SETTLEMENT OF TERRACES CONSTRUCTED ON
TWO IOWA SOILS

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INTRODUCTION

Terraces as a Soil Conservation Practice

The problem of preventing erosion caused by the forces of runoff water on the sloping agricultural lands of the United States has confronted agriculturalists since the native vegetation was destroyed. Many methods have been devised to combat these forces, some of which offer a greater degree of protection than others. In general they can be divided into two major categories. One group includes agronomic practices such as proper land use, utilization of grasses and legumes in the rotation, fertilizing and liming, and many other such methods. The other group includes mechanical methods such as contouring, terracing, waterways, ponds, and detention reservoirs. Only in rare circumstances can any one of these practices adequately control erosion, a combination of practices usually being required. Also more intensive use of the land for increased production of food requires an increase in the use of the conservation practices as well as a greater care and precaution in their use.

Terraces are one of the mechanical methods that fit into a farm conservation plan. They are a very important portion of the water disposal system on cultivated hillsides.

At the Conservation Experiment Station, Bethany, Missouri, Smith and others (27, p. 5) stated that, "Terraces have proved to be the most effective supporting conservation practice on the station."

The development of terraces can be traced through many periods of trial and error. Hall (10) discusses the stages of development of terraces previous to and including the broadbase channel-type terrace as developed by P. H. Mangum at Wake Forest, North Carolina. This broadbase channel-type terrace is in use today with modifications to suit the various demands of specific localities. Benedict (2) gives a history of terracing in Iowa, outlining its development from about 1926 when the first terraces were constructed to 1948 when 8,780 miles of terraces had been built in the state.

Settlement as a Factor in Effective Terrace Construction

As progress is made in the design of terraces to adequately serve the purpose of soil conservation, many factors arise which require a scientific approach to more adequately determine the requirements of such terraces. Guy (9) made a study of the design of level terraces as affected by hydrologic factors. As further progress is made in this respect, the need for an adequate terrace at the time of construction increases in importance.

The importance of adequate terraces has been stressed time and time again by different investigators. Investigating the possibility of small size terraces, Holman (13, p. 7) found that

Terraces one-fourth and one-half size have proven entirely unsatisfactory even with excess grades of 8 in. in 100 ft. and permanent meadow cover. Terraces of this type whose original dimensions were 8 ft. in width, 8 in. in height, and which had a uniform grade of 8 in. in 100 ft. lost their effectiveness almost completely in a period of three years during which their average height decreased to less than 4 in. and their cross-sectional area decreased to less than 1.3 sq. ft.

A study of the effect of terraces on corn yields was made by Zingg and Whitt (34). They found that corn yields were reduced in the terrace channel because of the thin layer of topsoil. The corn yield was directly related to the depth of top soil up to a certain point. Clark and Wooley (4) stated that a layer of good productive soil will accumulate in the channel if frequent rebuilding is not required. Therefore, adequate construction which would help to reduce frequent rebuilding is important in any terrace system.

Frequent rebuilding of terraces must be distinguished from normal maintenance. Normal maintenance simply replaces soil in its original position on the terrace ridge. Frequent rebuilding removes soil from the channel area in an amount that leaves only subsoil for the root zone.

Hermesmeier (12) in evaluating the performance of different machines in the construction of terraces found that a prediction of the change or the settlement of terraces was necessary in order to properly evaluate the advantages and disadvantages of each machine. Cost comparisons of the different machines could not be made without a prediction of settlement.

Construction of adequate terraces is important. A terrace built to specifications with no allowance for settlement could be inadequate after settlement. The damage from one intense rain could then cause the entire water disposal system to become inoperative. On the other hand, if very large terraces are built the cost of building will be increased and farming operations hindered. Therefore, a knowledge of the settlement of terraces following construction is imperative if (a) adequate terraces are to be constructed to specific design specifications, (b) if the evaluation of efficiency in constructing terraces is to be attempted, or (c) if frequent rebuilding is to be reduced to prevent the periodic covering of excessive fertile soil on terraced land.

REVIEW OF LITERATURE

Present Practices of Checking Terraces

Terraces should be checked with respect to grade and capacity immediately following construction, not only in order to prevent the disastrous results of a possible intense rain but also because additional building can be done more economically while the machine is in the field. Specifications for grade, capacity, and shape have been developed for different areas and regions, and there is general agreement among engineers as to the size of a settled terrace.

Field engineers use several methods of checking terraces to determine if specifications have been met and if suitable allowance for settlement has been made. While the grade variation may be determined directly, the capacity is usually determined after an estimate of the future settlement is made. In order to estimate the settlement, some engineers use their past experience. Others require the tractor or other machine used in building the terrace to drive across the terrace. Measurements are then made in the tracks. In many cases terraces are built excessively large to allow for settlement. If the terrace is too large natural deterioration

of the terrace ridge may be allowed until the desired size is obtained. Such a practice is definitely not economical and causes unnecessary hinderance to farming operations. Still other contractors and farmers follow the recommendation of Clark and Wooley (4) who stated that it was more economical to build terraces with the moldboard plow by building the base of the terrace ridge one year and completing the ridge of the terrace the following year, assuming settlement to then be complete. This practice presents an unnecessary hazard as one heavy rain can make the entire water disposal system ineffective.

Previous Work on Settlement of Terraces

The only previous work available on the investigation of the settlement of terraces was carried out by Hermsmier (12) in connection with the performance of five types of machines used in terrace construction in western Iowa. He found that a knowledge of settlement was necessary in order to evaluate the different machines. Hermsmier's approach to the problem was to take core samples both in the newly constructed terrace ridge and in the undisturbed area adjacent to the terrace. The apparent specific gravity was determined for each. The ratio of the apparent specific gravity of the soil in the terrace ridge immediately after construction

into the apparent specific gravity of the undisturbed soil in the immediate vicinity was called the index of compaction.

Table 1 as presented by Hermsmier (12, p. 84) gives the average index of compaction. These indexes were based on a set of six pairs of samples taken on each of two terraces constructed with each type of equipment.

Table 1
Average Index of Compactness¹

Equipment	Ratio of apparent specific gravity	Confidence limits	
		.05	.01
Moldboard plow	1.05	1.13 - 0.97	1.17 - 0.94
Whirlwind terracer	1.28	1.37 - 1.19	1.41 - 1.15
Bulldozer	1.17	1.28 - 1.06	1.33 - 1.02
Motor Patrol	1.01	1.10 - 0.92	1.14 - 0.88
Elevating grader A	1.31	1.40 - 1.23	1.44 - 1.19

¹ Table reproduced from Hermsmier (12, p. 84).

The index of compactness was interpreted by Hermsmier (12, p. 84, 91) by the following example:

The index of compactness of 1.05 for the moldboard plow indicates that the undisturbed soil has an apparent specific gravity 1.05 times as much as the apparent specific gravity of the soil in the terrace ridge, indicating that the soil in the terrace ridge is not as compact as the

undisturbed soil. Assuming the soil in the terrace ridge will settle until it resumes its original apparent specific gravity, this soil will reduce in volume $\frac{1.05 - 1.00}{1.05} = 4.76$ per cent.

In reference to the compaction by the different machines, Hermismier (12) stated that when the soil was pushed, carried, or thrown on to the terrace ridge and not compacted by the equipment during construction, the index of compaction was about the same irrespective of the type of equipment used or the method of moving the soil. He also stated that the index of compaction averaged about 1.00 when the machinery operated over the terrace ridge during construction.

Present Recommendations for Predicting Settlement

There are numerous publications on terraces where general recommendations are made concerning allowance for settlement. Clyde (5) stated that a terrace ridge should be built to a height of 16 to 18 inches so that it will be at least 12 inches high after settlement. McKittrick (17) recommended that the terrace ridge should be from 12 to 15 inches after settlement. Clark and Wooley (4, p. 35) state that

Terraces built to specifications will look unnecessarily large when first constructed. Settling of as much as 15 to 25% will first reduce the size. Farming will further lower the ridge and

the soil will drag or settle into the channel materially reducing the effective height of the structure.

A similar statement by Holman (13, p. 8) concerning the settlement of terraces is that

The minimum net height of new terraces should be 18 to 20 inches. The height of compacted terraces should be 16 to 18 inches. For corn or other clean cultivated crops a minimum net height of 16 to 18 inches will be reduced about 3 inches by cultivation to a net height of 13 to 15 inches at the end of the growing season. A net height of 13 inches is considered the minimum safe height for terraces in undisturbed condition.

All of the above investigators present recommendations or give their observations as to terrace settlement. No research data were given nor was any differentiation made with respect to the type of machine used or as to the many other variables affecting the settlement of terraces. With respect to farming operations, the authorities quoted agree that cultivation reduces the terrace cross-section. Schoenleber (24, p. 478) in a study of terrace dimension changes found that

.....Terrace dimension changes, when different crops are grown, are due primarily to the method and type of tillage operations performed.

Average terrace cross-sections will probably increase when all tillage operations are performed parallel to the terrace ridge and when plowing is performed by back furrowing to ridge, leaving dead furrow in channel and throwing all furrows uphill.

It would seem that even if plowing will maintain or slightly increase the terrace ridge height when certain crops are grown, the gradual diminishing of size during the growing season and the settlement following construction must be predicted at time of construction if a satisfactory and effective terrace is to be attained. It must be noted that the increase of terrace cross-sections as reported by Schoenleber was accomplished by using a two-way plow. When conventional one-way plows are used, dead furrows and back furrows are left within the terrace interval making the maintenance more difficult.

ANALYSIS OF THE PROBLEM

Factors Affecting Settlement of Terraces

As stated by Biot (3, p. 155), "Settlement is caused by a gradual adaptation of the soil to the load variation. This process is known as soil consolidation." In the case of terraces the load causing settlement is not of a known constant magnitude as with a concrete structure constructed on soil. Instead it varies with climatological forces, load of the soil particles upon supporting soil particles, and loads applied through farming operations. The total settlement of terraces would be a function of the loads and, also, the condition or void ratio of the soil upon which such loads are applied. In other words the settlement is due to the stress-strain characteristic of the soil. If a material is truly elastic it will obey Hooke's law and the strain will be proportional to the stress applied, and when the stress is removed the material will regain its initial dimension. Soil is known to be non-elastic, non-homogenous, and non-isotropic (29). However if pressure is applied to soil and then released, the soil will expand to a void ratio lower than it originally had at zero pressure. Therefore, soil can be considered as partially elastic. With simplifying assumptions

a theory of soil consolidation has been developed by Terzaghi based on the outflow of pore water caused by the increased hydrostatic pressure (29).

The void ratio and unit pressure relationship for soil, which is usually used instead of unit stress and unit strain, is approximately logarithmic indicating that a small increment of load will reduce the void ratio much more when the soil is at a high void ratio than the same increment of load on a soil with a small void ratio.

Settlement throughout this study will be defined as the total decrease in volume of the terrace ridge. Although settlement is a direct result of the loads applied by the external forces mentioned above, the amount of settlement is also a function of the condition of the terrace as its void ratio or other characteristics. Soil movement from the terrace ridge to the channel or to the interval below will also result in a decrease in volume of the terrace ridge. Soil movement is not true consolidation but its effect would necessarily be included with any terrace measurements if such measurements involved the entire terrace ridge and not just a sample. Therefore, comparisons of the settlement of terraces will be based on the combined effects of all relationships.

The load of soil particles on other supporting soil particles would contribute only slightly to settlement, if

at all. The pressure on a square foot at the bottom of a fill of a terrace ridge would be at a maximum load of about 200 pounds. If the void ratio of the soil is high enough so that such a load would have an effect, settlement would probably take place during construction. In reference to the minimum apparent specific gravity of soil, Doner (7, p. 299) states

The density or apparent specific gravity of a granular medium varies from that assumed when loosely packed by its own weight, to a maximum attained by rearrangement of particles through slipping without crushing due to a relatively large external force.

The settlement of terraces is probably caused by compaction or possibly the movement of soil to another location. Markwich (15) gave the basic principles of compacting as pressure (rolling), impact (raming), and vibration. Terraces would be subject to pressure and impact. The movement of soil to another location would give an apparent settlement but would not be true consolidation. Soil movement could be accomplished by splash and runoff water flowing off the terrace, and by farm machinery during normal farming operations.

The factors affecting settlement of terraces could be listed as soil, machinery and construction procedure, slope, shape of terrace, moisture content of the soil, vegetative cover, climatological forces, and farming operations. Many of these factors are interrelated.

Soil

The soil type upon which terraces are constructed has a definite influence on the amount the terrace will settle. The soil type is a classification of soil based on its geological history as well as many other properties and characteristics.

The textural classification is included within the soil type. Both total settlement and the rate of settlement would be affected by the proportion of various size particles. For instance, pure sand or gravel would settle very little; all consolidation would take place immediately and very little rearrangement would take place with additional load. A well graded soil if subjected to a load would compact to a very dense mass. If such a soil were not subjected to a load immediately, settlement would take place when later load increments are applied. In contrast to sands and gravels, heavy compaction produces the greatest increase of density in the case of heavy clays (15).

Structure is another soil property influencing settlement of terraces. Included with structure would be the porosity or void ratio and the organic content. As stated by Spangler (29), soil structure is the pattern of arrangement of the individual particles or of aggregations and combinations of particles. Settlement must be accompanied by a change in structure. As the soil is moved into the terrace

ridge, the original structure is partially destroyed. Undisturbed soil is in equilibrium with external environmental forces. If the void ratio of the soil is increased as the terrace is built, the soil will probably settle until equilibrium soil conditions are met. On the other hand if compaction takes place during construction, the original structure is destroyed. The soil will then remain in a compacted condition that will withstand any of the environmental forces which tend to consolidate the material.

A major portion of the soil moved in building a terrace contains organic matter. The organic matter tends to maintain the soil in its original structure regardless of whether forces occurring during construction tend to compact or loosen the soil. A terrace ridge containing clods would probably settle less during the earlier stages; therefore, its rate of settlement would be less than that of a terrace made up of a finely divided soil or even one having a single grained structure.

Machinery and procedure used in construction

The machinery used in the construction would definitely have an effect upon the future settlement that would take place after the terrace is completed. Since settlement is a function of the void ratio or porosity of the soil in the terrace ridge, less settlement would be expected from those terraces where compaction by the machine during construction

is greatest. Reed (21, p. 285) found that

.....Preliminary data obtained with a power driven soil resistance recorder indicate that all types of traction units pack the soil to a considerable depth, and that this packing effect is vectored out appreciable distance beyond the edge of the tread.

The amount of compaction of the soil in a terrace ridge would seem to be of varying degrees depending upon the machine's method of moving the soil, upon the procedure used in construction, and upon the weight of the machine.

Insofar as compaction is concerned, machines used in constructing terraces are of two basic types (12). Machines that throw, lift, drop or push the soil onto the terrace ridge without the machine traveling over the newly constructed ridge are of the first type. Examples include the whirlwind terracer, the elevating grader, and the bulldozer. The second type machine moves the soil into the terrace ridge by rolling, pushing, or scraping as it travels over the terrace ridge during construction. Examples of this type are the moldboard or disc plow, the bulldozer, and the motor grader, commonly referred to as a motor patrol. Therefore, the different machines used in constructing terraces would affect settlement because of the varying degrees of compactive energy exerted upon the terrace ridge during construction. The classification of the machines is based on the fact that a small amount of compactive energy decreased the void ratio

of the terrace to a very large extent when the void ratio is large. The same compactive energy has only a slight effect upon the void ratio when the terrace is in a compact state. The reason can possibly be explained by noting the logarithmic form of a void ratio-pressure curve where at low void ratios increased compaction gives slight decreases in the void ratios compared to large increases at the high void ratio points on the curve. Wilson and Browning (32, p. 128) in investigating Loessial soil as construction material for earth dams found

.....in general, regardless of the moisture content, the density increased rather rapidly with a given amount of work to a certain point after which additional labor gives small density increases.

Maximum settlement might be expected on a terrace constructed by a machine which throws or drops the soil onto the terrace ridge without traveling over the terrace ridge. Of the machines that travel over the terrace during construction, the heavier machines compact the soil more for equal number of passes. However, heavier machines usually construct terraces with fewer passes.

The procedure of construction is an important factor affecting settlement. If the procedure is such that the base of the terrace ridge is formed in the early stages of construction, all subsequent passes over the terrace ridge

will exert additional energy which must be absorbed by the soil in its final position in the terrace ridge. If the procedure is such that movement begins on the extreme edges of the terrace and the soil is gradually moved to the terrace ridge, much of the compaction will have little effect on the final apparent specific gravity of the soil in the terrace ridge. In this case the compacted soil is broken up or disturbed during later stages of construction. Only during the final stages of construction will successive passes be over the same soil in its final position.

Slope

The slope of the land upon which terraces are constructed may not have a direct effect upon settlement but does have many indirect effects. Building a terrace on a steep slope would require a greater number of passes by a machine than building a terrace on a shallow slope. A machine traveling over a terrace during the early stages of construction would be on more of an incline. This incline would shift the center of gravity of the machine putting more weight on one wheel than on the other. Slope would affect the shape of terraces. Terraces on steep slopes do not have as broad a base in proportion to the height as on shallow slopes. The amount of soil moved in constructing a terrace is necessarily greater on steeper slopes. The above factors are examples

of the many indirect effects slope has upon the settlement of terraces.

Shape of terrace

The shape of the terrace is determined by the machine, construction procedure, and the slope. The shape of the terrace, therefore, depends upon many of the factors previously discussed. The shape of the terrace does influence settlement. For instance, lateral movement or shearing of the soil is sometimes due to the excess weight of a machine on a terrace which would be more prevalent on narrow steep terraces. Also, a narrow steep terrace ridge would allow splash erosion to cause a greater soil movement from the terrace ridge giving an apparent settlement.

Moisture content of the soil

The effect of moisture content on the compaction of terrace ridges during construction is uncertain. That the optimum moisture for maximum density varies with the compactive energy as well as with the soil type has been pointed out by many authors (19, 20, 32, 15). The compactive energy of the machine during terrace construction varies with the machine, the number of passes in building the terrace, and the procedure. As stated by Markwisch (15, p. 312), "When soil is drier than optimum, it is possible to apply additional rolling to compensate for the dryness."

Certain investigators (26, 4, 27) emphasized the importance of moisture content on the ability of a plow to move the soil into the terrace. When the soil is not at optimum moisture for efficient soil movement, more passes are necessary to obtain a satisfactory ridge.

Therefore, there are two optimum moistures influencing the amount of compaction accomplished by a given machine. One is the optimum moisture content for maximum compaction for a given soil which varies with the compactive energy. The other is the optimum moisture for efficient soil movement which would vary the compactive energy by varying the number of passes necessary to construct a terrace. The interrelation of these two moisture contents are not known.

For construction machinery that employs the principle of throwing the soil, the moisture content may affect settlement in a different manner. The binding of soil particles varies with the moisture content. Clay particles bind together with a greater force when dry, but sand particles bind with a greater force when wet. It would seem that the binding of the soil particles would have an effect on the performance of the machine as well as the apparent density of the deposited material which would influence settlement as pointed out in the discussion on soil structure.

Vegetative cover at time of construction

The vegetative cover or the lack of cover upon the soil

on which terraces are constructed may be expected to affect settlement. There are many factors interrelated with the cover of the soil including the performance of the machine, the binding of the soil particles, and the shock-absorbing effect of the vegetation against compaction. If the effectiveness of the machine is reduced, additional passes may be necessary to build the terrace thus exerting additional compactive energy within the terrace ridge. On the other hand, the absorption of such energy by the vegetation would reduce the compaction.

It would definitely seem that the vegetation incorporated with the soil in the terrace ridge would influence the rate of settlement as the vegetation decomposes. The decaying of vegetation would leave pores in the soil. Forces acting upon the soil would then cause settlement which previously had been resisted by the vegetation.

Climatological influences

The climatological forces previously mentioned as causes of settlement are also factors affecting settlement. They include such loads as imposed on the soil by rainfall, wind, temperature variation, and atmospheric pressure variation. Rainfall would probably be of the greatest magnitude because of the tremendous energy of the raindrop that must be dissipated by the soil. The energy of falling rain

would aid in compacting the soil causing settlement. The apparent settlement of terraces caused by the movement of soil to another location in the field could be contributed partly to climatological influences. Splash erosion and runoff water could cause such soil movement.

The temperature variation would have its effect upon the rearrangement of soil particles by the action of freezing and thawing. The amount of settlement expected by such phenomena is questionable; in fact, freezing in many cases would cause expansion. A frost layer on the surface of a terrace could also protect the terrace from other external forces which would otherwise cause settlement. The rate of settlement would then be reduced.

The other climatological forces mentioned above would probably play a minor role in causing the rearrangement of soil particles producing settlement.

Farming operations

Farming operations along with rainfall is probably one of the main causes of settlement of terraces and would therefore be a factor affecting settlement of terraces. Operation of machinery over terraces would contribute to settlement in two ways. One would be the weight of the machine. Tractors and farming implements traveling over the terrace exert a considerable pressure on the soil. Machinery operating over

the terrace during construction would compact the soil to a lower void ratio. Consequently, the settlement resulting from the forces of machinery during farming operations would be more for those terraces not compacted during construction.

The other way in which machinery would contribute to settlement would be by the mechanical agitation of the upper part of the terrace. Such agitation would destroy structure and allow for rearrangement of particles into a more dense condition. In addition to destroying structure, cultivation of the soil tends to reduce the size of the terrace ridge by moving the soil downhill causing an apparent settlement. Even after maximum consolidation of the soil has taken place, cultivation and plowing continue to tear down the terrace unless proper maintenance measures are used.

Another factor which would give the appearance of settlement is the sedimentation in the terrace channel. Although such deposition also has the effect of reducing channel capacity, it is not true settlement.

The Problem

The purpose of this study was to determine the amount and rate of settlement and to develop methods of predicting settlement of terraces following construction. The study included the construction and measurement of terraces built under field conditions with different machines and on different slopes of two important Iowa soils. Only further investigations or usage can determine if results obtained from this experiment are applicable to other soil types. The investigation included a study of moisture variation with all other controlled factors constant. Apparent specific gravity and soil hardness measurements were included to determine if such measurements are valuable in predicting settlement.

Objectives of study

The objectives of this study were:

1. To compare the effect of the different variables affecting terrace settlement.
 - a. The slope of the land upon which the terraces are built.
 - b. The machine used in constructing terraces.
 - c. The soil type.
 - d. The moisture content of the soil at the time of construction.

2. To obtain information and investigate methods to aid in predicting settlement of terraces at time of construction.
 - a. Cross-sections of experimental terraces.
 - b. Apparent specific gravity determinations.
 - c. Penetrometer measurements.

Selection of Factors to be Investigated

The factors affecting settlement selected for study were limited because of time, money, and availability of suitable sites. In order to attempt to achieve the objectives of this study, as many of the factors affecting settlement of terraces as practical were incorporated into the design.

Those variables incorporated into the overall experiment were soil, slope, machine, and moisture content. It was impossible to study all of the above variables in the same experiment, so by separating the experiment into three parts at least one or more of the variables were fixed in every case.

The two Iowa soils selected were those which constitute a large portion of land which is at present being terraced or indicate potential terraced land in the future. The Clarion soil, selected as representative of the glacial till soils covering most of Iowa, ranges in slope from 2 to 12 per cent. A field on the Ankeny Experimental Farm was

selected for this part of the study. The Ida soil, selected as representative of the loess soils of Iowa, ranges in slope from 8 to 20 per cent. It is in the loess soils that most terraces have been constructed. A field on the Western Iowa Experiment Farm was selected for this second part of the study.

The slope of the land was considered important because of the many indirect effects it could have upon the settlement as stated in discussing factors of settlement. Slopes were selected within the range encountered by field engineers in routine practice.

It was not possible to obtain two slopes common to both soil sites available; therefore, two slopes, 4 and 8 per cent, within the range of Clarion soil and two slopes, 12 and 16 per cent, within the range of Ida soil were selected. It was not feasible to attempt to replicate the experiments on the two widely separated locations because of the difference of slope, cover, moisture content and time of construction.

Due to the number and variety of machines employed at the present time to construct terraces in Iowa, it was obviously impractical to investigate every machine available to the farmer today. Two machines for each the Clarion and Ida experiments were selected. One was of a type machine that throws the soil on to the terrace ridge with a minimum

of traveling over the terrace, and the other machine was of a type that scraped or rolled the soil on to the terrace ridge and while doing so traveled over the terrace during construction. The whirlwind terracer and the moldboard plow were selected for the Clarion experiment, and the whirlwind terracer and the motor grader were selected for the Ida experiment.

It was felt that the moisture content of the soil at the time of construction could play a major role in the settlement of terraces. The slope and machinery experiments were of such magnitude and covered such a large area that it was not considered feasible to control the moisture content for all terraces on both sites. Therefore, moisture contents at time of construction were determined on both the Clarion and Ida experiments but a separate experiment was set up on the Clarion soil site specifically for moisture study. A system of irrigations were used to obtain moisture differentials with all other factors constant.

There were several factors affecting settlement omitted from the experiments. Farming operations and climatological forces are two factors not included because of the limited time allotted for study. Conditions typical of normal terrace construction, such as soil cover and standard construction procedures, were held constant.

EXPERIMENTAL

The investigation was conducted primarily as a field experiment, laboratory investigations being used only in the evaluation of field samples.

Design of Experiments

The experiments were designed so that a statistical analysis could be made. Limitations encountered were due mainly to the topography and cover of the sites selected. The selection of observation sections for each site was conducted with as much care as possible to avoid introducing additional variables.

Slope and machinery

The slope and machinery investigation was set up on two separate soil sites. Due to the topography, cover, possible differences in moisture content, the equipment adaptable to the construction of terraces on each, and probable differences in climatological influences, the experiments on the two different soils were considered as two separate experiments. They will be referred to as the slope and machinery experiment on the Clarion soil site and the slope and machinery experiment on the Ida soil site.

Two slopes and two machines were investigated on each of the two soil sites. Six 50 foot sections of terrace were selected of a particular slope on each soil. The terraces were constructed in such a manner that each machine would build three sections of the same slope on each of the particular soils.

On the Clarion soil experiment the twelve sections selected would be sufficient so that the combined variables would equal four so called treatments at three locations. Calling the two slopes low and medium, the moldboard plow would build three of the sections on the low slope and three sections on the medium slope. The whirlwind terracer would likewise build three sections on the low slope and three sections on the medium slope.

On the Ida soil experiment, twelve sections were again selected so as to give three locations of four so called treatments. Calling the two slopes high and very high, the motor grader would build three of the sections on the high slope and three of the sections on the very high slope. The whirlwind terracer would likewise build three sections on the high slope and three sections on the very high slope.

Field layouts. The slope and machinery experiment on the Clarion soil site was designed and set up first. Two terraces of 850 and 1700 feet in length were staked out with a grade of .10 feet per 100 feet, the minimum grade

recommended for the Clarion soil area. After the terraces were staked out, the slope at each 50 foot station was determined by the use of a hand level, rod, and chain. Six sections, 50 feet in length, were selected with a slope as near as possible to 4 per cent, and six sections, 50 feet in length, were selected with a slope as near as possible to 8 per cent.

Three points on the staked line within the 50 foot length were established for locating observation lines where cross-section measurements would be taken. The three points for locating the observation lines were selected by using a table of random numbers from among the 5, 13, 21, 29, 37, 45 plus stations from the beginning of the section. All cross-sections were thus at a distance of 8 feet or a multiple of 8 feet from an adjacent cross-section and at least 5 feet within the 50 foot section.

Observation lines were established as nearly perpendicular as could be determined by eye to the staked channel line of the terrace at each of three points within the 50 foot section. Control points, one located 20 feet above and the other 35 feet below the staked line, were permanently marked.

The terrace or portions of terrace were selected that could be built by one machine or the other to satisfy the requirement of each machine building three sections on each

slope class. The machines were then selected to build the particular terrace or portions of terrace by chance. Figure 1 is a map showing the layout of the slope and machinery experiment on the Clarion soil site.

The slope and machinery experiment on the Ida soil site was set up in the same manner as the one on the Clarion soil site. Two level terraces of 1250 and 500 feet in length were staked out. Level terraces are normally used in this loess soil area in preference to graded terraces. The slope was determined for each 50 foot station as before. Six sections, 50 feet in length, were selected with a slope as near as possible to 12 per cent, and six sections 50 feet in length were selected with a slope as near as possible to 16 per cent.

The points for establishing the observation lines were selected at random intervals within the 50 foot section as on the Clarion soil site. The control points for the observation lines were established 35 feet above and 20 feet below the staked line on the Ida experiment since the staked line was the proposed ridge line. Using the staked line as the ridge line is customary in level terrace layout.

The portion or portions of each terrace that would be built by one machine or the other were then selected. Again the selection of the machine to be used on the different portions was determined by chance. Figure 2 is a map showing the layout of the slope and machinery experiment on the Ida soil site.

Fig. 1. Field Layout of Slope and Machinery Experiment. Clarion Soil Site.

Fig. 2. Field Layout of Slope and Machinery Experiment.
Ida Soil Site.

Moisture control

The moisture controlled experiment was designed to make possible a comparison of the effects of different soil moisture contents at time of construction upon the settlement of terraces. This experiment was performed only on Clarion soil, on one slope, and with one machine. The terrace was constructed on a 6 per cent slope by a moldboard plow. This machine was selected because of the compactive energy exerted by it during construction.

The experiment was designed as a randomized complete block experiment with three treatments within three blocks on the same terrace. Therefore, by constructing the entire terrace at one time, each block and each section or plot making up a block would be subjected to equal number of passes by the tractor and equipment. In each block there would be three sections with a different soil moisture treatment. No attempt was made to cover the entire range of field moisture conditions from wilting point to field capacity, but rather to get three different moisture contents of the soil. The moisture differences were obtained by irrigating one section in each block with one inch of water three days prior to construction, one set of sections one day prior to construction, and leaving the remaining set of sections not irrigated.

Field layout. The moisture controlled study was carried

out on the third terrace on the Clarion soil site. Three portions of this 1450 foot terrace were selected for the three blocks as shown in Figure 3.

Within each block three observation sections were staked out, each being 20 feet in length and having at least a 10 foot border section. The 20 foot sections were used in the moisture controlled experiment instead of the 50 foot sections in the other studies because of the limited facilities available for irrigation. It was necessary to haul the water to the field in a fire truck and the application of one inch of water to three sections 20 feet long and 40 feet wide was as much as could be completed satisfactorily in a day.

The observation sections being only 20 feet in length, the observation lines were located at equal intervals within the section at the 6 foot and 14 foot plus stations. With the above selection each cross-section was 8 feet from the other within the same section and 6 feet from the beginning and end of the section. The control points were located 20 feet above and 35 feet below the staked or proposed channel line.

The moisture treatments for each section of the three blocks were selected by using a table of random numbers.

Fig. 3. Field Layout of Moisture Controlled Experiment.
Clarion Soil Site.

Procedure

The explanation of procedures will include only the methods pertinent to this experiment. Such procedures and decisions as spacing of terraces, staking out terraces, and checking terraces were done in the usual manner, and would have little or no effect upon the results of this study.

Construction of terraces

The construction of all terraces on the Clarion site and the whirlwind constructed terrace on the Ida site were done with machines owned by the Ankeny Farm Service and operated by the author of this report or other staff members or employees of Iowa State College. The motor grader used on the Ida site was a rented machine and operated by its regular operator.

Clarion soil site. The construction of the terraces for the slope and machinery and for the moisture controlled study on the Clarion soil site was done in a similar manner where the same machine was used. For the plow constructed terrace, a John Deere tractor and a two-bottom moldboard plow were used. The jointers were removed from the plows. (See Figure 4.) The procedure used was the "island method" of terrace construction developed by Paul M. Pittinger and others of the Soil Conservation Service (26). The procedure

Fig. 4. Moldboard Plow Used to Construct Terraces on the Clarion Soil Site.

Fig. 5. Whirlwind Terracer Used to Construct Terraces on Both Clarion and Ida Soil Sites.

is described by Samsel (23) and, also, Schwab, Frevert and Barnes (25).

Both portions of the terrace of the slope and machinery investigation built by the moldboard plow required approximately 30 to 36 rounds. The terraces on which the moisture controlled experiment was conducted required approximately 42 to 45 rounds. Since this terrace was built approximately ten days later than the slope and machinery experimental terraces, the soil was slightly drier except for the wetted sections. A whirlwind terracer manufactured by the Servis Equipment Company powered by a Farmall M. tractor was used to build the whirlwind constructed terrace. (See Figure 5.) The procedure used in constructing the whirlwind terrace was developed by members of the Extension Service at Iowa State College and illustrated by Schwab, Frevert and Barnes (34). Slight modifications in the final stages of construction were necessary to obtain a more desirable shape to the terrace. Approximately 30 to 36 rounds were necessary to construct the terraces. Soil was thrown uphill from the lower side of the terrace during the first 12 rounds only.

Ida soil site. The same whirlwind terracer used on the Clarion soil site was used on the Ida soil site. The procedure in the earlier stages of construction or for the first 24 passes was the same as used on the Clarion soil, but due to the steep slopes and the number of rounds required,

adjustments were made as deemed necessary to accomplish the desired soil movement. (See Figure 6.) Approximately 70 to 90 passes with only the first 12 passes returning on the lower side throwing the soil uphill were used to build the terrace. The procedure as used on both the Clarion and Ida soil required that a small portion of the trips by the machine be made on the front slope of the terrace ridge. The number is small compared to other machines that travel over the terrace ridge during construction. Therefore, the whirlwind terracer is considered a machine which builds terraces with a minimum amount of compaction.

The machine used to construct the grader built terraces on the Ida soil was a caterpillar number 12 motor grader with its normal 12 foot blade. This machine is commonly referred to as a motor patrol. (See Figure 7.) The procedure used with the motor grader is a general procedure only and not published as a round by round method.

The general principles of the procedure were to build the toe of the ridge first, moving all of the soil from the upper side of the terrace, and gradually moving the machine uphill cutting into undistributed soil on each pass. The procedure was repeated until the desired depth of channel was obtained. The final terrace was completed by a smoothing operation with a cut on the upper slope of the channel, the bottom of the channel, and two rounds on each side of the ridge.

Fig. 6. Whirlwind Terracer in Operation on a 16 Per Cent Slope on the Ida Soil Site.

Fig. 7. Motor Grader in Operation on a 12 Per Cent Slope on the Ida Soil Site.

Methods of measurement

The obtaining of data necessary to accomplish the objectives desired included cross-section measurements, soil samples for apparent specific gravity determination, soil hardness measurement, and moisture determinations. Moisture determination was determined by the standard method of obtaining a sample, drying the sample to constant weight in an oven between 100° C. and 110° C. and calculating the percent moisture based on dry weight. Particular methods were used for the cross-sectioning, apparent specific gravity determination, and soil hardness and will be described separately.

Cross-section measurements and core sample determinations were made at each of the 90 observation lines selected prior to construction on the original ground, immediately following construction during September or October, 1951, and also during April or May, 1952. Soil hardness measurements were obtained at time of construction.

Cross-sections. For accurate determination of the amount of soil moved in constructing a terrace as well as the settlement following construction, complete cross-sections were necessary. The common method of using an engineers level and rod seemed too laborious and slow for the number of cross-sections that were necessary to measure the same day the terraces were construction. Therefore, other possible

methods were considered which would fulfill the following requirements:

1. Give accurate measurements.
2. Operated by a maximum of two men.
3. Require a minimum of delay in setup.
4. Give horizontal as well as vertical control.
5. Are simple and durable.

After a certain amount of trial and error with preliminary tests the use of a string or cord was selected as the equipment for vertical control and a steel tape chain stretched between the two control points to serve as horizontal control.

Part of the equipment consisted of a wooden 2 x 2 hub driven in the ground at the upper control point of the observation line with a nail in the wooden hub to attach the cord. In later measurements with the control point below the surface, a similar wooden hub was braced in the hole behind the control point instead of being driven into the ground. The wooden stand (see Figure 8) which could be transported and erected easily by one man was used for the attachment of the string and chain at the lower control point. A strong but light 25 pound test nylon fish cord was used. The cord was attached to the upper hub and hung across a C-clamp on the stand with a seven pound weight attached. A piece of wood with a groove was attached to the C-clamp to prevent the cord

Fig. 8. Measuring Cross-sections on Undisturbed Area.

Fig. 9. Measuring Cross-sections on Completed Terrace.

from being cut by the steel. The seven pound weight was used to give a constant tension on the string at each setup and with sufficient tension to limit the sag in the cord to less than .01 of a foot. A steel tape chain clamped on the side of the upper hub pulled taut and clamped to the side of the stand served as horizontal control. A Philadelphia rod was then used to measure the distance from the cord to the surface of the ground or terrace. In other words, the cord served as the height of instrument and foresight readings were made on the terrace.

The procedure for making the measurements after elevations of all hubs had been obtained by differential leveling was to loop the cord over the nail and clamp the chain to the upper hub. The stand was picked up and set in place behind the lower hub. The C-clamp which served as a pulley for the cord was attached to the stand at a position approximately level with the upper nail on the hub. The weight was lowered in place and the chain pulled taut and clamped just under the C-clamp pulley. The C-clamp pulley was then lowered or raised so that the precalculated difference between the two hubs could be read on a Philadelphia rod when set on top of the lower hub. The string was then set in a level position. One member would read and record the foresight at each foot mark on the chain (see Figure 9). A total of 55 feet horizontally was measured on each cross-section.

All hubs above the ground were replaced immediately following construction by iron hubs 12 to 15 inches below the surface of the soil. The reason for doing so was to prevent destruction by farming operations. When making readings at all subsequent times, the same procedure was followed except that the height of the cord above the upper hub was measured and added to the precalculated difference to set the cord over the lower hub.

In order to make the above data usable and be consistent with measurements taken at different times, all foresight readings were converted to elevations by subtraction from the elevation of the cord. The elevation of the cord was the elevation of the upper hub, or the elevation of the upper hub plus the observed reading as was the case when holes were dug to locate the iron stakes several months after construction.

Using the elevations obtained, the cross-sections were then plotted on 4 by 20 profile paper. The scale for the horizontal distance was 4 feet to one inch and the vertical scale was one foot to one inch. The areas of cut, fill, and fill after settlement were measured with a planimeter. A minimum of three readings were made on each. The area of cut was the area below the original ground line as determined by the measurements immediately following construction. The fill area was the area of soil above the original ground

line immediately following construction. The fill after settlement was the area above the original ground line as obtained from the measurements made during the spring of 1952.

Figures 10, 11, 12, and 13 show typical cross-sections for each combination of machine and slope on the Clarion and Ida soils. Figure 14 shows typical cross-sections of the three moisture treatments of the moisture controlled experiment. Each cross-section selected for illustration was one of nine cross-sections of the same slope and machine and one of six of the same moisture treatment. The cross-section selected as typical was the one that very nearly approached the mean settlement with a minimum of correction.

The variations above and below the terrace between the fall and spring cross-sections were due to plowing. The plowing of the interval on the Clarion soil site extended from the toe of the upper terrace ridge to the center of the lower terrace channel. On the Ida soil site the plowed soil extended from the ridge toe to the upper edge of the channel. This variation did not affect any of the cross-sectional areas measured.

The volume of cut or fill was the measured area obtained by planimetering each cross-section of fill or cut times a unit length along the terrace. Three separate volumes of cut, fill, and settled fill were obtained for each observation section. Equal weight on each cross-section measurement

Fig. 10. Typical Terrace Cross-sections of Slope and Machinery Experiment. Clarion Soil Site. Low Slope Class (4%).

Fig. 11. Typical Terrace Cross-sections of Slope and Machinery Experiment. Clarion Soil Site. Medium Slope Class (8%).

Fig. 12. Typical Terrace Cross-sections of Slope and Machinery Experiment. Ida Soil Site. High Slope Class (12%).

Fig. 13. Typical Terrace Cross-sections of Slope and Machinery Experiment. Ida Soil Site. Very High Slope Class. (16%).

Fig. 14. Typical Terrace Cross-sections of Moisture Controlled Experiment.

is thus obtained by using this method regardless of their location within the section.

In order to evaluate properly the area of fill per unit length to the area of cut per unit length, a correction was necessary on the curved portions of the terrace. When the terrace was constructed on an outside curve the soil removed from the channel was spread over a greater length of ridge. The opposite is true for an inside curve. In other words, the actual volume of terrace to be considered would be the shape of a wedge, or commonly speaking, a slice of pie.

The curvature correction was accomplished by measuring with a steel tape chain a specified distance, usually 100 feet, in the channel of the completed terrace. A perpendicular distance was measured to the ridge and two points established. The distance between the two points on the ridge was measured along the curve of the ridge. The channel and ridge distances established two concentric arcs at a known distance apart. The radius of curvature could then be calculated for any concentric line.

Core samples. Core samples were obtained in order to determine the apparent specific gravity of the original soil and the soil in the terrace ridge. The ratio of the two were used as one method of calculating the index of potential settlement.

The determination of apparent specific gravity or volume

weight as it is sometimes referred to was done by the use of core samples rather than the many other possible methods because of the range of compaction of the soil upon which samples were required. The oil, water and membrane, and the kerosene methods were considered, but were decided unsuitable particularly in cases where samples were needed of soil in a very loose condition.

The core sampler used (Figure 15) was one designed to take undisturbed samples of soil. Figure 16 shows the method of operation of the core sampler. The same type sampler has been used by numerous investigators (14) to take undisturbed samples for permeability measurements. It is similar in principle to samplers used by Coile (6) and others for volume weight, porosity, or permeability determinations. The sampler consists of a cylindrical housing with a cutting edge, aluminum cores or cylinders, an apparatus to hold the core in place, and a weight designed to slide on the handle shaft for driving the core into the ground. The core being 3 in. in diameter and 3 in. long contained a volume .01227 cu. ft. or 347.45 cu. cm. of soil.

The samples were obtained prior to construction in the original ground, in the terrace ridge immediately after construction, and in the terrace ridge after settlement for the interval of time investigated. The points for taking the samples were in the immediate vicinity but not exactly on the

Fig. 15. Core Sampler with Parts Separately.

Fig. 16. Taking Core Samples in Completed Terrace Ridge.

observation line. Precautions were taken not to take a sample on the observation line as it may cause errors in later cross-section measurements. In all cases the sample was obtained by removing approximately 4 inches of soil with a shovel and then driving the sampler into the soil. The soil from the ends of the cores was cut off with a knife. A wire type cheese cutter was tried, but proved unsatisfactory due to the vegetation within the soil.

The apparent specific gravity was then determined from the known volume and the dry weight. The dry weight was calculated by using a small sample to determine the moisture content and applying this moisture correction to the entire core.

Soil hardness. The measurement of soil hardness has been attempted by a number of investigators. Proctor (20) developed a soil plasticity needle for use in construction of earth dams. The principle was that of forcing a needle of known area at the point into the soil and measuring the resistance in pounds per square inch. Stone (31) and associates developed a penetrometer called the Rototiller penetrometer based on the principle of the distance a probe is forced into the ground by the kinetic energy of the falling body. McKibben and Hull (16) used the rototiller penetrometer and the Iowa penetrometer in connection with predicting the rolling resistance of transport wheels. The

Iowa penetrometer is based on the principle of a falling body forcing a flat surface into the soil. A definite correlation was found between the rototiller and the Iowa penetrometer and the Procter plasticity needle by McKibben and Hull (16). The same authors found that the rototiller penetrometer gave slightly better results and had the advantage of being simpler.

Beach (1) established a very close correlation between the three types of penetrometers while designing one for use to measure the soil hardness in evaluating the performance of tile ditching machines. Renoll (22) used the penetrometer in connection with tillage investigations. Frevert (8) developed a penetrometer which operated at a uniform rate of penetration by the use of a pendulum. He used the penetrometer in connection with tillage studies.

Penetrometer readings were made on the terraces in this study to get some indication of its value in predicting settlement. The Rototiller penetrometer developed by Stone and associates (31) was used.

The penetrometer used in this study (see Figure 17) consisted of a hollow tube 1-1/2 inches in diameter and 55 inches in height with a 6 inch square base at the bottom. The tube has a slot near the bottom where measurements can be made. The probe or penetrator is 22 inches long, 1-1/8 inches at the top with the lower 18 inches of the probe

Fig. 17. Penetrometer Used to
Measure Soil Hardness.

tapered to one-quarter inch at the bottom. The probe is dropped from a height of 36 inches and has a weight of 3 pounds and 3 ounces.

The first experimental terraces constructed for this study were those for the slope and machinery experiment on the Clarion soil site. Penetrometer measurements were made at that time only on the completed ridge of the terrace immediately following construction.

On the remaining terraces penetrometer readings were taken on the ridge of the terrace immediately following construction and on the undisturbed area just above the ridge measurement.

The procedure for making the penetrometer measurements was to select a point sufficiently level for the penetrometer to stand upright, drop the probe, and record the reading. Grass or other vegetation was removed where the penetrometer was to be dropped so that the impact of the probe would be directly on the soil. The soil was not disturbed, only the vegetation above the ground surface was removed. The points selected were in the immediate vicinity of the observation lines of each location.

Irrigation of moisture controlled experiment

In order to accomplish a moisture differential between the different plots or sections of the moisture controlled

experiment some method of water application was necessary. There was no water source available at the site, but a fire truck with a capacity of 300 gallons was available to haul water to the field. The 300 gallons were sufficient to apply one-half inch of water to a plot 20 feet by 40 feet. Using an irrigation efficiency of 83 per cent, two full loads of the fire truck would be capable of applying 1 inch of water to the plot.

For sprinkling the water on the soil, a 20 foot length of 2-inch diameter Perf-O-Rain Type C perforated irrigation pipe was purchased. Perforated irrigation pipe was selected because of its characteristic rectangular pattern. The pipe selected was calibrated by the manufacturer to apply water to the soil at the rate of 1 inch per hour on a strip 40 feet wide at approximately 20 pounds pressure (see Figure 18).

The greatest amount of soil moved during the construction of the terrace would be within the upper one foot. Therefore, one inch of water was decided as sufficient to obtain a sufficient moisture differential, if some moisture was in the soil at time of irrigation. Although a greater application was desirable, one inch was used because of the time necessary to apply the water. The 1 inch per hour rate of application was faster than recommended for the particular area. For complete irrigation within a day the minimum amount and maximum rate of application was necessarily selected.

Fig. 18. Irrigation on Moisture
Controlled Experiment.

The greater the length of time to irrigate, the greater would be the variation of treatments within plots due to the drying effect of the wind and sun. Therefore, an application of one inch of water on one set of sections three days prior to construction and one inch of water on one set of sections one day prior to construction were the treatments decided.

The procedure was to apply one-half inch to each section and then repeat with the second one-half inch to each section. Such a procedure would tend to equalize more nearly the time between water application and time of construction as well as reduce runoff due to the fast rate of application. By applying one-half of the water at one time and the other half several hours later, time was allowed for infiltration of the water held in surface detentions.

Establishing, mapping, and relocating control points

The control points for a cross-section measurement consisted of one point above and one point below the terrace at each observation line. There were 90 observation lines within the three experiments making a total of 180 control points. Wooden stakes were put in originally at the desired locations. In order to establish accurate control points for all future measurements, permanent stakes were installed and placed so that all farming operations could continue throughout the area in a normal manner. In addition, a method of relocating the points was established.

Iron stakes located with the top of the stake at least 12 inches below the surface of the ground were considered sufficient. Discarded steel reinforcement rods of approximately $3/4$ inch in diameter cut in lengths from 18 to 24 inches were used. They were installed into the correct position by marking the point of the wooden hub and digging a hole of the desired depth. With the use of a plumb bob, the location in the bottom of the hole was established. The iron stake was then driven into the ground and checked in its position below the plumb line.

Elevations were determined for the iron stakes, as with the wooden hubs, by differential leveling. A bench mark was established in each field with an assumed elevation of 100 feet. The bench mark consisted of an iron stake located in a fence row. Differential leveling was also used to determine the difference in elevation from the bench mark to a more permanent structure so that if freezing and thawing or other possible accidents moved the bench mark or any of the control points, the elevation could be re-established. A concrete culvert near the Clarion soil site and the concrete floor of the machine shed on the Western Iowa Experiment Farm near the Ida soil site were used as the permanent reference levels.

The mapping of the control points consisted of running a transit-tape traverse from the bench mark to at least one control point in a section, or one in several sections where

the sections were grouped, and returning to the bench mark. At each turning point on the transit-tape traverse, the transit was set up and by radiation the azimuth was measured as the clockwise angle from the back line or a line on the previous turning point. A complete map as obtained from each field is contained in the Appendix. (See Figures 19 and 20.)

The control points were relocated by repeating the transit-tape traverse. The position of each point was determined by its azimuth and distance. Each stake was capped with a 6 by 6 inch 28 gage galvanized sheet metal so that the stake could be found with greater ease. A short probe was used to identify the point.

The use of a mine detector was tried in locating the iron stakes but proved unsuccessful. The unsuccessful attempt could be contributed to the fact that the operator was inexperienced and the soil surface was very rough and moist. It was felt that the transit-tape traverse would pinpoint the control points more accurately and probably with greater ease than a mine detector under such circumstances.

Method of Analysis

Since the time allowed for the study was insufficient for complete settlement of the experimental terraces, the analyses, including comparisons and predictions were based on

certain estimates and assumptions. The study being one phase of an overall program required results based on conditions expected at a future time.

Even though the experiment will be continued, an analysis of the data taken during the first fall and spring of the newly constructed terraces was necessary. The data taken for the time interval of investigation exclude any effect of tillage, cultivation, or travel of equipment over the terrace. No provisions were made in this study to investigate the effect of farming operations, but the study of such effects is dependent upon a thorough analysis of the possible predicted settlement. The settlement of terraces as affected by farming operations must be calculated from the observed differences of the terraces as measured following a growing season and the results of the predicted settlement as obtained from this study.

Calculations

The calculations desired were such that comparisons could be made of the terraces built by different machines on different slopes regardless of size. A ratio of the terrace fill to the original soil called the index of potential settlement was used. This index of potential settlement is exactly the same numerically as the index of compaction initiated by Hermsmier (12). It was felt that the use of the

term index of potential settlement more clearly symbolizes the condition of the terrace because a higher index, if numerically greater than unity, indicates greater potential settlement. A smaller index denotes a terrace with greater compaction, a lower void ratio or porosity and a correspondingly lower potential settlement.

The index of potential settlement was calculated from two sources of measurement. One was from the apparent specific gravity measurements as obtained from the core samples. The index of potential settlement would be the apparent specific gravity of the original soil divided by the apparent specific gravity of the soil in the terrace ridge. This is the same method as used by Hermsmier (12). An index of unity would denote an apparent density of the soil in the terrace ridge equal to the apparent density of the original ground. Thus an index of potential settlement of one would indicate no potential settlement because it is in equilibrium with all external forces normally subjected to the field in question.

The index of potential settlement was also calculated from the volume of fills and cuts as derived from the cross-section measurements. Since the apparent specific gravity is inversely proportional to the volume or equal to the reciprocal of the volume for a unit mass, the calculation of the index of potential settlement was accomplished by

dividing the fill or total volume of the disturbed soil in its final position by the total cut or original volume.

The index of potential settlement was calculated from the measurements made immediately following construction and also after an elapsed time of 5-1/2 to 7-1/4 months varying with the different experiments from both sources of measurement.

Correction factors. Certain correction factors were employed in calculating the index of potential settlement from the cross-sections of the terraces. One of these corrections was for the cut area refilled during construction. This correction was felt necessary because there is always a certain volume of soil removed and replaced below the original ground line in terrace construction. When the volume of cut is computed from the cut area of the terrace in its final form, this disturbed replaced soil is not included. It is neither included with the fill area which is measured above the original ground. Since the settlement of a terrace would be a function of the amount of filled area plus the disturbed area below the fill it was necessary that this cut and refilled area below the original ground line be known. The index of potential settlement was determined from the total cut and fill volumes. The total cut volume would be the measured cut volume plus the volume of disturbed soil below the original ground line. The total fill volume would be

the fill measured above the original ground line plus the same disturbed volume. Therefore, the cut volume refilled during construction would be a constant for both measurements and will be referred to as the K volume.

In determining the K area it was considered that the disturbed area would be the same for all portions of the terrace constructed at the same time by a particular machine. Therefore, the product of the average depth times the average width was used rather than trying to compute a separate disturbed area for each cross-section. All K areas for the same terrace should be equal because the first phase of soil movement which contributed to the K area was consistent throughout the terrace.

The procedure for determining the K area was first to investigate each cross-section as plotted and measure the depth of cut in the last furrow or furrows on the lower side of the terrace for all whirlwind and plow constructed terraces. The soil removed from the last furrow of the whirlwind constructed and the last several furrows of the plow constructed terrace were not replaced by other soil. Each of the depths were recorded for all cross-sections in the portion of the terrace built by the same machine at the same time with the same number of passes. It is realized that the depth of a plow cut is not always the same, but since the plow cuts in question were made on undisturbed soil

during the earliest phase of operation, the average of the depths obtained from the lower furrows of the cross-sections were considered as the average depth of cut throughout the terrace.

The breadth of the terrace or the distance from the channel cut area to the lower cut area was measured on each cross-section. Again, an average breadth was calculated for the portion of the terrace built at the same time. An island with an 11 foot width of undisturbed soil was left in the construction of the plow built terraces. The island began at the 20 foot marker on the cross-section measurement. It was considered that the soil in the first foot of the island was disturbed; therefore, 10 feet were subtracted from each distance measured across the breadth of the terraces built by the plow. A 3 foot island was left undisturbed at the center of the ridge on those terraces constructed by the whirlwind terracer; therefore, three feet were subtracted from the breadth for each whirlwind constructed terrace.

The K area was then determined for the particular portion of terrace by multiplying the average depth times the average corrected breadth. This constant disturbed area was also corrected for curvature as with all areas on the curved portions of the terrace and an equivalent unit volume was computed.

The constant or K area for those terraces constructed

with the motor grader was obtained by calculating the average of the areas below the original ground line and above a line drawn from the final channel to the original staked line where the first cut was made. This area of soil was considered as moved and replaced by other soil during the construction process.

In order to evaluate the effect of an error in determining the K area upon the final index of potential settlement a particular case was chosen and the effect of maximum possible error was determined. It was obvious that the maximum error in the index of potential settlement would occur where the index is large and the constant or K volume is small. Such a case was investigated. The K volume in the selected case was 5.04 cubic feet and the index of potential settlement was 1.40. It was found that if the K area was in error 2 square feet or approximately 40 per cent, the index of potential settlement would be a maximum of 5.3 per cent in error. In most cases, the same error of 2 square feet would affect the index of potential settlement about 1.0 per cent.

The data for each K area and volume are included with the other pertinent data recorded or calculated in Tables 17, 18 and 19 of the appendix.

The other correction factor necessary for the calculation of the index of potential settlement from the cut and fill areas was that of correcting for the curvature of the terrace.

The procedure for field measurements and for the computation of radii and arcs has been previously explained. The next step was to calculate the volumes based on an equivalent unit length. In calculating the volumes while correcting for curvature, the unit distance along the terrace at the original staked line was used. The original staked line was the proposed terrace channel line on the Clarion soil site and the proposed ridge line on the Ida soil site. The ridge and channel did not always fall on the staked line as shown from the plotted cross-sections. The actual channel or ridge line was used in calculating the radius, but the staked line was still used as the unit length along the terrace.

The horizontal distances to the centroids of the cut areas, fill areas, and K areas were estimated from the plotted cross-sections. The centroid of the lower cut area was also determined where a portion of the terrace was built from the down-hill side, and the volume calculated separately.

The horizontal distances to the points of channel line, ridge line, the centroid of cut, the centroid of fill, the centroid of the K area or cut area refilled during construction, and the staked line were recorded. The curvature correction factor was then determined for the area in question by equating the ratio of the unit length of one foot to the radius of curvature of the staked line, and the ratio of

the desired channel curvature correction factor to the radius of curvature of the centroid of the channel cut area. In the same manner the curvature correction factor was determined for centroid of the fill area, the centroid of the K area below the ridge, and when applicable, was also determined for the lower cut area.

It must be pointed out that using the unit length as one foot along the staked line was purely arbitrary. Therefore, the corrected volume of soil is not quantitative. The volume of soil in one cross-section will not be equal to the corrected volume of another cross-section, but the ratios of volume fill to volume cut or the index of potential settlement is quantitative and can be compared and evaluated.

The only data obtained for use in the curvature correction procedure which could cause discrepancies in the final result would be the estimated centroids. Due to the irregularities of the areas, an exact centroid could not be calculated. The error of the index of potential settlement due to an error in estimating the centroids was determined for a case where the error would be a maximum. The case was based on the smallest radius of curvature measured of 48 feet. It was found that if both the centroids of cut and the ridge were estimated 2 feet in error and in opposite directions, the maximum error of the index of potential settlement would be 7.7 per cent. If the centroids were in error one

foot in opposite directions the maximum error would be 3.5 per cent. If the centroids were estimated 2 feet in error in the same direction the error of the index of compaction would be less than 1.0 per cent. It was then considered that the method was justified since the majority of curves were of a radius much greater than 48 feet, and even with a 48 foot radius it seemed unlikely to be as much as two feet in error in estimating the centroid of the areas. The chance of being in error in opposite directions was also considered remote.

Per cent settlement. The total per cent settlement expected of a terrace or the per cent settlement for the interval of time between two determinations of the index of potential settlement can be calculated from the index of potential settlement. Calling I_a the index of potential settlement immediately after construction and I_s the index of potential settlement after settlement for a given period of time, the total predicted per cent settlement would be

$$S_t = \frac{I_a - 1}{I_a} \times 100,$$

and the per cent settlement for a given interval time from construction to when I_s was measured would be

$$S_s = \frac{I_a - I_s}{I_a} \times 100.$$

The relations can be illustrated best by using an example.

If $I_a = 1.25$ and $I_s = 1.15$, then

$$S_t = \frac{1.25 - 1.00}{1.25} \times 100\% = \frac{.25}{1.25} = 20\% ,$$

and

$$S_s = \frac{1.25 - 1.15}{1.25} \times 100\% = \frac{.10}{1.25} = 8\% .$$

Therefore, it could be said of the terrace upon which the measurements were made in the example, that the total predicted settlement would be 20 per cent and that the terrace had settled 8 per cent at the time I_a was measured. If the fill of the terrace in question was 18 inches in height, then the final height of the terrace would be

$$18 - .20 \times 18 = 14.4 \text{ inches} .$$

In making calculations from the data of this study, certain assumptions were made. They are listed below.

1. The index of potential settlement as calculated by the volume cut and volume fill method was based on the assumption that movement of soil along the terrace into the cross-sectional area is equal to the soil moved out of the cross-sectional area. All machines in building terraces move soil forward during construction. It is obvious that the soil cut from one cross-sectional area will be deposited some distance along the terrace.

2. The apparent specific gravity throughout the entire terrace ridge was assumed equal to the apparent specific gravity as obtained from a core sample taken between the 4 and 8 inch depth of the terrace.

3. The total per cent settlement as predicted from the index of potential settlement was based on the assumption that the soil will settle until it establishes an equilibrium with all external forces normally subjected to the soil in the area. Settlement would therefore continue until the soil attains an apparent specific gravity of the original soil, or the index of potential settlement will reduce to unity.

4. The per cent settlement based on volume measurement can be used to estimate the per cent settlement for a given height if the assumption is made that settlement will be proportional to depth of fill throughout the terrace. This reasoning is based on the assumption that the apparent specific gravity of each increment of soil in the terrace ridge is homogeneous.

5. The per cent settlement as calculated from the index of potential settlement assumes no soil movement caused by erosion or farming operations. Or it could be assumed that soil movement down the front and back slopes of the terrace will be replaced by terrace maintenance.

6. If the index of potential settlement is less than

unity, the predicted settlement is zero. The soil in such condition has been compacted to an apparent density greater than the original soil. There would possibly be a slight expansion due to the action of freezing and thawing, but would not be sufficient to attain an index of one for the entire terrace.

Statistical

The index of potential settlement was used for most of the statistical analysis with the exception of the penetrometer data and the per cent settlement. This index was derived from the calculations of cross-section and core sample data. The penetrometer data was based on field measurements. The per cent settlement for the period of study was computed from indexes of potential settlement.

The index of potential settlement is a ratio that describes future terrace settlement. Computing the percentage of total predicted settlement would have given a false impression of those terraces compacted to a greater density than the original soil. For accurate comparison, it would have been necessary to employ a negative settlement. There is no justification for making an assumption that sufficient expansion will take place to attain an index of potential settlement of unity. Therefore, the index of potential settlement was considered the best criterion for comparisons of

terraces constructed under different slope, machine, and moisture conditions as well as predicting settlement.

The index of potential settlement as obtained from the partially settled terrace would again describe the possibility of future settlement. In order to include an analysis of the settlement period, even though settlement was not complete, a calculation of per cent settlement was required. A statistical analysis of the calculated per cent settlement was also completed.

The penetrometer was a tool used primarily as a possible means of predicting terrace settlement. A complete analysis was made of the penetrometer data including comparisons as well as correlations with the index of potential settlement data.

The comparisons of the different factors studies, namely, machine, slope, and moisture content, were obtained by applying the F-test (28) to an analysis of variance. For comparing the whirlwind terracer and the moldboard plow and the low and medium slope classes within the same experiment on the Clarion soil site, an analysis of variance with resulting degrees of freedom is shown in Table 2. The mean square of locations within machine and slope was used as the experimental error for testing. The same analysis of variance table was set up in comparing the motor grader and the whirlwind terracer on the high and very high slope classes within the same experiment on the Ida soil site.

Table 2

Form of Analysis of Variance Table Used for
Slope and Machinery Experiments

Source	Degrees of freedom	Sum of squares	Mean square
Machine	1		
Slope	1		
Machine x Slope	1		
Location within Machine and Slope	8		
Subsampling	<u>24</u>		
Total	35		

An analysis of variance was also set up for comparing the different moisture treatments on the moisture controlled experiment. This particular experiment was a randomized complete block type experiment. The analysis of variance is shown in Table 3. The mean square of the interaction of blocks times treatments was used as the experimental error for testing.

Table 3

Form of Analysis of Variance Table Used for
Moisture Controlled Experiment

Source	Degrees of freedom	Sum of squares	Mean square
Blocks	2		
Treatments	2		
Blocks x Treatments	4		
Subsampling	<u>9</u>		
Total	17		

The estimation of the true index of potential settlement was accomplished by calculating the mean with confidence limits. The mean was calculated for the indexes measured at different times as well as those obtained by different methods of measurement. The source of data or combined sources of data which produced no significant difference in the statistical F-test were used to compute the mean. For example, if the slope was found non-significant from the analysis of variance, then the mean and confidence interval was found for all indexes measured at the same time by the same method for all cross-sections built by the same machine.

Correlations of the different methods of measuring index of potential settlement as well as the correlations of

penetrometer readings with index of potential settlement were required. The confidence intervals gave an indication of the errors of sampling by the different methods but did not give any indication of the accuracy of the method itself. Therefore, correlation coefficients for the different methods of measurement were determined.

RESULTS

The results are presented as (a) comparisons of terrace settlement to be found under different slope, machine and moisture conditions, (b) the total predicted settlement of the terraces, and (c) the settlement for the period of study. The indexes of potential settlement obtained from calculations tabulated in Tables 17, 18, and 19 of the appendix were used in determining and presenting the results of the experiments. The penetrometer data were used as obtained from the field measurements.

Comparisons

Slope and machinery

Clarion soil site. There were two separate experiments involving comparisons of slope and machinery. One of the experiments was on Clarion soil where comparisons were made on the settlement as affected by two machines, the moldboard plow and the whirlwind terracer, on two different slope classes. The low slope class included sections with a slope of approximately 4 per cent. The medium slope class included sections with a slope of approximately 8 per cent.

The indexes of potential settlement and penetrometer

readings for the slope and machinery experiment on the Clarion soil site are recorded in Table 4. The locations are designated by symbols based on soil, slope, section number and observation line number. C is used to denote Clarion soil; the L denotes the low slope class and M the medium slope class. The index of potential settlement calculated from readings taken immediately after construction are symbolized by I_a and those based on calculations taken after settlement for period of study are denoted by I_s . The symbol g denotes indexes calculated from the apparent specific gravity determinations. The penetrometer readings are denoted by P with a subscript o for those taken in the original soil and a subscript a for those taken in the newly constructed terrace ridge. There were no penetrometer readings made on the slope and machinery experiment on the Clarion soil site before construction; therefore, only P_a readings are listed. The per cent settlement for the period of study, denoted by the symbol S_s , are also listed in the table.

The index of potential settlement is a ratio symbolizing potential settlement. Based on assumptions previously listed, an index of unity indicates no predicted settlement. The index of potential settlement immediately after construction (designated by I_a) is a ratio that describes the total potential settlement. The index of potential settlement after

partial settlement for period of study (designated by I_s) is a ratio that describes potential settlement expected after that time. I_a and I_{ag} for the slope and machinery experiment on the Clarion soil site were based on measurements made prior to and immediately after construction on September 11, 1951. The P_a measurements were also taken immediately after construction on September 11, 1951. I_s and I_{sg} were based on measurements made prior to construction and on May 2, 1952. The index of potential settlement data, I_a , I_s , I_{ag} , I_{sg} , and the penetrometer readings, P_a , were used in the comparisons.

The significance of the different variables, machine, slope, and machine slope interaction, was determined by applying the F-test to the mean squares of the analysis of variance for each and determining significance at the 1 per cent and 5 per cent levels. If the value of the calculated F exceeded the values tabulated by Snedecor (28, p. 222) for 1 and 8 degrees of freedom, the null hypothesis of difference was rejected. The calculated F with significance denoted by S or N at the 1 per cent and 5 per cent levels for the different criteria of measurement of the slope and machinery experiment on the Clarion soil site are recorded in Table 5. The calculated F values are omitted for ratios where the error mean square was larger. A check was made of those omitted to verify non-significance of the reciprocal ratio for F at 8 and 1 degrees of freedom.

Table 4

Summary of Settlement and Penetrometer Data
Slope and Machinery Experiment
Clarion Soil Site

Location	Machine	Slope	Index of potential settlement				Penetrometer (inches)		Per cent settlement
			I _a	I _s	I _{ag}	I _{sg}	P _o	P _a	
CL1-1	Plow	Low (4%)	1.40	1.32	1.23	1.04		5.0	5.71
2	Plow	Low (4%)	1.22	1.15	1.52	1.03		4.7	5.74
3	Plow	Low (4%)	1.21	1.15	1.14	0.97		6.6	4.96
CL2-1	Plow	Low (4%)	1.16	1.12	1.22	0.99		4.8	3.45
2	Plow	Low (4%)	1.33	1.20	1.01	0.96		5.0	9.77
3	Plow	Low (4%)	1.12	1.06	1.27	1.00		5.9	5.36
CL3-1	Whirlwind	Low (4%)	1.29	1.19	1.48	1.31		9.8	7.75
2	Whirlwind	Low (4%)	1.31	1.24	1.35	1.24		8.0	5.34
3	Whirlwind	Low (4%)	1.29	1.18	1.49	1.39		9.9	8.54
CL4-1	Whirlwind	Low (4%)	1.27	1.16	1.47	1.21		9.2	8.66
2	Whirlwind	Low (4%)	1.26	1.16	1.61	1.25		11.1	7.94
3	Whirlwind	Low (4%)	1.32	1.19	1.41	1.28		10.3	9.86
CL5-1	Whirlwind	Low (4%)	1.31	1.19	1.33	1.25		11.0	9.16
2	Whirlwind	Low (4%)	1.31	1.21	1.35	1.39		10.7	7.63
3	Whirlwind	Low (4%)	1.19	1.04	1.51	1.30		11.0	12.61
CL6-1	Plow	Low (4%)	1.21	1.08	1.16	0.99		10.0	10.74
2	Plow	Low (4%)	1.36	1.21	1.15	1.04		8.8	11.03
3	Plow	Low (4%)	1.23	1.11	1.24	1.02		7.5	9.76

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Table 4 (Concluded)

Location	Machine	Slope	Index of potential settlement			Penetrometer (inches)		Per cent settle- ment
			I _a	I _s	I _{ag}	I _{sg}	P _o	P _a
CM1-1 2 3	Whirlwind	Medium (8%)	1.27	1.13	1.39	1.15	10.9	11.10
	Whirlwind	Medium (8%)	1.48	1.32	1.50	1.20	12.7	10.81
	Whirlwind	Medium (8%)	1.40	1.22	1.49	1.31	12.7	12.86
CM2-1 2 3	Whirlwind	Medium (8%)	1.38	1.20	1.48	1.30	11.2	13.04
	Whirlwind	Medium (8%)	1.52	1.33	1.40	1.28	9.7	12.50
	Whirlwind	Medium (8%)	1.39	1.21	1.47	1.32	13.3	12.95
CM3-1 2 3	Whirlwind	Medium (8%)	1.41	1.29	1.49	1.25	14.6	8.51
	Whirlwind	Medium (8%)	1.37	1.20	1.33	1.19	13.8	12.41
	Whirlwind	Medium (8%)	1.41	1.25	1.25	1.04	14.0	11.31
CM4-1 2 3	Plow	Medium (8%)	1.21	1.11	1.11	1.04	13.0	8.26
	Plow	Medium (8%)	1.16	1.06	1.13	1.01	11.8	8.62
	Plow	Medium (8%)	1.23	1.13	1.16	1.12	11.8	8.13
CM5-1 2 3	Plow	Medium (8%)	1.09	1.04	1.11	1.10	12.2	4.59
	Plow	Medium (8%)	1.25	1.15	1.10	1.18	12.9	8.00
	Plow	Medium (8%)	1.24	1.14	1.13	0.95	11.3	8.06
CM6-1 2 3	Plow	Medium (8%)	1.28	1.10	1.22	1.05	8.4	14.06
	Plow	Medium (8%)	1.42	1.12	1.18	1.15	8.6	21.13
	Plow	Medium (8%)	1.30	1.01	1.15	1.10	9.9	22.31

Table 5

Calculated F Values of the
Slope and Machinery Experiment
Clarion Soil Site¹

	I _a	I _s	I _{ag}	I _{sg}	P _a
Machine	13.363	23.916	64.103	77.848	7.681
1% level	S	S	S	S	N
5% level	S	S	S	S	S
Slope	4.488	---	2.217	---	14.830
1% level	N	N	N	N	S
5% level	N	N	N	N	S
Machine-slope interaction	5.606	14.525	---	7.789	1.427
1% level	N	S	N	N	N
5% level	S	S	N	S	S

¹ Tabulated F 1,8 (28, p. 222) = 11.26 (.01)
5.32 (.05) .

There are several inferences that could be made from the results of Table 5. One is the significant difference between the index of potential settlement between those terraces constructed with the moldboard plow and the whirlwind terracer at the 1 per cent level. Also, after 33 weeks there remains a significant difference of the potential settlement of the terraces constructed by the two different machines at the 1 per cent level. No inference is made about the

significance of the machine-slope interaction of the index of potential settlement measured 33 weeks after construction except that it could be due to soil variations.

The penetrometer measurements did not give a significant difference for the soil hardness at the 1 per cent level where terraces were constructed by the moldboard plow and the whirlwind terracer, but were significantly different at the 5 per cent level. The significance of slope might in part be contributed to soil differences because the steeper soils were lighter or sandier soils.

Ida soil site. The other experiment involving comparison of machines and slopes was on the Ida soil site. The design of the experiment with respect to locations and sampling was exactly like the slope and machinery experiment on the Clarion soil site. Again comparisons of settlement as affected by two machines were made. The two machines included in the study on the Ida soil site were the whirlwind terracer and the motor grader. The slope classes included a group of high slopes of approximately 12 per cent and group of very high slopes of approximately 16 per cent. The data used in comparisons included the index of potential settlement as calculated immediately after construction on October 30, 1951, by the two methods previously described, the index of potential settlement calculated from measurements after partial settlement from October 30, 1951, to April 16, 1952,

and the penetrometer readings as recorded immediately following construction.

The indexes of potential settlement and penetrometer readings are recorded for each location of the Ida soil site in Table 6. The symbols used are equal or equivalent to those used with respect to the Clarion soil site. Again I_a , I_{ag} , I_s , and I_{sg} denote indexes of potential settlement and P_o and P_a denote penetrometer readings. The locations are designated by section and line numbers along with I for Ida soil and H or VH for high or very high slopes respectively.

The significance of the variables were determined by applying the F-test. The calculated F with significance denoted by S or N at the 1 per cent and 5 per cent levels for the different criteria of measurement of the slope and machinery experiment on the Ida soil site are recorded in Table 7.

There are several definite inferences that can be made from the results of Table 7. One is the highly significant difference between the machines which in this case are the motor grader and whirlwind terracer. This highly significant difference between the machines is apparent by all methods of measurement. The significance of the index of potential settlement after 24 weeks of settlement indicates a large difference in the compaction of the soil even after the climatological effects of a winter season.

Table 6

Summary of Settlement and Penetrometer Data
Slope and Machinery Experiment
Ida Soil Site

Location	Machine	Slope class	Index of potential settlement				Penetrometer (inches)		Per cent settle- ment
			Ia	Is	Iag	Isg	Po	Pa	
IH1-1	Grader	High (12%)	0.518	0.522	0.94	0.89	2.1	4.8	-0.77
	Grader	High (12%)	0.679	0.641	0.97	0.96	2.0	2.5	6.00
	Grader	High (12%)	0.841	0.818	0.82	0.90	2.0	3.8	2.73
IH2-1	Grader	High (12%)	0.796	0.773	0.92	0.97	1.7	4.9	2.89
	Grader	High (12%)	0.885	0.880	1.01	0.98	2.0	3.4	0.56
	Grader	High (12%)	0.759	0.775	1.06	0.97	2.0	2.6	-2.11
IH3-1	Grader	High (12%)	0.732	0.662	0.96	1.01	2.1	3.4	9.26
	Grader	High (12%)	0.859	0.825	0.99	1.05	2.3	6.5	3.96
	Grader	High (12%)	0.873	0.843	0.97	1.02	2.2	4.1	3.44
IH4-1	Whirlwind	High (12%)	1.12	1.03	1.32	1.33	2.3	12.0	8.04
	Whirlwind	High (12%)	1.12	1.04	1.17	1.20	1.9	10.4	7.32
	Whirlwind	High (12%)	1.23	1.14	1.22	1.28	2.1	10.7	7.32
IH5-1	Whirlwind	High (12%)	1.22	1.11	1.35	1.23	2.1	12.8	9.02
	Whirlwind	High (12%)	1.06	1.03	1.33	1.28	2.1	12.5	2.83
	Whirlwind	High (12%)	1.14	1.07	1.45	1.21	2.2	14.0	6.14
IH6-1	Whirlwind	High (12%)	1.17	1.04	1.24	1.29	2.1	13.5	11.11
	Whirlwind	High (12%)	1.15	1.07	1.35	1.21	1.7	12.9	6.96
	Whirlwind	High (12%)	1.10	1.08	1.48	1.31	1.7	12.7	1.82

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Table 6 (Concluded)

Location	Machine	Slope class	Index of potential settlement				Penetrometer (inches)		Per cent settle- ment
			I _a	I _s	I _{ag}	I _{sg}	P _o	P _a	
IVH1-1	Whirlwind	Very high (16%)	1.27	1.17	1.27	1.18	2.5	12.7	7.87
2	Whirlwind	Very high (16%)	1.23	1.16	1.36	1.15	2.2	11.8	5.69
3	Whirlwind	Very high (16%)	1.24	1.14	1.37	1.25	1.8	12.6	5.79
IVH2-1	Whirlwind	Very high (16%)	1.14	1.08	1.43	1.16	2.2	14.6	5.26
2	Whirlwind	Very high (16%)	1.17	1.10	1.40	1.22	2.1	11.2	5.98
3	Whirlwind	Very high (16%)	1.22	1.17	1.49	1.29	2.9	15.7	4.10
IVH3-1	Whirlwind	Very high (16%)	1.14	1.07	1.50	1.34	2.2	19.6	6.14
2	Whirlwind	Very high (16%)	1.25	1.14	1.37	1.25	2.6	11.2	8.80
3	Whirlwind	Very high (16%)	1.23	1.17	1.31	1.24	2.4	15.7	4.88
IVH4-1	Grader	Very high (16%)	0.719	0.749	0.81	0.83	2.7	2.8	-4.17
2	Grader	Very high (16%)	0.613	0.621	0.86	0.90	2.3	2.8	-1.31
3	Grader	Very high (16%)	0.569	0.589	0.86	0.90	2.6	2.5	-3.51
IVH5-1	Grader	Very high (16%)	0.679	0.711	0.98	1.01	2.1	3.7	-4.87
2	Grader	Very high (16%)	0.728	0.741	1.05	1.05	2.0	3.7	-1.79
3	Grader	Very high (16%)	0.847	0.843	1.02	1.02	1.6	4.9	0.47
IVH6-1	Grader	Very high (16%)	0.708	0.741	0.93	0.98	1.7	2.8	-0.42
2	Grader	Very high (16%)	0.802	0.829	0.91	0.95	1.8	4.0	-3.36
3	Grader	Very high (16%)	0.856	0.862	0.98	1.01	1.9	5.0	0.70

Table 7

Calculated F Values of the
Slope and Machinery Experiment
Ida Soil Site¹

	I _a	I _s	I _{ag}	I _{sg}	P _o	P _a
Machine	155.894	134.168	110.812	84.8600	---	327.924
1% level	S	S	S	S	N	S
5% level	S	S	S	S	N	S
Slope	---	---	---	---	1.4745	---
1% level	N	N	N	N	N	N
5% level	N	N	N	N	N	N
Machine-slope interaction	2.614	1.633	1.406	---	---	1.888
1% level	N	N	N	N	N	N
5% level	N	N	N	N	N	N

¹ Tabulated $F_{1,8}$ (28, p. 222) = 11.26 (.01)
5.32 (.05) .

Another inference that can be made is that there is no effect of slope on the index of potential settlement. The non-significance of penetrometer data taken in the original soil indicates no difference of soil hardness. The high significance of differences of soil hardness measured in the terraces built by the different machines indicates that soil hardness is affected by the different machines.

Moisture content

The experiment setup for comparisons of different soil moisture contents at time of construction was the moisture controlled experiment performed on Clarion soil on slopes of approximately 6 per cent on terraces constructed with the moldboard plow. The different moisture levels included Treatment No. 0 signifying no irrigation, Treatment No. 1 signifying the application of one inch of water 3 days prior to terrace construction, and Treatment No. 2 signifying the application of one inch of water one day prior to terrace construction.

Table 8 shows the moisture treatment and the measured moisture content, along with the indexes of potential settlement and penetrometer readings for each location. The locations are designated by symbols using W to denote the moisture controlled experiment with A, B, and C as the block designations in addition to the section number and observation line number. I_a , I_{ag} , I_s , and I_{sg} denote the different indexes of potential settlement as previously described as well as the P_o and P_a which symbolize the penetrometer readings in the original soil and after construction.

The variation in moisture samples taken along the same observation line as well as the variation within each section can be noted from Table 8. The moisture content as measured

Table 8

Summary of Settlement and Penetrometer Data
Moisture Controlled Experiment
Clarion Soil Site

(6% slope, plow constructed)

Location	Moisture treatment ¹	Per cent moisture	Index of potential settlement				Penetrometer (inches)		Per cent settlement	
			Index of potential settlement							
			I _a	I _s	I _{ag}	I _{sg}	P _o	P _a		
WA1-1	1	25.8	26.7	1.36	1.19	1.33	1.10	2.6	9.7	12.50
2	1	26.1	27.8	1.42	1.29	1.34	1.09	3.3	9.7	9.15
WA2-1	0	23.2	22.4	1.24	1.16	1.15	1.22	2.0	6.6	6.45
2	0	22.2	22.1	1.36	1.30	1.33	1.26	2.3	10.0	4.41
WA3-1	2	23.9	24.8	1.32	1.22	1.13	1.01	2.9	9.7	7.57
2	2	23.2	23.8	1.16	1.10	1.09	0.98	2.5	8.5	5.17
WB1-1	1	18.8	22.5	1.35	1.23	1.23	1.06	2.0	8.8	8.89
2	1	23.0	23.0	1.28	1.20	1.23	1.05	3.0	7.8	6.25
WB2-1	2	26.0	18.9	1.22	1.22	1.15	1.04	1.8	7.4	0.00
2	2	20.4	24.6	1.22	1.17	1.08	0.96	2.5	9.0	4.10
WB3-1	0	21.8	20.8	1.44	1.38	1.14	1.08	2.3	6.5	4.17
2	0	19.7	23.5	1.44	1.30	1.16	1.00	1.5	5.4	9.72
WC1-1	2	28.8	17.3	1.48	1.39	1.17	1.02	2.8	7.9	6.08
2	2	22.7	16.6	1.38	1.26	0.99	1.09	2.5	8.3	8.70

(Concluded on next page)

Table 8 (Concluded)

Location	Moisture ¹ treatment	Per cent moisture	Index of potential settlement				Penetrometer (inches)		Per cent settle- ment	
			I _a	I _s	I _{ag}	I _{sg}	P _o	P _a		
WC2-1 2	1	24.0	18.8	1.29	1.19	1.05	0.93	2.2	8.5	7.75
	1	22.9	19.8	1.29	1.24	1.08	1.03	2.3	7.0	3.85
WC3-1 2	0	20.8	17.2	1.35	1.24	1.09	1.11	1.9	8.5	8.15
	0	16.5	17.7	1.39	1.28	1.18	0.99	1.9	7.0	7.91

¹ Moisture treatments:

- No. 0 = not irrigated,
- No. 1 = irrigated with 1" of water three days prior to construction,
- No. 2 = irrigated with 1" of water one day prior to construction.

does not show the effect of the irrigation. This fact was known early in the experiment, but the possibility of the variation of moisture samples being caused by different depths of the wetted soil warranted continuation of the experiment basing comparison on the treatment and not the moisture contents as obtained from the result of the treatments.

The data used in comparison of the different moisture treatments included the indexes of potential settlement and the penetrometer readings made before and immediately after construction on September 21, 1951. The index of potential settlement as calculated from measurements after settlement from September 21, 1951, to May 2, 1951, was also used in comparing the moisture treatments.

The significance of the variables were determined by the F-test in the same manner as with the slope and machinery experiments. Significance was apparent if the calculated F values exceeded F values as tabulated by Snedecor (28, p. 222) for 2 and 4 degrees of freedom at the 1 per cent and 5 per cent levels.

The calculated F values with significance denoted by S or N at the 1 percent and 5 per cent levels for the different criteria of measurement on the moisture controlled experiment are recorded in Table 9.

The inference that can be made from the results of

Table 9
Calculated F Values of the
Moisture Controlled Experiment¹

	I _a	I _s	I _{ag}	I _{sg}	P _o	P _a
Treatments	---	---	2.1775	1.2829	6.5537	3.289
1% level	N	N	N	N	N	N
5% level	N	N	N	N	N	N
Block	---	---	3.2500	1.1857	3.1251	4.493
1% level	N	N	N	N	N	N
5% level	N	N	N	N	N	N
¹ Tabulated F _{2,4} (28, p. 222) = 18.00 (.01) 6.94 (.05) .						

Table 9 is that there is no significant difference of the index of potential settlement between the moisture treatments immediately after construction or after partial settlement by either method of measurement. The only significance found in the analysis is the difference between the treated areas of soil hardness measured in the original soil. Since soil hardness varies with moisture content, this significance at the 5 per cent level indicates that the soil was affected by the irrigation treatments.

Predicting Total Settlement

The prediction of the total settlement of terraces can be made on a percentage basis if the index of potential settlement is known, measured or estimated. The indexes of potential settlement determined by this study can be used within certain limits as an estimate of the settlement of terraces under similar circumstances provided the assumptions stated previously are made.

Two methods were employed to calculate the index of potential settlement while only one method was used to measure soil hardness. The method of cross-section measurements for calculating the index of potential settlement is considered more accurate than the method of core samples, the reason being that the cross-section data was based on actual measurement of the entire cross-section rather than a small sample. Also, the standard errors of the cross-section data were smaller than the core sample data. The index of potential settlement was not calculated from the penetrometer data. The penetrometer was used since it might provide a simple possible means of predicting settlement.

Cross-section data

The indexes of potential settlement recorded in Table 10 are based on the cross-section measurements made before and

Table 10

Average Index of Potential Settlement
Based on Cross-section Measurements
Immediately After Construction

Experi- ment	Soil	Machine	No. of obs.	Ave- rage I_a	Confidence limits	
					5%	1%
Slope and machinery	Clarion	Whirlwind	18	1.34	1.38-1.30	1.40-1.20
		Moldboard	18	1.25	1.29-1.21	1.30-1.19
Slope and machinery	Ida	Whirlwind	18	1.18	1.23-1.13	1.25-1.11
		Motor grader	18	0.75	0.80-0.70	0.82-0.68
Moisture control	Clarion	Moldboard	18	1.34	1.40-1.27	1.43-1.24

immediately after construction. The indexes are separated according to the variables found significant for each of the three experiments. The averages for the individual slopes and moisture treatments are not computed separately because the analysis of variance did not prove them significant. Since there was a significant difference between machines, the average is based on the total of all observations built by the same machine.

The lower index of potential settlement of the whirlwind terracer on the Ida soil compared to the Clarion soil is not necessarily a result of soil textural differences alone. Larger size terraces were necessary on Ida soil requiring a greater amount of soil to be moved and a greater number of

passes to be made with the machine. The only apparent explanation for the differences of the average index of potential settlement of terraces built by the moldboard plow on the two Clarion soil experiments is in differences of soil properties within the field. The moisture controlled experiment was located on heavier soil on the third terrace. As observed from the moisture content data of the two experiments, the difference could not be contributed to different moisture contents. The procedure was the same for all terraces constructed with the plow except that the moisture controlled terrace required approximately six more passes than did the other terraces. The additional passes would exert greater compactive energy and should theoretically lower the initial index of potential settlement. The results are converse to this reasoning, strongly indicating that procedure is not accountable for the difference. The only difference in cover would be the additional 10 days' growth of the alfalfa which could have contributed slightly more vegetation to the terrace ridge of the moisture controlled experiment.

The smaller confidence interval for the moldboard plow on the slope and machinery experiment gives an indication of better accuracy for that particular experiment.

As shown previously, the total predicted per cent settlement can be computed by the following formula:

$$S_t = \frac{I_a - 1.00}{I_a} \times 100 ,$$

where

S_t = total predicted per cent settlement

I_a = index of potential settlement immediately after construction.

The above formula is used with the assumption that the soil in the terrace ridge will settle until it attains an apparent specific gravity equal to the original soil. It is also assumed that soil movement by erosion and farming operations will be replaced by terrace maintenance.

An index of potential settlement of less than 1.00, such as the value of 0.75 for the motor grader, indicates a very compact terrace and should not be used in the above formula. There is as yet no basis for assuming that such a terrace will loosen and attain an index of potential settlement of unity. Such slight expansion as was found with a majority of the cross-sections after the first winter was negligible. The per cent settlement for terraces compacted to a greater density than the original soil should be considered zero.

The per cent predicted settlement calculated from the mean index of potential settlement was 25.4 per cent and 20.0 per cent for the whirlwind terracer and moldboard plow, respectively, on the Clarion soil, 15.3 per cent and 0 per cent for the whirlwind terracer and motor grader, respectively,

on the Ida soil, and 25.4 per cent for the moldboard plow on the moisture controlled terrace on Clarion soil.

The per cent total settlement as calculated from the index of potential settlement can be applied to the height of fill of terrace ridge even though the index was derived from volume measurements. Application of the per cent settlement to some unit of height is based on the assumption of equal proportion of settlement throughout the terrace ridge. That is, the soil will settle an amount directly proportional to the height of fill above the undisturbed soil.

The use of such a procedure in predicting settlement of terraces can best be explained by an example. Take for instance, a whirlwind constructed terrace on Clarion soil. The experimental data shows the average index of potential settlement as 1.34. The per cent total predicted settlement would be

$$S_t = \frac{1.34 - 1.00}{1.34} \times 100\% = 25.4\%.$$

If the height of fill at the highest point on the ridge was 1.5 feet or 18 inches, then the settlement would reduce the height

$$25.4 \times 1.50 = .38 \text{ ft. or } 4.6 \text{ in.}$$

The net height of the terrace would be

$$1.50 - 0.38 = 1.12 \text{ ft. or } 13.4 \text{ in.}$$

For field application of the settlement data, the height of fill must be known, calculated, or estimated. In most cases terraces are completed before they are checked. In such cases the fill height can be estimated or calculated by interpolating between elevations taken on undisturbed area above and below the terrace and subtracting from the ridge height. From observation of the cross-sections of these experimental terraces it is reasonably safe to use the height of ridge above the channel as the height of fill on the low and medium slopes. The height of fill in most cases was equal to or slightly less than the height of ridge above the channel. On the steeper slopes, the height of fill exceeded the height of ridge above the channel from as much as 10 per cent to 30 per cent. Therefore, the height of ridge above the channel should not be used as the height of fill. The height varies with slope of land, procedure of construction and shape of terrace.

Core sample data

The index of potential settlement based on core sample data taken before and immediately after construction is given in Table 11.

The index of potential settlement as computed from core samples was not equal to the index of potential settlement calculated from the cross-section data. In order to evaluate

Table 11

Average Index of Potential Settlement
Based on Core Sample Data
Immediately After Construction

Experi- ment	Soil	Machine	No. of obs.	Ave- rage I_{ag}	Confidence limits	
					5%	1%
Slope and machinery	Clarion	Whirlwind	18	1.43	1.48-1.38	1.50-1.37
		Moldboard	18	1.18	1.23-1.13	1.25-1.11
Slope and machinery	Ida	Whirlwind	18	1.36	1.41-1.30	1.44-1.28
		Motor grader	18	0.95	1.00-0.90	1.03-0.87
Moisture content	Clarion	Moldboard	18	1.16	1.21-1.12	1.22-1.10

the two methods of measurements, correlation coefficients were determined. Using the symbols previously defined (I_a for the index of potential settlement based on cross-section measurements immediately after construction and I_{ag} for the index of potential settlement based on core samples taken immediately after construction), the correlation coefficient of $I_a I_{ag}$ on Clarion soil was 0.513. On Ida soil the correlation coefficient of $I_a I_{ag}$ was 0.386. The tabulated value of the correlation coefficient for significance was 0.632 at the 5 per cent level and 0.765 at the 1 per cent level (28). The correlation coefficient of $I_a I_{ag}$ on the moisture controlled experiment was 0.526 with 0.811 and 0.917 at 5 per cent and 1 per cent, respectively,

needed for significance. Therefore, the accuracy of the core samples as a measure of predicting settlement is questionable.

It is noted when comparing I_{ag} with I_a that for all whirlwind and grader constructed terraces, I_{ag} is higher than I_a . For all plow constructed terraces I_{ag} is lower than I_a . If the position within the terrace where the core sample was obtained is considered with respect to the procedure of construction for each of the three types of machines, a probable explanation can be derived. The procedure of construction of both the whirlwind terracer and motor grader are such that the base of the ridge was formed at the very beginning of operation. Consequently, there is more compaction by either the machine or soil at the base of the terrace ridge than near the surface. On the other hand, the base of the ridge of the plow constructed terraces is not formed until the latter stages of construction. Consequently, the compaction by the machine would have a greater effect upon the upper portion of the terrace than upon the base or lower sections of the fill material. The core samples were obtained between the 4 inch and 8 inch depths of the terrace ridge. If the above hypothesis is correct, core samples taken from a deeper point in the terrace ridge would provide a more accurate indication of the apparent specific gravity of the entire terrace ridge.

Soil hardness

The possibility of using a measure of soil hardness as a means of predicting terrace settlement was investigated. The penetrometer was used to measure soil hardness and a statistical analysis of the data was carried out.

Comparisons of the different terraces based on penetrometer data were carried out in conjunction with comparisons based on index of potential settlement (see Tables 5, 7, and 9). In order to evaluate the accuracy of penetrometer readings as a method of predicting settlement, correlation coefficients were determined for the penetrometer readings in the newly constructed terrace, P_a , in relation to the index of potential settlement calculated from cross-section measurements immediately after construction, I_a . The correlation coefficient of $I_a P_a$ for the slope and machinery experiment on Clarion soil was 0.472 and on Ida soil 0.207 with 0.632 and .765 being significant at the 5 per cent and 1 per cent levels, respectively. The correlation coefficient of $I_a P_a$ for the moisture controlled experiment on Clarion soil was 0.209 with 0.811 and 0.917 being significant at the 5 per cent and 1 per cent levels, respectively. Therefore, it is concluded that penetrometer readings as used in this study are not satisfactory for predicting settlement.

Settlement for Period of Study

The actual rate of settlement of terraces throughout the time from construction to complete stabilization is not within the scope of this study. Only the settlement for the time interval from fall to spring is reported here. However, additional data is to be taken at a later date. It would seem reasonable to assume that the rate of settlement would not be constant for any unit of time but would vary as climatological and other physical forces act on the terraces. Even though it is probable that the rate of settlement is not constant, an analysis of the settlement from the time of construction to the time of the first seed-bed preparation is an important part of the overall knowledge of terrace settlement.

The spring measurements of the experimental terraces were made prior to any farming operations. Therefore, all of the settlement for the interval of time investigated can be contributed to climatological forces. The dates of construction, date of spring measurement, and resulting time interval are recorded in Table 12 along with the precipitation data for both the slope and machinery experiment and moisture controlled experiment on the Clarion soil site. The same information for the Ida soil site is recorded in Table 13. The information presented in these tables is for

Table 12
Precipitation at Clarion Soil Site
During Settlement Study

Period	Number days	Total precipitation (inches)	Melted snow (inches)	Per cent snow
Sept. 11, 1951 ¹	10	0.35		
Sept. 21, 1951 ²	9	0.20		
Sept. 30, 1951	31	2.81		
Oct. 31, 1951	30	1.27	0.03	2%
Nov. 30, 1951	31	0.44	0.35	80%
Dec. 31, 1951	31	0.80	0.25	31%
Jan. 31, 1952	29	0.39	0.28	72%
Feb. 29, 1952	31	3.49		
Mar. 31, 1952	30	1.54		
April 31, 1952	2	0		
May 2, 1952 ³				
Totals	234	11.29	0.91	8%

¹ Construction completed and measurements made on slope and machinery experimental terraces.

² Construction completed and measurements made on moisture controlled experimental terraces.

³ Measurements made at end of settlement study.

Table 13
Precipitation at Ida Soil Site
During Settlement Study

Period	Number days	Total precipitation (inches)	Melted snow (inches)	Per cent snow
Oct. 30, 1951 ¹	1			
Oct. 31, 1951	30	0.31	0.25	81%
Nov. 30, 1951	31	0.46	0.46	100%
Dec. 31, 1951	31	1.10	0.15	14%
Jan. 31, 1952	29	0.87	0.17	20%
Feb. 29, 1952	31	2.83	1.83	65%
Mar. 31, 1952	16	1.55		
April 16, 1952 ²				
Totals	169	7.12	2.86	40%

¹ Construction completed on slope and machinery
experimental terraces.

² Measurements made at end of settlement study.

observation of the climatological forces for the period. No attempt has been made to analyze the relation of this data to the actual settlement. Only after many years of intensive investigations could such an analysis be made.

Per cent settlement

The per cent settlement for the time intervals from terrace construction in the fall to measurements in the spring was computed for each cross-section. This per cent settlement was not computed from the core sample data. Using the same symbols as previously used, the per cent settlement was computed from the formula

$$S_s = \frac{I_a - I_s}{I_a} \times 100 .$$

An analysis of variance was computed on per cent settlement for each experiment for the time interval investigated. No significant difference was found between machines or slopes on the slope and machinery experiment on Clarion soil, nor was there significant difference between treatments or blocks on the moisture controlled experiment. On the slope and machinery experiment on Ida soil a significant difference with respect to machines was found at the 1 per cent level and with respect to slopes and machine-slope interaction was found at the 5 per cent level. Since the total predicted

per cent settlement for the grader constructed terraces was zero, such high significance would be expected.

Averages with confidence limits were then computed for the per cent settlement for each experiment where no significant differences were found between variables and separated according to the variable factors where significance was found. Table 14 gives the average per cent settlement of the terraces for the time interval from fall of 1951 to spring of 1952.

Table 14 shows that the per cent settlement falls far short of the total predicted per cent settlement that can be calculated from the data of Table 10. This means that settlement was probably incomplete at the time spring measurements were made. One exception, of course, is the grader constructed terrace of which no settlement would be expected. The negative settlement of the grader terrace on the very high slope class shows a slight expansion which may be due to the action of freezing and thawing. However, the amount of expansion is very small considering the size of terrace. The small per cent settlement of the grader constructed terraces on the high slope class could possibly be due to a small amount of loose non-compacted soil on the back slope of the terrace ridge which settled more than enough to compensate for the slight expansion. There is no reason to believe that a different amount of expansion would have taken place on the very high slopes.

Table 14

Average Per Cent Settlement for Period of Study
Based on Cross-section Measurements

Experiment	Soil	Machine and (slope)	No. of obs.	Ave. Ss	Confidence limits		
					5%	1%	
Slope and machinery	Clarion	Whirlwind and plow (all)	36	9.85	12.00 - 7.65	12.79 - 6.90	
	Ida	Whirlwind (high)	9	6.71	8.08 - 5.34	8.67 - 4.74	
Slope and machinery		Whirlwind (very high)	9	6.06	7.42 - 4.69	8.02 - 4.09	
		Grader (high)	9	2.89	4.26 - 1.52	4.85 - 0.92	
		Grader (very high)	9	-2.03	0.66 - -3.40	0.06 - -3.99	
Moisture control	Clarion	Plow	18	6.71	8.43 - 4.99	9.07 - 4.35	

Potential settlement

The index of potential settlement based on terrace measurements taken several months after construction does not give a true indication of the changes which have taken place within the terrace. Instead, it describes future changes expected after the time such measurements were made. A better indication of change was per cent settlement presented in the previous section which was the actual settlement that had taken place. The index of potential settlement based on spring measurements does warrant presentation since it describes the future predicted settlement although not total predicted settlement as was computed from the initial readings after construction. For instance, the mean I_s of the whirlwind constructed terraces on Clarion soil of 1.21 indicates the future settlement that would be expected after May 2, 1952. Initially the index of potential settlement after construction, I_a , on September 11, 1951 for the same terraces was 1.34. It is assumed in both cases that the index of potential settlement will attain unity when settlement is complete.

Table 15 gives the average index of potential settlement with confidence limits based on calculations from the cross-section measurements taken during the spring of 1952. They are listed for each experiment or separated within the

Table 15

Average Index of Potential Settlement
Based on Cross-section Measurements
After Settlement for Period of Study

Experiment	Soil	Machine	No. of obs.	Ave. I_s	Confidence limits	
					5%	1%
Slope and machinery	Clarion	Whirlwind	18	1.21	1.23-1.18	1.24-1.17
		Plow	18	1.13	1.15-1.10	1.16-1.09
Slope and machinery	Ida	Whirlwind	18	1.10	1.15-1.05	1.17-1.03
		Grader	18	0.75	0.80-0.70	0.81-0.69
Moisture control	Clarion	Plow	18	1.24	1.29-1.20	1.31-1.18

experiment for those variable factors found significant from the analysis of variance.

It is noted by comparing Table 15 with Table 10 that a difference of the index of potential settlement for those terraces constructed by different machines still remains 24 to 33 weeks after construction. This difference was proven significant and recorded in Table 5. The order of rank of the indexes of potential settlement after partial settlement is approximately the same as the indexes immediately after construction. One exception is that the index of the plow constructed terrace has not decreased to the same extent as the plow constructed terrace of the slope and machinery experiment. The rate of settlement would of course be less

which can be noted from Table 14. The only plausible theory that could account for the inconsistent settlement would be the soil differences as was pointed out in discussing the difference of the initial indexes of potential settlement of the two moldboard constructed terraces.

The index of potential settlement of the terrace after partial settlement was determined by core sample measurements in addition to cross-section measurements. The average indexes of potential settlement based on core sample data are presented with confidence limits in Table 16.

Table 16
Average Index of Potential Settlement
Based on Core Sample Data
After Settlement for Period of Study

Experiment	Soil	Machine	No. of obs.	Ave I_{sg}	Confidence limits	
					5%	1%
Slope and machinery	Clarion	Whirlwind	18	1.26	1.30-1.22	1.31-1.21
		Plow	18	1.13	1.08-1.00	1.09-0.99
Slope and machinery	Ida	Whirlwind	18	1.25	1.29-1.20	1.31-1.18
		Grader	18	0.97	1.01-0.92	1.03-0.90
Moisture controlled	Clarion	Plow	18	1.06	1.11-1.00	1.13-0.99

Again when I_{sg} is compared with I_s as I_{ag} was compared with I_a , the indexes of potential settlement based on core samples compared with those based on cross-sections

are notably lower for the terraces constructed with the moldboard plow and higher for the terraces constructed with the whirlwind terracer and motor grader.

CONCLUSIONS

Listed below are the conclusions derived from results and observations of this study.

1. There was a significant difference between the index of potential settlement of terraces built with the whirlwind terracer and moldboard plow on Clarion soil and the whirlwind terracer and motor grader on Ida soil.

2. The per cent predicted settlement calculated from the mean index of potential settlement based on cross-section measurements was 25.4 per cent and 20.0 per cent for the whirlwind terracer and moldboard plow, respectively, on the Clarion soil, 15.3 per cent and 0.0 per cent for the whirlwind terracer and motor grader, respectively, on the Ida soil, and 25.4 per cent for the moldboard plow on the moisture controlled terrace on Clarion soil.

3. Differences were observed in the index of potential settlement of terraces constructed within the same field in two separate experiments by the moldboard plow. These differences are probably due to soil variations between the two experiments.

4. There were no significant differences in the rate

of settlement of the terraces for the first winter of installation except on the Ida soil site where the grader constructed terraces had a predicted settlement of zero.

5. Slope does not have any apparent effect upon the index of potential settlement as was proven by the non-significant differences when 4 per cent and 8 per cent slopes were compared on Clarion soil and 12 per cent and 16 per cent slopes were compared on Ida soil.

6. The index of potential settlement was not affected by the different moisture treatments used in this study. However, due to the fairly wet season, all moisture contents were within a fairly narrow range of available moisture. The moisture treatments of no irrigation, application of 1 inch of water three days prior to construction, and application of 1 inch of water one day prior to construction did not give enough difference in moisture content of the soil. It is quite possible that a wider range would have given different results.

7. Differences in the probable settlement of terraces constructed with the whirlwind terracer were observed on the Ida and Clarion soils. Due to the impossibility of replicating the experiment, the differences are confounded with slope, size, and the number of passes by the machine in building the terraces.

8. The computation of index of potential settlement

from core samples taken between 4 and 8 inch depths was not comparable to the index calculated from cross-sections. Indications were that samples taken at deeper depths could have given satisfactory results. The standard error, which indicates accuracy, was only slightly higher for the indexes calculated from core samples than the standard error of the indexes calculated from cross-sections.

9. The direct measurement of soil hardness by the use of the penetrometer did not give a satisfactory indication of predicted settlement as compared to index of potential settlement calculated from cross-section data.

10. The use of a fish cord and rod was a satisfactory method of obtaining accurate cross-sections in a minimum of time.

SUGGESTIONS FOR FUTURE STUDY

Observations during the study that indicate the need for further investigation include:

1. Continuation of measurements of the experimental terraces used in this study to evaluate the effect of farming operations on the reduction of the terrace size.
2. A study of the effect of vegetative cover at time of construction on the settlement of terraces.
3. Expanding this study or setting up a similar experiment to investigate settlement on additional soils.
4. An investigation of the effect of different methods of terrace construction on soil properties such as structure and permeability.
5. An analytical study of the compactive energy exerted on a terrace during construction and determination of optimum moisture for the compactive energy.
6. A study of the relationships of optimum moisture for maximum compaction and the optimum moisture for efficient soil movement in construction.
7. A study of the possible improvements of methods and procedures for effective terrace maintenance.

SUMMARY

This study was conducted for the purpose of determining the amount and rate of settlement that would be expected of a terrace after construction. Methods of predicting settlement and comparisons of the different factors that affect settlement were incorporated into the study. The investigation consisted of field experiments of actual terrace construction and measurement designed to accomplish the objectives as completely as possible.

The variable factors incorporated into the experiments were soil, slope, machine, and moisture content. The measurements included cross-sections, apparent specific gravity determinations from core samples, and penetrometer readings.

The investigation was divided into three separate experiments. They were: (1) the slope and machinery experiment on Clarion soil, of glacial origin, (2) the slope and machinery experiment on Ida soil, a loess deposit, and (3) the moisture controlled experiment. The slope and machinery experiment on Clarion soil included 36 observations. Half of the observations were on a low slope class of approximately 4 per cent and half on a high slope class of approximately 8 per cent. Part of those on each slope class were built by a whirlwind terracer and part with a moldboard plow. The

slope and machinery experiment on Ida soil was designed in a similar manner as on the Clarion soil except that the slope classes were high and very high at approximately 12 and 16 per cent, respectively. The two machines studied on the Ida soil were the whirlwind terracer and the motor grader. The moisture controlled experiment was conducted on Clarion soil on approximately a 6 per cent slope constructed entirely with a moldboard plow. This experiment included three moisture treatments within each of three blocks. There were two observations made within each treatment within each block making a total of 18 observations.

All of the terraces were constructed during the fall of 1951. Measurements were made prior to construction, immediately after construction, and 24 to 33 weeks after construction during the spring of 1952. The index of potential settlement, a ratio of the volume of fill to the volume of cut, was derived from the cross-section measurements and core sample measurements immediately after construction and again after spring measurements. Penetrometer readings were taken only at time of construction.

The comparisons of data showed a significant difference at the 1 per cent level of the index of potential settlement of terraces constructed by the whirlwind terracer and the moldboard plow on Clarion soil. No significant difference was found between the low and medium slope classes. There

were highly significant differences beyond the 1 per cent level between the index of potential settlement of terraces constructed by the whirlwind terracer and motor grader on Ida soil. The comparisons of high and very high slopes on Ida soil showed no significant difference. There were no significant differences between the moisture treatments on Clarion soil, but the moisture treatments did not give satisfactory moisture differences.

The average indexes of potential settlement based on cross-section measurements were 1.34 and 1.25 for the whirlwind and plow constructed terraces, respectively, on the Clarion soil. The average indexes of potential settlement on the Ida soil for the whirlwind terracer and motor grader were 1.18 and 0.75 respectively. The plow constructed terrace of the moisture controlled experiment on Clarion soil gave an average index of potential settlement of 1.34. Soil variation within the same field probably caused the difference of the indexes of potential settlement of the plow constructed terraces of the different experiments. The index of potential settlement of 1.25 for the slope and machinery experiment is considered more reliable because of its smaller confidence interval.

There were no significant differences between the rates of settlement within the three experiments except on the Ida soil. A difference of the rate of settlement on Ida soil

would be obvious since the total predicted settlement of those terraces built by the motor grader was zero while the average predicted settlement of the whirlwind constructed terrace was 15.3 per cent.

The other methods of predicting settlement such as core sample measurements and penetrometer readings were compared with the cross-section measurements. The correlation coefficients were fairly low indicating that core samples and penetrometer readings are inaccurate methods of investigating or predicting settlement of terraces if used in the same manner as in this study. Indications are that the discrepancies found in this study could be corrected by further refinements of the methods used here.

SELECTED REFERENCES

1. Beach, W. E. Factors affecting performance of tile ditching machines. Unpublished M. S. Thesis. Ames, Iowa. Iowa State College Library. 1948.
2. Benedict, R. H. Methods and cost of terrace construction under Iowa conditions. Unpublished M. S. Thesis. Ames, Iowa. Iowa State College Library. 1948.
3. Biot, M. A. General theory of three-dimensional consolidation. J. Applied Physics. 12:155-164. 1941.
4. Clark, M. W. and Wooley, J. C. Terracing for erosion control. Mo. Agr. Exp. Sta. Bul. 507. 1947.
5. Clyde, A. W. Terracing to reduce erosion. Iowa State College Agr. Ext. Serv. Bul. 172. 1934.
6. Coile, T. S. Soil sampler. Soil Sci. 42:139-142. 1936.
7. Doner, R. D. A theory of arch action in granular media. Agr. Eng. J. 17:299-304. 1936.
8. Frevert, R. K. Mechanics of tillage. Unpublished M. S. Thesis. Ames, Iowa. Iowa State College Library. 1940.
9. Guy, H. P. Level terrace design as affected by hydrologic factors. Unpublished M. S. Thesis. Ames, Iowa. Iowa State College Library. 1951.
10. Hall, A. R. Terracing in the southern piedmont. Agr. Hist. 23:96-109. 1949.
11. Hamilton, C. L. Terracing for soil and water conservation. U. S. Dept. of Agr. Farmers Bul. 1789. 1938.
12. Hermismier, L. F. Terraces constructed with five types of machines in western Iowa. Unpublished M. S. Thesis. Ames, Iowa. Iowa State College Library. 1950.

13. Holman, A. T. Terrace cross-sections as influenced by soil, crop, land slopes, and farm machinery. Agr. Eng. J. 18:5-8. 1937.
14. Johnson, H. P. Seepage through loessal earth dams. Unpublished M. S. Thesis. Ames, Iowa. Iowa State College Library. 1950.
15. Markwich, A. H. D. Basic principles of soil compaction. Surveyor. 104:311-312. 1945.
16. McKibben, E. G. and Hull, D. O. Soil penetration test as a means of predicting rolling resistance. Agr. Eng. J. 21:231-234. 1940.
17. McKittrick, J. L. Terracing to save soil. Univ. of Ky. Agr. Ext. Ser. Bul. 473. 1949.
18. Musgrave, G. W. and Norton, R. A. Soil and water conservation investigation at the Soil Conservation Experiment Station Missouri Valley Loess Region, Clarinda, Iowa. Progress Report 1931-1935. U. S. Dept. of Agr. Tech. Bul. 558. 1937.
19. Proctor, R. R. Design and construction of rolled earth filled dams. I. Fundamentals of soil compaction. Eng. News Rec. 111:245-248. 1933.
20. ———. Design and construction of rolled earth filled dams. II. Description of field and laboratory methods. Eng. News Rec. 111:286-289. 1933.
21. Reed, I. F. Method of studying soil packing by tractors. Agr. Eng. J. 21:281-282, 285. 1940.
22. Renoll, E. S. Tillage, weed control, and corn yields on certain Iowa soils. Unpublished M. S. Thesis. Iowa State College Library. 1949.
23. Samsel, L. G. Building and maintaining terraces with ordinary farm machinery. Agr. Eng. J. 24:337-338, 342. 1943.
24. Schoenleber, L. H. Terrace dimension changes and the movement of terrace ridges. Agr. Eng. J. 21:477-478. 1940.
25. Schwab, G. O., Frevert, R. K., and Barnes, K. K. Manual of soil and water conservation engineering. Dubuque, Iowa. Wm. C. Brown Co. 1950.

26. Shipman, R. C. and Cole, R. O. Building terraces with the moldboard plow. Agr. Eng. J. 25:15-16. 1944.
27. Smith, D. D. and others. Investigation in erosion control and reclamation of eroded shelby and related soils at the Conservation Experiment Station, Bethany, Mo. 1930-1942. U. S. Dept. of Agr. Tech. Bul. 883. 1945.
28. Snedecor, G. W. Statistical methods. 4 ed. Ames, Iowa. Iowa State College Press. 1946.
29. Spangler, M. G. Soil engineering. Scranton. International Textbook Company. 1951.
30. Stone, A. A. and Williams, I. L. Measurement of soil hardness. Agr. Eng. J. 20:25-26. 1939.
31. Springer, D. E. Terrace construction by plowing. Agr. Eng. J. 23:284, 286. 1942.
32. Wilson, H. A. and Browning, G. M. Loessial soil in western Iowa as construction material for earth dams. Soil Sci. Soc. of Amer. Proc. 11:127-130. 1946.
33. Zingg, A. W. Soil movement within the surface profile of terraced land. Agr. Eng. J. 23:93-94. 1942.
34. _____ and Whitt, D. M. Distribution of corn yields on farm terraces on the shelby soil. Agr. Eng. J. 23:126, 128. 1942.

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APPENDIX

List of Symbols and Abbreviations
(Used in Tables 17, 18, and 19)

Loc.	Location designation of observation sections and lines
	C Clarion soil
	I Ida soil
	L Low slope class (4%)
	M Medium slope class (8%)
	H High slope class (12%)
	VH Very high slope class (16%)
	W Moisture controlled terrace
Mac.	Machine used in construction of terrace
	Wh'lw'd Whirlwind terracer
	Plow Moldboard plow
	Grader Motor grader
S.C.	Slope class
S	Slope measured from original ground line of cross-section in per cent
m.t.	Moisture treatment
	0 Not irrigated
	1 Irrigated with one inch of water three days prior to construction
	2 Irrigated with one inch of water one day prior to construction
m	Moisture content of soil at time of constructing terrace in per cent
	m ₁ Sample No. 1
	m ₂ Sample No. 2
A _{cu}	Area of cut from the upper portion of terrace cross-section in sq. ft.
A _{cl}	Area of cut from the lower portion of the terrace cross-section in sq. ft.
A _{fa}	Area of fill immediately following construction in sq. ft.
A _{fs}	Area of fill after settlement for the time interval investigated in sq. ft.
A _k	Area of cut refilled during construction in sq. ft.

R_L	Radius of curvature of staked line of terrace in ft.
R_{Acu}	Radius of curvature of cut area on the upper portion of terrace cross-section in ft.
R_{Acl}	Radius of curvature of cut area on the lower portion of the terrace cross-section in ft.
R_{Af}	Radius of curvature of fill area in ft.
R_{Ak}	Radius of curvature of cut area refilled during construction
Z_{cu}	Curvature correction factor of upper cut area
Z_{cl}	Curvature correction factor of lower cut area
Z_f	Curvature correction factor of fill area
Z_k	Curvature correction factor of cut area refilled during construction
V_{cu}	Volume of cut from upper portion of terrace equivalent to a unit length along staked line of terrace in cu. ft.
V_{cl}	Volume of cut from lower portion of terrace equivalent to a unit length along staked line of terrace.
V_{fa}	Volume of fill immediately after construction equivalent to a unit length along staked line of terrace in cu. ft.
V_{fs}	Volume of fill after settlement for time interval investigated equivalent to a unit length along staked line of terrace in cu. ft.
V_k	Volume of cut area refilled during construction equivalent to a unit length along staked line of terrace in cu. ft.
$V_c + k$	Total volume of cut in cu. ft.
$V_{fa} + k$	Total volume of fill immediately after construction in cu. ft.
$V_{fs} + k$	Total volume of fill after settlement for time interval investigated in cu. ft.
I_a	Index of potential settlement based on cross-section measurements immediately after construction.

I _s	Index of potential settlement based on cross-section measurements after settlement for time interval investigated.
W _{do}	Dry weight of core sample taken from original ground in gms.
D _o	Bulk density of original soil in lbs./cu. ft.
G _o	Apparent specific gravity of original soil
W _{da}	Dry weight of core sample taken from newly constructed terrace ridge.
D _a	Bulk density of soil of newly constructed terrace ridge in lbs./cu. ft.
G _a	Apparent specific gravity of soil of newly constructed terrace ridge.
W _{ds}	Dry weight of core sample taken from settled terrace ridge at end of time interval investigated in gms.
D _s	Bulk density of soil in terrace ridge after settlement for time interval investigated in lbs./cu. ft.
G _s	Apparent specific gravity of soil in terrace ridge after settlement for time interval investigated
I _{ag}	Index of potential settlement immediately following construction based on core sample measurements
I _{sg}	Index of potential settlement after settlement for time interval investigated based on core sample measurements.
P _o	Penetrometer measurements in original soil in ins.
P _a	Penetrometer measurements in newly constructed terrace ridge in ins.

Table 17

Measurements and Calculations
Slope and Machinery Experiment
Clarion Soil Site

Line No.	Loc.	Mac.	S.C.	S	m	A _{cu}	A _{cl}	A _{ra}
1	CL1-1	Plow	L (4%)	5.0	25.8	5.40	2.64	13.16
2	2	"	"	4.1	23.7	5.84	3.68	12.68
3	3	"	"	3.9	21.1	5.40	4.12	12.68
4	CL2-1	Plow	L (4%)	3.5	17.5	6.16	3.36	11.80
5	2	"	"	3.7	19.6	5.32	3.32	13.16
6	3	"	"	3.0	21.6	5.68	3.72	11.12
7	CL3-1	Wh'lw'd	L (4%)	3.5	24.5	5.44	1.12	11.18
8	2	"	"	4.6	23.0	4.88	1.20	10.88
9	3	"	"	4.2	26.0	5.24	1.20	11.04
10	CL4-1	Wh'lw'd	L (4%)	4.1	20.7	4.60	2.12	11.16
11	2	"	"	3.9	24.6	5.08	1.80	11.12
12	3	"	"	4.5	24.0	5.00	1.56	11.72
13	CL5-1	Wh'lw'd	L (4%)	4.4	16.1	5.24	1.32	11.60
14	2	"	"	4.8	17.7	5.04	1.16	11.08
15	3	"	"	4.7	20.3	5.60	2.00	10.80
16	CL6-1	Plow	L (4%)	4.1	27.5	5.96	2.96	12.16
17	2	"	"	4.3	21.6	5.36	2.84	13.48
18	3	"	"	3.5	25.7	5.28	3.40	12.16
19	CM1-1	Wh'lw'd	M (8%)	7.0	21.9	5.16	1.36	10.68
20	2	"	"	6.9	24.3	3.84	0.88	11.56
21	3	"	"	6.7	24.0	4.36	1.60	12.20
22	CM2-1	Wh'lw'd	M (8%)	8.1	18.9	4.44	1.68	12.44
23	2	"	"	7.7	20.5	4.48	0.72	13.36
24	3	"	"	9.0	20.6	5.00	1.68	13.32
25	CM3-1	Wh'lw'd	M (8%)	8.1	13.8	5.16	1.72	13.56
26	2	"	"	8.4	8.9	4.64	1.04	11.16
27	3	"	"	8.8	11.6	4.32	1.00	11.00
28	CM4-1	Plow	M (8%)	6.9	15.6	7.12	3.52	14.44
29	2	"	"	7.2	14.9	7.36	3.36	13.68
30	3	"	"	7.7	13.0	6.60	3.08	13.64
31	CM5-1	Plow	M (8%)	8.3	15.7	6.68	4.40	13.00
32	2	"	"	8.2	13.4	5.80	2.92	12.68
33	3	"	"	8.1	15.9	6.12	3.12	13.12
34	CM6-1	Plow	M (8%)	9.0	20.3	6.12	2.36	12.60
35	2	"	"	9.1	22.7	5.20	2.00	12.92
36	3	"	"	8.2	20.2	5.76	2.00	11.92

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Table 17 (Continued)

Line No.	A _{fs}	A _k	R _L	R _{Acu}	R _{Acl}	R _{Af}	R _{Ak}	Z _{cu}
1	12.08	4.80	206	200	230	211	216.5	0.971
2	11.68	"	"	"	"	"	"	"
3	11.80	"	"	"	"	"	"	"
4	11.28	4.80	206	200	230	211	216.5	0.971
5	11.32	"	"	"	"	"	"	"
6	10.28	"	"	"	"	"	"	"
7	9.60	9.54						1.000
8	9.92	"						1.000
9	9.24	"						1.000
10	9.36	9.54						1.000
11	9.48	"						1.000
12	9.56	"						1.000
13	9.60	9.54						1.000
14	9.52	"						1.000
15	8.24	"						1.000
16	10.16	6.32						1.000
17	11.32	"						1.000
18	10.40	"						1.000
19	8.32	10.40	112	111	136.5	122.5	125	0.991
20	9.16	"	"	"	"	"	"	"
21	9.36	"	"	"	"	"	"	"
22	9.36	10.40						1.000
23	10.36	"						1.000
24	10.24	"						1.000
25	11.34	10.40	53.6	52	76.6	62.6	65.6	0.971
26	8.36	"	"	"	"	"	"	"
27	8.68	"	"	"	"	"	"	"
28	12.60	6.32	117	112	142	121	131	0.957
29	11.80	"	"	"	"	"	"	"
30	11.84	"	"	"	"	"	"	"
31	12.16	6.32	117	112	142	121	131	0.957
32	11.20	"	"	"	"	"	"	"
33	11.60	"	"	"	"	"	"	"
34	9.96	6.32						1.000
35	8.80	"						1.000
36	7.88	"						1.000

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Table 17 (Continued)

Line No.	Z _{cl}	Z _f	Z _k	V _{cu}	V _{cl}	V _{fa}	V _{fs}	V _k
1	1.117	1.025	1.05	5.24	2.95	13.50	12.40	5.04
2	"	"	"	5.67	4.11	13.00	11.95	"
3	"	"	"	5.24	4.60	13.00	12.10	"
4	1.117	1.025	1.05	5.98	3.75	12.10	11.55	5.04
5	"	"	"	5.17	3.71	13.50	11.60	"
6	"	"	"	5.52	4.15	11.40	10.53	"
7	1.000	1.000	1.000	5.44	1.12	11.18	9.60	9.54
8	1.000	1.000	1.000	4.88	1.20	10.88	9.92	"
9	1.000	1.000	1.000	5.24	1.20	11.04	9.24	"
10	1.000	1.000	1.000	4.60	2.12	11.16	9.36	9.54
11	1.000	1.000	1.000	5.08	1.80	11.12	9.48	9.54
12	1.000	1.000	1.000	5.00	1.56	11.72	9.56	"
13	1.000	1.000	1.000	5.24	1.32	11.60	9.60	9.54
14	1.000	1.000	1.000	5.04	1.16	11.08	9.52	"
15	1.000	1.000	1.000	5.60	2.00	10.80	8.24	"
16	1.000	1.000	1.000	5.96	2.96	12.16	10.16	6.32
17	1.000	1.000	1.000	5.36	2.84	13.48	11.32	"
18	1.000	1.000	1.000	5.28	3.40	12.16	10.40	"
19	1.219	1.093	1.116	5.11	1.66	11.68	9.10	11.60
20	"	"	"	3.80	1.07	12.65	10.05	"
21	"	"	"	4.32	1.95	13.34	10.23	"
22	1.000	1.000	1.000	4.44	1.68	12.44	9.36	10.40
23	1.000	1.000	1.000	4.48	0.72	13.36	10.36	"
24	1.000	1.000	1.000	5.00	1.68	13.32	10.34	"
25	1.43	1.168	1.222	5.01	2.46	15.84	13.22	12.71
26	"	"	"	4.50	1.49	13.02	9.76	"
27	"	"	"	4.19	1.43	12.84	10.12	"
28	1.213	1.033	1.12	6.82	4.27	14.95	13.10	7.07
29	"	"	"	7.05	4.08	14.13	12.25	"
30	"	"	"	6.32	3.74	14.10	12.30	"
31	1.213	1.033	1.12	6.39	5.34	13.43	12.60	7.07
32	"	"	"	5.55	3.54	13.10	11.60	"
33	1.213	1.033	1.12	5.85	3.79	13.60	12.02	"
34	1.000	1.000	1.000	6.12	2.36	12.60	9.96	6.32
35	1.000	1.000	1.000	5.20	2.00	12.92	8.80	"
36	1.000	1.000	1.000	5.76	2.00	11.92	7.88	"

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Table 17 (Continued)

Line No.	V _c +k	V _{fa} +k	V _{fs} +k	I _a	I _s	W _{do}	D _o	G _o
1	13.23	18.54	17.44	1.40	1.32	523	93.95	1.51
2	14.82	18.04	16.99	1.22	1.15	534	95.95	1.54
3	14.88	18.04	17.14	1.21	1.15	519	93.27	1.49
4	14.77	17.14	16.59	1.16	1.12	526	94.51	1.51
5	13.91	18.54	16.64	1.33	1.20	529	95.08	1.52
6	14.71	16.44	15.57	1.12	1.06	557	100.07	1.60
7	16.10	20.72	19.14	1.28	1.19	541	97.20	1.56
8	15.62	20.42	19.46	1.31	1.24	511	91.83	1.47
9	15.98	20.58	18.78	1.29	1.18	521	93.57	1.50
10	16.26	20.70	18.90	1.27	1.16	534	95.95	1.54
11	16.42	20.66	19.02	1.26	1.16	543	97.51	1.56
12	16.10	21.27	19.10	1.32	1.19	518	93.08	1.49
13	16.10	21.14	19.14	1.31	1.19	588	105.62	1.69
14	15.74	20.62	19.06	1.31	1.21	562	100.94	1.62
15	17.14	20.34	17.78	1.19	1.04	575	103.31	1.65
16	15.24	18.48	16.48	1.21	1.08	508	91.27	1.46
17	14.52	19.80	17.64	1.36	1.21	504	90.53	1.45
18	15.00	18.48	16.72	1.23	1.11	515	92.52	1.48
19	18.37	23.28	20.70	1.27	1.13	489	87.83	1.41
20	16.42	24.25	21.65	1.48	1.32	499	89.64	1.49
21	17.87	24.94	21.82	1.40	1.22	523	93.95	1.51
22	16.52	22.84	19.76	1.38	1.20	574	103.13	1.65
23	15.60	23.76	20.76	1.52	1.33	559	100.44	1.61
24	17.08	23.72	20.74	1.39	1.21	550	98.76	1.58
25	20.18	28.55	25.93	1.41	1.29	591	106.19	1.70
26	18.70	25.73	22.47	1.37	1.20	580	104.19	1.67
27	18.33	25.55	22.83	1.41	1.25	528	94.89	1.52
28	18.16	22.02	20.17	1.21	1.11	553	99.32	1.59
29	18.20	21.20	19.32	1.16	1.06	539	96.82	1.55
30	17.13	21.17	19.37	1.23	1.13	593	106.56	1.71
31	18.80	20.50	19.67	1.09	1.04	555	99.69	1.60
32	16.16	20.17	18.67	1.25	1.15	559	100.45	1.61
33	16.71	20.67	19.09	1.24	1.14	542	97.39	1.56
34	14.80	18.92	16.28	1.28	1.10	513	92.14	1.48
35	13.52	19.24	15.12	1.42	1.12	514	92.33	1.48
36	14.08	18.24	14.20	1.30	1.01	489	87.84	1.48

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Table 17 (Concluded)

Line No.	W _{da}	D _a	G _a	W _{ds}	D _s	G _s	I _{ag}	I _{sg}	P _a
1	424	76.16	1.22	504	90.6	1.45	1.23	1.04	5.0
2	352	63.24	1.01	516	92.7	1.49	1.52	1.03	4.7
3	457	82.09	1.31	535	96.1	1.54	1.14	0.97	6.6
4	430	77.29	1.24	529	95.1	1.52	1.22	0.99	4.8
5	520	93.45	1.50	550	98.8	1.58	1.01	0.96	5.0
6	440	79.03	1.27	557	100.1	1.60	1.27	1.00	5.9
7	366	65.73	1.05	412	74.0	1.19	1.48	1.31	9.8
8	380	68.30	1.09	412	74.1	1.19	1.35	1.24	8.0
9	350	62.86	1.01	375	67.4	1.08	1.49	1.39	9.9
10	364	65.42	1.05	439	78.9	1.26	1.47	1.21	9.2
11	337	60.56	0.97	436	78.3	1.26	1.61	1.25	10.1
12	367	65.92	1.06	404	72.6	1.16	1.41	1.28	10.3
13	444	79.78	1.28	472	84.8	1.36	1.33	1.25	11.0
14	416	74.73	1.20	405	72.8	1.17	1.35	1.39	11.7
15	381	68.48	1.10	442	79.4	1.27	1.51	1.30	11.0
16	436	78.35	1.26	512	92.0	1.47	1.16	0.99	10.0
17	438	78.72	1.26	486	87.3	1.40	1.15	1.04	8.8
18	415	74.54	1.19	503	90.4	1.45	1.24	1.02	7.5
19	352	63.24	1.01	425	76.4	1.22	1.39	1.15	10.9
20	332	59.62	0.96	414	74.4	1.19	1.50	1.20	12.7
21	350	62.86	1.01	399	71.7	1.15	1.49	1.31	12.7
22	387	69.48	1.11	442	79.4	1.27	1.48	1.30	11.2
23	398	71.48	1.14	436	78.3	1.26	1.40	1.28	9.7
24	373	67.05	1.07	416	74.7	1.20	1.47	1.32	13.3
25	397	71.36	1.14	473	85.0	1.36	1.49	1.25	14.6
26	442	79.41	1.27	488	87.7	1.41	1.33	1.19	13.8
27	422	75.85	1.22	506	90.9	1.40	1.25	1.04	14.0
28	497	89.27	1.43	529	95.1	1.52	1.11	1.04	13.0
29	477	85.71	1.37	535	96.1	1.54	1.13	1.01	11.8
30	509	91.46	1.47	530	95.2	1.53	1.16	1.12	11.8
31	497	89.27	1.43	502	90.2	1.45	1.11	1.10	12.2
32	508	91.27	1.46	472	84.8	1.36	1.10	1.18	12.9
33	482	86.59	1.38	574	103.1	1.65	1.13	0.95	11.3
34	420	75.48	1.21	489	87.9	1.41	1.22	1.05	8.4
35	434	77.97	1.25	445	80.0	1.28	1.18	1.15	8.6
36	426	76.54	1.23	445	80.0	1.28	1.15	1.10	9.9

Table 18

Measurements and Calculations
Slope and Machinery Experiment
Ida Soil Site

Line No.	Loc.	Mac.	S.C.	S	m	A _{cu}	A _{cl}	A _{fa}
1	IH1-1	Grader	H (12%)	11.5	30.7	28.76		10.40
2	2	"	"	10.9	28.8	33.52		17.92
3	3	"	"	11.1	28.8	32.24		22.48
4	IH2-1	Grader	H (12%)	11.6	31.3	33.72		22.00
5	2	"	"	11.3	29.0	30.40		22.52
6	3	"	"	10.8	29.1	28.40		17.30
7	IH3-1	Grader	H (12%)	11.0	21.1	27.36		18.68
8	2	"	"	12.5	28.0	23.16		19.20
9	3	"	"	12.3	30.6	22.00		18.56
10	IH4-1	Wh'lw'd	H (12%)	9.3	29.3	15.36	1.32	23.44
11	2	"	"	9.6	32.4	17.40	0.88	26.00
12	3	"	"	11.8	27.6	17.36	1.56	30.24
13	IH5-1	Wh'lw'd	H (12%)	11.2	17.8	19.68	0.96	21.72
14	2	"	"	11.2	19.7	21.12	1.52	19.08
15	3	"	"	10.5	20.8	19.48	1.48	20.00
16	IH6-1	Wh'lw'd	H (12%)	10.4	20.6	20.12	0.72	20.52
17	2	"	"	9.9	21.8	19.92	1.04	20.19
18	3	"	"	9.8	19.1	23.12	1.64	22.08
19	IVH1-1	Wh'lw'd	VH (16%)	16.1	28.8	21.08	1.28	31.48
20	2	"	"	16.1	24.4	20.28	2.40	30.48
21	3	"	"	16.0	26.2	20.96	1.60	29.64
22	IVH2-1	Wh'lw'd	VH (16%)	14.5	18.5	20.80	1.48	26.92
23	2	"	"	14.9	22.9	20.96	1.04	27.72
24	3	"	"	15.6	19.7	20.16	1.12	28.56
25	IVH3-1	Wh'lw'd	VH (16%)	15.7	20.4	21.40	1.72	27.84
26	2	"	"	15.9	18.3	20.84	1.36	30.42
27	3	"	"	15.8	20.8	21.04	1.16	30.00
28	IVH4-1	Grader	VH (16%)	15.7	26.1	27.72		19.88
29	2	"	"	14.7	26.2	32.52		19.36
30	3	"	"	14.8	26.7	31.52		16.84
31	IVH5-1	Grader	VH (16%)	13.7	28.9	30.48		16.00
32	2	"	"	13.7	30.3	29.56		17.00
33	3	"	"	12.0	28.5	26.35		18.28
34	IVH6-1	Grader	VH (16%)	13.0	19.7	26.08		15.84
35	2	"	"	13.2	21.5	27.00		19.24
36	3	"	"	14.1	26.3	24.88		19.32

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Table 18 (Continued)

Line No.	Afs	Ak	RL	RAcu	RAcl	RAf	RAk	Zcu
1	10.52	5.10	126.5	109.5		127.5	123.5	0.865
2	16.67	"	"	"		"	"	"
3	21.76	"	"	"		"	"	"
4	21.24	5.10	126.5	109.5		127.5	123.5	0.865
5	22.40	"	"	"		"	"	"
6	17.72	"	"	"		"	"	"
7	16.40	5.10						1.000
8	18.24	"						1.000
9	17.72	"						1.000
10	20.92	11.00	59	75	45.5	61	59	1.272
11	23.20	"	"	"	"	"	"	"
12	27.00	"	"	"	"	"	"	"
13	18.84	11.00	62	45	75.5	61	64	0.726
14	18.44	"	"	"	"	"	"	"
15	18.08	"	"	"	"	"	"	"
16	16.80	11.00	62	45	75.5	61	64	0.726
17	17.84	"	"	"	"	"	"	"
18	21.64	"	"	"	"	"	"	"
19	28.16	11.00						1.000
20	28.00	"						1.000
21	27.04	"						1.000
22	24.80	11.00						1.000
23	25.40	"						1.000
24	26.72	"						1.000
25	25.56	11.00						1.000
26	26.76	"						1.000
27	27.88	"						1.000
28	20.96	5.10	219	234		218	223	1.068
29	19.68	"	"	"		"	"	"
30	17.68	"	"	"		"	"	"
31	17.04	5.10	118	103		121	116	0.873
32	17.36	"	"	"		"	"	"
33	18.12	"	"	"		"	"	"
34	16.81	5.10	313	294		313	308	0.939
35	20.12	"	"	"		"	"	"
36	19.46	"	"	"		"	"	"

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Table 18 (Continued)

Line No.	Z _{cl}	Z _f	Z _k	V _{cu}	V _{cl}	V _{fa}	V _{fs}	V _k
1		1.008	0.976	24.85		10.48	10.60	4.98
2		"	"	29.00		18.08	16.80	"
3		"	"	27.90		22.65	21.90	"
4		1.008	0.976	29.15		22.18	21.40	4.98
5		"	"	26.30		22.70	22.57	"
6		"	"	24.55		17.42	17.86	"
7		1.000	1.000	27.36		18.68	16.40	5.10
8		1.000	1.000	23.16		19.20	18.24	"
9		1.000	1.000	22.00		18.56	17.72	"
10	0.771	1.033	1.000	19.53	1.02	24.25	21.60	11.00
11	"	"	"	22.10	0.68	26.90	24.00	"
12	"	"	"	22.05	1.20	31.30	27.90	"
13	1.218	0.984	1.032	14.29	1.17	21.36	18.54	11.36
14	"	"	"	15.32	1.85	18.77	18.14	"
15	"	"	"	14.14	1.80	19.68	17.80	"
16	1.218	0.984	1.032	14.60	0.88	20.20	16.53	11.36
17	"	"	"	14.46	1.27	19.85	17.57	"
18	"	"	"	16.80	2.00	21.73	21.30	"
19	1.000	1.000	1.000	21.08	1.28	31.48	28.16	11.00
20	1.000	1.000	1.000	20.28	2.40	30.48	28.00	"
21	1.000	1.000	1.000	20.96	1.60	29.64	27.04	"
22	1.000	1.000	1.000	20.80	1.48	26.92	24.80	11.00
23	1.000	1.000	1.000	20.96	1.04	27.72	25.40	"
24	1.000	1.000	1.000	20.16	1.12	28.56	26.72	"
25	1.000	1.000	1.000	21.40	1.72	27.84	25.56	11.00
26	1.000	1.000	1.000	20.84	1.36	30.42	26.76	"
27	1.000	1.000	1.000	21.04	1.16	30.00	27.88	"
28		0.996	1.018	29.60		19.80	20.85	5.19
29		"	"	34.75		19.28	19.60	"
30		"	"	33.45		16.80	17.60	"
31		1.026	0.983	26.60		16.41	17.48	5.02
32		"	"	25.80		17.43	17.80	"
33		"	"	23.00		18.75	18.60	"
34		1.000	0.984	24.50		15.84	16.81	5.02
35		"	"	25.35		19.24	20.12	"
36		"	"	23.40		19.32	19.46	"

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Table 18 (Continued)

Line No.	V _c +k	V _{fa} +k	V _{fs} +k	I _a	I _s	W _{do}	D _o	G _o
1	29.83	15.46	15.58	0.518	0.522	443	79.60	1.28
2	33.98	23.06	21.78	0.679	0.641	448	80.47	1.29
3	32.88	27.63	26.88	0.841	0.818	408	73.29	1.17
4	34.13	27.16	26.38	0.796	0.773	461	82.84	1.33
5	31.28	27.68	27.55	0.885	0.880	483	86.77	1.39
6	29.53	22.40	22.84	0.759	0.775	485	87.15	1.40
7	32.46	23.78	21.50	0.732	0.662	455	81.78	1.31
8	28.26	24.30	23.34	0.859	0.825	471	84.65	1.36
9	27.10	23.66	22.82	0.873	0.843	454	81.59	1.31
10	31.55	35.25	32.60	1.12	1.03	436	78.35	1.26
11	33.78	37.90	35.00	1.12	1.04	424	76.16	1.22
12	34.25	42.30	38.90	1.23	1.14	472	84.78	1.36
13	26.82	32.72	29.90	1.22	1.11	478	85.90	1.38
14	28.53	30.13	29.50	1.06	1.03	479	86.09	1.38
15	27.30	31.04	29.16	1.14	1.07	455	81.78	1.31
16	26.84	31.56	27.89	1.17	1.04	471	84.65	1.36
17	27.09	31.21	28.93	1.15	1.07	475	85.34	1.37
18	30.16	33.09	32.66	1.10	1.08	491	88.21	1.41
19	33.36	42.48	39.16	1.27	1.17	446	80.16	1.28
20	33.68	41.48	39.00	1.23	1.16	434	77.97	1.25
21	33.56	40.64	38.04	1.21	1.14	466	83.72	1.34
22	33.28	37.92	35.80	1.14	1.08	445	79.97	1.28
23	33.00	38.72	36.40	1.17	1.10	469	84.28	1.35
24	32.28	39.56	37.72	1.22	1.17	465	83.53	1.34
25	34.12	38.84	36.56	1.14	1.07	473	84.96	1.36
26	33.20	41.42	37.76	1.25	1.14	443	79.60	1.28
27	33.20	41.00	38.88	1.23	1.17	438	78.72	1.26
28	34.79	24.99	26.04	0.719	0.749	432	77.60	1.24
29	39.94	24.47	24.79	0.613	0.621	457	82.09	1.32
30	38.64	21.99	22.79	0.569	0.589	460	82.65	1.32
31	31.62	21.43	22.50	0.678	0.711	468	84.09	1.35
32	30.82	22.45	22.82	0.728	0.741	478	85.90	1.38
33	28.02	23.77	23.62	0.847	0.843	475	85.34	1.37
34	29.52	20.86	21.83	0.708	0.741	474	85.15	1.36
35	30.35	24.26	25.14	0.802	0.829	475	85.34	1.37
36	28.42	24.34	24.48	0.856	0.862	492	88.40	1.42

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Table 18 (Concluded)

Line No.	W _{da}	D _a	G _a	W _{ds}	D _s	G _s	I _{ag}	I _{sg}	P _o	P _a
1	470	84.47	1.35	498	89.6	1.43	0.94	0.89	2.1	4.8
2	463	83.22	1.33	467	84.0	1.35	0.97	0.96	2.0	2.5
3	498	89.46	1.43	453	81.5	1.30	0.82	0.90	2.0	3.8
4	498	89.46	1.43	476	85.5	1.37	0.92	0.97	1.7	4.9
5	477	85.71	1.37	491	88.2	1.41	1.01	0.98	2.0	3.4
6	458	82.25	1.32	500	89.9	1.44	1.06	0.97	2.0	2.6
7	474	85.15	1.36	449	80.8	1.29	0.96	1.01	2.1	3.4
8	478	85.90	1.38	446	80.2	1.28	0.99	1.05	2.3	6.5
9	468	84.09	1.35	445	80.0	1.28	0.97	1.02	2.2	4.1
10	331	59.49	0.95	327	58.8	0.94	1.32	1.33	2.3	12.0
11	363	65.24	1.05	353	63.4	1.02	1.17	1.20	1.9	10.4
12	386	69.36	1.11	368	66.2	1.06	1.22	1.28	2.1	10.7
13	353	63.43	1.02	389	70.0	1.12	1.35	1.23	2.1	12.8
14	359	64.49	1.03	373	67.1	1.07	1.33	1.28	2.1	12.5
15	313	56.25	0.90	375	67.5	1.08	1.45	1.21	2.2	14.0
16	379	68.11	1.09	365	65.6	1.05	1.24	1.29	2.1	13.5
17	353	63.43	1.02	393	70.6	1.13	1.35	1.21	1.7	12.9
18	332	59.68	0.96	378	67.6	1.08	1.48	1.31	1.7	12.7
19	353	63.43	1.02	377	67.7	1.09	1.27	1.18	2.5	12.7
20	318	57.12	0.92	378	67.9	1.09	1.36	1.15	2.2	11.8
21	340	61.12	0.98	372	66.8	1.07	1.37	1.25	1.8	12.6
22	312	56.06	0.90	382	68.6	1.10	1.43	1.16	2.2	14.6
23	336	60.37	0.97	383	68.8	1.10	1.40	1.22	2.1	11.2
24	311	55.87	0.90	360	64.7	1.04	1.49	1.29	2.9	15.7
25	315	56.62	0.91	354	63.6	1.02	1.50	1.34	2.2	14.6
26	324	58.25	0.93	355	63.9	1.02	1.37	1.25	2.6	11.2
27	335	60.18	0.96	352	63.2	1.01	1.31	1.24	2.4	15.7
28	532	95.64	1.53	521	93.6	1.50	0.81	0.83	2.7	2.8
29	534	95.95	1.54	509	91.5	1.47	0.86	0.90	2.3	2.8
30	533	95.76	1.53	509	91.5	1.47	0.86	0.90	2.6	2.5
31	476	85.53	1.37	460	82.7	1.32	0.98	1.01	2.1	3.7
32	456	81.91	1.31	454	81.6	1.31	1.05	1.05	2.0	3.7
33	464	83.34	1.34	467	83.9	1.34	1.02	1.02	1.6	4.9
34	512	92.02	1.47	483	86.8	1.39	0.93	0.98	1.7	2.8
35	522	93.77	1.50	503	90.4	1.45	0.91	0.95	1.8	4.0
36	502	90.21	1.46	485	87.2	1.40	0.98	1.01	1.9	5.0

Table 19

Measurements and Calculations
Moisture Controlled Experiment
Clarion Soil Site

Line No.	Loc.	Mac.	S	m.t.	m ₁	m ₂	A _{cu}	A _{cl}
1	WA1-1	Plow	4.7	1	25.8	26.7	4.84	2.52
2	2	"	4.9	"	26.1	27.8	4.60	1.60
3	WA2-1	Plow	5.6	0	23.2	22.4	4.92	3.00
4	2	"	5.7	"	22.2	22.1	4.72	2.08
5	WA3-1	Plow	6.2	2	23.9	24.8	5.36	2.96
6	2	"	6.3	"	23.2	23.8	6.20	2.60
7	WB1-1	Plow	6.0	1	18.8	22.5	5.32	2.84
8	2	"	5.8	"	23.0	23.0	6.04	3.16
9	WB2-1	Plow	6.0	2	26.0	18.9	5.96	3.56
10	2	"	5.8	"	20.4	24.6	5.80	3.68
11	WB3-1	Plow	5.4	0	21.8	20.8	4.76	2.48
12	2	"	5.1	"	19.7	23.5	4.24	2.48
13	WC1-1	Plow	5.6	2	28.8	17.3	4.12	2.52
14	2	"	5.7	"	22.7	16.6	4.92	3.08
15	WC2-1	Plow	5.8	1	24.0	18.8	5.56	3.12
16	2	"	5.9	"	22.9	19.8	5.40	2.96
17	WC3-1	Plow	6.2	0	20.8	17.2	4.44	2.60
18	2	"	5.9	"	16.5	17.7	4.92	2.72

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Table 19 (Continued)

Line No.	A _{fa}	A _{fs}	A _k	Z _{c&f}	V _{c+k}	V _{fa+k}	V _{fs+k}
1	12.88	10.28	7.85	1.00	15.21	20.73	18.13
2	12.12	10.24	"	1.00	14.05	19.97	18.09
3	11.76	10.44	7.85	1.00	15.77	19.61	18.29
4	12.12	11.24	"	1.00	14.65	19.97	19.09
5	13.52	11.88	7.85	1.00	16.17	21.37	19.73
6	11.48	10.44	"	1.00	16.65	19.33	18.29
7	13.72	11.92	7.85	1.00	16.01	21.57	19.77
8	13.92	12.60	"	1.00	17.05	21.77	20.45
9	13.28	13.28	7.85	1.00	17.37	21.13	21.13
10	13.24	12.40	"	1.00	17.33	21.09	20.25
11	13.84	12.92	7.85	1.00	15.09	21.69	20.77
12	13.08	11.04	"	1.00	14.57	20.93	18.84
13	13.56	12.24	7.85	1.00	14.49	21.41	20.09
14	13.96	12.08	"	1.00	15.85	21.81	19.93
15	13.40	11.92	7.85	1.00	16.53	21.25	19.77
16	13.04	12.32	"	1.00	16.21	20.89	20.17
17	12.24	10.56	7.85	1.00	14.89	20.09	18.41
18	13.64	11.92	"	1.00	15.49	21.49	19.77

(Continued on next page)

Table 19 (Continued)

Line No.	I _a	I _s	W _{do}	D _o	G _o	W _{da}	D _a
1	1.36	1.19	457	82.09	1.32	345	61.99
2	1.42	1.29	472	84.78	1.36	353	63.43
3	1.24	1.16	452	81.22	1.30	392	70.42
4	1.36	1.30	498	89.46	1.43	374	67.12
5	1.32	1.22	511	91.83	1.47	453	81.41
6	1.16	1.10	509	91.46	1.47	467	83.90
7	1.35	1.23	528	94.89	1.52	430	77.35
8	1.28	1.20	526	94.52	1.51	425	76.35
9	1.22	1.22	532	95.58	1.53	465	83.53
10	1.22	1.17	533	95.76	1.53	496	89.15
11	1.44	1.38	537	96.51	1.55	471	84.65
12	1.44	1.30	484	86.96	1.39	417	74.91
13	1.48	1.39	527	94.70	1.52	449	80.66
14	1.38	1.26	533	95.76	1.53	539	96.82
15	1.29	1.19	556	99.88	1.60	531	95.39
16	1.29	1.24	507	91.08	1.46	481	86.40
17	1.35	1.24	476	85.53	1.37	436	78.35
18	1.39	1.28	521	93.58	1.50	442	79.41

(Concluded on next page)

Table 19 (Concluded)

Line No.	G _a	W _{ds}	D _s	G _s	I _{ag}	I _{sg}	P _o	P _a
1	0.99	414	74.3	1.19	1.33	1.10	2.6	9.7
2	1.02	433	77.8	1.25	1.34	1.09	3.3	9.7
3	1.13	372	66.8	1.07	1.15	1.22	2.0	6.6
4	1.08	396	71.1	1.14	1.33	1.26	2.3	10.0
5	1.30	506	90.9	1.45	1.13	1.01	2.9	9.7
6	1.34	522	93.8	1.50	1.04	0.98	2.5	8.5
7	1.24	498	89.5	1.43	1.23	1.06	2.0	8.8
8	1.22	501	90.0	1.44	1.23	1.05	3.0	7.8
9	1.34	513	92.1	1.48	1.15	1.04	1.8	7.4
10	1.43	556	99.9	1.60	1.08	0.96	2.5	9.0
11	1.36	498	89.5	1.43	1.14	1.08	2.3	6.5
12	1.20	485	87.1	1.40	1.16	1.00	1.5	5.4
13	1.29	516	92.7	1.49	1.17	1.02	2.8	7.9
14	1.55	489	87.8	1.41	0.99	1.09	2.5	8.3
15	1.53	599	107.6	1.72	1.05	0.93	2.2	8.5
16	1.38	490	88.0	1.41	1.08	1.03	2.3	7.0
17	1.26	427	76.7	1.23	1.09	1.11	1.9	8.5
18	1.27	525	94.3	1.51	1.18	0.99	1.9	7.5

Table 20

Azimuths and Distances for Locating Control Points
on Slope and Machinery Experiment
and Moisture Controlled Experiment
Clarion Soil Site

Station	Clockwise azimuth from backline	Distance feet	Location designation	Station	Clockwise azimuth from backline	Distance feet	Location designation
A 0			CM6-1U	E 0			CL6-1U
A 1	189° 47'	6.49	CM6-2U	E 1	356° 55'	113.06	CL5-1U
A 2	183° 12'	31.01	CM6-3U	E 2	356° 50'	97.88	CL5-2U
A 3	241° 52'	64.06	CM6-3L	E 3	356° 57'	90.73	CL5-3U
A 4	261° 03'	56.77	CM6-2L	E 4	182° 35'	7.17	CL6-2U
A 5	273° 17'	54.96	CM6-1L	E 5	181° 30'	23.72	CL6-3U
B 0			CM1-1L	E 6	244° 29'	61.62	CL6-3L
B 1	95° 05'	54.85	CM1-1U	E 7	258° 02'	56.39	CL6-2L
B 2	101° 51'	55.83	CM1-2U	E 8	268° 15'	55.05	CL6-1L
B 3	108° 50'	58.33	CM1-3U	E 9	324° 17'	101.51	CL5-3L
B 4	179° 17'	21.23	CM1-3L	E10	326° 53'	110.08	CL5-2L
B 5	181° 34'	17.74	CM1-2L	E11	330° 39'	124.55	CL5-1L
C 0			CL1-3U	E12	80° 24'	105.48	CM2-1U
C 1	345° 17'	23.29	CL1-1U	E13	84° 05'	102.35	CM2-2U
C 2	344° 43'	8.31	CL1-2U	E14	93° 57'	96.14	CM2-3U
C 3	164° 49'	25.69	CL2-1U	E15	57° 21'	60.84	CM2-1L
C 4	162° 57'	33.38	CL2-2U	E16	63° 16'	54.46	CM2-2L
C 5	155° 16'	55.93	CL2-3U	E17	74° 10'	46.30	CM2-3L
C 6	189° 27'	91.40	CL2-3L	F 0			CM5-1U
C 7	218° 55'	66.11	CL2-2L	F 1	321° 27'	37.40	CM6-1U
C 8	226° 14'	62.27	CL2-1L	F 2	319° 18'	30.22	CM6-2U
C 9	250° 16'	54.98	CL1-3L	F 3	317° 39'	23.79	CM6-3U
C10	258° 33'	55.04	CL1-2L	F 4	128° 31'	5.56	CM5-2U
C11	276° 23'	58.87	CL1-1L	F 5	124° 17'	19.86	CM5-3U
D 0			CL4-1U	F 6	198° 10'	57.02	CM5-3L
D 1	297° 11'	47.70	CL3-1U	F 7	216° 52'	54.75	CM5-2L
D 2	297° 08'	39.45	CL3-2U	F 8	228° 20'	55.00	CM5-1L
D 3	296° 49'	25.01	CL3-3U	F 9	258° 27'	63.04	CM6-3L
D 4	115° 35'	7.69	CL4-2U	F10	266° 16'	67.41	CM6-2L
D 5	115° 51'	32.16	CL4-3U	F11	272° 46'	72.02	CM6-1L
D 6	175° 47'	63.64	CL4-3L	F12	48° 02'	76.17	CM3-1U
D 7	196° 12'	55.73	CL4-2L	F13	52° 28'	77.15	CM3-2U
D 8	205° 24'	55.07	CL4-1L	F14	57° 11'	78.80	CM3-3U
D 9	232° 54'	61.10	CL3-3L	F15	91° 24'	32.82	CM3-3L
D10	246° 05'	70.45	CL3-2L	F16	76° 24'	25.52	CM3-2L
D11	250° 47'	75.83	CL3-1L	F17	50° 21'	21.45	CM3-1L
WA 0			WA1-1U	WB 6	198° 14'	85.16	WB3-2L
WA 1	155° 14'	8.33	WA1-2U	WB 7	202° 30'	79.75	WB3-1L
WA 2	157° 43'	31.63	WA2-1U	WB 8	219° 38'	64.10	WB2-2L
WA 3	158° 01'	39.46	WA2-2U	WB 9	226° 43'	60.66	WB2-1L
WA 4	159° 22'	63.24	WA3-1U	WB10	249° 54'	54.73	WB1-2L
WA 5	159° 52'	70.05	WA3-2U	WB11	259° 07'	54.94	WB1-1L
WA 6	199° 20'	86.13	WA3-2L	WC 0			WC2-2U
WA 7	203° 03'	78.86	WA3-1L	WC 1	331° 22'	32.33	WC1-1U
WA 8	214° 17'	66.07	WA2-2L	WC 2	329° 07'	25.83	WC1-2U
WA 9	220° 15'	61.75	WA2-1L	WC 3	328° 10'	7.11	WC2-1U
WA10	239° 23'	55.09	WA1-2L	WC 4	146° 03'	42.78	WC3-1U
WA11	247° 18'	54.97	WA1-1L	WC 5	146° 04'	50.52	WC3-2U
WB 0			WB1-1U	WC 6	194° 39'	73.16	WC3-2L
WB 1	162° 19'	8.04	WB1-2U	WC 7	200° 05'	67.70	WC3-1L
WB 2	161° 57'	28.59	WB2-1U	WC 8	234° 08'	54.89	WC2-2L
WB 3	160° 53'	36.40	WB2-2U	WC 9	244° 36'	55.26	WC2-1L
WB 4	159° 16'	55.41	WB3-1U	WC10	269° 48'	63.49	WC1-2L
WB 5	158° 07'	63.24	WB3-2U	WC11	277° 28'	67.37	WC1-1L

FIG. 19 MAP FOR LOCATING CONTROL POINTS OF SLOPE AND MACHINERY AND MOISTURE CONTROLLED EXPERIMENT. CLARION SOIL SITE, ANKENY EXPERIMENTAL FARM.

Table 21

Azimuths and Distances for Locating Control Points
on Slope and Machinery Experiment
Ida Soil Site

Station	Clockwise azimuth from backline	Distance feet	Location designation	Station	Clockwise azimuth from backline	Distance feet	Location designation
A 0			IH1-3U	F 0			IVH1-1L
A 1	314° 00'	38.58	IH1-1U	F 1	107° 44'	54.38	IVH1-1U
A 2	312° 50'	13.55	IH1-2U	F 2	115° 02'	55.42	IVH1-2U
A 3	130° 22'	7.15	IH2-1U	F 3	135° 08'	62.83	IVH1-3U
A 4	129° 39'	13.77	IH2-2U	F 4	195° 20'	33.60	IVH1-3L
A 5	120° 22'	37.16	IH2-3U	F 5	193° 48'	10.80	IVH1-2L
A 6	170° 06'	70.76	IH2-3L	G 0			IH5-1U
A 7	200° 41'	57.75	IH2-2L	G 1	167° 16'	6.38	IH5-2U
A 8	209° 00'	55.71	IH2-1L	G 2	154° 56'	12.43	IH5-3U
A 9	221° 06'	54.82	IH1-3L	G 3	124° 21'	21.81	IH6-1U
A 10	238° 46'	57.01	IH1-2L	G 4	121° 46'	26.73	IH6-2U
A 11	258° 54'	66.61	IH1-1L	G 5	107° 25'	37.05	IH6-3U
B 0			IVH5-3U	G 6	148° 45'	76.88	IH6-3L
B 1	274° 00'	22.19	IVH5-2U	G 7	171° 43'	68.10	IH6-2L
B 2	273° 31'	32.16	IVH5-1U	G 8	179° 01'	64.55	IH6-1L
B 3	212° 36'	62.66	IVH5-1L	G 9	229° 17'	56.84	IH5-3L
B 4	206° 18'	59.13	IVH5-2L	G 10	238° 29'	56.58	IH5-2L
B 5	182° 45'	54.65	IVH5-3L	G 11	247° 28'	54.95	IH5-1L
C 0			IVH6-2U	H 0			IVH2-3U
C 1	337° 36'	13.65	IVH6-1U	H 1	154° 39'	26.04	IVH3-1U
C 2	268° 05'	57.93	IVH6-1L	H 2	153° 00'	39.55	IVH3-2U
C 3	250° 27'	54.72	IVH6-2L	H 3	152° 08'	47.09	IVH3-3U
C 4	241° 51'	54.46	IVH6-3L	H 4	198° 44'	74.46	IVH3-3L
C 5	156° 22'	9.38	IVH6-3U	H 5	203° 28'	70.15	IVH3-2L
D 0			IH3-3L	H 6	217° 22'	61.06	IVH3-1L
D 1	18° 27'	8.52	IH3-2L	H 7	241° 23'	54.37	IVH2-3L
D 2	18° 05'	33.34	IH3-1L	H 8	258° 43'	56.31	IVH2-2L
D 3	81° 50'	60.53	IH3-1U	H 9	265° 51'	58.69	IVH2-1L
D 4	104° 06'	54.64	IH3-2U	H 10	333° 59'	23.48	IVH2-1U
D 5	110° 43'	54.84	IH3-3U	H 11	333° 56'	16.33	IVH2-2U
E 0			IH4-1L	J 0			IVH4-1U
E 1	129° 50'	54.82	IH4-1U	J 1	256° 35'	23.72	IVH4-2U
E 2	137° 45'	54.46	IH4-2U	J 2	256° 39'	33.35	IVH4-3U
E 3	168° 11'	57.65	IH4-3U	J 3	315° 29'	63.60	IVH4-3L
E 4	239° 52'	16.60	IH4-3L	J 4	321° 15'	60.22	IVH4-2L
E 5	224° 17'	8.91	IH4-2L	J 5	344° 35'	54.42	IVH4-1L

FIG. 20 MAP FOR LOCATING CONTROL POINTS OF SLOPE AND MACHINERY EXPERIMENT. IDA SOIL SITE, WESTERN IOWA EXPERIMENTAL FARM.