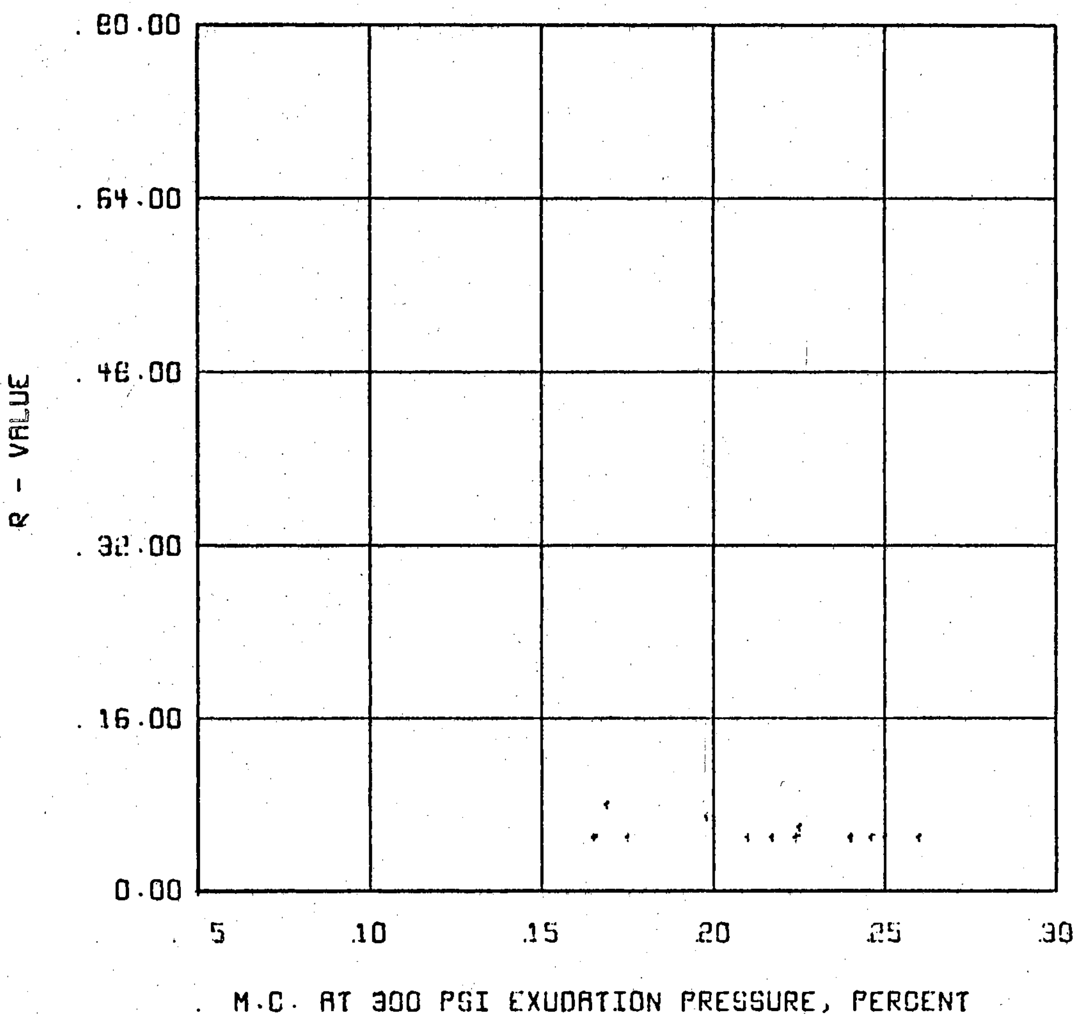

Figure 12. R-value vs. Moisture Content at 300 psi Exudation Pressure; for Soils with Group Indices Ranging from 10 to 20.

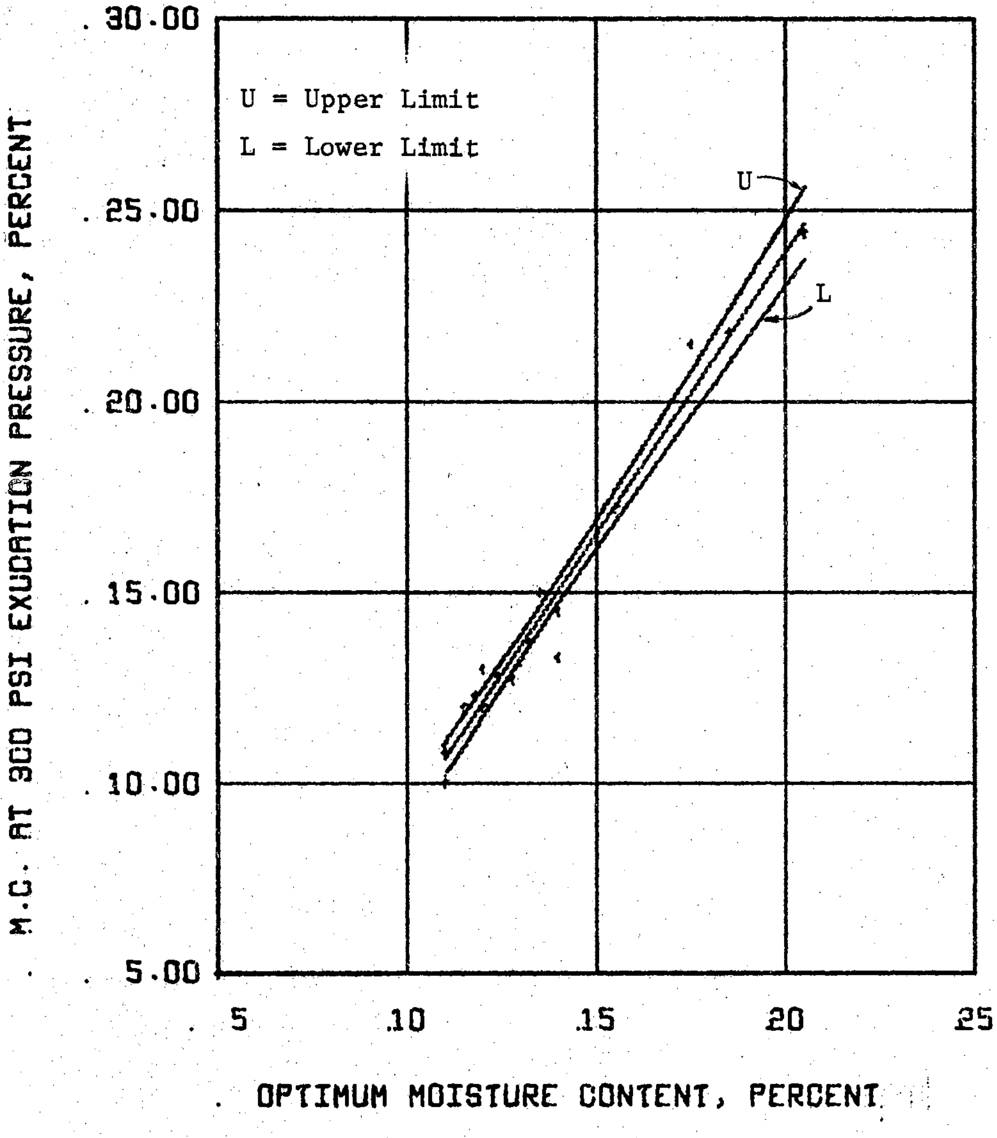

Figure 13. Moisture Content at 300 psi Exudation Pressure vs. Optimum Moisture Content; for Soils with Group Indices Ranging from 0 to 4.

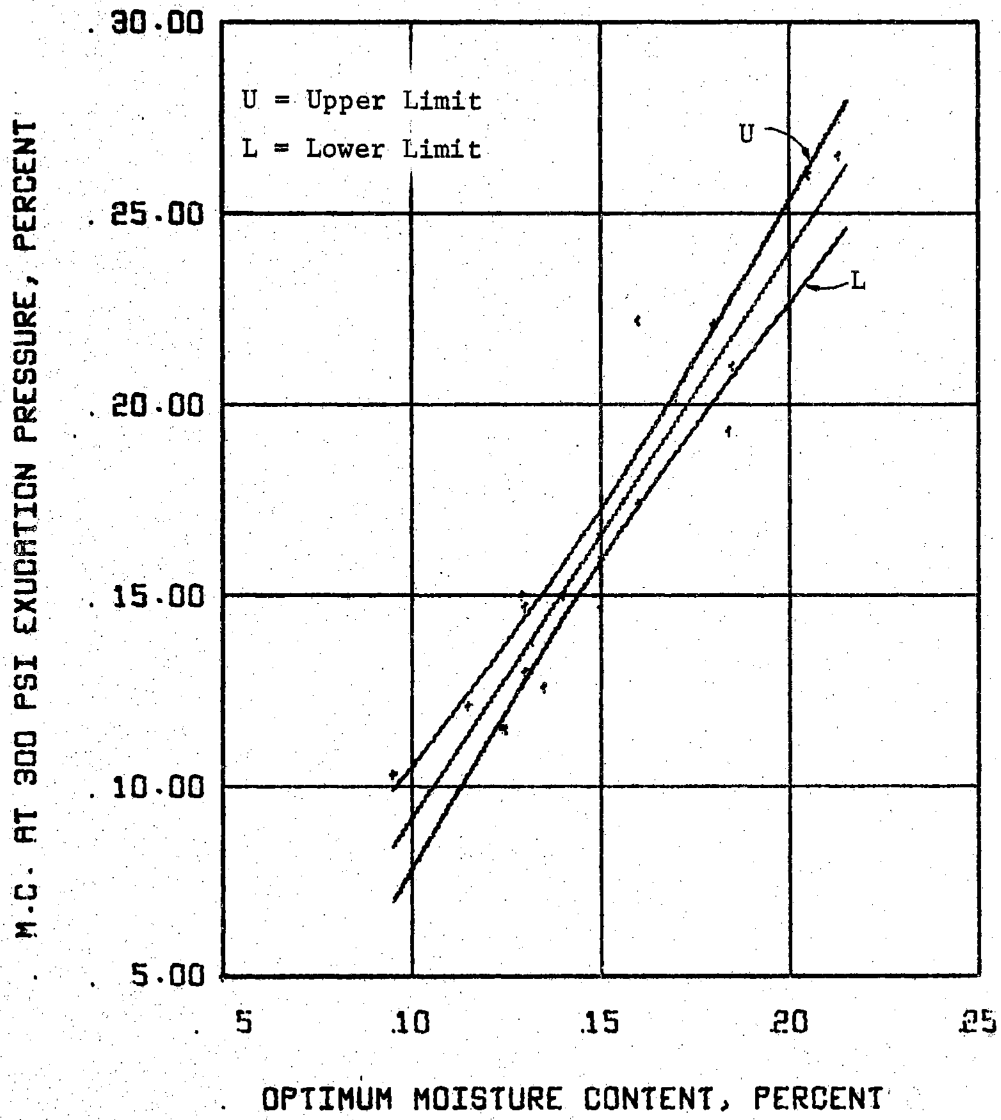

Figure 14. Moisture Content at 300 psi Exudation Pressure vs. Optimum Moisture Content; for Soils with Group Indices Ranging from 5 to 9.

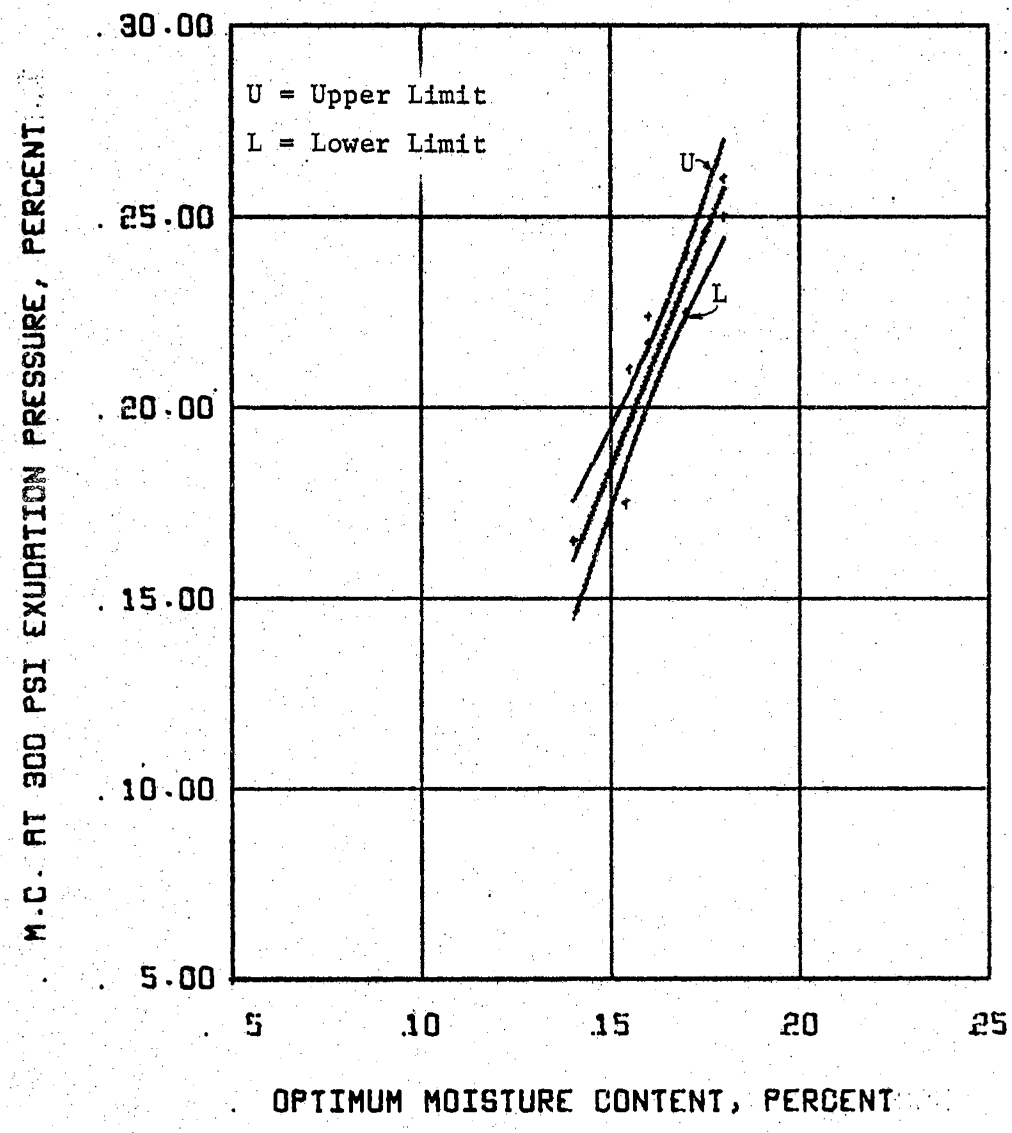

Figure 15. Moisture Content at 300 psi Exudation Pressure vs. Optimum Moisture Content; for Soils with Group Indices Ranging from 10 to 20.

where Y = soil resistance value

X = moisture content at 300 psi exudation pressure, percent

α = asymptotic value of Y

β = change in Y when X passes from 0 to ∞

ρ = factor by which the deviation of Y from its asymptotic value is reduced as a unit step along X-axis is taken

ε = random error

An asymptotic regression analysis method developed by W. L. Stevens (1951) and programmed for computer usage by U.C.L.A. was applied to the plotted data. This least squares computer program was written in Fortran IV language and was designated as BMD 06R in the published index (University of California, 1968).

The results of the analyses are shown in Appendix A. They provide the values and standard deviations of coefficients A, B, and R which are estimates of the parameters α, β, and ρ in Eq. (6). Also indicated in Appendix A are the following: an Analysis of Variance, a table of residuals, and a graph showing the averaged and the predicted R-values.

In order to evaluate the sources of variation, it is necessary to cast Eq. (6) into a somewhat more rigorous statistical model. The model of this regression analysis has the form:

$$Y = \mu + \alpha + \beta\rho^{x} + \varepsilon_{e} + \varepsilon_{t} \qquad (7)$$

where Y = soil resistance value

X = moisture content at 300 psi exudation pressure, percent

μ = population mean of soil resistance values

α, β, ρ = regression coefficients

ε_e = experimental error

ε_t = technical error

The sources of variation are composed of: (1) experimental error, (2) technical error, (3) nature of the model, (4) lack of fit. Table II details the Analysis of Variance for the soil having group index from 0 to 4 ("good"). Analysis of Variance (AOV) for the "fair" soils (group index 5 - 9) is tabulated in Table III. The procedures for computing each sum of squares are illustrated by an example in Appendix B.

As indicated in the last column of the AOV tables, the sum of squares of the variation due to model takes up a large portion of the total corrected sum of squares. The experimental error, technical error and lack of fit share the remainder. As a result, it may be concluded that the model in Eq. (7) is adequate in describing the data. By comparing the two AOV tables it may be noted that the model describes the data obtained from the "fair" soils somewhat better than that obtained from the "good" soils, in that the sum of squares of the variation due to model is a larger percentage of the total corrected sum of squares for the "fair" soils than that for the "good" soils.

The smooth curves in Figures 10 and 11 show the variations in R-value which were represented by computer output points in Appendix A.

The apparent linearity of the relationship between R-value and moisture content of the "poor" soils (Fig. 12) suggested the use of a simple linear regression analysis for the data. The straight line model used to fit the data is

$$Y = \Theta + \eta X + \varepsilon \qquad (8)$$

TABLE II

ANALYSIS OF VARIANCE - R-VALUE vs. MOISTURE

CONTENT AT 300 psi EXUDATION PRESSURE

(G.I. = 0 to 4)

Source	d.f.	SS	MS	% of total SS (corr.)
Total	27	25440.0		
Mean	1	17633.3		
Total (corr.)	26	7806.6		100.0
Among samples with same moisture content (Experimental error)	4	172.9	43.2	2.2
Among sub-samples with same moisture content (Technical error)	5	47.2	9.4	0.6
Residual	17	7586.5		
Deviation from curve	23	820.2		
Due to model	3*	6986.4		89.5
From curve with exp. & tech. errors removed (Lack of fit)	14*	600.1		7.7

C.V. of experimental error = 26%

C.V. of technical error = 12%

*Degrees of freedom is approximate due to the non-linearity of the regression model.

Notation:

d.f. = degrees of freedom
SS = sum of squares
MS = mean square
C.V. = coefficient of variability - error standard deviation expressed as a percentage of the mean of all R-values.

TABLE III

ANALYSIS OF VARIANCE - R-VALUE vs. MOISTURE CONTENT AT 300 psi EXUDATION PRESSURE

(G.I. = 5 to 9)

Source	d.f.	SS	MS	% of total SS(corr.)
Total	31			
Mean	1			
Total (corr.)	30	9645.9		100.0
Among samples with same moisture content (Experimental error)	3	92.9	31.0	1.0
Among sub-samples with same moisture content (Technical error)	5	31.5	6.3	0.3
Residual	22	9521.5		
Deviation from curve	27	618.8		
Due to model	3*	9027.1		93.6
From curve with exp. & tech. errors removed (Lack of fit)	19*	494.5		5.1

C. V. of experimental error = 24.5%

C. V. of technical error = 11%

*Degrees of freedom is approximate due to the non-linearity of the regression model.

where Y = soil resistance value

X = moisture content at 300 psi exudation pressure, percent

Θ = intercept of Y

η = slope of the line

ε = random error

The computer center provides a least squares program to perform the linear regression analysis. Appendix C shows the computer output which consists of the estimates of the parameters Θ and η, an Analysis of Variance and the calculated residuals.

As stated in the Graphical Method, the R-value does not change as the moisture content varies. This phenomenon is further confirmed by the analysis of variance which is tabulated in Appendix C. Either the F or T test can be used to show that the regression coefficient is not significantly different from zero. This implies that the slope of the straight line is close to null, and that the soil resistance has no linear functional relationship with the moisture content at 300 psi exudation pressure. In other words, the moisture content at 300 psi exudation pressure is of little value in predicting the plastic soil resistance to deformation.

B. Relationship Between Moisture Content at 300 psi Exudation Pressure and Optimum Moisture Content

The scatter diagrams in Figures 13 through 15 indicate an apparent linear relationship between the two variables. A linear regression analysis was therefore performed on the data from these observations. The straight line equation $Y = \Theta + \eta X$ was again chosen to be the regression formula. However, Y and X denote the moisture content at 300 psi exudation pressure and optimum moisture content, respectively, in this analysis.

As previously described, the electronic computer was utilized for the computation of the coefficients in this equation. The procedure of analysis was similar to that which was used to analyze the R-value vs. moisture content at 300 psi exudation pressure for the "poor" class of soils.

Appendix D shows the results of the linear regression analyses on all three soil groups. For each soil group, the estimates of Θ and η, an Analysis of Variance and a table listing the residuals are given.

The regression analyses introduced three equations of estimating the moisture content at 300 psi exudation pressure for the "good", "fair" and "poor" soil groups. They are:

$$\hat{Y} = -5.56 + 1.47X \qquad (9)$$

$$\hat{Y} = -5.58 + 1.47X \qquad (10)$$

$$\hat{Y} = -18.13 + 2.44X \qquad (11)$$

Equations (9) and (10) are almost identical. However, it is not suggested that one equation should be replaced by the other or one could use either one of these estimates for both types of soils. A more detailed discussion concerning the use of these equations are given in Chapter VI.

The high values of the correlation coefficients shown in Appendix D indicate a very close relationship between moisture content at 300 psi exudation pressure and optimum moisture content.

The precision of estimate can be visualized from the small values of standard error of estimate shown in Appendix D.

Confidence interval values for the estimated average moisture content at 300 psi exudation pressure are tabulated in Table IV for a number of optimum moisture contents. The confidence belts are also drawn in Figures 13 through 15 for the soils with group indices of 0 to 4, 5 to 9, and 10 to 20 respectively. In tabulating the confidence interval and drawing the confidence belts the formula used is

$$C.L.(\hat{Y}) \begin{matrix} L \\ U \end{matrix}\} = Y \mp s_{yx}\sqrt{\frac{1}{n} + \frac{(X - \bar{x})^2}{\Sigma x^2}} \qquad (12)$$

where $\hat{Y}$ = estimated average moisture content at 300 psi exudation pressure, percent

L = lower limit of $\hat{Y}$, percent

U = upper limit of $\hat{Y}$, percent

s_{yx} = standard error of estimate, percent

n = number of observations

X = any value of optimum moisture content, percent

$\bar{x}$ = mean value of X, percent

$\Sigma x^2 = \Sigma(X - \bar{x})^2$

Summary

The formulae derived from the regression analyses are summarized in Table V. For each formula, this table also gives the number of data observations and the range of independent variable values within each regression analysis from which the formula was established.

Using the first two equations in Table V, two curves are drawn on Fig. 16 to summarize the soil resistance versus the moisture content at 300 psi exudation pressure relationships. The straight line

TABLE IV

CONFIDENCE INTERVAL OF ESTIMATED MOISTURE CONTENT AT 300 PSI EXUDATION PRESSURE

GROUP INDEX = 0 - 4

OPT M.C.	LOWER LIMIT M.C.	EST. M.C.	UPPER LIMIT M.C.
11.00	10.20	10.66	11.12
11.50	10.98	11.40	11.81
12.00	11.75	12.13	12.51
12.50	12.52	12.87	13.22
13.00	13.27	13.61	13.94
13.50	14.02	14.35	14.67
13.53	14.07	14.40	14.73
14.00	14.75	15.08	15.42
14.50	15.47	15.82	16.17
15.00	16.18	16.56	16.93
15.50	16.89	17.30	17.70
16.00	17.58	18.03	18.48
16.50	18.27	18.77	19.27
17.00	18.96	19.51	20.05
17.50	19.65	20.24	20.84
18.00	20.33	20.98	21.63
18.50	21.01	21.72	22.42
19.00	21.70	22.46	23.22
19.50	22.38	23.19	24.01
20.00	23.06	23.93	24.81
20.50	23.73	24.67	25.60

TABLE IV (CONT'D)

GROUP INDEX = 5 - 9

OPT M.C.	LOWER LIMIT M.C.	EST. M.C.	UPPER LIMIT M.C.
9.50	6.97	8.43	9.90
10.00	7.81	9.18	10.54
10.50	8.66	9.92	11.18
11.00	9.50	10.66	11.83
11.50	10.33	11.40	12.48
12.00	11.16	12.15	13.13
12.50	11.99	12.89	13.79
13.00	12.80	13.63	14.46
13.50	13.61	14.38	15.14
14.00	14.40	15.12	15.84
14.50	15.17	15.86	16.55
15.00	15.93	16.60	17.28
15.05	16.01	16.69	17.36
15.50	16.66	17.35	18.03
16.00	17.38	18.09	18.80
16.50	18.08	18.83	19.59
17.00	18.76	19.58	20.39
17.50	19.43	20.32	21.20
18.00	20.10	21.06	22.03
18.50	20.75	21.81	22.86
19.00	21.40	22.55	23.69
19.50	22.05	23.29	24.53
20.00	22.69	24.03	25.37
20.50	23.33	24.78	26.22
21.00	23.97	25.52	27.07
21.50	24.61	26.26	27.92

TABLE IV (CONT'D)

GROUP INDEX = 10 - 20

OPT M.C.	LOWER LIMIT M.C.	EST. M.C.	UPPER LIMIT M.C.
14.00	14.45	16.00	17.55
14.50	15.93	17.22	18.51
15.00	17.39	18.44	19.49
15.50	18.80	19.66	20.52
16.00	20.13	20.88	21.62
16.24	20.76	21.49	22.22
16.50	21.35	22.10	22.84
17.00	22.46	23.32	24.18
17.50	23.48	24.53	25.59
18.00	24.46	25.75	27.04

NOTATION -

OPT. M.C. = OPTIMUM MOISTURE CONTENT, IN PERCENT
M.C. = MOISTURE CONTENT AT 300 PSI EXUDATION PRESSURE, IN PERCENT

TABLE V

SUMMARY OF ESTIMATED FORMULAE

Relationship	Soil Type, G.I.	Equation	Number of Observations	Range of X
R vs M.C.	0 to 4	$\hat{Y} = 1.28 + 748.57(0.78)^X$	27	10% to 24.4%
R vs M.C.	5 to 9	$\hat{Y} = 6.16 + 5281.67(0.63)^X$	31	10.3% to 26.5%
R vs M.C.	10 to 20	$\hat{Y} = 8.63 - 0.15X$	15	16.5% to 26%
M.C. vs O.M.C.	0 to 4	$\hat{Y} = -5.56 + 1.47X$	19	11% to 20.5%
M.C. vs O.M.C.	5 to 9	$\hat{Y} = -5.68 + 1.48X$	22	9.5% to 21.3%
M.C. vs O.M.C	10 to 20	$\hat{Y} = -18.13 + 2.44X$	12	14% to 18%

Notation:

G.I. = Group Index
M.C. = Moisture content at 300 psi exudation pressure
O.M.C. = Optimum moisture content

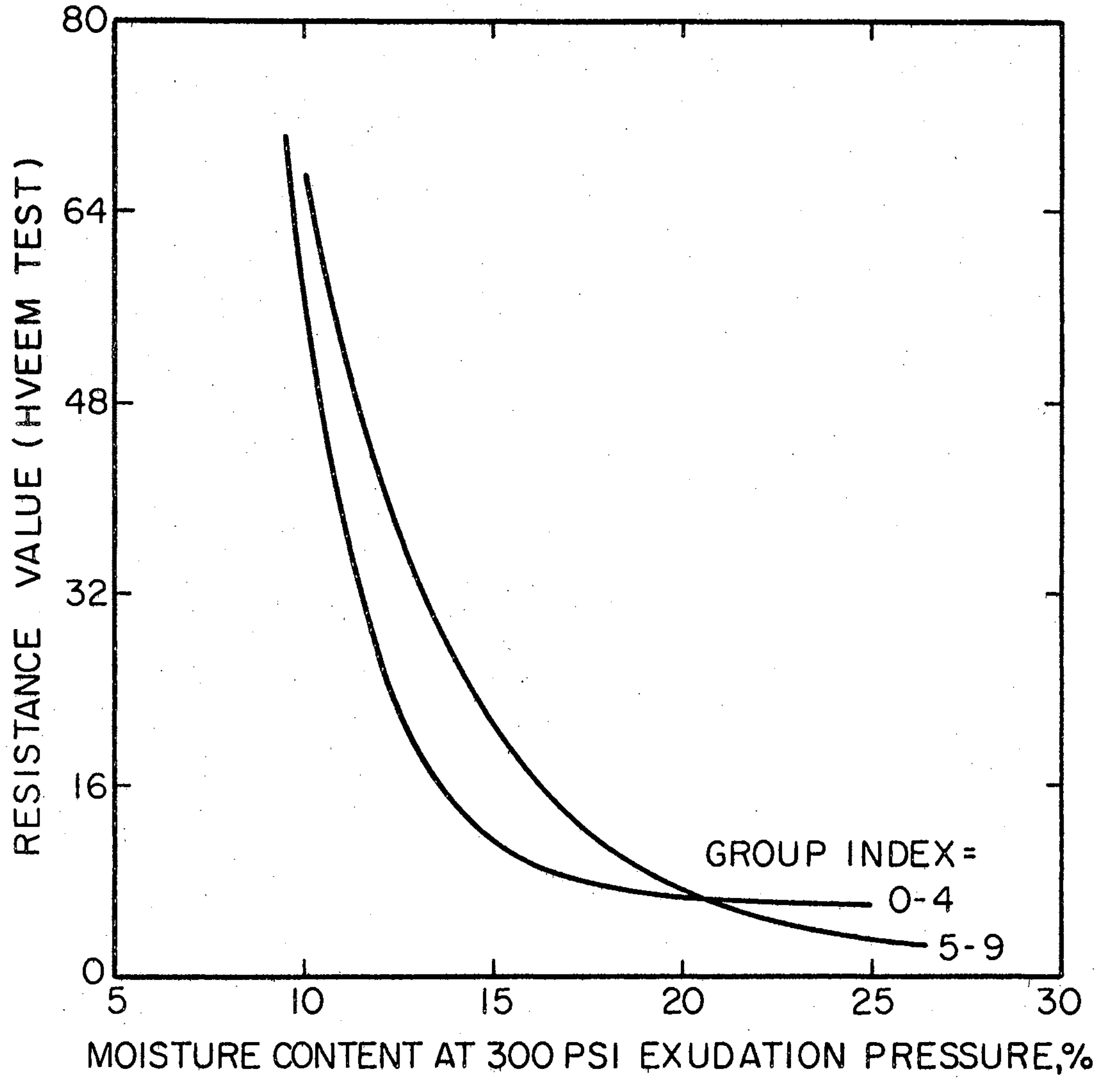

Figure 16. Estimated Curves for Soil Resistance Value Evaluation

relationships between the moisture content at 300 psi exudation pressure and optimum moisture content are shown in Fig. 17.

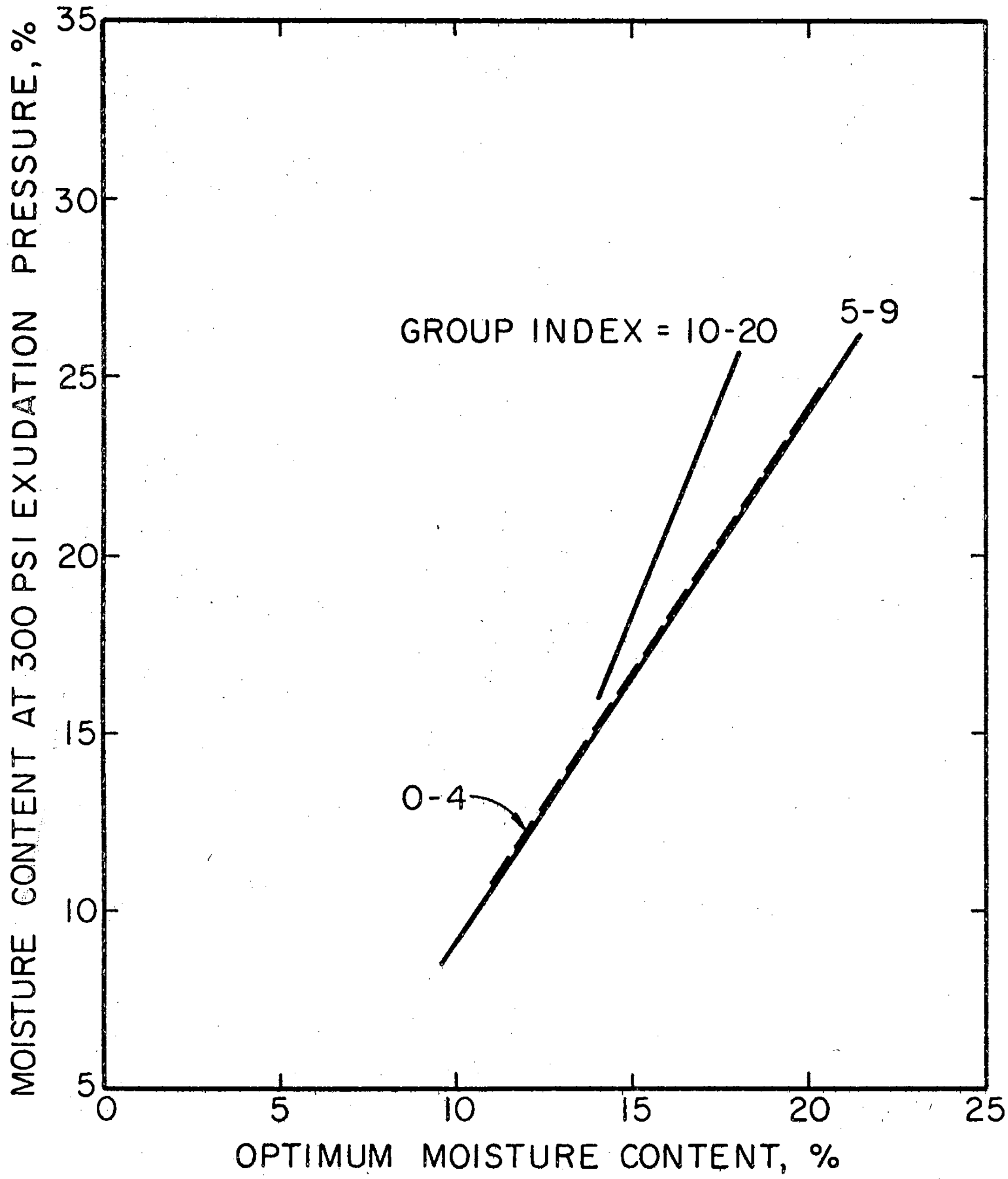

Figure 17. Estimated Curves for Evaluation of Moisture Content at 300 psi Exudation Pressure

CHAPTER VI

DISCUSSION

One must use caution in extending the soil resistance curves beyond the range of original data, shown in the last column of Table V, since the extrapolation of any curve obtained from this research gives a result which is not based upon the statistical evidence. The statistical analyses indicate only the relations which are within the range of the experiment observations, and within the confidence intervals for the established relations. Suppose a value of X (moisture content at 300 psi exudation pressure) which is less than 5% is taken to predict the resistance value on an extension of the curve. The resulting R-value would be greater than 100. This is an obvious contradiction to soil behavior. The extension of X to <u>large</u> values is an exception to the above. In this case, experience shows that soils do not gain strength by increasing the water content. Extension of the curve similarly predicts an R-value that is equal to 5.

The two substantially identical equations (4th and 5th) shown in Table V for predicting the moisture content at 300 psi exudation pressure should not be combined or used interchangeably since these two equations do not have similar confidence belts. As indicated in Table V, the fourth equation predicts the moisture in a narrower range of independent variable values than that of the fifth equation. In some instances, if the fifth equation were used for estimating the moisture content at 300 psi exudation pressure for soils with Group Index of 0 to 4, values outside the range of the fourth equation might be obtained. Thus unwarranted extrapolation might unwittingly result.

The curves developed during the course of this study for predicting the soil resistance value merely describe the mathematical expressions. Hence, the question of how the values of soil resistance approach an asymptote other than 5 can be explained mathematically. However, in soil behavior, the asymptote can only be 5. Therefore, in predicting the soil resistance at high water content, the values which are lower than 5 must be replaced by 5.

In applying the established equations to predict the R-value, one must make certain that the soil whose resistance value is being estimated is a plastic soil, since the materials used in this research were plastic embankment soils.

In addition to that mentioned in the last paragraph, the swelling characteristics of the plastic soils having high plasticity indices must be taken into consideration in pavement design. When soils of such type are used in highway embankments, the pavement thickness must be designed to withstand the expansion pressure of the soil.

It should be noticed from Tables II and III, that, for both soil groups, the standard deviations of the technical errors are more than 10% of the means and those of the experimental errors are more than 20% of the means. However, there is no information based on which the aforementioned percentages are to be judged as being outside the tolerant limits. The variation among the samples within the same value of moisture content (experimental error) has numerous sources. It is impossible to attempt to find every causation; but, based on the soil behavior theory, within the same classification of soil, resistance varies according to texture, gradation, shape of particles and other factors. Therefore, in order to account for some of these sources of variation, this research would ideally have been conducted in such a way that the grouping of soils would be based on many classification systems.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the analyses performed on the data observed in this research, the resistance value of a soil having a Group Index in the range from 0 to 9 may be predicted by the moisture content. Although the R-value of "poor" soils stays practically constant, as indicated by this study, the author does not intend to conclude that the "poor" soils in general cannot have higher resistance to deformation. The analysis herein is limited to the data obtained in this research. The paucity of soils which have a Group Index between 10 and 20 and low moisture content at 300 psi exudation pressure may be responsible for the narrow range of moisture contents. There is no evidence that it is impossible to obtain "poor" soils with moisture contents lower than 16.5% which corresponds to the lowest value of the moisture range of the third equation listed in Table V.

The linear regression analysis shows that the moisture content at 300 psi exudation pressure can be predicted by the optimum moisture content for the three types of soils studied in this research.

By utilizing those two types of functional relationships, one may estimate the soil resistance value by the soil optimum moisture content.

Recommendations

Although there is no evidence that the coefficients of variation of the experimental errors are large, the variation among the samples that have the same values of moisture content can be minimized by conducting this research in such a way that the classification of soils would be based on many systems. Within practical and economic limits, experiments may most feasibly be performed on the 20 soil groups which are categorized by the group index classification system.

For embankment compaction, tamping rollers are employed quite extensively. Pressures at the feet of the roller can be varied from less than 100 psi up to 1000 psi to meet the design requirements. Therefore, it would be desirable to conduct experiments similar to the one presented in this paper, but simulating different compaction efforts. This would provide a group of formulae for the use of engineers, whenever the design involving the use of special foot pressure appears to be more suitable. The principal hindrance to such an extensive investigation would be the consumption of testing materials.

The technique of the asymptotic regression analysis needs to be improved and developed so that the analysis of this type of research can provide more definite information concerning the estimates of sources of variation, e.g., the variations due to model, lack of fit, and the parameters α, β, and ρ.

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APPENDIX A

COMPUTER OUTPUTS FOR ASYMPTOTIC REGRESSION ANALYSIS - RESISTANCE VALUE VS. MOISTURE CONTENT AT 300 PSI EXUDATION PRESSURE

ANALYSIS OF "GOOD" SOILS

REGRESSION EQUATION

$$Y = A + B.R^{X}$$

PROBLEM CARD

PROBLEM CODE	R-PRD		
NO. OF X VALUES	22	INPUT PATTERN	XY
X RE-SCALED		SORT	YES
PRINT RESIDUALS	YES		
X TRANS CODE	0	OUTPUT DATA	YES
X CONSTANT	-0.0	VARIABLE FORMAT	1

THE VARIABLE FORMAT IS (F3.1,3F3.0)

ORIGINAL DATA

NO.	X VALUE	Y VALUE
1	13.7000	11.0000
2	24.4000	5.0000
3	15.0000	10.0000
4	12.0000	36.0000
5	12.0000	21.0000
6	17.2000	7.0000
7	13.2000	20.0000
8	10.0000	57.0000
9	12.0000	24.0000
9	12.0000	20.0000
10	10.8000	31.0000
11	10.0000	60.0000
11	10.0000	63.0000
11	10.0000	59.0000
12	13.5000	22.0000
13	21.8000	7.0000
14	12.8000	32.0000
15	14.5000	8.0000
16	13.3000	18.0000
17	12.7000	27.0000
18	12.3000	34.0000
19	11.0000	30.0000
19	11.0000	35.0000
20	13.0000	12.0000
20	13.0000	18.0000
21	21.5000	5.0000
22	13.5000	18.0000

FIT NO. 1

TRANSFORMATION CARD

CODE	CONSTANT	PASS NO.
0	-0.0	1

INITIAL ESTIMATE OF R= 0.7778

ITERATION NO.	A	B	R	SUM(E(Y)-MEAN(Y))**2
1	8.645752	***************	0.300816	724837.062500
2	12.814941	2737333.000000	0.357428	6044.117187
3	11.405762	480841.500000	0.419654	3695.151855
4	9.836914	99826.687500	0.484383	2101.923096
5	8.345215	26730.097656	0.545102	1172.514893
6	7.185547	10434.203125	0.592228	790.960449
7	6.510254	6375.542969	0.618374	697.982666
8	6.243652	5459.335937	0.627045	684.063965
9	6.174316	5307.226562	0.628747	682.261230
10	6.161621	5285.769531	0.629005	682.029785
11	6.159180	5281.781250	0.629053	681.988770
12	6.158936	5280.832031	0.629062	681.976563
13	6.158936	5281.953125	0.629053	681.994141
14	6.158691	5281.671875	0.629057	681.991699

INFORMATION MATRIX

27.00000000	0.09915543	1.78784847	Y(0)=	689.99975586
0.09915543	0.00061459	0.01041939	Y(1)=	3.85674763
1.78784847	0.01041939	0.17823964	Y(2)=	66.04293823

INVERSE OF INFORMATION MATRIX

0.25982487	253.08377075	-17.40075684	Y(0)=	689.99975586
253.08216858	428340.18750000	-27578.12109375	Y(1)=	3.85674763
-17.40066528	-27578.14453125	1792.28955078	Y(2)=	66.04293823

	FINAL ESTIMATES	STANDARD DEVIATIONS
A=	6.1587	2.9799
B=	5281.6719	3826.0591
R=	0.6291	0.0469

ANALYSIS OF VARIANCE

DEVIATIONS	SUM OF SQUARES
FROM MEAN	7806.6250
FROM X(I) MEANS	47.1667
FROM CURVE	820.2114
OF X(I) MEANS FROM CURVE	773.0447

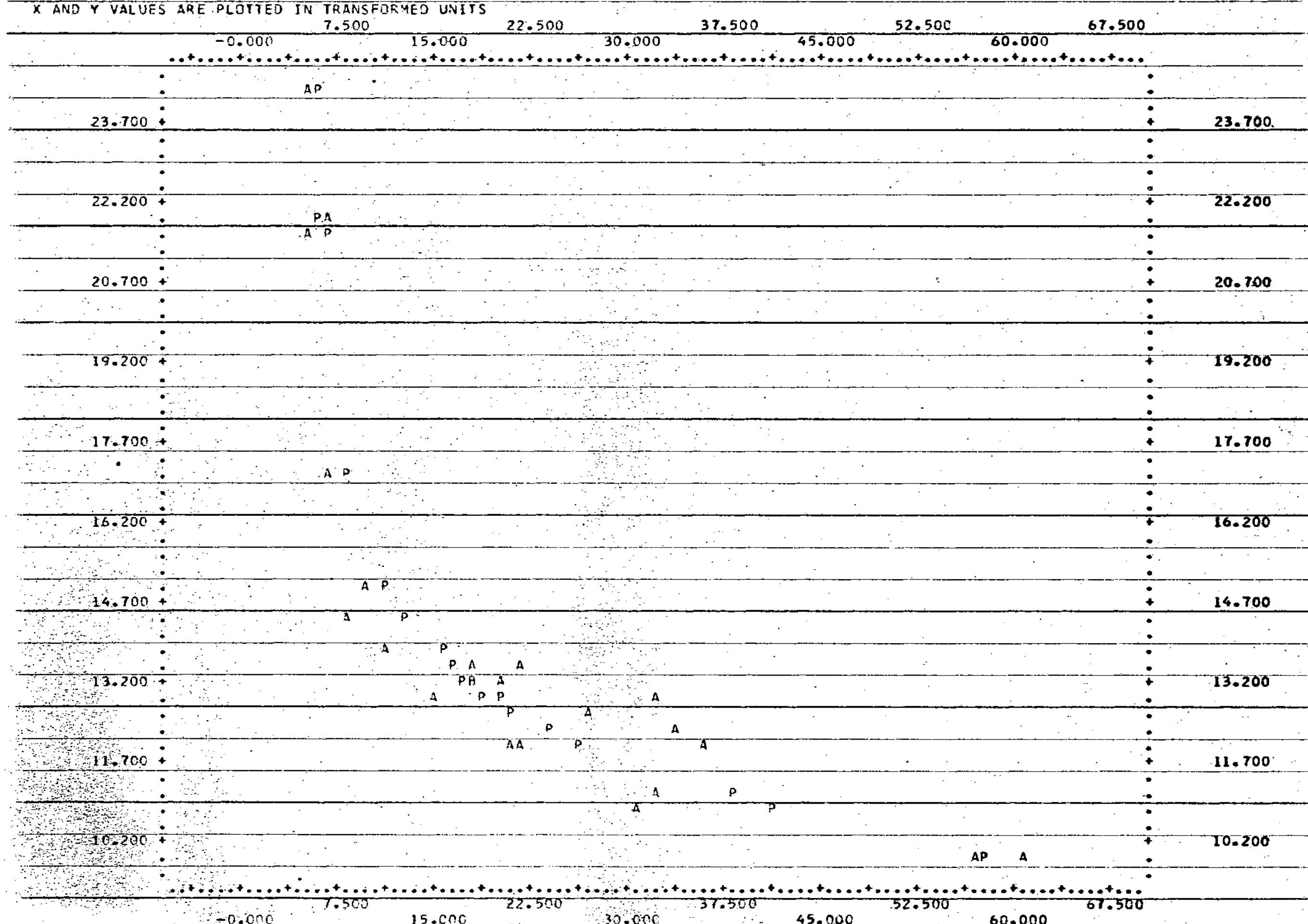
****

TABLE OF RESIDUALS

NO.	X VALUE	Y VALUE	Y PREDICTED	RESIDUAL
1	10.0000	57.0000	57.4056	-0.4056
2	10.0000	60.0000	57.4056	2.5944
2	10.0000	63.0000	57.4056	5.5944
2	10.0000	59.0000	57.4056	1.5944
3	10.8000	31.0000	41.5274	-10.5274
4	11.0000	30.0000	38.3959	-8.3959
4	11.0000	35.0000	38.3959	-3.3959
5	12.0000	21.0000	26.4377	-5.4377
6	12.0000	36.0000	26.4377	9.5623
7	12.0000	24.0000	26.4377	-2.4377
7	12.0000	20.0000	26.4377	-6.4377
8	12.3000	34.0000	23.8050	10.1950
9	12.7000	27.0000	20.8185	6.1815
10	12.8000	32.0000	20.1545	11.8455
11	13.0000	12.0000	18.9153	-6.9153
11	13.0000	18.0000	18.9153	-0.9153
12	13.2000	20.0000	17.7859	2.2141
13	13.3000	18.0000	17.2592	0.7408
14	13.5000	22.0000	16.2764	5.7236
15	13.5000	18.0000	16.2764	1.7236
16	13.7000	11.0000	15.3806	-4.3806
17	14.5000	8.0000	12.5233	-4.5233
18	15.0000	10.0000	11.2067	-1.2067
19	17.2000	7.0000	7.9794	-0.9794
20	21.5000	5.0000	6.4068	-1.4068
21	21.8000	7.0000	6.3746	0.6254
22	24.4000	5.0000	6.2234	-1.2234

GRAPH CODES A=AVERAGED Y P=PREDICTED Y B=BOTH

X AND Y VALUES ARE PLOTTED IN TRANSFORMED UNITS



ANALYSIS OF "FAIR" SOILS

REGRESSION EQUATION

$$Y = A + B.R^{X}$$

PROBLEM CARD

PROBLEM CODE	R-PRD		
NO. OF X VALUES	26	INPUT PATTERN	XY
X RE-SCALED		SORT	YES
PRINT RESIDUALS	YES		
X TRANS CODE	0	OUTPUT DATA	YES
X CONSTANT	-0.0	VARIABLE FORMAT	1

THE VARIABLE FORMAT IS (F3.1,3F3.0)

ORIGINAL DATA

NO.	X VALUE	Y VALUE
1	10.3000	56.0000
1	10.3000	59.0000
2	12.1000	35.0000
3	11.5000	60.0000
4	13.0000	30.0000
4	13.0000	35.0000
5	15.0000	26.0000
5	15.0000	23.0000
6	16.0000	18.0000
6	16.0000	16.0000
7	13.8000	33.0000
8	22.2000	5.0000
9	14.7000	20.0000
10	17.4000	7.0000
11	19.3000	5.0000
12	12.6000	34.0000
13	15.7000	15.0000
14	26.5000	5.0000
15	21.0000	6.0000
16	16.6000	12.0000
17	22.1000	5.0000
18	14.7000	18.0000
19	11.5000	50.0000
19	11.5000	54.0000
20	26.0000	6.0000
21	16.2000	11.0000
22	24.0000	5.0000
23	14.9000	30.0000
24	23.0000	5.0000
25	15.0000	16.0000
26	20.2000	5.0000

FIT NO. 1

TRANSFORMATION CARD

CODE	CONSTANT	PASS NO.
0	-0.0	1

INITIAL ESTIMATE OF R= 0.7431

ITERATION NO.	A	B	R	SUM(E(Y)-MEAN(Y))**2
1	1.247803	869.283936	0.777754	538.538330
2	1.204834	744.261230	0.785154	523.862549
3	1.289307	749.542725	0.784439	523.476074
4	1.279297	748.396729	0.784557	523.587646
5	1.281006	748.634521	0.784533	523.562256
6	1.280518	748.569092	0.784538	523.569336

INFORMATION MATRIX

31.00000000	0.88873595	15.08651543	Y(0)=	705.00000000
0.88873595	0.04158740	0.64009422	Y(1)=	32.27009583
15.08651543	0.64009422	10.08978081	Y(2)=	498.48803711

INVERSE OF INFORMATION MATRIX

0.27212703	18.98107910	-1.61104774	Y(0)=	705.00000000
18.98106384	2344.43481445	-177.11161804	Y(1)=	32.27009583
-1.61104774	-177.11161804	13.74392796	Y(2)=	498.48803711

	FINAL ESTIMATES	STANDARD DEVIATIONS
A=	1.2805	2.4524
B=	748.5691	227.6275
R=	0.7845	0.0233

ANALYSIS OF VARIANCE

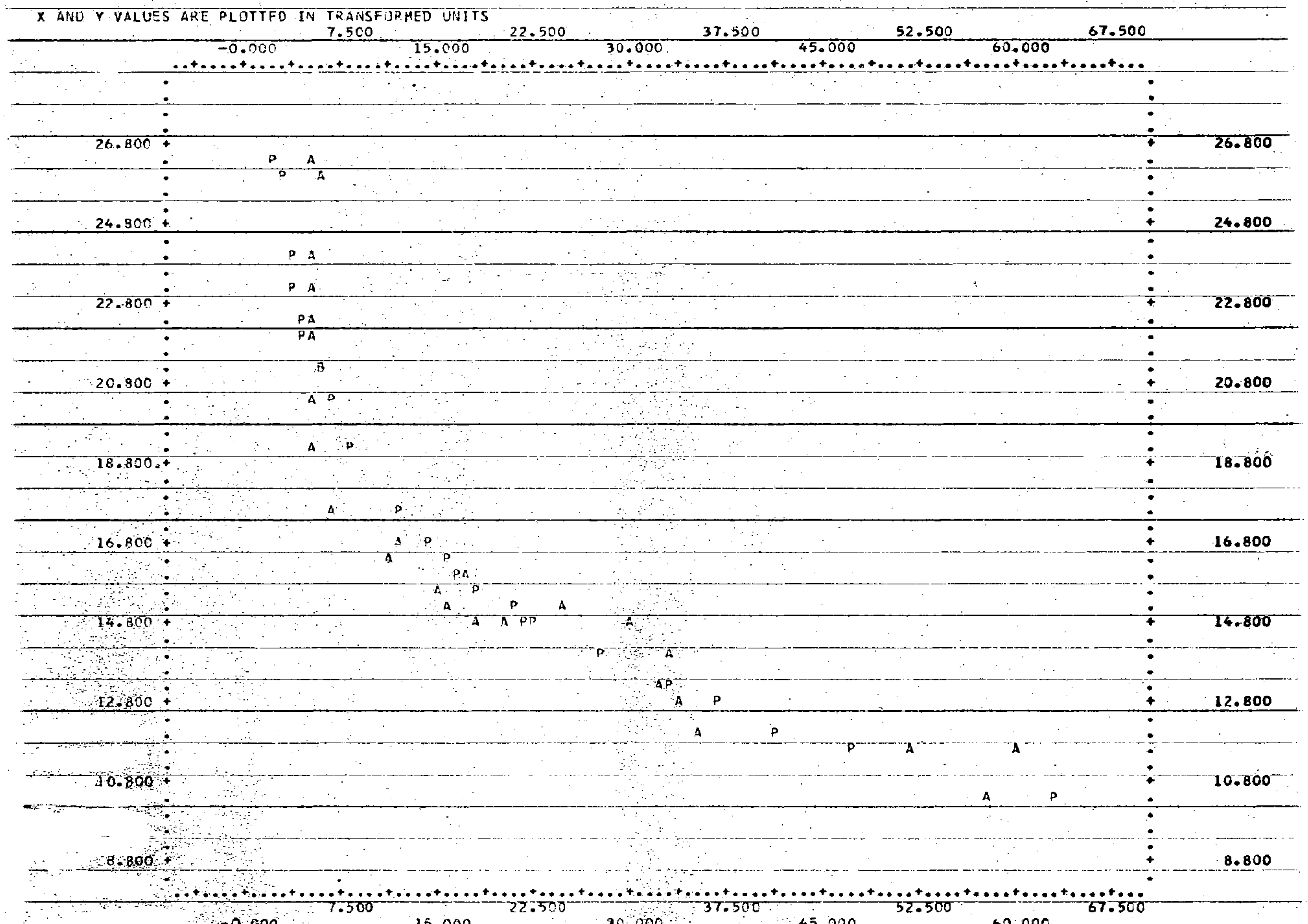
DEVIATIONS	SUM OF SQUARES
FROM MEAN	9645.8711
FROM X(I) MEANS	31.5000
FROM CURVE	618.8274
OF X(I) MEANS FROM CURVE	587.3279

TABLE OF RESIDUALS

NO.	X VALUE	Y VALUE	Y PREDICTED	RESIDUAL
1	10.3000	56.0000	62.7634	-6.7634
1	10.3000	59.0000	62.7634	-3.7634
2	11.5000	60.0000	47.2310	12.7690
3	11.5000	50.0000	47.2310	2.7690
3	11.5000	54.0000	47.2310	6.7690
4	12.1000	35.0000	41.0051	-6.0051
5	12.6000	34.0000	36.4662	-2.4662
6	13.0000	30.0000	33.2114	-3.2114
6	13.0000	35.0000	33.2114	1.7886
7	13.8000	33.0000	27.5773	5.4227
8	14.7000	18.0000	22.4180	-4.4180
9	14.7000	20.0000	22.4180	-2.4180
10	14.9000	30.0000	21.4167	8.5833
11	15.0000	26.0000	20.9340	5.0660
11	15.0000	23.0000	20.9340	2.0660
12	15.0000	16.0000	20.9340	-4.9340
13	15.7000	15.0000	17.8637	-2.8637
14	16.0000	18.0000	16.6994	1.3006
14	16.0000	16.0000	16.6994	-0.6994
15	16.2000	11.0000	15.9690	-4.9690
16	16.6000	12.0000	14.6103	-2.6103
17	17.4000	7.0000	12.2582	-5.2582
18	19.3000	5.0000	8.2033	-3.2033
19	20.2000	5.0000	6.8451	-1.8451
20	21.0000	6.0000	5.8632	0.1368
21	22.1000	5.0000	4.7896	0.2104
22	22.2000	5.0000	4.7055	0.2945
23	23.0000	5.0000	4.1012	0.8988
24	24.0000	5.0000	3.4934	1.5066
25	26.0000	6.0000	2.6426	3.3574
26	26.5000	5.0000	2.4869	2.5131

GRAPH CODES A=AVERAGED Y P=PREDICTED Y B=BOTH

X AND Y VALUES ARE PLOTTED IN TRANSFORMED UNITS



APPENDIX B

EXAMPLE FOR COMPUTATION OF SUM OF SQUARES

EXAMPLE FOR COMPUTATION OF SUM OF SQUARES

Observed Data from Stabilometer Test (G.I. = 0 - 4)

Sample No.	No. of Replicates	X (Moisture Content)	Y (R-value)
1	1	13.7	11.0
2	1	24.4	5.0
3	1	15.0	10.0
4	1	12.0	36.0
5	1	12.0	21.0
6	1	17.2	7.0
7	1	13.2	20.0
8	1	10.0	57.0
9	2	12.0	24.0,20.0
10	1	10.8	31.0
11	3	10.0	60.0,63.0,59.0
12	1	13.5	22.0
13	1	21.8	7.0
14	1	12.8	32.0
15	1	14.5	8.0
16	1	13.3	18.0
17	1	12.7	27.0
18	1	12.3	34.0
19	2	11.0	30.0, 35.0
20	2	13.0	12.0, 18.0
21	1	21.5	5.0
22	1	13.5	18.0

R-Values at Same Moisture Content

X	Sample No.	No. of Replicates	Y
12.0	4	1	36.0
	5	1	21.0
	9	2	24.0,20.0
10.0	8	3	57.0
	11	3	60.0,63.0,59.0
13.5	12	1	22.0
	22	1	18.0

Procedure for Computation

1. Total SS = $11.0^2 + 5.0^2 + . . . + 18.0^2$

2. Mean SS = $(11.0 + 5.0 + . . . + 18.0)^2/27$

3. Total SS (corrected) = Total SS - Mean SS

4. Experimental Error SS = $36^2 + 21^2 + \frac{(24 + 20)^2}{2} - \frac{(36+21+24+20)^2}{4}$

$$+ 57^2 + \frac{(60+63+59)^2}{3} - \frac{(57+60+63+59)^2}{4}$$

$$+ 22^2 + 18^2 - \frac{(22 + 18)^2}{2}$$

5. Technical Error SS = $24^2 + 20^2 - \frac{(24 + 20)^2}{2}$

$$+ 60^2 + 63^2 + 59^2 - \frac{(60 + 63 + 59)^2}{3}$$

$$+ 30^2 + 35^2 - \frac{(30 + 35)^2}{2}$$

$$+ 12^2 + 18^2 - \frac{(12 + 18)^2}{2}$$

6. Residual SS = Total SS (corr.) - Exp. error SS - Technical Error SS

7. Deviation from curve SS = obtained from the regression analysis (See Appendix A)

8. Due to model SS = Total SS (corr.) - Dev. from curve SS

9. Lack of fit SS = Residual SS - Due to Model SS

APPENDIX C

COMPUTER OUTPUTS FOR LINEAR REGRESSION

ANALYSIS - RESISTANCE VALUE VS.

MOISTURE CONTENT AT 300 PSI

EXUDATION PRESSURE

ANALYSIS OF "POOR" SOILS

```
MULTIPLE LINEAR REGRESSION
OKLAHOMA STATE UNIVERSITY (APRIL,1969)
A VERSION OF THE REGRESSION PROGRAM CONTAINED,
IN IBM'S SYSTEM/360 SCIENTIFIC SUBROUTINE PACKAGE.

PROBLEM CODE...........................R-MC
NUMBER OF VARIABLES....................     2
DATA INPUT ON.......................... CARDS
NUMBER OF VARIABLE FORMAT CARDS........     1
THE FOLLOWING FORMAT WILL BE USED IN READING THE INPUT DATA FOR THIS PROBLEM.
(F3.1,F2.0)

NUMBER OF OBSERVATIONS.................    15
```

INPUT TO MULTIPLE REGRESSION
PROBLEM CODE....R-MC

OBSERVATION	VARIABLE INDEX	
	1	2
1	16.500000	5.000000
2	22.399994	5.000000
3	24.599991	5.000000
4	22.500000	6.000000
5	24.000000	5.000000
6	21.699997	5.000000
7	26.000000	5.000000
8	25.000000	5.000000
9	16.899994	8.000000
10	19.799988	7.000000
11	24.000000	5.000000
12	24.000000	5.000000
13	21.000000	5.000000
14	17.500000	5.000000
15	24.000000	5.000000

MULTIPLE REGRESSION

PROBLEM CODE....R-MC

MODEL 1 OF THE SELECTION CODED 'GI1020'

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	5.00000	6.20585	-1.20585
2	5.00000	5.34034	-0.34034
3	5.00000	5.01761	-0.01761
4	6.00000	5.32567	0.67433
5	5.00000	5.10563	-0.10563
6	5.00000	5.44303	-0.44303
7	5.00000	4.81223	0.18777
8	5.00000	4.95893	0.04107
9	8.00000	6.14718	1.85282
10	7.00000	5.72176	1.27824
11	5.00000	5.10563	-0.10563
12	5.00000	5.10563	-0.10563
13	5.00000	5.54572	-0.54572
14	5.00000	6.05916	-1.05916
15	5.00000	5.10563	-0.10563

MATRIX OF CORRELATION COEFFICIENTS
PROBLEM CODE...R-MC

2 ROWS 2 COLUMNS

COLUMN	1	2
ROW 1	1.000000	-0.492244
ROW 2	-0.492244	1.000000

MATRIX OF SUMS OF CROSS-PRODUCTS OF DEVIATIONS FROM MEAN
PROBLEM CODE...R-MC

2 ROWS 2 COLUMNS

COLUMN	1	2
ROW 1	0.130609E 03	-0.191600E 02
ROW 2	-0.191600E 02	0.116000E 02

MULTIPLE REGRESSION

PROBLEM CODE....R-MC

MODEL 1 OF THE SELECTION CODED 'GI1020'

NUMBER OF OBSERVATIONS............ 15

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	21.99332	3.05438	-0.49224	-0.14670	0.07195	-2.03894
DEPENDENT 2	5.40000	0.91026				

INTERCEPT 8.62636

MULTIPLE CORRELATION 0.49224

STD. ERROR OF ESTIMATE 0.82225

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	1	2.81072	2.81072	4.15727
DEVIATION FROM REGRESSION	13	8.78928	0.67610	
TOTAL	14	11.60000		

APPENDIX D

COMPUTER OUTPUTS FOR LINEAR REGRESSION ANALYSIS - MOISTURE CONTENT AT 300 PSI EXUDATION PRESSURE VS. OPTIMUM MOISTURE CONTENT

ANALYSIS OF "GOOD" SOILS

MULTIPLE LINEAR REGRESSION
OKLAHOMA STATE UNIVERSITY (APRIL,1969)
A VERSION OF THE REGRESSION PROGRAM CONTAINED,
IN IBM'S SYSTEM/360 SCIENTIFIC SUBROUTINE PACKAGE.

PROBLEM CODE..........................MC-OMC
NUMBER OF VARIABLES..................... 2
DATA INPUT ON.......................... CARDS
NUMBER OF VARIABLE FORMAT CARDS........ 1
THE FOLLOWING FORMAT WILL BE USED IN READING THE INPUT DATA FOR THIS PROBLEM.
(F3.1,F4.1)

NUMBER OF OBSERVATIONS................. 19

INPUT TO MULTIPLE REGRESSION
PROBLEM CODE....MC-OMC

OBSERVATION	VARIABLE INDEX 1	2
1	13.200000	13.700000
2	20.500000	24.399994
3	13.500000	15.000000
4	12.000000	12.000000
5	11.500000	12.000000
6	15.500000	17.199997
7	13.000000	13.200000
8	11.000000	10.000000
9	12.000000	12.000000
10	11.000000	10.799999
11	18.500000	21.799988
12	12.400000	12.799999
13	14.000000	14.500000
14	14.000000	13.299999
15	12.799999	13.200000
16	11.799999	12.299999
17	11.000000	11.000000
18	12.000000	13.000000
19	17.500000	21.500000

MULTIPLE REGRESSION

PROBLEM CODE....MC-OMC

MODEL 1 OF THE SELECTION CODED 'GI 0-4'

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	13.70000	13.90856	-0.20856
2	24.39999	24.67281	-0.27281
3	15.00000	14.35093	0.64907
4	12.00000	12.13910	-0.13910
5	12.00000	11.40183	0.59817
6	17.20000	17.30003	-0.10004
7	13.20000	13.61365	-0.41365
8	10.00000	10.66454	-0.66454
9	12.00000	12.13910	-0.13910
10	10.80000	10.66454	0.13546
11	21.79999	21.72371	0.07628
12	12.80000	12.72892	0.07108
13	14.50000	15.08822	-0.58822
14	13.30000	15.08822	-1.78822
15	13.20000	13.31875	-0.11875
16	12.30000	11.84418	0.45582
17	11.00000	10.66454	0.33546
18	13.00000	12.13910	0.86090
19	21.50000	20.24915	1.25085

MATRIX OF CORRELATION COEFFICIENTS
PROBLEM CODE...MC-OMC

2 ROWS 2 COLUMNS

COLUMN	1	2
ROW 1	1.000000	0.986419
ROW 2	0.986419	1.000000

MATRIX OF SUMS OF CROSS-PRODUCTS OF DEVIATIONS FROM MEAN
PROBLEM CODE...MC-OMC

2 ROWS 2 COLUMNS

COLUMN	1	2
ROW 1	0.128904E 03	0.190076E 03
ROW 2	0.190076E 03	0.288048E 03

MULTIPLE REGRESSION

PROBLEM CODE....MC-OMC

MODEL 1 OF THE SELECTION CODED 'GI 0-4'

NUMBER OF OBSERVATIONS............ 19

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	13.53684	2.67606	0.98642	1.47456	0.05955	24.76166
DEPENDENT 2	14.40525	4.00033				

INTERCEPT -5.55555

MULTIPLE CORRELATION 0.98642

STD. ERROR OF ESTIMATE 0.67610

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	1	280.27734	280.27734	613.14063
DEVIATION FROM REGRESSION	17	7.77100	0.45712	
TOTAL	18	288.04834		

ANALYSIS OF "FAIR" SOILS

```
MULTIPLE LINEAR REGRESSION
OKLAHOMA STATE UNIVERSITY (APRIL,1969)
A VERSION OF THE REGRESSION PROGRAM CONTAINED,
IN IBM'S SYSTEM/360 SCIENTIFIC SUBROUTINE PACKAGE.

PROBLEM CODE..........................MC-OMC
NUMBER OF VARIABLES...................   2
DATA INPUT ON......................... CARDS
NUMBER OF VARIABLE FORMAT CARDS........  1
THE FOLLOWING FORMAT WILL BE USED IN READING THE INPUT DATA FOR THIS PROBLEM.
(F3.1,F4.1)

NUMBER OF OBSERVATIONS................  22
```

INPUT TO MULTIPLE REGRESSION
PROBLEM CODE....MC-OMC

OBSERVATION	VARIABLE INDEX	
	1	2
1	9.500000	10.299999
2	11.500000	12.099999
3	12.400000	11.500000
4	13.000000	13.000000
5	12.900000	15.000000
6	15.000000	16.000000
7	13.200000	13.799999
8	16.000000	22.199997
9	13.000000	14.700000
10	16.000000	17.399994
11	18.399994	19.299988
12	13.500000	12.599999
13	15.000000	15.700000
14	21.299988	26.500000
15	18.500000	21.000000
16	15.000000	16.599991
17	18.000000	22.099991
18	15.000000	14.700000
19	12.500000	11.500000
20	20.500000	26.000000
21	14.000000	15.000000
22	17.000000	20.199997

MULTIPLE REGRESSION

PROBLEM CODE....MC-OMC

MODEL 1 OF THE SELECTION CODED 'GI 5-9'

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	10.30000	8.43769	1.86231
2	12.10000	11.40938	0.69062
3	11.50000	12.74664	-1.24664
4	13.00000	13.63814	-0.63814
5	15.00000	13.48956	1.51044
6	16.00000	16.60983	-0.60983
7	13.80000	13.93532	-0.13532
8	22.20000	18.09569	4.10431
9	14.70000	13.63814	1.06186
10	17.39999	18.09569	-0.69569
11	19.29999	21.66170	-2.36171
12	12.60000	14.38107	-1.78107
13	15.70000	16.60983	-0.90983
14	26.50000	25.97064	0.52936
15	21.00000	21.81029	-0.81029
16	16.59999	16.60983	-0.00984
17	22.09999	21.06737	1.03262
18	14.70000	16.60983	-1.90983
19	11.50000	12.89522	-1.39522
20	26.00000	24.78198	1.21802
21	15.00000	15.12399	-0.12399
22	20.20000	19.58153	0.61847

MATRIX OF CORRELATION COEFFICIENTS
PROBLEM CODE...MC-OMC

2 ROWS 2 COLUMNS

COLUMN	1	2
ROW 1	1.000000	0.947441
ROW 2	0.947441	1.000000

MATRIX OF SUMS OF CROSS-PRODUCTS OF DEVIATIONS FROM MEAN
PROBLEM CODE...MC-OMC

2 ROWS 2 COLUMNS

COLUMN	1	2
ROW 1	0.183094E 03	0.272050E 03
ROW 2	0.272050E 03	0.450318E 03

MULTIPLE REGRESSION

PROBLEM CODE....MC-OMC

MODEL 1 OF THE SELECTION CODED 'GI 5-9'

NUMBER OF OBSERVATIONS............. 22

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	15.05454	2.95276	0.94744	1.48585	0.11219	13.24369
DEPENDENT 2	16.69087	4.63073				

INTERCEPT	-5.67784
MULTIPLE CORRELATION	0.94744
STD. ERROR OF ESTIMATE	1.51811

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	1	404.22461	404.22461	175.39520
DEVIATION FROM REGRESSION	20	46.09302	2.30465	
TOTAL	21	450.31763		

ANALYSIS OF "POOR" SOILS

MULTIPLE LINEAR REGRESSION
OKLAHOMA STATE UNIVERSITY (APRIL,1969)
A VERSION OF THE REGRESSION PROGRAM CONTAINED,
IN IBM'S SYSTEM/360 SCIENTIFIC SUBROUTINE PACKAGE.

PROBLEM CODE..........................MC-OMC
NUMBER OF VARIABLES...................   2
DATA INPUT ON......................... CARDS
NUMBER OF VARIABLE FORMAT CARDS........   1
THE FOLLOWING FORMAT WILL BE USED IN READING THE INPUT DATA FOR THIS PROBLEM.
(F3.1,F4.1)

NUMBER OF OBSERVATIONS................   12

INPUT TO MULTIPLE REGRESSION
PROBLEM CODE....MC-OMC

OBSERVATION	VARIABLE INDEX	
	1	2
1	14.000000	16.500000
2	16.000000	22.399994
3	17.500000	24.599991
4	17.000000	22.500000
5	16.000000	21.699997
6	18.000000	26.000000
7	18.000000	25.000000
8	15.000000	16.899994
9	15.599999	19.799988
10	15.500000	21.000000
11	15.400000	17.500000
12	17.000000	24.000000

MULTIPLE REGRESSION

PROBLEM CODE....MC-OMC

MODEL 1 OF THE SELECTION CODED 'GI1020'

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	16.50000	16.00609	0.49391
2	22.39999	20.88219	1.51781
3	24.59999	24.53925	0.06075
4	22.50000	23.32022	-0.82022
5	21.70000	20.88219	0.81781
6	26.00000	25.75827	0.24173
7	25.00000	25.75827	-0.75827
8	16.89999	18.44414	-1.54414
9	19.79999	19.90695	-0.10696
10	21.00000	19.66316	1.33684
11	17.50000	19.41936	-1.91936
12	24.00000	23.32022	0.67978

MATRIX OF CORRELATION COEFFICIENTS
PROBLEM CODE...MC-OMC

2 ROWS 2 COLUMNS

COLUMN	1	2
ROW 1	1.000000	0.942714
ROW 2	0.942714	1.000000

MATRIX OF SUMS OF CROSS-PRODUCTS OF DEVIATIONS FROM MEAN
PROBLEM CODE...MC-OMC

2 ROWS 2 COLUMNS

COLUMN	1	2
ROW 1	0.172700E 02	0.421050E 02
ROW 2	0.421050E 02	0.115509E 03

MULTIPLE REGRESSION

PROBLEM CODE....MC-OMC

MODEL 1 OF THE SELECTION CODED 'GI1020'

NUMBER OF OBSERVATIONS............ 12

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	16.24998	1.25300	0.94271	2.43805	0.27283	8.93618
DEPENDENT 2	21.49165	3.24050				

INTERCEPT	-18.12656
MULTIPLE CORRELATION	0.94271
STD. ERROR OF ESTIMATE	1.13380

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	1	102.65405	102.65405	79.85519
DEVIATION FROM REGRESSION	10	12.85503	1.28550	
TOTAL	11	115.50908		

VITA

Samuel Yu-Wai Ng

Candidate for the Degree of

Doctor of Philosophy

Thesis: EVALUATION OF PLASTIC SOIL RESISTANCE TO DEFORMATION

Major Field: Engineering

Biographical:

Personal Data: Born in Hong Kong, October 21, 1940, the son of Fok-Man and Kwok-Ching Ng.

Education: Graduated from Chui-Hai College, Kowloon, Hong Kong in 1958; received the Bachelor of Science degree from Hong Kong Baptist College, with a major in Civil Engineering, in June, 1962; received the Master of Science degree from the University of Mississippi, with a major in Civil Engineering, in January, 1965; completed requirements for the Doctor of Philosophy degree in May, 1970.

Professional Experience: Teaching Assistant and Instructor at Hong Kong Baptist College, with teaching duties in Soil Mechanics and Materials of Construction Laboratory, Engineering Drawing and surveying, 1962-1963; graduate research assistant at the University of Mississippi, performing investigation on the behavior of continuously reinforced concrete pavement structures, 1963-1965; research assistant at Engineering Experiment Station, University, Mississippi, 1965; graduate assistant at Oklahoma State University, performing research on AASHO Road Test Equations, 1965-1969, and computer application to Civil Engineering problems, 1969-1970.

Professional Societies: Associate member of the American Society of Civil Engineers; member of the Engineering Institute of Canada and Association for Computing Machinery.