A FLUID DAMPENED PENDULUM FOR GRADE
CONTROL OF A TILE TRENCHER

A Thesis
Presented in Partial Fulfillment of the Requirements
for the Degree Master of Science

by

Robert Giffen Holmes

The Ohio State University
1962

Approved by

Glenn O. Schwab
Adviser
Department of Agricultural Engineering
ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the following:

Professor Glenn O. Schenck for his guidance throughout the investigation.

Mr. James L. Fousay for technical advice given during the course of this investigation.

The Agricultural Research Service for the loan of the fluid dampened pendulum.

Mr. Norman Fausey and Mr. James Miller for assistance in collecting data.

His wife, Linda Holmes, whose assistance, patience and encouragement made the completion of this investigation possible.

All others who have contributed to this investigation.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. REVIEW OF THE LITERATURE</td>
<td>4</td>
</tr>
<tr>
<td>Target and Bar Method</td>
<td>5</td>
</tr>
<tr>
<td>Pipe and Cord Method</td>
<td>8</td>
</tr>
<tr>
<td>Fluid Manometer Method</td>
<td>8</td>
</tr>
<tr>
<td>III. INVESTIGATION.</td>
<td>12</td>
</tr>
<tr>
<td>Theory of the Pendulum Grade Control Device</td>
<td>12</td>
</tr>
<tr>
<td>Force Analysis of a Tile Trencher</td>
<td>15</td>
</tr>
<tr>
<td>Description of the trenching machine</td>
<td>15</td>
</tr>
<tr>
<td>Operating variables</td>
<td>16</td>
</tr>
<tr>
<td>Soil reaction on the digging wheel</td>
<td>19</td>
</tr>
<tr>
<td>Discussion of the results of the force analysis</td>
<td>33</td>
</tr>
<tr>
<td>Equipment</td>
<td>38</td>
</tr>
<tr>
<td>Fluid dampaned pendulum</td>
<td>38</td>
</tr>
<tr>
<td>Machine modifications</td>
<td>45</td>
</tr>
<tr>
<td>Hydraulic system</td>
<td>48</td>
</tr>
<tr>
<td>Electrical system</td>
<td>52</td>
</tr>
<tr>
<td>Testing Procedure</td>
<td>55</td>
</tr>
<tr>
<td>Field Test Results</td>
<td>58</td>
</tr>
<tr>
<td>IV. DISCUSSION</td>
<td>77</td>
</tr>
<tr>
<td>V. CONCLUSIONS</td>
<td>80</td>
</tr>
<tr>
<td>Chapter</td>
<td>Page</td>
</tr>
<tr>
<td>------------------</td>
<td>------</td>
</tr>
<tr>
<td>VI. SUMMARY</td>
<td>81</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>62</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Results of the Force Analysis of the Tile Trencher</td>
<td>34</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>Target and bar method of grade control</td>
</tr>
<tr>
<td>2.</td>
<td>Fluid manometer method of grade control</td>
</tr>
<tr>
<td>3.</td>
<td>Line drawing of a typical wheel type trencher equipped with a shoe</td>
</tr>
<tr>
<td>4.</td>
<td>Dimensions of the digging mechanism for the tile trencher.</td>
</tr>
<tr>
<td>5.</td>
<td>Reaction of the soil against the buckets on the digging wheel</td>
</tr>
<tr>
<td>6.</td>
<td>Area of soil being removed by each bucket as a function of forward speed, trench width and angle θ</td>
</tr>
<tr>
<td>7.</td>
<td>Position of the resultant soil reaction on the digging wheel</td>
</tr>
<tr>
<td>8.</td>
<td>Trench depth vs. angle θ to the resultant soil reaction on the digging wheel</td>
</tr>
<tr>
<td>9.</td>
<td>External forces acting on the digging mechanism of a tile trencher during operation</td>
</tr>
<tr>
<td>10.</td>
<td>Assumed force distribution of the soil reaction against the shoe of a tile trencher</td>
</tr>
<tr>
<td>11.</td>
<td>Details of the driving mechanism of roller A</td>
</tr>
<tr>
<td>12.</td>
<td>Forces acting on the digging wheel of a tile trencher</td>
</tr>
<tr>
<td>13.</td>
<td>Details of the fluid dampened pendulum used for grade control of a tile trencher</td>
</tr>
<tr>
<td>14.</td>
<td>Right side and rear view of the pendulum and &quot;A&quot; frame</td>
</tr>
<tr>
<td>15.</td>
<td>Fluid dampened pendulum showing the limit switches</td>
</tr>
<tr>
<td>16.</td>
<td>Pendulum calibration scale, channel iron mounting bracket and clamp used on the fluid dampened pendulum</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>17.</td>
<td>The pendulum grade control device mounted on the Buckeye 1844 trencher</td>
</tr>
<tr>
<td>18.</td>
<td>Denison hydraulic pump mounted under the engine radiator</td>
</tr>
<tr>
<td>19.</td>
<td>Single acting hydraulic cylinder mounted vertically for grade control of the tile trencher</td>
</tr>
<tr>
<td>20.</td>
<td>Schematic drawing of the hydraulic grade control system</td>
</tr>
<tr>
<td>21.</td>
<td>Location of the hydraulic solenoid valve (A), pressure gauge (B), oil reservoir (C), pressure relief valve (D), and the flow restrictor valve (E)</td>
</tr>
<tr>
<td>22.</td>
<td>Electrical circuit for the pendulum grade control device</td>
</tr>
<tr>
<td>23.</td>
<td>Electrical control box located in front of the operator's platform</td>
</tr>
<tr>
<td>24.</td>
<td>Field test number 2 using the pendulum grade control device</td>
</tr>
<tr>
<td>25.</td>
<td>Field test number 3 using the pendulum grade control device</td>
</tr>
<tr>
<td>26.</td>
<td>Field test number 4 using the pendulum grade control device</td>
</tr>
<tr>
<td>27.</td>
<td>Field test number 5 using the pendulum grade control device</td>
</tr>
<tr>
<td>28.</td>
<td>Field test number 6 using the pendulum grade control device</td>
</tr>
<tr>
<td>29.</td>
<td>Field test number 7 using the pendulum grade control device</td>
</tr>
<tr>
<td>30.</td>
<td>Field test number 8 using the pendulum grade control device</td>
</tr>
<tr>
<td>31.</td>
<td>Field test number 9 using the pendulum grade control device</td>
</tr>
<tr>
<td>32(a)</td>
<td>Field test number 10 using the pendulum grade control device</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>32(b).</td>
<td>Field test number 10 using the pendulum grade control device</td>
</tr>
<tr>
<td>32(c).</td>
<td>Field test number 10 using the pendulum grade control device</td>
</tr>
<tr>
<td>33.</td>
<td>Field check number 1 with grade control provided by the target and bar method</td>
</tr>
<tr>
<td>34.</td>
<td>Field check number 2 with grade control provided by the target and bar method</td>
</tr>
<tr>
<td>35.</td>
<td>Field check number 3 with grade control provided by the target and bar method</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

A uniform grade for the tile is essential for efficient functioning of a drainage system. The grade of most present-day trenching machines is controlled by the operator using a line of sight with grade targets for reference. This type of grade control has several limitations; among these are the time required to set the targets to the proposed grade and operator errors causing deviations from the proposed grade line with resultant humps and dips in the drain. Thus, a grade control device is needed which would not only be more accurate and less dependent on the machine operator than present methods but also reduce the time spent in setting grade targets.

Poor drainage causes inefficient farm operations and losses in crop production. To combat this situation, subsurface drains have been and are being installed. Schwab (1959) estimated that in Ohio alone there are three million acres of agricultural land that need additional subsurface drainage for optimum production. Much of this total is located in the lakebed region where the drain gradient is critical for satisfactory functioning of the tile system.

Today practically all tile drains are installed in trenches dug to the proper grade by machines. When in the hands of a skilled and conscientious operator, a modern trenching machine will give excellent results. However, the grade control methods used with the machine trencher are essentially the same as those used fifty years ago by the manual worker. As a result, the accuracy of installation
of a drainage system is dependent to a large extent on the operator. Even a very skillful and normally careful operator may perform his duties ineffectively as a result of fatigue. The American Society of Agricultural Engineers Drainage Equipment Committee (1958) recognized this problem as early as 1958 when they reported that present-day grade holding and sighting techniques were, in general, inadequate. At that time it was recommended that research be conducted into possible methods of grade control which would reduce the strain imposed on the operator by present grading techniques.

The most widely used method of grade control involves the setting of targets at fifty to one hundred foot intervals along the proposed drain. Most drainage contractors spend from ten to fifteen per cent of their time setting these targets. This is time during which the machine usually stands idle. Consequently, a method of grade control which would eliminate or reduce the target setting time could significantly reduce the over-all installation costs.

The objectives of this investigation were to develop a method of grade control for a tile trencher which would:

1. Be more accurate than present methods.
2. Reduce the strain on the operator by making the grade control automatic.
3. Eliminate the need to set grade stakes for grade control.

In developing a grade control system commensurate with the objectives stated above, the hypothesis was proposed that a definite angular relationship existed between the proposed grade line and the slope of the digging wheel frame. A force analysis of the digging mechanism
was conducted to evaluate possible effects that changes in operating conditions would have on the proposed relationship. A fluid dampened pendulum was mounted on the trencher digging wheel frame as a vertical reference from which the slope of the frame could be sensed. This experimental device was designed, built, and tested under actual field conditions.
II. REVIEW OF THE LITERATURE

Historically, the practice of installing tile drains for agricultural drainage dates back several centuries to Europe and England. Sutton (1957) reported that the first drain tile used in the United States were made and installed by hand in 1835 by John Johnson. Reiman (1958) estimated that since 1835 more than 280 thousand miles of tile drains have been installed in this country; however, many of these drains have ceased to function because of tile breakage, sedimentation problems, improper installation, and other factors.

There have been many advances in subsurface drainage practices during the past fifty years. By the beginning of the present century, manual workers had perfected excellent procedures of laying tile. However, during the last half century the installation of drain tile has changed from a manual to a mechanical operation. Roe et al. (1954) indicated that during this time the trenching machine has been developed to the extent that a modern machine can dig as much trench as thirty to fifty skilled men. At the same time that the trenching machine was being perfected mechanically, grade holding techniques remained virtually static. The result has been that present grade control methods are essentially the same as those used a half century ago by manual workers. These grade control systems can be characterized as systems using a reference plane parallel to the desired grade line.
Target and Bar Method

Boe et al. (1954) indicated that the target and bar method of grade control is by far the most widely accepted. With this method a series of targets is set ahead of the machine in such a manner that as the machine operator sights along the targets, his line of sight forms a line parallel to the proposed grade line. (See Figure 1). The machine is equipped with a sight bar that is rigidly attached to the digging wheel frame. During operation the operator sights over the sight bar which he attempts to keep in the horizontal plane described by the cross members on the targets. Thus, the lowest point on the periphery of the digging wheel is held on the established grade line.

In the hands of a skillful operator, the target and bar method results in reasonable accuracy. However, it has certain limitations and tendencies to err which are difficult or even impossible to eliminate. One of the most important of these limitations is the effect of operator fatigue on his ability to perform satisfactorily. The operator's platform follows the contour of the ground since it is rigidly attached to the traction base of the machine, while the sight bar is at a constant height above the ditch bottom. This condition forces the operator to assume positions from squatting to standing on tip-toe in order to keep the sight bar in line with the targets. At the same time, he is required to adjust the vertical control levers, steer the machine, watch for obstructions, and adjust the tension in the transport cables. These complex activities carried on for many hours cause a great strain on the human body and are
Figure 1. Target and bar method of grade control.
generally quite fatiguing. The result is that, with the customary target spacing of one hundred feet, inaccuracies in grade are almost certain to occur. Roe et al. (1954) have indicated this inaccuracy may be as much as one-tenth to four-tenths of a foot or more depending on the sensitiveness of the individual operator. The fatiguing activities of the operator have been partially eliminated on some machines by providing an operator’s seat that moves vertically in synchronism with the digging unit. However, even this provision does not completely eliminate the problem of operator fatigue and does nothing to reduce the errors of a careless operator.

Another limitation of the target and bar grade control method is the time required to set the targets to the desired grade. Trenching contractors have indicated that this task alone requires ten to fifteen per cent of the operator’s time. Because the trenching machine normally stands idle during this time, the productivity is hampered when using this type of grade control.

Sack (1933) in Germany attempted to modify the target and bar method in order to eliminate target setting by using a very narrow beam of light directed parallel to the proposed grade line. This beam replaced the reference plane normally established by targets. With this device the operator viewed the light source through a small gunsight and controlled the trenching machine to keep the narrow light beam within the limits of the gunsight. Since the gunsight was

---

1 Statements by Fred Galehouse, Robert Davis, and Bayless Brothers trenching contractors, personal interviews.
mounted rigidly to the digging wheel frame, the resulting grade line was parallel to the light beam. This device did eliminate target setting but was accurate only for short distances and did nothing to eliminate operator fatigue.

Pipe and Cord Method

An attempt to overcome some of the disadvantages of the target and bar method has resulted in the pipe and cord grade control device as described by Roe et al. (1954). A cord or wire which is stretched above the ground at the proposed drain gradient is fastened to pipes driven about five feet to the side of the proposed trench and spaced approximately fifty feet apart to prevent undue sag. An arm attached to the digging wheel frame straddles or rides on the wire. By using electrical contacts on the arm, it has been possible to completely automate the grade control of the machine. The great advantage of this device is that it does away with sighting on the part of the operator. Therefore, operator errors are reduced. With this device it has been possible to maintain the finished grade to within five-hundredths of a foot of the proposed grade line. However, the great limitation of this type of grade control system has been the time required to set the wire to the desired grade, a task which is even more time consuming than setting targets. Any advantage this method may have over others in grade line accuracy is quickly lost by the increased time required to set the wire to the desired grade.

Fluid Manometer Method

The fluid manometer method was developed by Hansen (1957) and
consists of a pair of fluid containers joined by a hose that permits free passage of the fluid between the containers. (See Figure 2). One of the containers is mounted on the digging wheel frame and the other on a movable tripod placed over a hub stake. When mounted in this way, the fluid level in each container is equal only if the containers are at the same elevation. Hence, it is possible to have the bottom of the digging wheel operating at the proposed grade elevation by placing the container on the tripod at the proper elevation. Then, as the digging wheel moves through the ground toward the tripod, the container on the machine is lowered relative to the forward travel by a power screw arrangement. The fluid containers are maintained at the same elevation by a hydraulic cylinder which raises or lowers the digging mechanism in response to a change in the fluid level in the containers. The resulting grade is a function of the speed at which the container on the machine is lowered compared to the forward speed of the machine. When the digging mechanism reaches the first hub, the container positioned on the tripod is moved to the next hub, and the process is repeated throughout the route of the ditch.

The principal limitations of this method are the time required to set and determine the elevation of the hub stakes, the time needed to reset the tripod, and the cumbersome procedure of having a hose drag alongside the machine.

All of the methods of grade control reviewed make use of some type of reference plane which is external to the machine. Hence, each of these methods involves the setting of apparatus which describe
Figure 2. Fluid manometer method of grade control.
that reference plane and require considerable set-up time. In a study of trenching machine costs, De Vries (1951) found that if the trenching machine could be operated thirty minutes more per day, a decrease of about ten per cent in the cost of installing the drain could be realized. On this basis, if only half of the time normally used to set targets could be converted to digging time, a savings of approximately ten to fifteen per cent in the cost of installing a tile drain could be expected.
III. INVESTIGATION

A preliminary study of the geometric relationships of a wheel type trencher equipped with a shoe indicated that under most operating conditions a definite angular relationship should exist between the slope of the resulting ditch bottom and the slope of the digging wheel frame. As a result of this analysis, the pendulum grade control device was proposed.

Theory of the Pendulum Grade Control Device

Figure 3 shows a line drawing of a typical wheel type trencher equipped with a shoe. During normal operation the shoe supports the rear of the digging wheel frame while the hydraulic cylinder supports the front of the frame through the pin joint 1. The slope of the resulting ditch bottom is determined by the relative elevations of points J and R. Point J is located at the bottom periphery of the digging wheel, and point R is the resultant reaction of the shoe against the ditch bottom. If it is assumed that the digging wheel has only very small vertical displacements relative to the digging wheel frame and that the shoe does not sink into the trench bottom, then it can be concluded that the line J\(\overline{R}\) is parallel to the resulting ditch bottom as shown in Figure 3. Grade control of the digging mechanism is provided by raising and lowering point R. As point R is raised or lowered, the digging wheel frame tends to rotate about the shoe reaction R. Hence, raising point R causes the slope of line J\(\overline{R}\) to be increased with a subsequent increase in the slope of the
resulting ditch bottom. Similarly, lowering point f reduces the slope of the ditch bottom by reducing the slope of line JR. Since it was assumed that the digging wheel was restricted to very small vertical displacements relative to the digging wheel frame, it can be concluded that the slope of line JR has a fixed angular relationship to the slope of the digging wheel frame represented by the beam in Figure 3. Therefore, by geometric compatibility the slope of the resulting ditch bottom and the slope of the digging wheel frame have a constant angular relationship. Consequently, it was concluded that if the digging wheel frame could be maintained at a constant slope, a characteristic grade line would result.

Following this analysis it was proposed that a simple fluid dampened pendulum be mounted on the digging mechanism as a constant vertical reference from which the slope of the digging wheel frame could be sensed. This pendulum would essentially act as an error detector to indicate deviations from the desired grade. Therefore, the use of a hydraulic-electric grade control system would allow the pendulum to automatically make the indicated grade corrections.

The use of a vertical reference for grade control is the basic difference between the pendulum device and conventional grade control methods which employ a reference parallel to the proposed grade line. This difference allows the pendulum grade control device to be carried entirely on the trenching machine with no external reference except the ditch bottom. Hence, set-up time can be reduced significantly over grade control methods which use an external reference. However, the elimination of a constant external reference introduces
the possibility of accumulative grade line errors due to changes in
the angular relationship between the slope of the ditch bottom and the
slope of the digging wheel frame. Hence, a theoretical force analysis
of the digging mechanism was conducted to investigate possible sources
of grade line error.

Force Analysis of a Tile Trencher

During the operation of a tile trencher, the forces acting on
the digging mechanism change subject to changes in the operating con-
ditions. In order to evaluate the effects of the force variations
upon the pendulum grade control device, information was needed con-
cerning the magnitude and degree of variation that these forces could
be expected to assume. After a search of the literature revealed no
information concerning the forces to be expected on a trenching ma-
chine, the following force analysis was made.

Description of the trenching machine. Figure 3 shows a line
drawing of a typical wheel type trencher equipped with a shoe. This
is the type of trencher that was used in this investigation and for
which the pendulum grade control device was designed. As the digging
mechanism is shown in Figure 3, the digging wheel rotates clockwise
with the vertical and horizontal motion of the digging wheel restrained
by rollers at A, B, and C. Power to drive the digging wheel is sup-
plied through gears located on each side of the digging wheel at
roller A. The digging mechanism, including the digging wheel and
digging wheel frame, is connected to the front part of the trencher
by the pin joint f. Vertical motion of point f, which provides grade
control of the digging mechanism, is restrained by the hydraulic cylinder shown immediately above point f. During normal operation the machine travels from right to left as shown with the cables attached to the rear of the digging wheel frame in a slack condition. When tightened by a winch, these cables serve to lift the digging mechanism during transport. As the machine moves forward with the digging wheel in the trench, the buckets mounted on the digging wheel scoop out bites of soil and transport it to the top of the digging wheel where it is deposited on a cross conveyor. This conveyor carries the soil to the side of the trench where it is convenient for backfilling the trench.

The shoe, shown in Figure 3 directly behind the digging wheel, supports the rear of the digging mechanism when the machine is in the operating position. This shoe slides behind the digging wheel smoothing and forming the bottom of the trench for proper tile alignment.

The trencher that was used in this investigation had a simple I-beam as the principal digging wheel frame member. However, it is common on modern trenching machines to find this I-beam replaced by a more rigid, trussed pipe or angle iron frame.

Figure 4 shows the important dimensions of the digging mechanism used in this investigation.

Operating variables. The principal operating variables that cause variation in the forces acting on the digging mechanism were assumed to be: (1) trench depth, (2) trench width, (3) forward speed, (4) digging wheel rotational speed, and (5) soil draft coefficient.
Figure 4. Dimensions of the digging mechanism for the tile trencher
The trench depth normally ranges from twenty-four to sixty inches. The trench width is usually fixed within rather narrow limits for a given machine; however, small changes in trench width are made possible by changing the digging wheel side cutters. For the machine used in this investigation, the trench width was fifteen inches. Forward speed has a wide variation on practically all machines. As the digging forces increase, the forward speed normally must be reduced due to power limitations. A forward speed range of from three to eleven and one-half feet per minute was available on the machine tested. The wheel rotational speed for the trencher employed in this investigation was controlled entirely by the engine speed and had a maximum value of eight revolutions per minute. However, on some machines the wheel rotational speed can be varied by a selection of gear ratios.

The soil draft coefficient is a measure of the force required to move a given tool through a particular soil under a given set of conditions. Richeney (1961) indicated that this coefficient depends on the soil moisture content, soil texture, structure, and density, cohesive and shearing strength properties of the soil, and tool shape and velocity. The units of this soil coefficient are force per unit of cross-sectional area of disturbed soil. This cross-sectional area is measured perpendicular to the direction of travel. Baimer et al. (1955) list values of unit draft for moldboard plows in sandy soil to be two to five pounds per square inch and for heavy gumbo soils to be fifteen to twenty pounds per square inch. These results were obtained from tests which were conducted at a speed of two and one-half miles
per hour. Bamer further reported that approximately fifty per cent of the total draft was required to cut the furrow slice, thirty per cent for elevating and pulverizing the soil, and twenty per cent for landside friction and miscellaneous forces.

When the trencher used in this investigation was operating at a wheel rotational speed of eight revolutions per minute, the buckets on the digging wheel had a peripheral velocity through the soil of approximately two and one-half miles per hour. Also, each bucket performed a cutting, lifting and pulverizing action on the soil. Therefore, it was reasoned that the draft coefficients found for the moldboard plow would be reasonable for the trencher. Consequently, the values of the soil draft coefficient applied in this analysis ranged from five to twenty-five pounds per square inch.

During this analysis the frictional forces within the bearings and rollers were not considered because it was reasoned that these forces were probably nearly constant for all operating conditions. Hence, any force variation due to bearing friction would be insignificant.

Soil reaction on the digging wheel. The forces from the soil acting on the cutting edge of each bucket were assumed to have two components: one acting perpendicular to and the second parallel to the tangential motion of the bucket. These forces are shown as $F'$ and $F$ in Figure 5. The magnitude of $F$ on each bucket was assumed to be equal to the product of the soil draft coefficient and the cross-sectional area of the soil perpendicular to the tangential motion of the bucket. Stated mathematically, $F = CA$. 
Figure 5. Reaction of the soil against the buckets on the digging wheel.

Figure 6. Area of soil being removed by each bucket as a function of forward speed, trench width and angle $\theta$. 

(a) Side view of bucket  (b) Normal view of bucket
From Figures 5 and 6 it was observed that the area $A$ equaled zero when $\theta$ equaled zero. Similarly, $A$ was a maximum when the bucket reached the soil surface or when $\theta$ equaled $\theta_m$. From Figure 5,

$$A = 1X$$

with,

$$1 = Y \cos (90 - \theta) = Y \sin \theta,$$

but,

$$Y = \frac{12S}{Nn}.$$  

Therefore,

$$F = CA = \frac{12KCS \sin \theta}{Nn}$$

where:

- $F$ = the force in pounds acting parallel to the cutting edge of each bucket in contact with the soil,
- $C$ = the soil draft coefficient in pounds per square inch,
- $A$ = cross-sectional area of soil being disturbed by the bucket in square inches,
- $X$ = trench width in inches,
- $Y$ = forward travel of the machine per bucket per digging wheel revolution,
- $S$ = forward speed in feet per minute,
- $\theta$ = angle in degrees to the location of the bucket measured as shown in Figure 5,
- $n$ = number of buckets on the digging wheel,
- $N$ = wheel rotational speed in revolutions per minute.

The force $F'$ acting perpendicular to $F$ was found by Clyde and McCall (1944) to depend primarily on the tool sharpness and soil hardness. They indicated that $F'$ could be in the range of ten to forty per cent of $F$. Therefore, for this analysis $F'$ was assumed to be twenty-five per cent of $F$. Hence,
\[ P' = 3 \frac{KCS \sin \Theta}{Nn} \]

As determined above \( P \) and \( P' \) refer only to the forces acting on a single bucket. Therefore, to get the total reaction of the soil against the digging wheel, the forces acting on all the buckets in contact with the soil were added. This was accomplished by obtaining the product of the average force acting on a single bucket and the average number of buckets in contact with the soil for any depth. The average force acting on a single bucket as it moved from \( \Theta = 0 \) to \( \Theta_m \) was determined by computing the work done as a bucket moved through the angle \( \Theta_m \) and dividing this work by the peripheral distance the bucket moved.

**Work = Force \times Distance**

\[
W = \int_{\Theta=0}^{\Theta_m} P r_o \, d\Theta = \int_{\Theta=0}^{\Theta_m} \frac{12 \, KCS \, r_o}{Nn} \sin \Theta \, d\Theta
\]

where:

- \( r_o \) = the outside digging wheel radius in inches.

Therefore,

\[
W = \frac{12 \, KCS \, r_o}{Nn} (1 - \cos \Theta_m),
\]

but from Figure 5 it is obvious that \( \Theta_m \) is a function of trench depth \( d \).

\[
r_o \cos \Theta_m = r_o - d
\]

Therefore,

\[
\cos \Theta_m = 1 - \frac{d}{r_o}
\]
Consequently,

\[ W = \frac{12 \times \text{XCS} \times r_{o}}{N_{n}} \left[ 1 - \left( 1 - \frac{d}{r_{o}} \right) \right] \]

\[ W = \frac{12 \times \text{XCS} \times d}{N_{n}} \]

Then, the average force acting on each bucket as it moves from \( \theta = 0 \) to \( \theta = \theta_{m} \) is

\[ F_{\text{avg.}} = \frac{\text{Work}}{\text{Distance}} \]

\[ F_{\text{avg.}} = \frac{12 \times \text{XCS} \times d}{N_{n} \times r_{o} \times \theta_{m}} \]

The total average force, \( F_{T \text{ avg.}} \), acting from the soil tangentially to the digging wheel was determined by the product of the average force per bucket and the average number of buckets in contact with the soil at any one time. If \( N_{a} \) = the average number of buckets in contact with the soil, then

\[ N_{a} = \frac{\theta_{m}}{360^\circ} \times n. \]

Therefore,

\[ F_{T \text{ avg.}} = F_{\text{avg.}} \times N_{a} \]

\[ F_{T \text{ avg.}} = \frac{12 \times \text{XCS} \times d}{N_{n} \times r_{o} \times \theta_{m}} \times \frac{\theta_{m}}{360^\circ} \times n. \]

Hence,

\[ F_{T \text{ avg.}} = \frac{6 \times \text{XCS} \times d}{N \times r_{o} \times \theta_{m}}. \]

The total resultant force acting on the digging wheel by the soil is defined as \( F_{R} \) as shown in Figure 7.
\[ F_R = \sqrt{(F_T \text{ avg.})^2 + (F_T' \text{ avg.})^2} \]

It was assumed that \( F' \) was equal to \( F/4 \).

Therefore,

\[ F_R = \frac{\delta \text{ XCS \ d}}{N \ r_o} \sqrt{1 + (1/4)^2} \]

which upon simplification yields

\[ F_R = \frac{1.97 \text{ XCS \ d}}{N r_o} \quad (1) \]

Equation (1) gives a general expression for the average resultant force of the soil against the digging wheel in terms of the trench width \( X \), trench depth \( d \), soil draft coefficient \( C \), forward speed \( S \), digging wheel outside radius \( r_o \), and the digging wheel rotational speed \( N \). For the machine used in this investigation, the values of \( X, N, \) and \( r_o \) were fifteen inches, eight revolutions per minute, and fifty-one inches, respectively. Therefore, equation (1), when applied to this specific trencher, reduced to

\[ F_R = 0.0725 \text{ CSD}. \quad (2) \]

This soil reaction force was assumed to be acting on the periphery of the digging wheel at the point given by \( \theta_R \) in Figure 7. This angle was approximated by reasoning that the resultant force would act near the point at which one-half the work was done as a bucket moved from \( \theta = 0 \) to \( \theta_m \). Thus, to find \( \theta_R \),

\[ \frac{W}{2} = F r_o \theta_R \]

or,

\[ \frac{12 \text{ XCS \ d}}{2 N} = \frac{12 \text{ XCS \ sin} \theta_R r_o \theta_R}{N} \].
Hence,

$$\sin \theta = \frac{d}{ \frac{2}{r_o} \Theta_R} \quad (3)$$

Values of $\Theta_R$ for various trench depths are shown in Figure 8. From this figure it was observed that equation (3) could be approximated by the straight line

$$\Theta_R = 16.8^\circ + d/2 \quad (4)$$

for trench depths from twenty-four to sixty inches. Since this is the normal range of trench depths, this approximation proves valuable as a simplifying expression for $\Theta_R$.

The resultant force $F_R$ was then reduced to horizontal and vertical components $F_h$ and $F_v$, respectively, as shown in Figure 7.

$$F_h = F_R \cos (\Theta_R - 14^\circ) \quad (5)$$

$$= 0.0725 \cos (\Theta_R - 14^\circ).$$

Similarly,

$$F_v = 0.0725 \sin (\Theta_R - 14^\circ). \quad (6)$$

Figure 9 shows the external forces acting on the digging mechanism. To evaluate the effects of these forces, the digging mechanism was taken as a freecbody. The position of the center of gravity, as shown in Figure 4, was determined by weighing the front and rear of the digging mechanism with hydraulic scales. These weights permitted the horizontal location of the center of gravity to be calculated.

A summation of moments about the hitch point f in Figure 9 yields

$$7 \cdot F_1 + F_h r_h + 128 R + 39 T \sin \phi$$

$$- 8.5 T \cos \phi - F_v r_v + 89.7 W = 0$$
Figure 7. Position of the resultant soil reaction on the digging wheel.

Figure 8. Trench depth vs. angle $\theta_R$ to the resultant soil reaction on the digging wheel.
Figure 9. External forces acting on the digging mechanism of a tile trencher during operation.

Scale: 1" = 30"
Substituting $F_L = \mu R$ and solving for $R$ gives

$$R = \frac{F_v r_v + 80.7 W - F_h r_h + T (8.5 \cos \theta - 39 \sin \theta)}{73 \mu + 128} \quad (7)$$

where:

$W$ = weight of the digging mechanism in pounds,

$r_v = 70 - r_o \sin \theta_R$ in inches,

$r_h = 24 + r_o \cos \theta_R$ in inches,

$\mu$ = coefficient of kinetic friction for soil against the steel shoe. Richay (1961) states that $\mu = 0.3$ is practically always applicable.

$T$ = twice the tension in the driving chains. Each chain has a tension of $T/2$.

$R$ = the reaction of the soil against the shoe in pounds.

The pressure distribution under the shoe was assumed to follow a triangular pattern as shown in Figure 10. Therefore, $R$ was assumed to be acting at a point two-thirds of the distance from the front of the shoe.

The summation of horizontal forces in Figure 9 yields

$$P = F_h + F_v - T \cos \theta. \quad (8)$$

Similarly, the summation of vertical forces gives

$$F_f = W + F_v - R - T \sin \theta. \quad (9)$$

The value of the tension in the driving chain was determined by summing moments about the center of rotation of the driving sprocket as shown in Figure 11. Hence,

$$T = \frac{F_v r_v}{r_s}$$

where:
Figure 10. Assumed force distribution of the soil reaction against the shoe of a tile trencher.

Figure 11. Details of the driving mechanism of roller A.
\( r_o \) = radius of the chain sprocket,
\( r_b \) = radius of driving gear,
\( F_p \) = tangential force between the driving gear and the digging wheel.

But \( F_p \) depends on the soil reaction force \( F_R \). Therefore, a summation of moments about the center of rotation of the digging wheel as shown in Figure 12 yields

\[
F_p = \frac{r_o \ F_R \ \cos 14^\circ}{r_i}
\]

where:

\( r_i \) = inside radius of the digging wheel,
\( r_o \) = outside radius of the digging wheel.

Hence,

\[
T = \frac{r_o \ F_R \ r_b \ \cos 14^\circ}{r_i \ r_b}
\]

For the machine used in this investigation, \( r_o = 51 \) inches, \( r_b = 4.5 \) inches, \( r_i = 40 \) inches, and \( z = 7.5 \) inches. Consequently, the expression for \( T \) reduces to

\[
T = 0.7425 \ F_R. \tag{10}
\]

From Figure 9 the angle \( \phi \) at which the driving chain acts with respect to the digging wheel frame depends on the trench depth with

\[
\tan \phi = \frac{z}{50}
\]

where:

\[
z = 51 - 73 + d = d - 22.
\]

Therefore,

\[
\tan \phi = \frac{d - 22}{50}. \tag{11}
\]

The solution of equations (1) through (11) permits all of the
\( r_1 = 30 \text{ inches} \)
\( r_c = 36 \text{ inches} \)
\( r_b = 40 \text{ inches} \)
\( r_h = 24 + r_o \cos \theta_R \text{ inches} \)
\( r_v = 20 - r_o (1 - \sin \theta_R) \text{ inches} \)
\( w_w = 1150 \text{ pounds} \)

Figure 12. Forces acting on the digging wheel of a tile trencher.
external forces acting on the digging mechanism to be evaluated. However, in addition to the external forces indicated in Figure 9, it was considered desirable to know the forces between the digging wheel rim and the rollers at A, B, and C. Consequently, the digging wheel was considered as a freebody as shown in Figure 12. However, before proceeding to write force resolution equations, some of the boundary conditions were evaluated. The first of these conditions was that the rollers could never exert a negative or tensile force against the digging wheel rim. Secondly, it was assumed that the digging wheel could be considered a rigid body due to its massive construction. Further, it was assumed that the preload applied to the rollers by the adjustable member shown in Figure 9 was small compared to the other forces acting on the rollers. These assumptions meant that the force at roller B was zero or very small when the soil reaction was zero. Similarly, when the soil reaction was sufficiently large to push the digging wheel back against roller B, the force at roller C diminished. Consequently, a very small amount of clearance was assumed to exist between roller B and the digging wheel rim when the digging wheel was out of the soil.

To solve for the forces at rollers B and C, moment equations were written about the point of contact of roller A with the digging wheel as shown in Figure 12. Then, setting $F_B = 0$ as occurred for small values of $F_R$, gives the following expression for $F_C$:

$$F_C = \frac{W_V r_I - F_V r_Y - F_H r_H}{r_C} \quad (12)$$

Values of $F_C$ were obtained until the right side of equation (12)
became negative as occurred for large values of $F_A$. Then $F_c$ was set equal to zero and $F_b$ calculated as follows:

$$F_b = \frac{F_A r_v + F_B r_h - W_b r_l}{r_b}$$

(13)

with $r_v$, $r_h$, $r_l$, $r_b$ and $r_c$ as shown in Figure 12.

The summation of horizontal forces in Figure 12 yields upon simplification

$$F_A = \frac{F_p \cos 52^\circ + F_q \cos 30^\circ + F_b - F_b \cos 48^\circ}{\cos 38^\circ}$$

(14)

An IBM 1620 computer program was written for the solution of equations (1) through (14) for four values of forward speed $S$, three values of soil draft coefficient $C$, and four values of trench depth $d$. The results of these calculations are shown in Table I.

**Discussion of the results of the force analysis.** The factors which would disturb the constant angular relationship of the digging wheel frame and the proposed grade line were considered to be:

1. **Deflections of the beam or digging wheel frame.**

2. **Vertical displacements of the digging wheel relative to the digging wheel frame due to clearance in the rollers.**

3. **Settlement of the shoe due to inadequate load carrying capacity of the soil in the trench bottom.**

Before making the force analysis of the digging mechanism, it was very difficult to predict just how significant each of these factors would be in causing errors in the pendulum grade control device. Even though the analysis that was conducted was far from exact and involved many assumptions which were difficult, if not impossible,
<table>
<thead>
<tr>
<th>C</th>
<th>S</th>
<th>d</th>
<th>( F_R )</th>
<th>( F_R )</th>
<th>( F_T )</th>
<th>( F_F )</th>
<th>( F_A )</th>
<th>( F_B )</th>
<th>( F_C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3</td>
<td>24</td>
<td>26</td>
<td>1776</td>
<td>19</td>
<td>539</td>
<td>1543</td>
<td>822</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>36</td>
<td>39</td>
<td>1774</td>
<td>29</td>
<td>540</td>
<td>1555</td>
<td>846</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>48</td>
<td>52</td>
<td>1773</td>
<td>39</td>
<td>540</td>
<td>1565</td>
<td>872</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>60</td>
<td>65</td>
<td>1774</td>
<td>48</td>
<td>539</td>
<td>1577</td>
<td>893</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>24</td>
<td>52</td>
<td>1768</td>
<td>39</td>
<td>542</td>
<td>1561</td>
<td>864</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>36</td>
<td>78</td>
<td>1763</td>
<td>56</td>
<td>544</td>
<td>1580</td>
<td>912</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>48</td>
<td>104</td>
<td>1761</td>
<td>77</td>
<td>544</td>
<td>1606</td>
<td>961</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>60</td>
<td>131</td>
<td>1762</td>
<td>97</td>
<td>542</td>
<td>1623</td>
<td>1010</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>24</td>
<td>104</td>
<td>1751</td>
<td>77</td>
<td>549</td>
<td>1591</td>
<td>950</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>36</td>
<td>136</td>
<td>1742</td>
<td>116</td>
<td>552</td>
<td>1629</td>
<td>1048</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>48</td>
<td>209</td>
<td>1739</td>
<td>155</td>
<td>553</td>
<td>1670</td>
<td>1148</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>60</td>
<td>261</td>
<td>1740</td>
<td>195</td>
<td>546</td>
<td>1716</td>
<td>1240</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>24</td>
<td>209</td>
<td>1717</td>
<td>155</td>
<td>562</td>
<td>1651</td>
<td>1120</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>36</td>
<td>313</td>
<td>1699</td>
<td>232</td>
<td>570</td>
<td>1727</td>
<td>1314</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>48</td>
<td>418</td>
<td>1693</td>
<td>310</td>
<td>571</td>
<td>1811</td>
<td>1510</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>60</td>
<td>522</td>
<td>1696</td>
<td>387</td>
<td>560</td>
<td>1902</td>
<td>1700</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>24</td>
<td>78</td>
<td>1759</td>
<td>58</td>
<td>545</td>
<td>1516</td>
<td>914</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>36</td>
<td>117</td>
<td>1752</td>
<td>87</td>
<td>548</td>
<td>1604</td>
<td>983</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>48</td>
<td>157</td>
<td>1750</td>
<td>116</td>
<td>549</td>
<td>1635</td>
<td>1034</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>60</td>
<td>196</td>
<td>1751</td>
<td>145</td>
<td>545</td>
<td>1670</td>
<td>1125</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>24</td>
<td>157</td>
<td>1734</td>
<td>116</td>
<td>555</td>
<td>1621</td>
<td>1034</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>36</td>
<td>235</td>
<td>1720</td>
<td>174</td>
<td>562</td>
<td>1678</td>
<td>1182</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>48</td>
<td>313</td>
<td>1716</td>
<td>232</td>
<td>562</td>
<td>1741</td>
<td>1328</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>60</td>
<td>392</td>
<td>1718</td>
<td>291</td>
<td>554</td>
<td>1809</td>
<td>1468</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>12</td>
<td>24</td>
<td>313</td>
<td>1683</td>
<td>232</td>
<td>575</td>
<td>1712</td>
<td>1205</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>12</td>
<td>36</td>
<td>470</td>
<td>1656</td>
<td>349</td>
<td>588</td>
<td>1825</td>
<td>1580</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>12</td>
<td>48</td>
<td>626</td>
<td>1646</td>
<td>465</td>
<td>588</td>
<td>1951</td>
<td>1870</td>
<td>27</td>
</tr>
<tr>
<td>15</td>
<td>12</td>
<td>60</td>
<td>783</td>
<td>1651</td>
<td>581</td>
<td>573</td>
<td>2087</td>
<td>2100</td>
<td>175</td>
</tr>
<tr>
<td>15</td>
<td>24</td>
<td>24</td>
<td>626</td>
<td>1582</td>
<td>465</td>
<td>615</td>
<td>1893</td>
<td>1742</td>
<td>200</td>
</tr>
<tr>
<td>15</td>
<td>24</td>
<td>36</td>
<td>940</td>
<td>1530</td>
<td>697</td>
<td>640</td>
<td>2119</td>
<td>2230</td>
<td>309</td>
</tr>
<tr>
<td>15</td>
<td>24</td>
<td>48</td>
<td>1253</td>
<td>1508</td>
<td>930</td>
<td>641</td>
<td>2371</td>
<td>2770</td>
<td>890</td>
</tr>
<tr>
<td>15</td>
<td>24</td>
<td>60</td>
<td>1366</td>
<td>1519</td>
<td>1162</td>
<td>642</td>
<td>2644</td>
<td>3210</td>
<td>1207</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
<td>24</td>
<td>131</td>
<td>1742</td>
<td>97</td>
<td>552</td>
<td>1606</td>
<td>992</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
<td>36</td>
<td>196</td>
<td>1731</td>
<td>145</td>
<td>557</td>
<td>1653</td>
<td>1115</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
<td>48</td>
<td>261</td>
<td>1727</td>
<td>194</td>
<td>557</td>
<td>1706</td>
<td>1240</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
<td>60</td>
<td>326</td>
<td>1729</td>
<td>242</td>
<td>551</td>
<td>1762</td>
<td>1354</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>6</td>
<td>24</td>
<td>261</td>
<td>1700</td>
<td>194</td>
<td>569</td>
<td>1681</td>
<td>1200</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>6</td>
<td>36</td>
<td>392</td>
<td>1678</td>
<td>291</td>
<td>579</td>
<td>1776</td>
<td>1450</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>6</td>
<td>48</td>
<td>522</td>
<td>1670</td>
<td>387</td>
<td>579</td>
<td>1881</td>
<td>1685</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>6</td>
<td>60</td>
<td>653</td>
<td>1673</td>
<td>484</td>
<td>566</td>
<td>1994</td>
<td>1915</td>
<td>10</td>
</tr>
<tr>
<td>25</td>
<td>12</td>
<td>24</td>
<td>522</td>
<td>1616</td>
<td>387</td>
<td>602</td>
<td>1833</td>
<td>1620</td>
<td>24</td>
</tr>
<tr>
<td>25</td>
<td>12</td>
<td>36</td>
<td>783</td>
<td>1571</td>
<td>581</td>
<td>622</td>
<td>2021</td>
<td>2023</td>
<td>347</td>
</tr>
<tr>
<td>25</td>
<td>12</td>
<td>48</td>
<td>1044</td>
<td>1555</td>
<td>775</td>
<td>624</td>
<td>2231</td>
<td>2475</td>
<td>597</td>
</tr>
<tr>
<td>25</td>
<td>12</td>
<td>60</td>
<td>1905</td>
<td>1563</td>
<td>968</td>
<td>598</td>
<td>2458</td>
<td>2840</td>
<td>861</td>
</tr>
<tr>
<td>25</td>
<td>24</td>
<td>24</td>
<td>1044</td>
<td>1446</td>
<td>775</td>
<td>669</td>
<td>2135</td>
<td>2230</td>
<td>912</td>
</tr>
</tbody>
</table>
Table 1 (Continued)

<table>
<thead>
<tr>
<th>C</th>
<th>S</th>
<th>d</th>
<th>$F_R$</th>
<th>R</th>
<th>T</th>
<th>$P$</th>
<th>$F_f$</th>
<th>$F_a$</th>
<th>$F_b$</th>
<th>$F_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>24</td>
<td>36</td>
<td>1566</td>
<td>1359</td>
<td>1162</td>
<td>710</td>
<td>2512</td>
<td>3030</td>
<td>1570</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>24</td>
<td>48</td>
<td>2088</td>
<td>1324</td>
<td>1549</td>
<td>712</td>
<td>2932</td>
<td>3920</td>
<td>2067</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>24</td>
<td>60</td>
<td>2610</td>
<td>1342</td>
<td>1937</td>
<td>660</td>
<td>3386.6</td>
<td>4700</td>
<td>2577</td>
<td>0</td>
</tr>
</tbody>
</table>

C = Soil draft coefficient, pounds per square inch

S = Forward speed, feet per minute

d = Trench depth, inches

$F_R$ = Resultant force on digging wheel, pounds

R = Resultant force on shoe, pounds

T = Tension in the driving chain, pounds

$P$ = Horizontal force on pin joint $f$, pounds

$F_f$ = Vertical force on pin joint $f$, pounds

$F_a$ = Force at roller A, pounds

$F_b$ = Force at roller B, pounds

$F_c$ = Force at roller C, pounds
to completely justify, the results certainly indicate the force trends which would be expected.

In computing the deflections of the digging wheel frame, the frame was treated as a simple I-beam. Since the pendulum was mounted to the rear, over-hanging portion of the beam, it was assumed that the deflections of major importance were those measured from a tangent to the rear portion of the beam. It was found that the maximum change in static deflection of roller A measured as indicated above was less than two-hundredths of an inch over the range of conditions encountered. Therefore, this source of error was considered negligible.

The second factor considered as a possible source of error in the pendulum grade control was evaluated by an examination of Table I. From this table it was noted that the force on roller B varied from zero to over 2500 pounds. However, it must be remembered that these values were obtained by assuming that the rollers were adjusted with clearance at roller B when the digging wheel was out of the ground. Therefore, the significance of these results is that if the rollers are adjusted to allow clearance between the digging wheel rim and the rollers, vertical deflections of the digging wheel would be expected to occur as the digging conditions changed. Hence, to eliminate or at least minimize this source of error with the pendulum grade control device, it is very important that the rollers be adjusted with sufficient preload to restrict the motion of the digging wheel.

The third factor expected to affect the accuracy of the pendulum
grade control device depends on the shoe reaction \( R \). Table 1 shows that this reaction does not change appreciably over the entire range of digging conditions and actually decreases as the soil reaction increases. The shoe reaction causes a unit stress to be applied to the soil under the shoe. This stress was assumed to be distributed from front to rear as shown in Figure 10 and uniformly distributed over the cross section of the shoe. Then, the following equation can be written relating the maximum stress \( s_{\text{max}} \) to the shoe reaction \( R \):

\[
R = 325 \ s_{\text{max}}
\]

or,

\[
s_{\text{max}} = R/325.
\]

For the maximum shoe reaction from Table 1,

\[
s_{\text{max}} = 773 \text{ pounds per square foot.}
\]

The settlement that this stress would be expected to cause is very difficult to evaluate because of the tremendous variation in soils. Certainly, considerable settlement of the shoe would be experienced under artesian or quicksand conditions. Taylor (1948) indicated that the resulting settlement of a soil depends primarily upon the escape of air and water from the voids. Considerable time is usually required for this compression to take place in clay soil. Therefore, the settlement expected under this load for normally saturated or unsaturated clay or loam soil would probably be very slight because of the extremely short time that the maximum stress would be applied. Due to the extreme variation in soil, it is conceivable that the pendulum grade control device would have to be recalibrated for widely varying soil conditions.
This force analysis tends to indicate that the force variations on the digging mechanism under most soil conditions are not sufficient to cause appreciable errors in the pendulum grade control device when the machine is properly adjusted.

**Equipment**

*Fluid dampered pendulum.* The grade control device employed in this investigation was a fluid dampered pendulum originally designed for an automatic leveling system on a sugar beet combine manufactured by the Scott Vinor Company, Columbus, Ohio. This pendulum was suspended from an angle iron "A" frame as shown in Figure 3. This "A" frame was originally designed for a mole plow and was adapted to the trencher by welding angle iron brackets to the trencher frame.

Figure 13 shows the internal details of the fluid dampered pendulum. The weight was a square, forty-pound block of cast iron machined to accept the four pistons and the threaded one-half-inch rod from which it was suspended. The pistons shown in Figure 13 (d) gave more severe dampering than would otherwise be possible. These pistons were made of one-eighth-inch sheet steel and had approximately one-sixteenth-inch diametrical clearance. The pistons were fastened to the fluid box by connecting rods pivoted at the outer end as shown in Figure 13 (b) and (d). Since this pendulum was originally intended for two-dimensional leveling control, four pistons were provided. However, for grade control of a tile trencher only one-dimensional movement of the weight was needed. Therefore, one-eighth-inch strips of steel were welded to the cover plate as
Figure 13. Details of the fluid dampened pendulum used for grade control of a tile trencher.
shown in Figure 13 (c). These strips restrained the motion of the weight in the direction perpendicular to the direction of travel. Hence, the weight was prevented from dragging along the side of the box when the digging mechanism leaned to one side as commonly occurred when the machine was operated on a hillside. A similar restriction of the weight could have been accomplished by fastening ball or roller bearings to the sides of the weight and allowing this bearing to roll along a race mounted to the inside of the fluid box.

The cast aluminum box which enclosed the dampening fluid was bolted to a four-inch by two-inch channel iron as shown in Figures 14 and 16. This channel iron was pivoted at the apex of the "A" frame indicated by A in Figure 14. Due to the moderately severe vibrations encountered, additional support for the fluid box was provided by the angle iron frame clamped under the box as shown in Figure 15.

The top of the rod from which the weight was suspended was clamped inside a section of wire-reinforced hydraulic hose shown as B in Figure 14. This section of hose provided a spherical pivot giving practically no horizontal restriction to the motion of the pendulous weight while still giving a vertically rigid connection.

Limit switches were mounted in front of and behind the pendulum rod as shown in Figures 13 and 15. These were overriding type, normally open, Microswitches which allowed extreme motions of the pendulum without damage to the switches. The mounting brackets for the limit switches were welded to the fluid box cover plate as shown in Figures 13 and 15. Four switches are shown in these figures because
Figure 14. Right side and rear view of the pendulum and "A" frame.
Figure 15. Fluid-damped pendulum showing the limit switches.

Figure 16. Pendulum calibration scale, channel iron mounting bracket, and clamp used on the fluid-damped pendulum.
the pendulum was originally developed to control the grade of a mole
plow having a hydraulic system which provided a fast and slow grade
correction. However, since the tile trencher had a relatively slow
forward speed, only one speed of correction was considered necessary.
Therefore, only the top pair of limit switches, shown as LS1 and LS2
in Figure 15, were needed in this investigation. These switches
were closed by the square brass block fastened to the pendulum rod
as shown in Figure 13. The position of the limit switches was ad-
justed so that approximately three-sixty-fourths of an inch clearance
was present between the brass block and each of the switches. In
other words, the brass block could move approximately three-thirty-
seconds of an inch from the time one switch opened until the other
closed.

During operation the "A" frame, channel iron, fluid box, and
limit switches were rigidly connected to the digging wheel frame.
At the same time, the pendulum was free to swing relative to the
fluid box and limit switches. Thus, when the digging wheel frame
deviated from the desired slope, the pendulum maintained its vertical
orientation and closed the appropriate limit switch. This signal was
then fed into the electric-hydraulic grade control system which made
the indicated correction to restore the digging wheel frame to the
original slope. As the digging wheel frame returned to the desired
slope, the limit switch was reopened discontinuing the grade cor-
rection. Hence, by repeated error messages, the pendulum was able
to maintain the digging wheel frame near the desired angular ori-
entation as indicated by the pendulum setting.
Changes in grade setting were accomplished by changing the angular orientation of the channel iron and fluid box with respect to the digging wheel frame. During this investigation this change involved loosening the clamp labeled C in Figure 16 and pivoting the channel iron about the apex of the "A" frame until the new slope setting was reached. Pivoting the channel iron in this manner caused the vertical pendulum rod to close one of the limit switches. Hence, when the operation of the machine was resumed, the automatic grade control system changed the slope of the digging wheel frame to the value indicated by the new slope setting.

The slope scale, shown by S in Figure 16, was developed experimentally during the initial field tests. This scale was calibrated in per cent slope and was clamped to the "A" frame cross member to indicate the proper pendulum setting. The range of this scale was from zero to four per cent and had an overall length of 1.44 inches. Hence, 0.36 of an inch represented one per cent slope. Each one per cent was further subdivided into five parts. Therefore, two-tenths of one per cent slope was represented on the scale by 0.072 of one inch.

Three viscosities of dampening fluid were tried during this investigation. These were 100 per cent hydraulic fluid, 100 per cent number two diesel fuel, and a mixture containing equal parts of the first two fluids. The hydraulic fluid was Sohivas 52, an SAE 20 weight paraffin base oil with a Saybolt viscosity of 320 at a temperature of 100°F. The Saybolt viscosity of the diesel fuel was approximately 35.8 at 100°F. The mixture was used during most of the
field tests and appeared to be the most satisfactory for air temperatures above 40°F.

**Machine modifications.** The tile trencher used for this investigation was a model 1844 Buckeye owned by the Ohio State University. This machine was at least forty-five years old and is shown in Figure 17.

![Image of the tile trencher](image)

**Figure 17.** The pendulum grade control device mounted on the Buckeye 1844 trencher.

Since this machine was not equipped with a hydraulic system, it was necessary to convert the grade control mechanism from cable-winch to hydraulic-electric control to accommodate the pendulum grade control device. This conversion was accomplished by installing a hydraulic pump, a single acting hydraulic cylinder, hydraulic flow control valves, and an electrical control system on the trencher. The hydraulic pump was mounted under the engine radiator as shown in Figure 18. It was driven from the engine crankshaft with a one-to-
one ratio by a V-belt. The hydraulic cylinder was mounted in an upright position as shown in Figure 19. The upper end of this cylinder was attached to the ends of the grade control cables normally fastened to the frame. Connecting the hydraulic cylinder to the cables in this manner permitted the cable winch grade control system to remain functional. Hence, it was possible to control the grade of the machine with the pendulum system completely inoperative. The double cable winch shown immediately to each side of the cylinder in Figure 19 was installed to keep the grade control cables even and thereby prevent the digging wheel frame from leaning to the left side due to the weight of the earth conveyor. With the cylinder mounted in this way, a two-to-one ratio existed between the vertical displacement of the hydraulic ram and the front of the digging wheel frame. Therefore, a trench depth variation of only fifteen inches was available from the thirty-inch hydraulic cylinder for any single cable setting. However, operation at the full range of trench depths was made possible by adjusting the grade control cables with the cable-winch control. Consequently, as the hydraulic cylinder approached the upper or lower limit, the machine operator manually adjusted the grade control cables with the winch to allow the hydraulic ram to return to a position somewhere near the center of its travel. The hydraulic cylinder was attached to the front of the digging wheel frame in such a manner that as the cylinder was extended by hydraulic pressure, the front of the digging wheel frame was raised. Conversely, the release of hydraulic pressure from the cylinder allowed the weight of the digging wheel frame to retract the cylinder,
Figure 18. Denison hydraulic pump mounted under the engine radiator.

Figure 19. Single acting hydraulic cylinder mounted vertically for grade control of the tile trencher.
lowering the front of the frame.

The hydraulic flow control valves, oil reservoir and pressure
gauge were mounted to the upright frame members as shown in Figure 21. This location permitted easy access from the control valves to the hydraulic cylinder.

The mounting brackets used to adapt the "A" frame to the trencher were made of one-fourth-inch by two-inch angle iron welded to the rear of the trencher frame. The "A" frame was then fastened to these brackets by four bolts.

**Hydraulic system.** The hydraulic system developed for the tile trencher was designed to give the following:

1. A vertical velocity of one inch per second to the front of the digging wheel frame during grade corrections.

2. A maximum safe hydraulic pressure of 1500 pounds per square inch.

3. A maximum vertical force at the front of the digging wheel frame of 6000 pounds.

A line drawing of the hydraulic system is shown in Figure 20. This system was designed around a Danison variable displacement piston pump which had a maximum output of two and one-half gallons per minute at 1000 pounds per square inch pressure when operating at 1000 revolutions per minute. This pump was equipped with a pressure relief valve which protected the system in case the outlet hose became blocked.
Figure 20. Schematic drawing of the hydraulic grade control system.

Figure 21. Location of the hydraulic solenoid valve (A), pressure gauge (B), oil reservoir (C), pressure relief valve (D), and the flow restrictor valve (E).
To give the desired speed of grade correction, a hydraulic cylinder with a two and one-half inch bore was selected. A cylinder of this diameter gave a piston area of slightly more than four and nine-tenths square inches. Hence, the vertical force requirement as specified by (3) above was easily exceeded. The cylinder selected was an International Harvester number 653-300-R92, which gave a thirty-inch stroke.

A Waterman number 434-3-12 three-way hydraulic solenoid valve was selected to control the flow of oil to the cylinder. This was a twelve-volt solenoid valve utilizing two solenoids as shown by A in Figure 21. When neither solenoid was energized, the flow of oil from the pump was directed to the oil reservoir with the cylinder blocked. (See Figure 20). Energizing solenoid U caused the flow from the pump to be directed to the cylinder extending the ram. When solenoid D was energized, the cylinder was unblocked allowing oil to flow from the cylinder to the reservoir.

A pressure relief valve set at 1250 pounds per square inch was installed on a by-pass around the solenoid valve to relieve the pressure from the hydraulic cylinder in case the digging wheel hooked under an obstruction. This valve is shown as B in Figure 21.

The pressure gauge shown as B in Figure 21 was installed in the hydraulic line connecting the cylinder to the solenoid valve. Hence, this gauge registered the pressure in the hydraulic cylinder and, therefore, gave an indication of the vertical force being applied to the front of the digging wheel frame. It was desired that this gauge be read from the operator's platform during operation. Consequently,
it was installed with the back showing as in Figure 21.

The initial field tests indicated that the pendulum grade control device tended to overcorrect downward when rocks were encountered. To correct this situation, an adjustable needle valve was installed in the oil line leading from the outlet of the solenoid valve to the reservoir. This valve is shown as E in Figure 21. Partially closing this valve reduced the speed of downward correction by restricting the flow of oil and creating additional back pressure in the oil line leading from the cylinder.

The oil reservoir, shown as C in Figure 21, was originally an oil filter tank. The filter elements were removed giving approximately three gallons of oil reserve.

One-half-inch hydraulic hose having a maximum bursting pressure of 1750 pounds per square inch was incorporated into this system. Design calculations indicated that three-eighths-inch lines were large enough to maintain the oil velocities below ten feet per second. However, the larger lines were selected to reduce the frictional head loss in the reasonably long oil lines.

Sohvis number 52, an SAE 20 paraffin base hydraulic oil, was used in this system.

The extent of the machine modifications that was necessary to adapt the pendulum grade control device to the trencher used in this investigation was considerably greater than would normally be necessary. Most modern trenching machines are equipped with a hydraulic grade control system. Consequently, the only major hydraulic modifications that would be necessary to adapt the pendulum grade control
device to a modern machine would be the installation of a hydraulic solenoid valve and a pressure relief valve.

**Electrical system.** The function of the electrical system was to pick up the grade error signal as indicated by the pendulum and then control the hydraulic grade control cylinder to correct the error.

A schematic drawing of the electrical system and a description of the important terms is shown in Figure 22. The Joint Industry Conference standard electrical symbols were used to denote the electrical elements.

The limit switches, LS1 and LS2, were located in front of and behind the pendulum, respectively. LS1 was closed when the pendulum swung forward relative to the "A" frame in response to a drop of the front of the digging wheel frame. Similarly, LS2 was closed when the front of the digging wheel frame was raised. Therefore, when the system was on automatic control (S2 closed) the closing of LS1 energized CR1, which in turn energized solenoid U giving an up correction. Also, the closing of LS2 energized CR3, which in turn energized solenoid D giving a down correction. At any time that one of the solenoids was energized, it was impossible to energize the other due to the electrical interlock between CR1 and CR3.

This system was designed so that the machine operator could assume grade control at any time regardless of whether the switch S2 was on automatic or manual control. This feature was accomplished by connecting the control relay, CR2, in series with the push buttons, FB1 and FB2. Hence, when either FB1 or FB2 was closed, the automatic
PB1 and PB2 - Push buttons for up and down corrections, respectively.
CR1, CR2, CR3 - Control relays.
S1 - On-off switch.
S2 - Automatic-manual selector switch.
LS1 - Limit switch located in front of the pendulum.
LS2 - Limit switch located behind the pendulum.
Sol. U - Solenoid on hydraulic valve giving up correction.
Sol. D - Solenoid on hydraulic valve giving down correction.
PLP - Pilot light indicating power.
PLU - Pilot light indicating up correction.
PLD - Pilot light indicating down correction.

Figure 22. Electrical circuit for the pendulum grade control device.
circuit was disconnected by the opening of the normally closed contacts on CR2.

The control relays CR1, CR2, and CR3 were Potter Bromfield number GPD 12-volt DC. These relays with the twenty ampere fuse, the automatic or manual selector switch S2, the push buttons PBI and PB2, and the three indicator lights were located in the electrical control box as shown in Figure 23.

![Electrical control box](image)

**Figure 23.** Electrical control box located in front of the operator's platform.

This control box was conveniently located immediately in front of the operator's platform.

Previous experiences with solenoid valves had indicated that low terminal voltage could cause erratic operation. Therefore, to
guard against excessive voltage drop, number fourteen multiple strand copper conductors were used throughout the system.

The electrical power supply was a twelve volt DC storage battery normally used to start the engine on the trencher. This battery was located to the left side of the engine and was recharged by a generator driven from the engine.

This electrical system was relatively inexpensive to build and provided practically trouble-free operation during this investigation.

**Testing Procedure**

In order to evaluate the pendulum grade control theory and to test the equipment developed, field tests were conducted which were designed to include a range of operating variables. Trench depths ranged from less than eighteen inches to over four and one-half feet. Forward speeds ranged from approximately three to eleven and one-half feet per minute. However, the range of soil variation was limited because all of the tests were conducted during the winter and early spring at The Ohio State University Farms. The soils encountered during the first seven tests were Miami Silt Loam and Brockton Silty Clay Loam. In tests eight and nine and in the three field checks of the target and bar method of grade control, the soil was Celina Silt Loam near field capacity. Crosby, Brockton, and Celina soils were encountered in test ten.

The initial field tests, during which no tile were installed, were conducted to eliminate malfunctions from the grade control system, permit the pendulum to be calibrated, and allow the investigator to become more familiar with the operation of the trenching
machine. For the first five tests the pendulum was set randomly to
give a range of trench bottom slopes. From these test results, a
scale calibrated in per cent was developed by linear interpolation
from the ditch bottom slopes obtained. This scale was then extrapo-
lated to include the points of zero and four per cent slope. The
accuracy of this scale was checked in tests six and seven by setting
the pendulum at the desired slope, as indicated by the scale, and
comparing this value to the slope calculated from the resulting ditch
bottom.

After the first seven tests indicated that the pendulum grade
control theory could be applied to a tile trencher, further field
tests were conducted on a drainage enterprise where the trencher was
operated by an Ohio State University employee who was familiar with
its operation. The proper pendulum setting for these tile drains was
determined by setting stakes at the approximate grade changes along
the route of the drain. Ground surface rod readings were determined
at these stakes and the proposed drain gradient was computed for
each section of the drain. This drain gradient was then recorded on
the stake preceding the section of the drain to which it applied.
Then, during the digging of the drain, the machine operator changed
the pendulum setting at each stake indicating a change in drain
gradient.

The method of evaluating the accuracy of the pendulum grade con-
trol device involved taking drain grade line rod readings along the
route of the trench. These data along with the average ground sur-
face rod readings were plotted on profile paper. From these plots
the deviations from the average grade line were determined. During the first seven field tests, the trench bottom and ground surface relative elevations were determined to the nearest hundredth of a foot at five-foot intervals along the drain. After test number seven, tile were being installed immediately behind the trencher. Therefore, the grade line was determined by taking relative elevations from the top of the tile rather than the trench bottom. These relative elevations were also determined to the nearest hundredth of a foot but were taken at ten rather than five-foot intervals. In all cases the readings were determined by a well-adjusted transit or level.

Information concerning the operating conditions such as rocks, operator errors, and other possible sources of grade line error were recorded as the grade line and ground surface data were being taken.

In order to be better able to evaluate the accuracy of the pendulum grade control device, data were needed on the accuracy of other methods of grade control. Hence, three drains were installed by the same trencher using the target and bar method of grade control. On two of these drains the data were taken after the entire tile line had been placed in the trench but not covered. Consequently, the operator did not know that the grade line was being checked. However, on the third drain the operator was aware that his work was being checked. As a result, he was doubly careful in setting the targets and in watching the sight bar.
Field Test Results

The results of the field tests that were conducted on the pendulum grade control device during this investigation are shown in Figures 24 through 32. Figures 33 through 35 show data from tile drains installed with the same trencher using the target and bar method of grade control.

The data from the second field test shown in Figure 24 indicates a maximum deviation from the average grade line of less than five-hundredths of a foot with no indication that the grade line was affected by ground surface irregularities. The results of the first field test are not shown because the investigator was familiarizing himself with the operation of the trencher; therefore, the results were not significant.

Contrasted to the excellent grade line in Figure 24 is the one shown in Figure 25, where a marked flattening of the grade line occurred when rocks were encountered. Rocks were observed to cause the digging mechanism to go deeper because the grade control device was overcorrecting downward. As a result of this observation, the flow restrictor valve was installed to reduce the speed at which the downward corrections could be made.

In Figure 26, where rocks were again encountered, a noticeable improvement in grade line accuracy over that shown in Figure 25 can be observed. However, a slight flattening of the grade still persisted as rocks were encountered. Also, for the first time in the field tests, slight grade line deviations due to ground surface irregularities appeared. These deviations are shown as a hump and
a dip approximately twenty-five and forty feet from the outlet, respectively. Not including the effects of the rocks at the upper end of the ditch bottom, the maximum deviation from the average grade line was still less than one-tenth of a foot.

From Figure 27, showing test number five, a grade line deviation due to ground surface irregularities similar to that shown in Figure 26 can be observed.

In tests six and seven, shown in Figures 28 and 29, practically no rocks were encountered. Also, the ground surface irregularities were not nearly as severe in these tests as was the case in Figures 26 and 27. As a result the grade line deviations in Figures 28 and 29 are less than four-hundredths of a foot from the average grade line. It is also noted that the grade line in Figure 29 remained practically horizontal while the prevailing ground surface had a negative slope.

Figure 30 presents the data from the first field test where tile were installed. During this test, targets were set as a check on the pendulum grade control device. The principal grade line error in this test occurred as a result of improperly set targets. Hence, the machine operator in attempting to keep the sight bar in line with the targets introduced the grade line error shown as operator error. As a result of this and other operator errors, it is difficult to make an accurate evaluation of the grade line deviation attributable to the pendulum device during this test.

In test number nine, Figure 31, many rocks were encountered with little or no noticeable affects. However, to some extent the
grade line appears to follow the shape of the ground surface profile with a maximum deviation from the average grade line of approximately fifteen-hundredths of a foot.

Figure 32 is presented in three separate parts as (a), (b), and (c). In part (a) the primary error occurred when the operator attempted to shift the length of the grade control cables with the digging wheel turning. With the exception of this error, the maximum deviation from the average grade line was less than five-hundredths of a foot for this section of drain. In part (b) the grade line appears to be affected somewhat by the hump in the ground surface profile at approximately 760 feet from the outlet. Part (c) shows slight grade line deviations caused by rocks as indicated. However, even with these grade line errors the maximum deviation from the average grade line appears to be less than five-hundredths of a foot for part (c). The relatively close correlation between the pendulum grade control setting and the resulting average slope of the grade line in test ten tends to indicate that the pendulum grade control device can be calibrated and set to give a predictable slope.

The relatively shallow trench as shown in Figure 32 (a) is undesirable from a tile drainage standpoint. However, the occurrence of this shallow drain was not caused by the pendulum grade control device but by the operator who erred in setting the pendulum at the outlet main. Consequently, the first 700 feet of this drain were installed at a depth less than intended.

Figures 33, 34, and 35 present data from tile drains installed with the same trencher except with the target and bar method of
grade control. During the installation of the drains shown in Figures 33 and 34, the operator did not know the grade line was going to be checked. In these tests the maximum deviation from the average grade line was fifteen-hundredths of a foot or more. During the installation of the drain shown as Figure 35, the operator knew the grade line was being checked and was, therefore, very careful of the grade and watched the sight bar almost constantly. However, even with these extra precautions, the resulting grade line errors were still at least one-tenth of a foot.

Although the data presented in Figures 24 through 32 represent the primary source of the results, other observations were recorded and are presented here for the information of possible future investigators.

The pendulum appeared to give the most accurate grade control when the limit switches were adjusted close enough to the actuating block to cause the system to continually hunt at a frequency of at least one grade correction every two to five seconds. The frequency at which this system hunted depended upon the limit switch clearance as well as the viscosity of the dampening fluid, which of course was affected by the outside air temperature. The most satisfactory results for air temperatures ranging from 40°F to 70°F were obtained with a dampening fluid composed of a mixture of equal parts of hydraulic oil and diesel fuel in combination with a limit switch clearance of three-sixty-fourths of an inch.

While the trencher was operating, the digging mechanism was observed to be vibrating at a frequency equal to the digging wheel
rotational speed times the number of buckets on the digging wheel. The vibrations appeared to be transmitted to the pendulum weight through the dampening fluid. Consequently, the pendulum weight and the fluid box were vibrating continuously, necessitating the relatively wide limit switch clearance.

It was estimated from the field tests that the set-up time for the pendulum grade control device was approximately one-third of that required for the target and bar method. Therefore, the productivity of the machine was increased by using the pendulum grade control device.

Although no data were recorded concerning operator fatigue, the pendulum grade control device noticeably reduced his work load. Consequently, the operator was able to devote more of his time to watching for obstructions which could damage the digging wheel.
Figure 24.
Field test number 2 using the pendulum grade control device.
Dampening fluid, diesel fuel.
Figure 23.

Field test number 3 using the pendulum grade control device.

Figure 26.

Field test number 4 using the pendulum grade control device.

Dampening fluid, diesel fuel.
Figure 27.
Field test number 5 using the pendulum grade control device.
Figure 28.
Field test number 6 using the pendulum grade control device.
Dampening fluid, a mixture of hydraulic oil and diesel fuel.
December, 1961.
Figure 29.

Field test number 7 using the pendulum grade control device.

Dampening fluid, a mixture of hydraulic oil and diesel fuel.
December, 1961.

Average ground surface

Avg. slope = 0.01%
Max. grade line deviation = 0.04 ft.

Ditch bottom

Distance from the outlet in feet

Relative elevation in feet
Figure 30.
Field test number 8 using the pendulum grade control device.
Dampening fluid, diesel fuel.
December, 1961.
Figure 31. Field test number 9 using the pendulum grade control device. December, 1961.

Average ground surface

15 inch rock

Many rocks

3:400 Distance from the outlet in feet

Relative elevation in feet
Figure 32(a)
Field test number 10 using the pendulum grade control device.
Damping fluid, a mixture of hydraulic oil and diesel fuel, April, 1963.
Figure 32(b)
Field cast number 10 using the pendulum grade control device.

Lampering fluid, a mixture of hydraulic oil and diesel fuel. April, 1962.
Figure 32(c).

Field test number 10 using the pendulum grade control device.

Dampening fluid, a mixture of hydraulic oil and diesel fuel. April, 1942.
Field check number 2 with grade control provided by the target and bar method.

Target spacing, fifty feet.
March, 1962.
Figure 35.

Field check number 3 with grade control provided by the target and bar method.

IV. DISCUSSION

The grade line results obtained during this investigation indicate that the pendulum grade control theory is valid for a wheel-type trencher under most conditions. A comparison of the grade lines obtained with the pendulum grade control device and the target and bar method show that the pendulum was equally as accurate as the target and bar method where rocks were encountered and perhaps more accurate where rocks were not present. When it is considered that the trenching machine employed in this investigation had seen considerable service and had appreciable clearance in the joints and bearings, the results obtained appear even better. More accurate grade lines would be expected when using the pendulum on a newer trenching machine with a more rigid digging wheel frame and bearings with closer tolerances.

The force analysis of the tile trencher indicated that clearances between the rollers and the digging wheel rim would allow vertical displacements of the digging wheel relative to the digging wheel frame with resultant grade line errors. Consequently, it was recommended that the rollers be adjusted to give a preload between the rollers and the digging wheel rim, thus giving greater vertical digging wheel rigidity. However, if the digging wheel rigidity should eventually prove to be a major limitation to the pendulum grade control device, consideration should be given to the possibility of redesigning the digging mechanism to give a digging wheel which
would rotate on a central bearing rather than on the rollers employed on present machines.

The tests conducted during this investigation were on soils where the bearing strength was sufficient to prevent the shoe from sinking into the trench bottom to any noticeable extent. Consequently, more extensive field tests should be conducted which would give a wider range of soil variation, including soils with relatively low bearing strengths. Under these conditions the shoe would be expected to sink into the trench bottom causing grade line errors. However, even extremely soft trench bottom conditions need not be a major limitation to the pendulum grade control device. It takes very little mechanical ingenuity to design a hydraulic pressure manifolding system which could be used to exert a specific tension on the transport cables. With such a device the soil reaction on the shoe could be reduced to a level that could be supported by practically any soil. Hence, the grade line errors introduced by the low bearing strength of soils could be minimised.

The major limitation of the pendulum grade control device employed in this investigation appeared to be the tendency to overcorrect downward as rocks were encountered. Certainly this is a problem which must not be overlooked as rocks are usually common where drain tile are installed. The occurrence of rocks tended to cause severe vibrations in the digging mechanism which in turn forced the pendulum to oscillate between the limit switches giving alternate up and down corrections. Since the hydraulic system did not have sufficient capacity to correct upward as rapidly as downward, the result was
a net downward correction. In an effort to equalize the rates of correction, a flow restrictor valve was installed in the outlet of the hydraulic cylinder. The installation of this valve did reduce the effects of rocks, but it also tended to cause the grade line to follow the ground surface profile to some extent. Before the pendulum grade control device can achieve widespread acceptance for tile trenchers, the detrimental effects caused by rocks need to be minimized or eliminated. Perhaps this could be accomplished by a hydraulic system giving a faster up correction. Or perhaps a pendulum mounting designed to damp out the severe vibrations could be developed. Another solution might be to employ a gyropendulum or the newly developed but highly accurate fluid gyroscope.

The fluid damped pendulum as a vertical reference for grade control of a tile trencher is very simple—so simple that by today's standards of technology it would almost seem crude. Therefore, the limitations found for the pendulum tested in this investigation are quite probably not limitations at all but rather engineering problems destined to be solved at some future date. Certainly the theory of using a vertical reference for grade control should not be abandoned but should be further refined and applied to other earth moving machines such as land levelers and motor graders.
V. CONCLUSIONS

As a result of the theoretical analysis and the field test results of the fluid dampened pendulum for grade control of a wheel-type trencher, it was concluded that:

1. There is a definite angular relationship between the slope of the digging wheel frame and the slope of the resulting ditch bottom for most operating conditions.

2. Rocks in the path of the digging wheel tend to cause the pendulum grade control device to overcorrect downward giving accumulative grade line errors.

3. If no rocks are encountered, grade line accuracies can be obtained with the pendulum grade control device which are better than those obtained with the target and bar method of grade control.

4. To prevent large-scale grade line errors with the pendulum grade control device, the rollers restricting the motion of the digging wheel should be adjusted to give a small amount of preload to all the rollers.

5. Distinct ground surface irregularities tend to cause minor grade line deviations.

6. The pendulum grade control device reduces set-up time by eliminating target setting. It also reduces operator fatigue by automating the grade control of the trencher.
VI. SUMMARY

A theoretical force and geometric analysis of a wheel-type trencher equipped with a shoe revealed that under most operating conditions a definite angular relationship exists between the slope of the ditch bottom and the slope of the digging wheel frame. During this investigation a simple fluid dampened pendulum was mounted on the rear of the digging wheel frame as a vertical reference from which the slope of the digging wheel frame was sensed. The grade line errors as indicated by the pendulum were fed into a hydraulic-electric system which automatically controlled the slope of the digging wheel frame. This pendulum grade control device was tested under limited field conditions at The Ohio State University and was found to significantly reduce set-up time and operator fatigue. The results of these field tests indicated that the theoretical analysis was basically correct. However, where rocks were encountered, the pendulum grade control device tended to overcorrect downward causing accumulative grade line errors. Other less-significant grade line errors resulted from improper machine adjustment and distinct ground surface irregularities. Where rocks were not encountered, grade line accuracies were obtained which compared favorably with those obtained with the same machine using the target and bar method of grade control.
REFERENCES


