A STUDY OF THE PERFORMANCE AND COST OF OPERATION OF WHEEL-TYPE DRAINAGE TRENCHING MACHINES

by

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DRAINAGE TRENCHING MACHINE PERFORMANCE AND COSTS

(suggested short title)

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ABSTRACT

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A STUDY OF THE PERFORMANCE AND COST OF OPERATION OF WHEEL-TYPE DRAINAGE TRENCHING MACHINES

A study of the effect of digging depth on the speed of wheel-type subdrainage trenching machines revealed an inverse linear relationship for the range of depths observed in several different soils. Both soil texture and machine characteristics affected the depth-speed relationship to a degree which prevented the use of a generalized formula for all machines in all soil types.

Data are presented for 20 delay factors which occurred during normal trenching operations. An analysis of these delays showed that an average of 58.6 percent of the available digging time was lost. Delays which could most easily be reduced included making junctions and setting grade targets.

The costs associated with the operation of trenching machines were shown in a proposed cost schedule. Results of a questionnaire revealed a large variation in costs between contractors.

Methods of increasing digging speed and reducing time losses and costs of operation were described.

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INTRODUCTION

The Project

The number of privately-owned trenching machines for the installation of subsurface drains in the province of Quebec has been increasing rapidly during the past four years. In 1967, two privately-owned trenchers were complementing the group of seventeen government machines. By 1970, the private enterprise force had increased to eighteen machines, while the government machine number had been reduced to twelve. This trend toward larger numbers of privately-owned trenching machines in the province is expected to continue, as the demand for agricultural subsurface drainage grows each year.

This project was initiated in 1969 to investigate the influence of tile-trenching machine performance on the cost of operation in Quebec. It was considered at that time, that there were enough privately-owned machines in the province to make such a study feasible, and since this work force was at such a young stage of development, the results of the investigation would be timely.

As free-enterprise continues to embark in the drainage business, it can be expected that greater competition will develop between contractors working in a particular area. It will become more important for each machine owner to be aware of his costs of operation and the factors affecting the efficiency of his machine. By increasing his efficiency, he will be able to decrease his cost per foot of drain, and be in a better position to compete with other contractors. At the same time, he must be aware of the break-even point between profit and loss for his own particular operation.

It is hoped that this investigation will provide further insight into subdrain installation operations, and thereby be beneficial, both to the contractor and to the farmer concerned.

Although drainage, in the general sense of the word, may denote either surface or subsurface drainage, the use of the word in this project refers only to subsurface installations.

Justification of the Study

With an increasing population and a decreasing farm-land area, it is becoming more important to improve the productivity of the arable land which is available. Although the province of Quebec contains approximately 335.5 million acres, only about 16.8 million acres, or 5 percent, is considered arable land (14, p.7). Furthermore, only 5.2 million acres, or 1.5 percent, are under cultivation (7). When compared to the rest of Canada, these figures indicate that, although Quebec is the largest province, it ranks fifth in its area under cultivation (10).

In 1967, a Royal Commission report on agriculture in Quebec (14, p.9) stated that the productivity of agriculture in Ontario was greater than that in Quebec by 26 percent, on the average. In the same report, la Corporation des Agronomes de la Province de Québec declared that in the opinion of the agronomes of all the regions of the province, one of the foremost causes of the low productivity of the land is poor drainage;

they recommended that it be considered as a problem of priority, and that the situation be remedied by all available means.

In 1967, an investigation by Jutras (10) showed that 3.18 million acres of good to fair improved land in Quebec would benefit from drainage. At the end of 1965, only 42,000 acres had already been tile-drained, or 1.33 percent of the underdrainage needs of the province. The corresponding figures for Ontario showed 2.2 million acres with tile drainage, or more than 30 percent of the land under cultivation (14,p.9).

With the objective of increasing the annual underdrainage installation to meet the needs of the province, the Royal Commission on agriculture in Quebec (14) presented a suggested schedule of installations up to the year 1980. The Quebec Department of Agriculture, through the Agricultural Hydraulics Division, also established a five year plan of action up to 1972 (11). These recommendations and forecasts are shown, up to 1971, in figure 1, along with the actual drainage installations, for both Quebec and Ontario.

Based on the foregoing discussion, the annual installation rate in Quebec can be expected to increase rapidly for the next several years. New contractors will be entering into the drainage business for the first time. They will want to know some facts about the economics of the operation before they invest their capital. In calculating their costs on an annual and per foot basis, both existing and new contractors may not be aware of all the economic factors to be taken into consideration, such as depreciation, interest on investment, and management charges.

In order to maximize their profits without excessively charging the farmer or sacrificing quality, the contractors must strive for

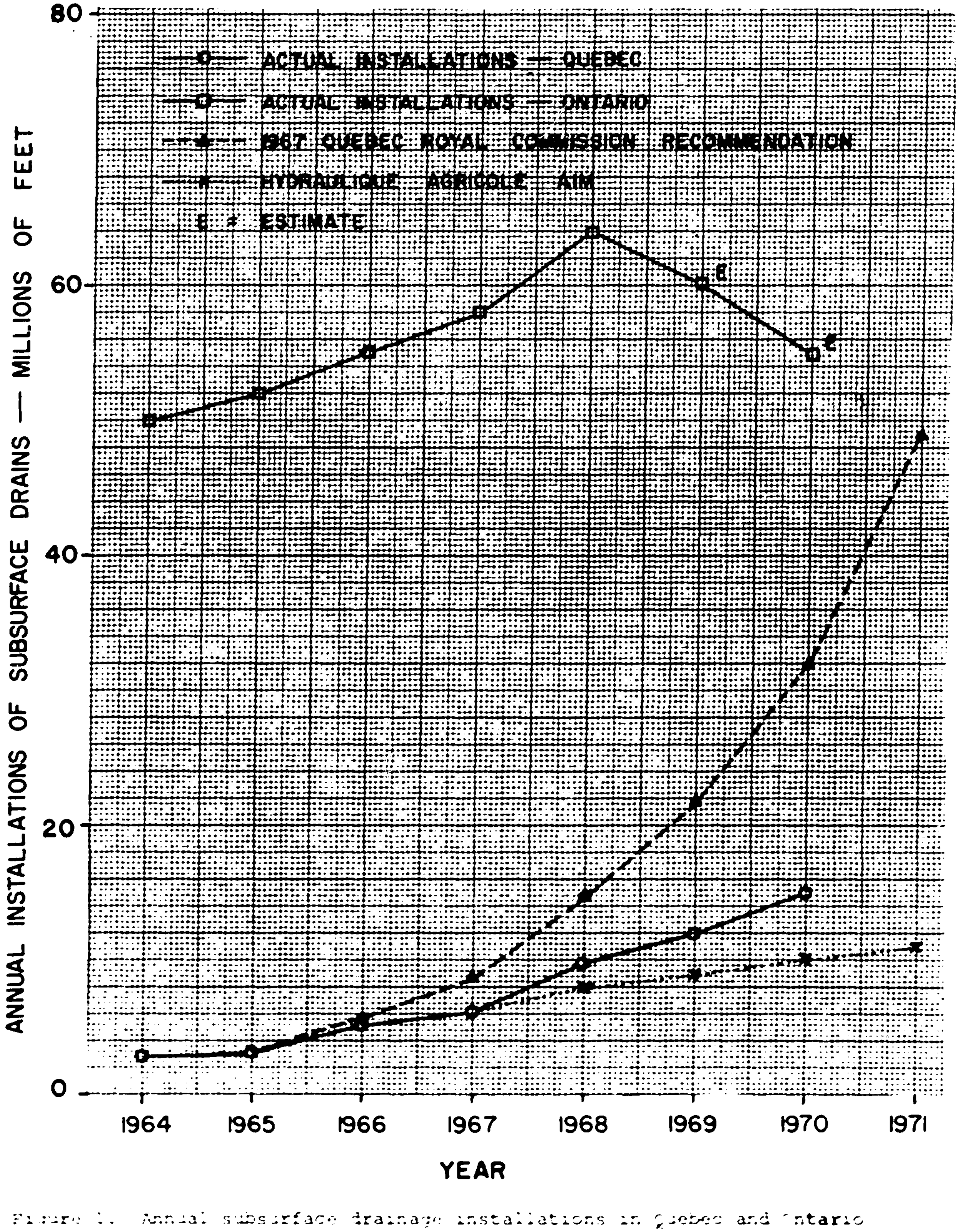


Figure 1. Annual subsurface drainage installations in Quebec and Ontario during the period 1964-71 (information extracted from 5,11,14).

better efficiency of their systems of drain installation. There are many time losses in the trenching operation of which they should be aware. Some of these, such as weather, are unavoidable, while others, such as making junctions and setting targets, can be reduced.

Soil and digging factors also affect the overall productivity of the machine. The digging depth especially could have a large influence on the speed of digging. A study of this relationship could lead to guidelines for including a depth factor in the charges for trenching.

Similar studies of machine performance have been undertaken in Europe and the United States (4, 6, 12) between 1948 and 1951, by various researchers. However, because of the increased cost and capacity of modern equipment, it was desirable to carry out observations of current operations in Quebec.

Objectives and Scope

On the basis of the foregoing discussion, the following objectives of this study were established:

1) to study the relationships between depth of digging and the digging speed in soils of different textures, while keeping other factors as constant as possible. These relationships might be used as guidelines for charging on a depth basis if there exits a considerable reduction in installation rate at greater depths.

2) to investigate the causes and duration of digging time losses for several machines, by means of a work study over a partial season, and by projecting the results onto a seasonal basis, to find the overall efficiencies of the machines. This could lead to recommendations of

of methods to decrease the field time losses and increase the productivity of the men and the machines.

3) to investigate the operating costs of trenching machines in order to determine the cost of operation on a seasonal and on a per foot basis. The analysis will be based on data obtained from the contractors and from information from other references.

Although other factors besides digging depth are likely to affect the speed of digging, it was not deemed within the scope of this thesis to include the multiple effects of such variables as soil moisture, soil hardness, machine age, etc. As each one of these parameters would require individual study, they were kept as constant as possible during the tests.

An underlying aim of the experiment was to establish a procedure which could be duplicated by individual contractors wishing to correlate their own operations with the results reported in this study. Only in this way can the findings be of most practical value to those involved in the subsurface drain installation business.

REVIEW OF LITERATURE

Machines and Materials in Use

There are presently over 150 drainage trenching machines in operation in Ontario, and 30 machines in the province of Quebec (including government-owned machines). These machines can be conveniently grouped into three main classes, according to the digging principle used - 1) the wheel-type trencher, 2) the endless-chain trencher, and 3) the trenchless drainlaying plow.

The vast majority of the machines in Quebec and Ontario are of the wheel-type (figures 2a & 2b), with the Buckeye Wheel Ditcher and the Speicher Farm Drainage Trencher being the most common trade names. There is also a limited number of endless-chain trenchers in use; the Vandenende Drainmaster is an example of this type (figure 3). The trenchless drainlaying plow is a more recent addition to the group; the Badger Minor is an example of a machine using this principle (figure 4).

Machines of classes 1 and 2 may be used to install both the conventional clay tile and the relatively new corrugated plastic drain tubing. The trenchless drainlaying plow, or machines in class 3, are confined to the use of plastic tubing only. However, since 1968 in Ontario, and 1970 in Quebec, corrugated plastic tubing is being produced commercially in large quantities and is available to contractors wishing to use it with any type of machine.

Figure 2(a). Wheel-type drainage trenching machine with rubber tires.

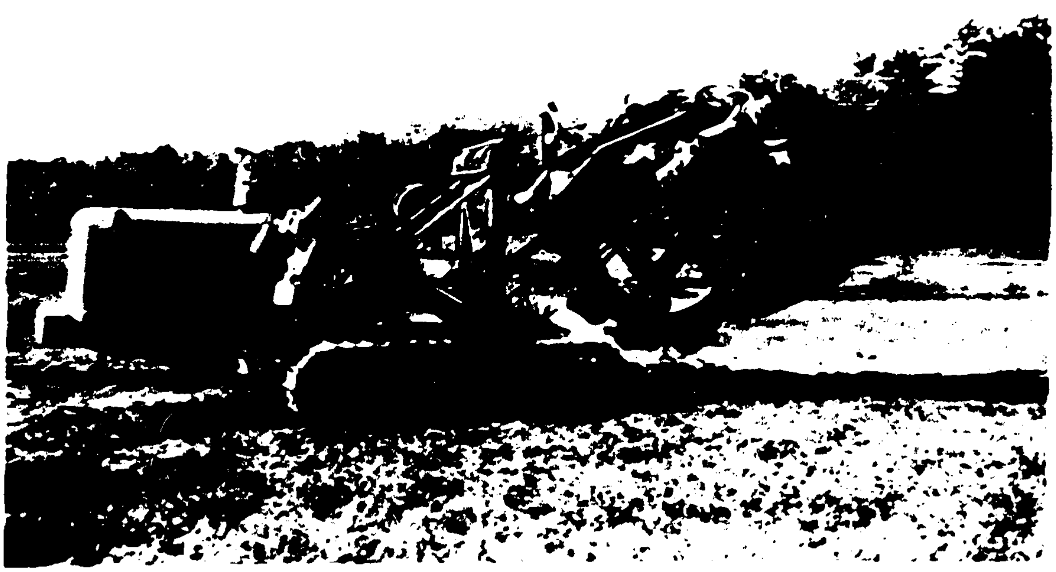
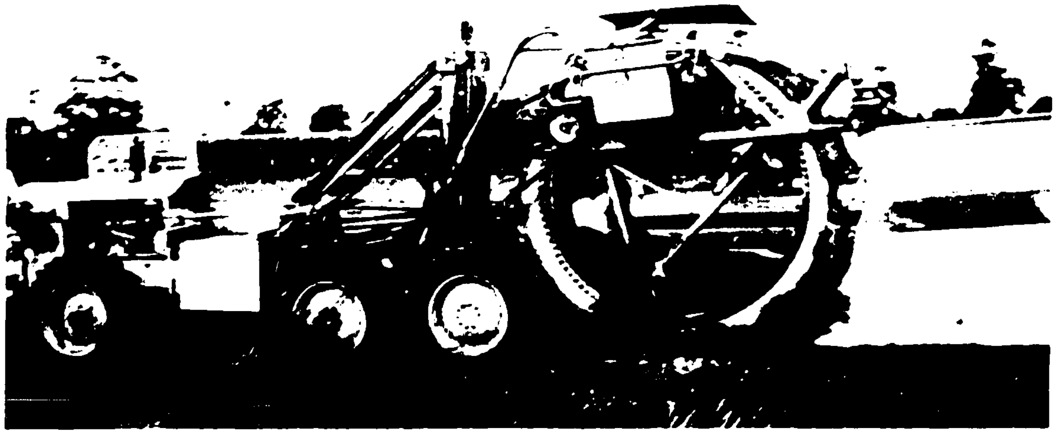


Figure 2(b). Wheel-type drainage trenching machine with tracks.



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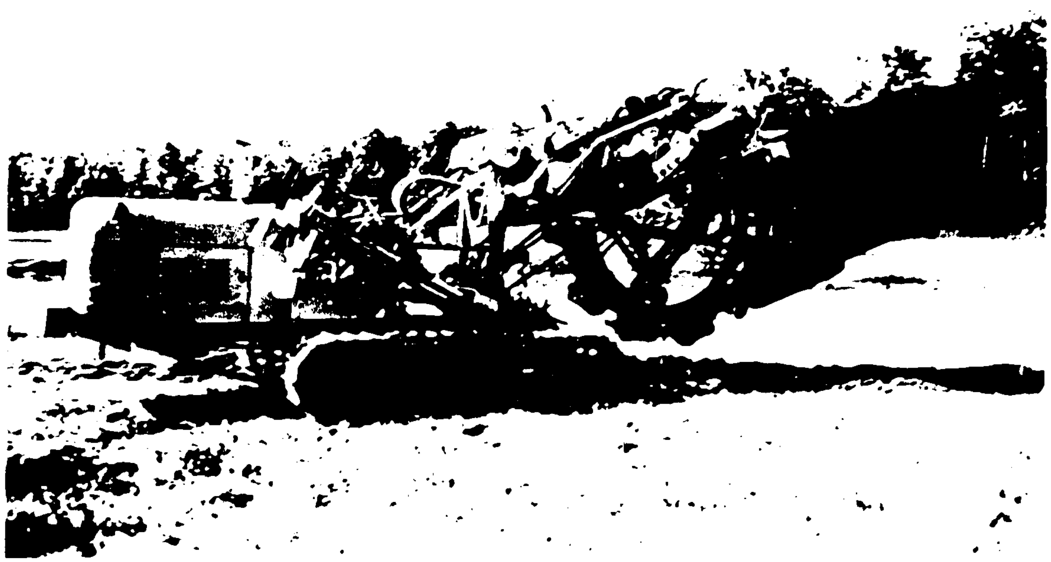


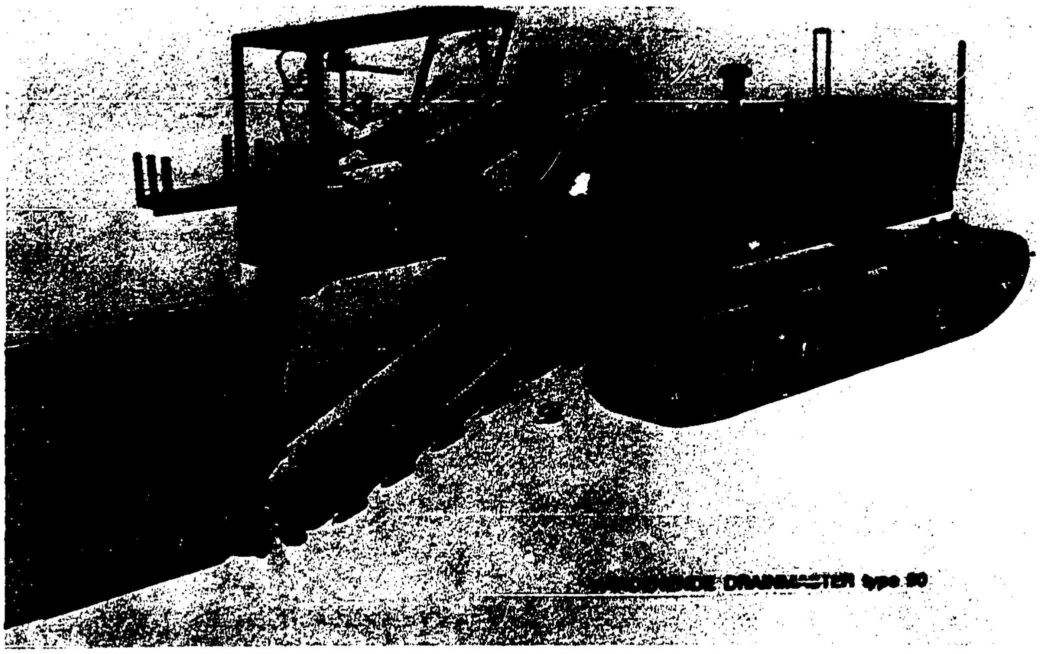


Figure 3. Endless-chain type drainage trenching machine.

Figure 4. Trenchless drainlaying plow.

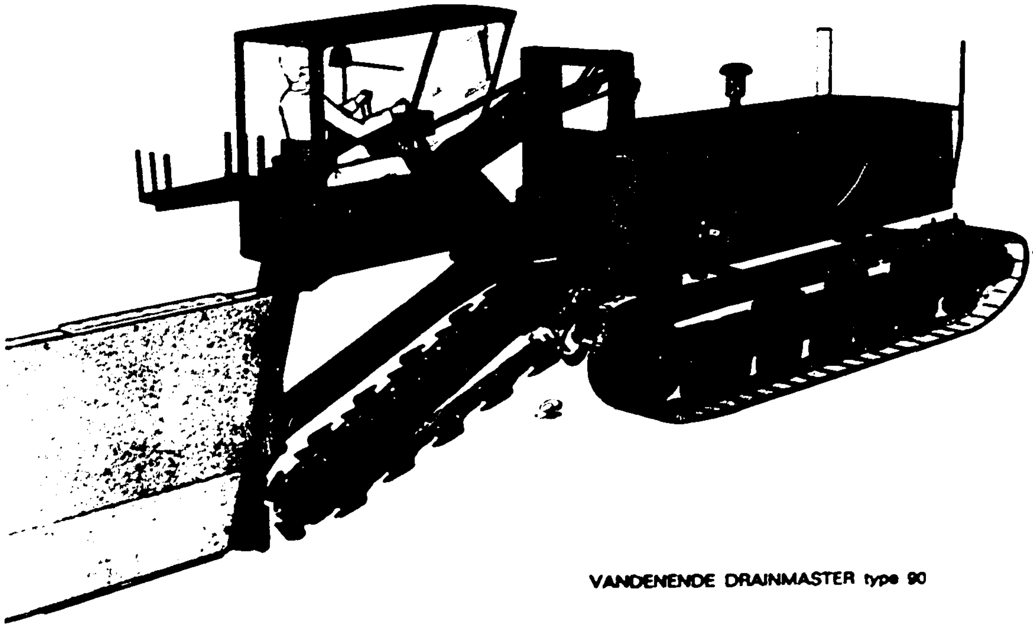


Figure [illegible]. Endless-chain type drainage trenching machine.

Although the trenchless drainlaying plow (such as the Badger Minor) is capable of installing drainage tubing at close to three times the rate of conventional trenchers, the initial cost of equipment and its cost of operation have limited its use in Canada up to this time. During 1970, there were three Badger Minors working commercially in the country (two in Ontario and one in British Columbia) and an additional machine is expected in 1971.

Digging Speed

Several researchers have investigated some of the factors which affect the rate of installation of drainage systems. Yarnell (19) cited the following three factors which govern the amount of work done per day - soil conditions, strength and efficiency of the machine and the skill of the workmen. During observations of several machines, he found that the variation in speed due to a combination of these factors could be quite pronounced. For instance, on one job, a wheel-type trencher digging at a depth of 40 inches in saturated loam soil advanced at an average rate of 192 feet per hour over a period of nine hours. A similar machine, digging in a sticky clay, at depths between 40 and 66 inches, advanced at an average rate of 100 feet per hour, over a period of ten hours, or almost one-half the first machine's rate. He did not indicate what proportion of this variation might be due to either the soil characteristics or the digging depth.

On another job which Yarnell observed, there were 5910 feet of main tile, at an average depth of 3.9 feet, and 99,910 feet of lateral tile which averaged 2.5 feet in depth. The average rates of progress, considering only the days of actual work, were 492 feet per day for the main and 2,040 feet per day for the laterals. Although some of the differences in digging rates could probably be attributed to the difference in tile sizes, a large proportion of the variation was more likely due to the difference in depth.

Research on the cost of drainage installation was done by Roe (15) in 1927. In considering the cost of labor, he states,

> "The amount of labor involved in digging trenches varies widely with the size of the tile, the depth of the trench and the character of the soil and subsoil, and this variation is not uniform.... it is therefore necessary to consider the average cut on any given project for the different sizes of tile and also the character of the digging as determined by the kind of soil.... the surface character of the land has no appreciable influence in fixing the unit rate of cost in this element."

Ohlson (12) conducted trials in Sweden from 1947 to 1949, to study the effect of soil texture on the digging speed of a Buckeye 301 and Parsons 200 trenching machine. He reported the following results:

Soil Type	Average Rate of Working (Feet/8-hr.day)
Clay - Morraine	525
Very Heavy to Medium Clay	1170
Light Clay and Sand	1430
Peat	1610

Although the data were not directly correlated to depth of digging, Ohlson did state that at depths between 2.6 feet and 3.9 feet, there was no appreciable effect on the digging speed, but at depths from 3.9 feet to a maximum of 5.5 feet, the rate of digging decreased with increasing depth. He also qualified that, although these results could be regarded as average for wheel-type machines, on some days the average might be exceeded considerably, while on other days, the rate could be far below the average.

A more comprehensive study of factors affecting the digging speed was made by Beach (4) in 1947. From an analysis of 17 ten-minute runs of Buckeye 301 trenching machines, he derived the following multiple regression equation for the continuous digging rate:

$$Y = 113.4138 - 23.4344X_1 - 0.515X_2 - 0.6635X_3 + 2.1843X_4$$

where Y = distance travelled in 10 minutes (feet)

X_1 = average depth of cut (feet)

X_2 = average penetrometer reading (psi)

X_3 = average moisture content (percent)

X_4 = average silt content (percent)

The multiple correlation coefficient R from the analysis showed that approximately 30.86 percent of the variability in Y was explained by X_1, X_2, X_3, and X_4. However, the coefficient was not significant at $P = 0.05$. Beach concluded that by increasing the sample size to 30, a significant multiple correlation coefficient would probably be obtained, if the amount of variability remained the same. His analysis also showed that the depth of cut and the silt content were the most important factors. An attempt to relate the dependent and independent variables by simple linear regression, however, showed no significance at $P = 0.05$.

As a continuation of Beach's work, DeVries (6) evaluated the depth-speed relationship while keeping all other variables as constant as possible. From an analysis of 56 ten-minute runs of a Buckeye 301 trenching machine, he derived the following linear regression equation for continuous digging rate:

$$Y = 130.569 - 20.611X$$

where Y = distance travelled in ten minutes (feet)

X = average depth of cut (feet)

The analysis showed that 67.8 percent of the variation in Y could be accounted for by a linear relationship with X. Further analysis of the data showed that a third-degree equation of the form

$$Y = 2.444X^3 - 24.417X^2 + 39.234X + 89.899$$

accounted for 83.1 percent of the variation. Both the linear and the cubic components of the regression were significant at $P = 0.01$. However, DeVries cautioned the use of the third-degree polynomial because the data was concentrated heavily at two digging speeds as a result of machine transmission characteristics. This fact was again emphasized by Schwab et al (17) where he referred to DeVries' work and stated,

> "Since these concentrations of data are a characteristic of the machine, it is doubtful that the third-degree curve gives a more accurate depth-speed relationship for all makes of machines and all soils than the linear equation."

Time Losses

Continuous digging rates do not represent the daily or even the hourly capacity of a trenching machine, since delays in operation are not taken into account. Observations and research by several workers indicate a large amount of lost time in the day-to-day operation of trenching machines.

Yarnell (19) cited examples of time losses during the installation of drainage systems. In one case, of the 100 days the machine was on the job, there were 14 Sundays, 61 days of machine work, and 25 days lost on account of repairs, rain and miscellaneous delays. On another job with a similar machine working a 60 hour week from August 3 to December 7, there were 636.75 actual operating hours, 221.75 hours lost due to repairs, 9.5 hours lost due to weather and 67 hours on account of moving between jobs. He also reported that the average digging hours of 15 machines operating in New York during 1918, was only four hours per 10-hour day, with the remainder of the time being spent on repairs, delays due to rocks, and frequent moving between farms.

Yarnell (19) summarized the importance of time losses in the following statement:

> "The matter of lost time is of great importance, for the owner usually is losing money when his machine is not digging. The portion of the year during which the machine does not work is surprisingly great, even to many drainage contractors, and will explain why trenching with a machine costs so much more than one ordinarily would expect, even after watching the machine work for several days under adverse conditions."

DeVries (6) kept accurate records of the time losses for a Buckeye 301 trencher during the complete season of 1950. The field and climatic conditions permitted the working season to continue from April 15 until November 22, or a total of 220 days. During this period, there were 35 Sundays and holidays, which resulted in 185 available working days. The distribution of these available working days, as reviewed by Schwab et al (17) was as follows:

Component	Duration (days)	% of 185 available working days
Weather	35.0	18.9
Repairs	26.4	14.3
Junctions	19.0	10.3
Moving to new job	15.5	8.4
Servicing	11.3	6.1
Miscellaneous delays	14.2	7.6
Machine operation	63.6	34.4
TOTAL	185.0	100.0

This research showed that the machine was actually operating only 34.4 percent of the time, with the remaining 65.6 percent being lost because of the various delay factors.

Cost of Operation

If a contractor is to operate a trenching machine at a profit, he must be aware of all the expenses involved. A machine owner may often overlook some of the factors which contribute to the total cost of operation. While some of the expenses may be accurately predicted, others may require careful estimation based on reliable norms.

The contractor's costs may be divided into overhead and operating expenses. Overhead (or fixed cost) is made up of costs which do not vary directly with the volume of work, and may include depreciation, interest, management and supervision, insurance, taxes and housing. The operating expenses include labour, payroll taxes, fuel and lubrication, machinery rentals, repairs, and all other items which vary with the volume of work done.

While a considerable amount of research has been done concerning the cost of operation of farm and construction machinery, studies of drainage trenching machines are rather limited. DeVries (6) estimated the cost of trenching machine operation by using the average figures of one machine over a period of three years. Beach (4) made a similar analysis using results of questionnaires and interviews with drainage contractors. Ohlson (12) reported the results of observations of several machines working in Sweden. No study was found to include more than the trenching machine cost itself in the initial investment.

Some trencher manufacturers and distributors (3, 8) have made estimates of operating costs based on reports from their customers. Although some of these may not be complete or representative of the average conditions, part of the information might be useful in a study of this type.

Other bulletins and standards of machinery operating costs are available from a number of sources, parts of which can be adapted to estimating trenching machine costs.

INVESTIGATION

As most of the drainage trenching machines used in both Quebec and Ontario are of the wheel type, rather than the endless-chain or the trenchless drainlaying plow types, this study was conducted solely on the wheel-type trenching machine. Furthermore, because of the increasing popularity and local availability of machines on rubber tires, the study was confined to wheel-type trenching machines on rubber tires (see figure 2a). This restriction should not, however, prevent the application of the results to the crawler-type machine, as all of the factors are similar except perhaps transportation time and costs.

The field work was initiated in July 1969. It was decided that the 1969 summer should be devoted to the study of one machine only, in order to become well acquainted with the operations involved in drainage trenching, and to establish a system of observations to be applied to other machines.

During the summer of 1970, from May until September, the performance of four different machines was investigated. In all cases, the same procedure was followed. Two main objectives were kept in mind - firstly, to correlate the digging speed with the digging depth in soils of various textures and secondly, to obtain a detailed daily account of all the time losses. A procedure was established whereby one field researcher could perform both studies simultaneously, without jeopardizing the accuracy of either one. To achieve this, it was found, early in the field study, that the equipment and instruments which the researcher had to carry with him must be kept to a minimum.

The economic study was done with the aid of questionnaires which were sent to contractors who were operating trenching machines in Ontario. Further data was collected through personal interviews with Quebec contractors.

Digging Speed

There are many factors which may influence the digging speed of trenching machines. During normal operation, a trencher might dig at a rate varying anywhere from one to thirty feet per minute. Under extraordinary circumstances, this range may even extend to over forty feet per minute. Since most contractors charge for drainage installation on a per-foot basis, information regarding the rate of installation is important.

Factors Affecting the Digging Speed

The following discussion is based on field observations by the author and is not supported by experimental data.

Characteristics of the machine. The characteristics and condition of the machine may have a pronounced effect on its digging speed. The engine determines the power which can be transmitted to the digging wheel, and thus the potential digging speed. The age of the machine does not seem to have as much effect as the mechanical condition of that machine. A trencher which is kept in good repair will perform as well as a new machine for many years. The bucket size, in some cases, may affect trencher performance. This becomes more noticeable as the bucket width decreases, since cohesive soils tend to pack tightly into these buckets and remain there for several revolutions of the digging wheel before being removed by the cleaning fingers. In more extreme cases, the machine must be stopped completely to permit cleaning by hand. With buckets of sixteen-inch width or greater, this trouble becomes less frequent. Worn digging parts also cause an accumulation of soil in the buckets and a lower capacity of the machine. The type of cutting equipment on the digging wheel should be matched with the type of soil for maximum performance. Rooter bits are best adapted to hard, dry soil or stoney conditions. Solid cutters perform best in wet, sticky soils, which are often encountered in the spring and fall.

Skill of the operator. The transmission gears of most trenchers permit the use of eight or more forward digging speeds at each throttle setting. For the most efficient performance, the operator must always use the highest possible gear for the given digging conditions. Knowing when a gear shift is possible is a result of experience, and could mean up to one hundred feet per hour more production.

Soil and moisture conditions. Under the normal range of moisture conditions, the digging speed does not seem to be significantly affected by variations of the soil moisture content. However, in cases of either extremely wet or dry soils, reduction of the digging speed is apparent. The wet condition causes the soil to be heavier, and consequently, the power requirement is greater. In clay soils, high moisture content causes excessive clogging of the buckets, as well as decreased traction of the machine. In sandy soils, it may result in frequent cave-ins of the trench wall, at or immediately behind the digging wheel. An extremely dry moisture condition causes the soil to become hard, especially in clay, and the digging speeds are reduced. Very dry sand tends to drop out of the buckets before reaching the conveyor belt, and must be moved several times. In general, the digging speed is faster in dry soil than in soil which is extremely wet, under stone-free conditions. However, in the presence of stones, the reverse is usually true.

Other soil properties which may affect the digging speed include cohesiveness, texture, structure, compaction and condition of the soil surface. As already mentioned, cohesive soils tend to stick in the buckets and reduce the digging speed, while soils with low cohesion drop out of the buckets before reaching the conveyor belt, and also cave excessively. Soils formed of large, hard clods sometimes require greater power for the cutters to break through. Some soils, such as organic soils, may not provide adequate bearing support for the heavy weight of the machine, and consequently can greatly reduce the rate of advance. The condition of the soil surface affects the traction and mobility of the trencher, and could be an important factor in some cases.

Cover crop. The vegetation on a field may affect the digging speed. Although normal grass or crop cover rarely decreases the rate of advance, heavy root systems or dense growth tend to clog the digging mechanism and cause delays. High-rising crops, such as corn, can clog the machine, as well as reduce the visibility of the operator. A field with no cover crop may not provide adequate traction, especially after a period of rain.

Tile size. When the digging and the tile-laying are done simultaneously, as is most often the case, the machine's rate of advance is dependent on the rate at which the tile can be handled by the men behind. While 4-inch clay tile weighs approximately eight pounds per foot, 6-inch tile weighs fourteen pounds and 8-inch weighs twenty pounds. It cannot be expected that a man will handle these large sizes with such ease and speed as the 4-inch tile for a long period of time. It has also been observed that the automatic tile-laying chutes on the machines operate more efficiently with the small diameter tiles. Adjustments of the spacing between tiles seem to occur more frequently when laying the collector lines. Some contractors find it advantageous to lay these large tiles directly into the trench by hand without passing them through the tile chute. However, this requires more time and effort and thus reduces the rate of advance.

Observations by the author of installation of corrugated plastic drain tubing indicate that the effect of tile size may be greatly reduced by the use of this new product. Plastic drain tubing requires much less handling and its weight is only a small fraction of that of clay tile.

Size and efficiency of the crew. Many of the field operations associated with trenching must be done by hand labour. Handling the tile, setting grade targets, making junctions and surveying all require a certain number of man-hours to complete. Any delay in these operations causes a reduction in the rate of installation. Frequently, the machine operator will merely reduce his digging speed in order to avoid a complete halt of the machine. In this event, the delay cannot be justified as a time loss, since the machine is still digging, but at a decreased rate. In general, the larger the crew, the less likely a delay of this type will occur.

Stoniness. Stones inevitably cause a reduction in the digging speed of a wheel-type trenching machine. Even if the stones are not large enough to cause a complete halt of the machine, the operator must proceed with caution in order to avoid costly and time-consuming repairs to the digging mechanism. The occurence of only one or two rocks may result in several minutes of slow digging while the operator assures himself that further obstructions are not forthcoming.

Depth of digging. The digging depth has a very noticeable effect on the digging speed. Many of the other factors already mentioned also affect the relationship between the depth of digging and the digging speed. For instance, the decrease in speed with depth in a sticky clay soil is more pronounced than the decrease in a light loam soil. Machines with large engines are affected less by depth than machines with small engines.

It has been observed that there may also be a reduction in digging speed at shallow depths (less than 2.5 feet). This is due mainly to the awkward position of the controls and grade-level arm when a machine set for normal and deep digging is used for very shallow trenches. Additionally, the tile chute is much higher than usual, and more effort is required to lift the tiles into it. Frequently, the texture of the upper layer of soil does not provide a clean trench bottom for the tile, and misalignment occurs unless speed is reduced.

As may be expected, some of these factors, such as characteristics of the machine, skill of the operator and crew size may be controlled by the machine owner, whereas others, such as soil properties, tile size and depth of digging are dependent on field conditions and the drainage system layout. It was assumed that the machine owner would attempt to optimize the controllable factors; therefore, no attempt was made to evaluate the effects of these items. As moisture content varies so widely during the season, and even within a given field area, it would be of little practical value to determine the effect of this factor on the digging speed. A contractor can merely schedule his jobs to avoid the extreme conditions of moisture content. Although it would be of interest to investigate the other soil properties, such as cohesiveness, hardness and structure, these measurements would involve taking numerous soil samples, which the contractor does not have time to do, thus making the results difficult to apply to field conditions.

The most noticeable factor affecting digging speed is the digging depth, and this item can easily be determined by the contractor for each job. In fields where the average depth of digging is greater than about 3.5 feet, the daily production of the machine may be significantly decreased. The contractor may wish to consider charging a reasonable extra price to compensate for this effect. The depth-speed relationship is therefore probably the most important, as this information might lead to a schedule of prices for charging on a depth basis.

Field Study Procedure

Tests were performed to investigate the relationship between the depth of digging and the digging speed of the machine. This was achieved by measuring the distance that the trencher advanced while digging continuously at its maximum capacity, and observing the corresponding time required by means of a stop-watch.

In order to eliminate or at least minimize the effects on digging speed due to local changes in soil hardness and moisture content during any single test-run, a minimum test duration had to be established. In similar tests by Beach (4) in 1948, this had been arbitrarily set at ten-minute runs of continuous digging. Delays that occurred during this period were eliminated from the readings by stopping the stop-watch for the duration of the delay. However, when this method was applied to the present study, it was found that inaccuracies occurred due to the sometimes slow build-up of digging speed immediately following the delay, thus reducing the overall continuous digging rate. In work reported by DeVries (6) in 1951, the test-run was again set arbitrarily at ten minutes of continuous digging, but any tests interrupted by delays were discarded. When this method was applied to the present study, it was found that, under the working conditions encountered by the majority of machines in the area, most of the tests would have to be discarded because of a delay of some type occurring during this 10-minute period.

In both of the above cases, the ten-minute period was chosen to allow a sufficient digging distance to be completed, so that localized changes in moisture content and soil hardness would not seriously affect the overall results. The recorded distances of continuous digging reported by Beach (4) ranged from 45 feet to 160 feet, and those by DeVries (6) from 28 feet to 81 feet.

Because of the greater power output of the present-day machines, it was found that 3-minute test runs could cover a range of digging distances from approximately 25 feet to 120 feet. Preliminary tests also showed that on any particular test-run, the feet per minute values calculated on the basis of three minutes, five minutes and ten minutes rarely differed by more than one foot per minute. On this basis, a test-run period of three minutes was established as representative of the given digging conditions. Any tests interrupted by a delay were discarded.

The depth of digging was calculated by taking the average of the measurements at the beginning, at the end, and at the mid-point of the test-run, as done in tests by DeVries (6). In order to facilitate the measuring operation, as well as to eliminate the inaccuracy of a flexible tape, a depth calibration was painted onto the shoe extension at the rear of the machine, adjacent to the trench wall. The graduations were in feet and tenths of a foot above the trench bottom. In this manner, the digging depth could be read instantaneously at any time.

In an attempt to eliminate the process of measuring distance by the use of a steel tape, which was time-consuming as well as requiring two men and interfering with other simultaneous field observations, preliminary tests were performed to compare the results of counting one-foot length clay tiles, as they entered the trench, with the results of direct measurement. During each of ten runs of 100 tiles, the two results had a difference of less than one foot. On this basis, tile counting was established as the method of measuring distances when clay tiles were used. In the case of corrugated plastic tubing, there seemed to be no alternative but to tape the distances. The distance was recorded to the nearest foot.

Although soil moisture content was not recorded as a variable parameter, soil samples were taken during arbitrarily selected test-runs in each field to observe the range of moisture contents upon which each set of tests was based. These samples were analyzed according to the methods prescribed in ASTM Designation D2216-63T (2).

The soil texture was also recorded for each test-run by using the field methods of determining soil texture described in the USDA Soil Survey Manual (18, p. 212). This procedure was chosen because of its practical applicability to direct use by the drainage contractor.

In order to categorize the results according to several independent variables, the tile size, the number of men, the machine identity and the engine rated-horsepower were also recorded for each test. The field work-sheet is shown in figure A-1.

The start of each test was selected arbitrarily when the machine was digging at its maximum capacity under the given field conditions. Data were collected on as large a range of depths as possible for each drainage system installed.

Results and Discussion

A total of 263 runs of depth versus speed observations was made with the five machines in various soil textures, as shown in table 1. The observed depths ranged from 2.1 feet to 4.8 feet, while the continuous digging speed ranged from 11.0 to 38.5 feet per minute. All of the data presented in this depth-speed study represent the laying of 4-inch drains only, as observations of the larger diameter drains were not sufficient to permit adequate analysis. Pertinent machine

Table 1. Results of Regression Analysis on Depth-Speed Relationship of the Form $\hat{Y} = b_0 + b_1 X$.

Machine	Soil Texture	No. of Observations (n)	b_0	b_1	t H_0: $\beta_1=0$	r^2	Range of X observed (feet)	Range of Moisture Content(%)
A	clay loam	55	41.751	-5.884	-7.803**	0.535	2.1 - 4.1	23 - 31
	clay loam(20") over clay	39	38.137	-6.379	-5.696**	0.468	2.1 - 3.9	33 - 38
	clay	19	41.672	-6.272	-4.368**	0.529	2.5 - 4.4	25 - 33
	sandy loam	9	28.570	-4.039	-3.858**	0.681	2.5 - 4.5	21 - 35
B	clay loam	31	31.415	-4.392	-8.133**	0.696	2.1 - 4.7	28 - 35
	silty loam	18	24.967	-1.672	-2.986**	0.359	2.4 - 4.0	21 - 23
	sandy clay loam	9	42.784	-6.520	-5.262**	0.797	3.4 - 4.8	23
C	clay loam	40	32.915	-2.909	-1.564 x	0.061	3.3 - 4.6	21 - 28
D	clay loam	22	40.680	-8.439	-6.740**	0.694	2.7 - 4.8	23 - 38
E	clay	21	26.577	-2.737	-3.791**	0.430	2.7 - 4.8	26 - 36

** - Probability of rejecting true hypothesis = 1%

x - Probability of rejecting true hypothesis = 20%

$\hat{Y}$ - Continuous digging speed - ft/min.

X - Average depth od digging - ft.

b_0 - Sample estimate of population parameter β_0

b_1 - Sample estimate of population parameter β_1

Table 2. Machine and Working-Crew Characteristics of the Five Machines Observed.

Characteristic	Machine A	Machine B	Machine C	Machine D	Machine E
Age of Machine	2 years	3 years	3 years	3 years	3 years
Mechanical Condition	very good	very good	very good	very good	very good
Rated Horsepower	54 hp at 1600 rpm	54 hp at 1600 rpm	75 hp at 2200 rpm	75 hp at 2200 rpm	75 hp at 2200 rpm
Width of Trench	20 inches	20 inches	21 inches	21 inches	16 inches
Size of Crew	3 men	3 men	4 men	4 men	3 men

and crew characteristics which correspond to these tests are tabulated in table 2.

As shown in table 1, the collected data was grouped firstly, according to machine and secondly, according to soil texture. A simple linear regression analysis was used on each of the 10 groups of machine and soil texture data separately to investigate the relationship between digging depth and continuous digging speed. The form of the regression equation used was:

$$\hat{Y} = b_0 + b_1 X$$

where $\hat{Y}$ = continuous digging speed - ft/min.

X = average depth of digging - ft

b_0 = sample estimate of the population parameter β_0

b_1 = sample estimate of the population parameter β_1

The results in table 1 show an inverse relationship between X and Y in all 10 cases, as expressed by the negative values of b_1. Further analysis to test the hypothesis H_0: $\beta_1 = 0$ revealed that this hypothesis could be rejected with 99% confidence, as indicated by the values of t, for nine of the ten cases. Thus, the alternate hypothesis $H_a : \beta_1 \neq 0$ may be accepted in the nine cases. In other words, the statistics suggest that an inverse relationship does exist between depth of digging and the digging speed, over the range of depths observed.

The extent to which the variation in Y could be attributed to X was investigated by correlation analysis. The resulting coefficients of determination r^2, as listed in table 1, show that from 35.9 to 79.7 percent of the observed variations in digging speed were due to the effects of depth, for the nine cases mentioned above. The tenth case, machine C working in clay loam, had an r^2 value of only 0.061, and the null hypothesis was rejected with 80% confidence.

The applications of quadratic and cubic regression equations to each set of data did not add significantly to a better fit, at the $P = 0.05$ level, and were therefore abandoned in favor of the linear expressions, for the range of X observed.

The data and the linear regression equations are presented graphically in figures 5,6 and 7. Figure 5 shows the depth-speed relationships for four different machines in one soil type. Figures 6 and 7 show these relationships for single machines in the stated soil types. It can be seen that, although the digging speed varies inversely with depth, there are apparent differences due to both soil texture and machine characteristics.

If these relationships were to be used as a basis for charging for depth of digging, it would be more desirable, from the practical standpoint, to have only one regression line which would suitably describe all the data. Therefore, the statistical analysis was continued, as outlined by Ostle (13, p.201), to investigate the possibility of 'pooling' the results shown within each of figures 5,6 and 7. The following hypothesis was tested in each case:

$$H_0 : \text{ one regression line for all data}$$

It was found, in all three cases, that the hypothesis was rejected with 99% confidence, which indicates that the variations caused by both machine characteristics and soil texture were too great to

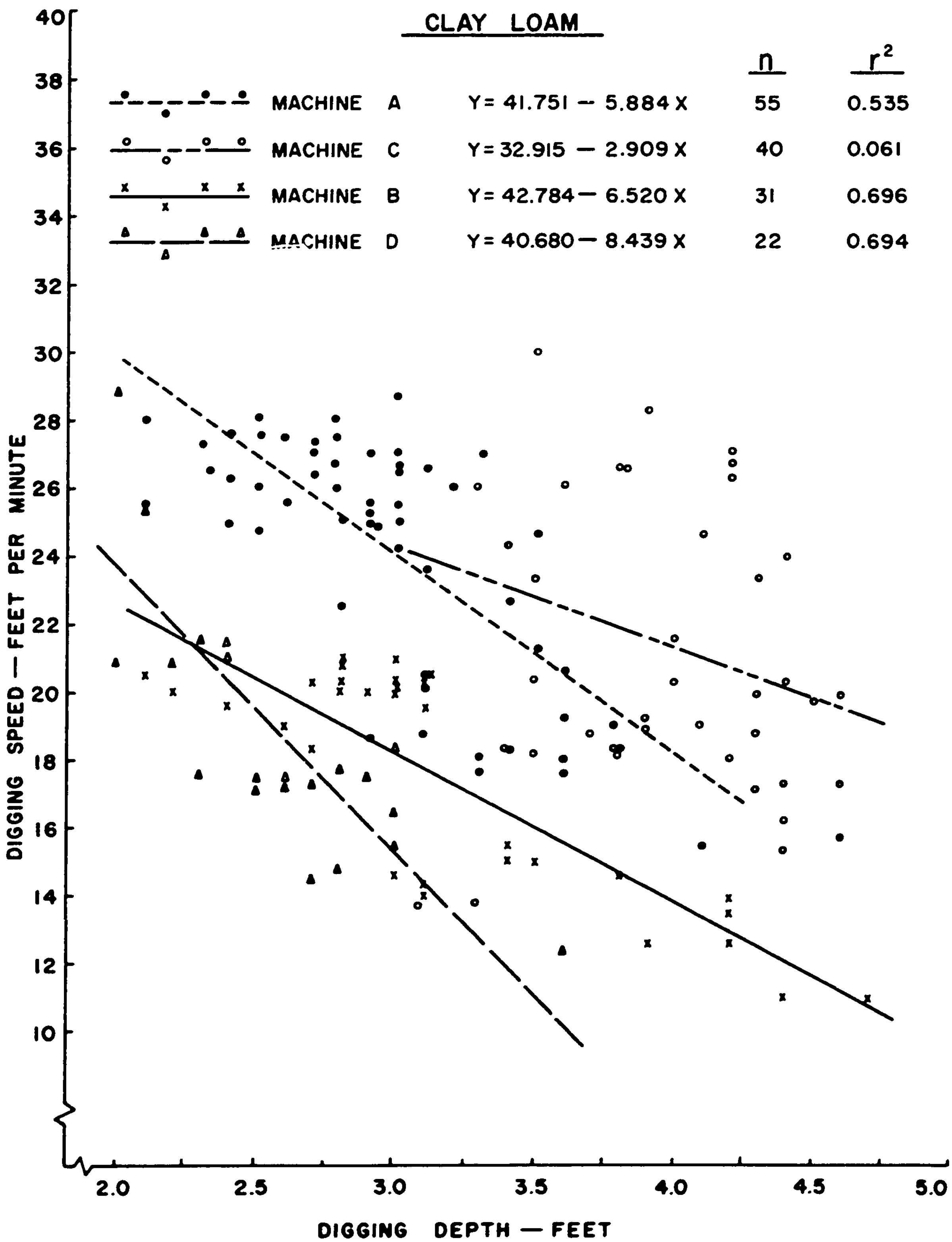


Figure 5. Depth-speed relationship of four machines digging in clay loam.

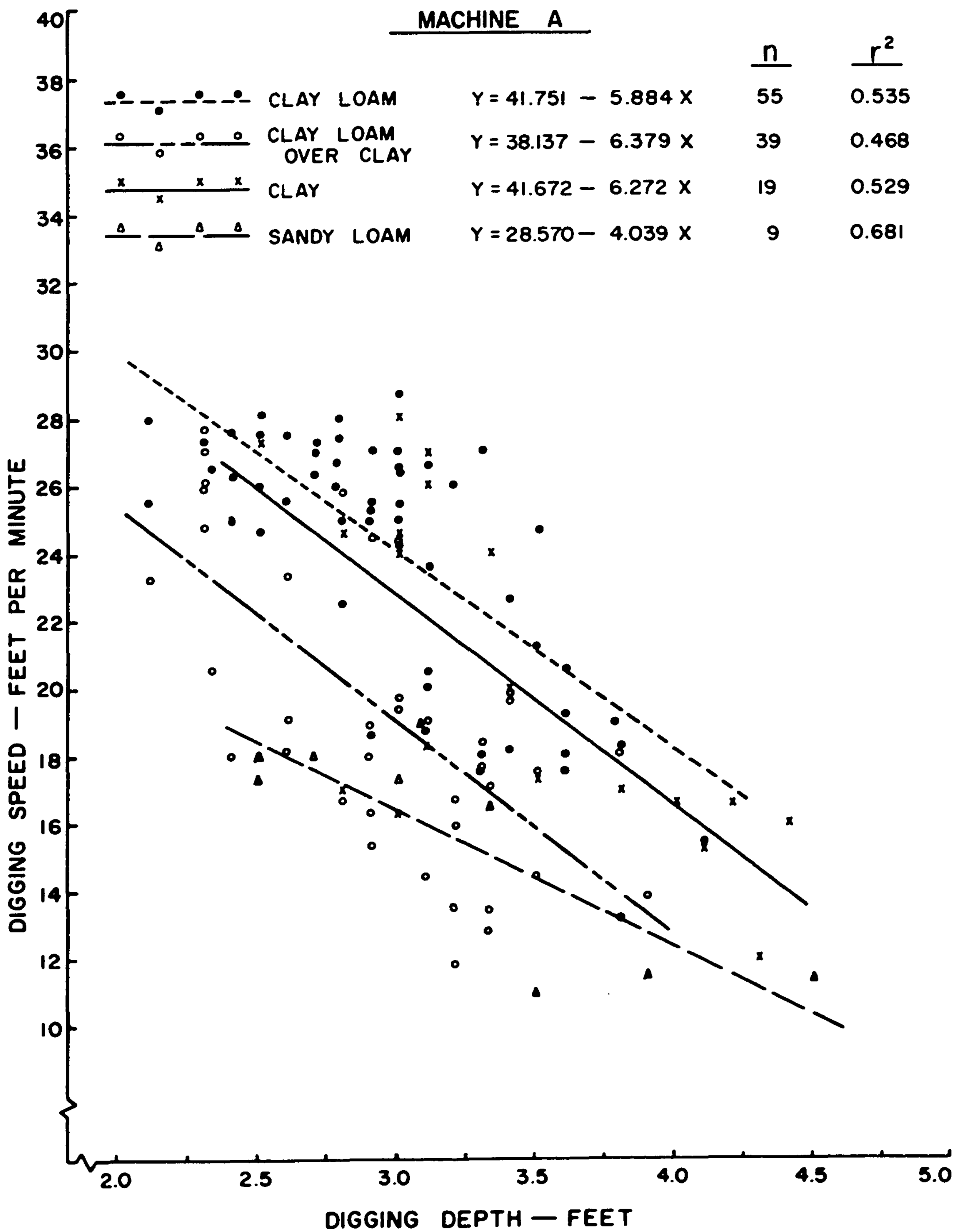


Figure 6. Depth-speed relationship of Machine A in four different soil textures.

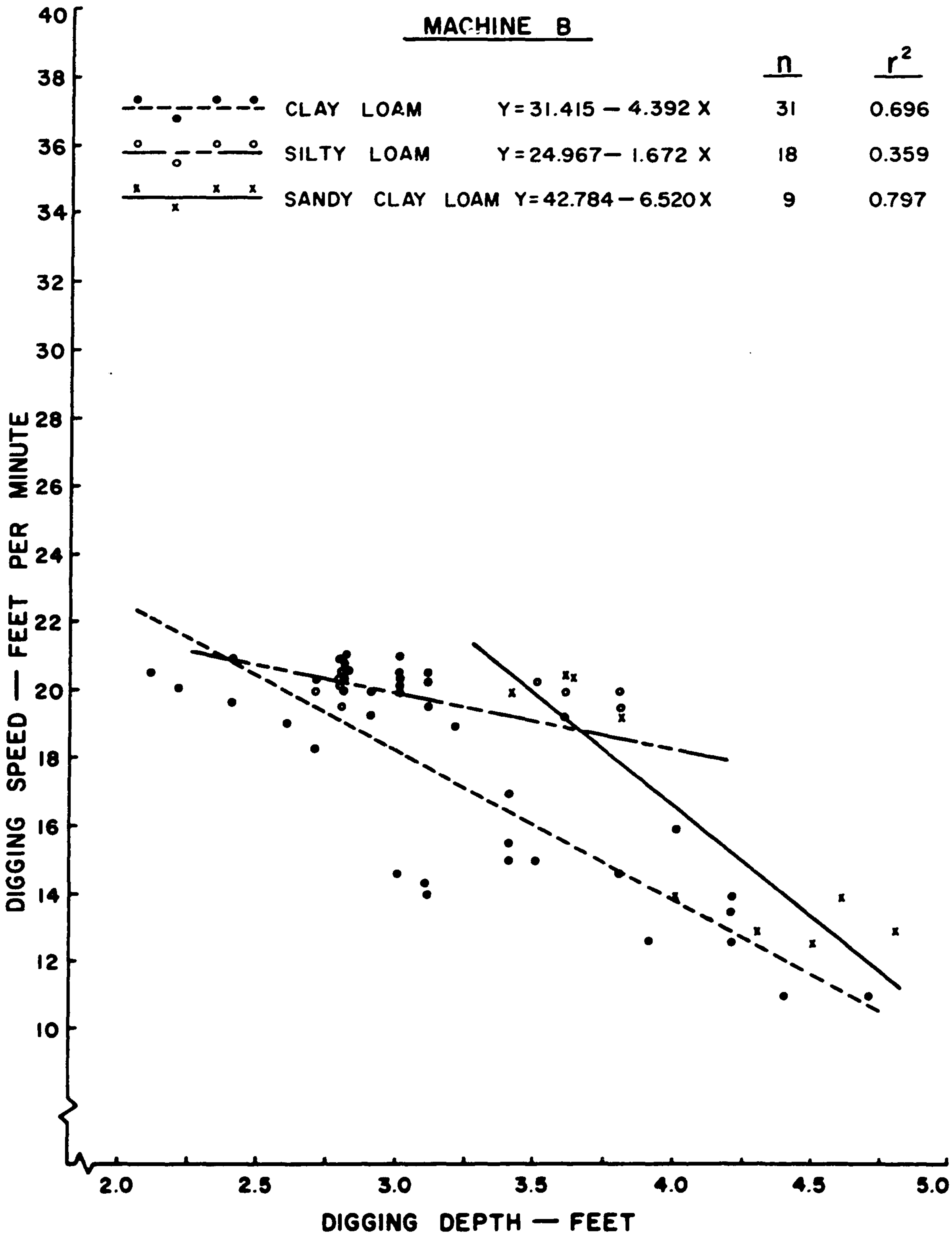


Figure 7. Depth-speed relationship of Machine B in three different soil textures.

permit the use of one simple linear regression equation.

It was concluded from the total analysis that a linear relationship between digging speed and depth is indicated for the range of depths observed, but that external factors, such as machine and crew characteristics or soil texture, change the degree to which depth affects the speed. Furthermore, even by grouping the data to keep these two external factors constant, only 35.9 to 79.7 percent of the variation in digging speed was 'explained' by changes in depth. Additional undetermined factors are contributing to the overall relationship. These might include the field cover crop, soil hardness, moisture content, cohesiveness, liquid and plastic limits, and even soil structure. Although the effect of soil moisture was not studied in this thesis, the range of moisture contents corresponding to each set of data is included in table 1, for comparative purposes.

The variation in results, caused by the large number of contributing factors, does not permit the construction of a general schedule of charges on a depth basis. Individual schedules, classified according to the many variables, would be of little use to the contractor because of the numerous tests he would have to perform in order to select the appropriate table. The study does, however, point out certain underlying characteristics of the depth-speed relationship which lead to suggestions of possible methods to improve the machine performance.

Methods of Increasing Digging Speed

Since there is a significant reduction in digging speed as the depth of digging is increased, it is to the contractor's advantage to avoid unnecessary deep cuts, whenever possible. If the contractor is involved in the planning and layout of a drainage system, it is often possible, by the use of good judgment, to introduce one or more changes of grade along the length of both mains and laterals. This may allow increased digging speed which more than compensates for the small amount of work involved in setting extra targets for these changes. The regression equation in figure 6, of machine A working in clay loam, indicates that by reducing the digging depth from four feet to three feet, the speed of continuous digging is increased from 18 to 24 feet per minute, or 33 1/3 percent. However, in planning a drainage system, care should be taken not to reduce depth to an extent that would seriously reduce the adequacy of the field drainage provided.

The study also revealed a significant difference between the digging speeds of different machines working in the same soil type. This variation was apparent even between machines which were considered identical at first inspection. From figure 5, it can be seen that the range of digging speeds of four machines, all working in clay loam, was from 11 to 23 feet per minute, at a depth of 3.5 feet.

The contractor should look critically at all machine characteristics which might be contributing to this discrepancy. Worn digging components, for instance, may have a pronounced effect on speed. Fine motor tuning is essential to develop the maximum horsepower output. The type of cutters on the digging wheel should be matched with the soil conditions for optimum performance, and the bucket cleaners must be functioning properly to avoid lifting soil more than once. There may be a loss of power through friction in worn bearings. It was also noted during the study that some machine engines stall under load more easily than others, thus requiring a change to a lower gear. Although this might be explained in some cases by the characteristic torque curve of the particular engine, it could possibly be a sign of poor engine tuning or governor malfunction or improper setting of the governed operating rpm. A setting of the operating engine speed which is not far enough above the peak torque speed results in reduced lugging ability.

Time Losses

The daily or annual production of a trenching machine cannot be predicted from the rate of continuous digging without considering the machine's working efficiency (the time the machine is digging ahead/ total field time). There are many factors which cause delays in operation, some of which are unavoidable, while others can be reduced or eliminated by good management. This study is an investigation of four machines, by observation of the causes and duration of all time losses during their normal operation.

Procedure

The activities of four trenching machines were observed for arbitrarily selected periods of time during two summers. Due to the length of the digging season, which normally extends from May until December, it was considered impractical to conduct the work study over the complete season. Instead, data were collected for a sufficient length of time to enable a reliable projection of efficiency to the seasonal basis.

An attempt was made to observe the complete duration of operating time for each day that observations were taken, to ensure that events which are dependent on the time of day were included in the results. Maintenance, for instance, might occur regularly at the beginning or end of the day, and would be missed if only partial days were observed.

A delay was considered as any factor which caused an interruption in the laying of the drains, as most contractors are paid for the actual number of feet installed. Every delay of five seconds or more was recorded. Meal breaks were not included in the analysis. Events, such as repairs, were recorded only when they occurred within normal working hours. Delays which caused the loss of a complete day were recorded as ten hours lost time. A field work sheet is shown in figure A-2.

Results and Discussion

A summary of the time losses occurring during the observed time of four machines is shown in table 3. The time losses were divided into 20 contributing factors, the sum of which equals the total delay time (T_d). The difference between the total observed time (T_f) and the total delay time (T_d) equals the total drainlaying time (T_w). Therefore, T_w represents the number of minutes that the trencher was actually doing profitable work, if drainlaying is charged on a per foot basis.

Since the total observed time of each machine was not the same, the figures in table 3 are not readily comparable. Table 4 shows the delay factors of each machine in a more useful form, as percentages of the total observed time in each case. The total drainlaying time, in this form, represents the machine efficiency, where

Table 3. Summary of Time Losses of Four Machines during the Observed Time.

Contributing Time Factor	MACHINE A Minutes	MACHINE B Minutes	MACHINE C Minutes	MACHINE D Minutes
Maintenance (fuel, etc.)	171.33	22.58	110.08	77.67
Adjustments - Minor Repairs	238.35	185.69	305.62	168.00
Major Repairs	924.00	250.00	490.92	116.12
Tile Flow into Trench	202.51	173.54	265.56	17.39
Wait for Tile Wagon	413.66	132.63	384.93	105.02
Commencing Laterals	559.13	249.02	390.10	201.13
Making Junctions	1002.55	341.25	22.85	73.79
Clean Machine	57.54	53.07	548.62	392.37
Moving Machine in Field	658.16	200.75	523.95	235.25
Move to New Job Site	300.00	180.00	162.50	357.71
Set Targets	1259.49	287.55	322.06	202.07
Digging Out Rocks	470.19	238.48	384.60	347.63
Short Coffee Breaks, etc.	149.25	4.50	109.55	70.19
Discussion on Site	213.02	134.71	16.79	0.00
Remove Targets	22.28	0.00	7.98	11.10
Backfill over Collector	74.18	19.53	25.05	17.01
Weather	974.25	210.00	0.00	600.00
No Supply of Tiles	2046.25	402.00	2165.00	0.00
No Plan Available	300.00	2280.00	600.00	0.00
Other	234.85	576.25	78.98	252.73
Total Observed Time (T_f)	15231.00	8748.00	10525.00	4937.00
Total Delay Time (T_d)	10270.99	5941.55	6915.14	3245.18
Total Drainlaying Time(T_w)	4960.01	2806.45	3609.86	1691.82

Table 4. Summary of Time Losses of Four Machines as Percent of Actual & Adjusted* Total Observed Time.

Time Factor \ Machine	Actual Percent as Observed: A	B	C	D	Average	Adjusted* Percent: A	B	C	D	Average
Maintenance (fuel, etc.)	1.12	0.26	1.05	1.57	1.00	1.32	0.37	1.42	1.57	1.17
Adjustments - Minor Repairs	1.56	2.12	2.90	3.40	2.50	1.84	3.06	3.93	3.40	3.06
Major Repairs	6.07	2.86	4.66	2.35	3.99	7.17	4.12	6.32	2.35	4.99
Tile Flow into Trench	1.33	1.98	2.52	0.35	1.55	1.57	2.86	3.42	0.35	2.05
Wait for Tile Wagon	2.72	1.52	3.66	2.13	2.51	3.22	2.19	4.96	2.13	3.13
Commencing Laterals	3.67	2.85	3.71	4.07	3.58	4.34	4.11	5.03	4.07	4.39
Making Junctions	6.58	3.90	0.22	1.49	3.05	7.78	5.62	0.30	1.49	3.80
Clean Machine	0.38	0.61	5.21	7.95	3.54	0.45	0.88	7.07	7.95	4.09
Moving Machine in Field	4.32	2.29	4.98	4.77	4.09	5.11	3.30	6.75	4.77	4.98
Moving to New Job Site	1.97	2.06	1.54	7.25	3.21	2.33	2.97	2.09	7.25	3.66
Set Grade Targets	8.27	3.29	3.06	4.09	4.68	9.78	4.74	4.15	4.09	5.69
Digging Out Rocks	3.09	2.73	3.65	7.04	4.13	3.65	3.94	4.95	7.04	4.90
Short Coffee Breaks, etc.	0.98	0.05	1.04	1.42	0.87	1.16	0.07	1.41	1.42	1.02
Discussion on Site	1.40	1.54	0.16	0.00	0.78	1.65	2.22	0.22	0.00	1.02
Remove Grade Targets	0.15	0.00	0.08	0.22	0.11	0.18	0.00	0.11	0.22	0.13
Backfill over Collector	0.49	0.22	0.24	0.34	0.32	0.58	0.32	0.33	0.34	0.39
Weather	6.40	2.40	0.00	12.15	5.24	7.57	3.46	0.00	12.15	5.78
No Supply of Tiles	13.43	4.60	20.57	0.00	9.65	0.00	0.00	0.00	0.00	0.00
No Plan Available	1.97	26.06	5.70	0.00	8.43	0.00	0.00	0.00	0.00	0.00
Other	1.54	6.59	0.75	5.12	3.50	1.82	9.50	1.02	5.12	4.37
Total Observed Time	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Total Delay Time	67.43	67.92	65.70	65.73	66.73	61.46	53.73	53.48	65.73	58.60
Total Drainlaying Time	32.57	32.08	34.30	34.27	33.27	38.54	46.27	46.52	34.27	41.40

* Adjusted values are based on the actual total observed time minus time losses due to no supply of tiles and no plan available.

NOTE: 1% time loss represents 15 hours of potential digging time in a 1500-hour season.

$$\% \text{ Efficiency} = \frac{T_w}{T_f} \times 100$$

A close look at the 20 contributing time factors reveals that although most of these are normal delays which may be expected in any trenching operation, two of them, namely no supply of tiles and no plan available, are extraordinary time losses which would not normally occur to the extent shown by the study. During the period of observation in Quebec (summers of 1969 and 1970), there was a major shortage of clay tiles throughout the province and corrugated plastic tubing had not yet become available. In addition, Quebec contractors, according to present drainage practices, are dependent on government agencies for the drainage plans, and may not proceed without them. During part of the observation period, these plans were not supplied at a fast enough rate to keep all of the machines working continuously.

Since the duration of these two delays, as observed during the study, is not representative of the percent time lost on a seasonal basis, and since it is not expected that these delays will normally occur in the future, table 4 also shows adjusted percent figures, where the effect of delays due to no supply of tiles and no plan available has been excluded. These adjusted values give a more representative resumé of the time losses during a complete season of operation. It can be seen that although the unadjusted percentages of total drainlaying time are very similar for all the observed machines, this similarity is due mainly to coincidence, as the more representative adjusted values show a range between 34.27 and 46.52 percent for the total drainlaying time. It should be noted again that these latter figures represent the efficiency of the machine operations, where the average of all four machines is 41.40 percent.

A delay shown in table 4 which might raise controversy is that of weather. As seen in the columns of adjusted values, this time loss ranges from zero to about twelve percent for the different machines. The extent to which weather affects the operating time depends on the length of season considered. Delays due to this factor are more frequent during the spring and late fall. Weather will therefore be a more apparent factor during a season extending from April to December than for one extending from June to November. This will also vary from year to year. The percent figures for weather shown in this study are dependent on the part of the season observed and cannot be individually projected to the seasonal basis for each machine. However, when taken as the average of all four machines, the value of 5.78 percent is a very close approximation of the actual time loss due to weather conditions, according to interviews and questionnaires from drainage contractors in the area.

Major repairs is a delay which depends on the age and condition of the machine, as well as the digging conditions encountered. These time losses presumably occur randomly during the season. It is possible, therefore, that figures based on observations of a partial season do not represent the actual percent delay over the complete season, for any particular machine. However, by again using the average value of all four machines, the resulting 4.99 percent agrees closely with the opinions of contractors in the area. This is, of course, taking into consideration that many repairs are done after normal working hours or during a period of rain, and do not enter as time losses.

The remaining time factors listed in table 4 are delays which may be expected to occur during the normal digging operation. It is assumed that the terminology used to describe these delays is self-explanatory to anyone familiar with the present trenching practice, and no further description is deemed necessary. The variation in the results between machines is due mainly to differences in the field procedure of each contractor and the efficiency with which his field crew executes each phase of the total operation. Although most of these delays cannot be eliminated completely, it is by reducing them to a minimum that a contractor can realize the maximum machine and crew efficiency and maximum production within the time available.

The length of the working season varies from year to year and depends largely on the climatic and soil conditions of the area in which the machine is operating. Additional variation occurs because some contractors work 5 days per week, while others work 5½ or 6 days per week.

The 1970 working season, based on the four machines under study, began about May 4 and continued until approximately December 12, or a total of 223 days. Considering a 5½-day week, 47 days were eliminated by Saturday afternoons and Sundays. An additional two days were holidays. Therefore, of the 223 days during the working season, 174 were available working days. This corresponds closely to the average number of working days reported by 34 Ontario contractors in a questionnaire, and shown in table 5, which was 170.5 days during the 1969 season.

By applying the average adjusted delay factors shown in table 4 to the 174 available working days, the equivalent of 10.1 days are lost because of weather, 8.7 days because of major repairs and 83.2 days because of the remaining operating time losses. The balance of 72 days is the period of profitable machine operation, or actual drainlaying time. The annual use and the distribution of time during the available working days is shown diagrammatically in figure 8.

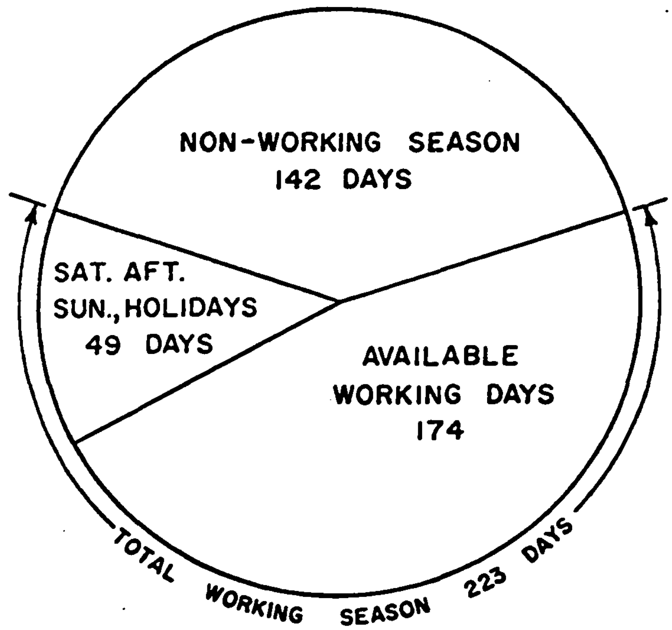
Methods of Reducing Time Losses

The adjusted figures in table 4 show a range of total delay times between 53.48 and 65.73 percent for the different machines. This indicates that some contractors are obtaining greater efficiency than others while doing the same basic operations.

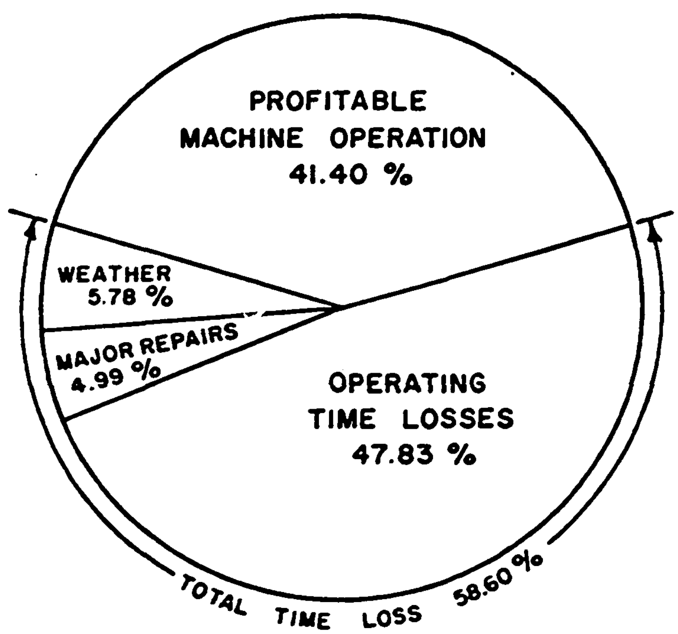
Much of the delay time is unavoidable as it is an integral part of the drain installation operation. A contractor who can attain over 50 percent efficiency is doing exceptionally well. However, many of the observed delays may be reduced by good management and careful planning.

The largest single delay factor shown in the adjusted table 4 is weather. Although this loss is generally unavoidable, the time can often be used to good advantage by making foreseeable repairs and planning new work. The major repair time, which is another large factor, may be reduced by maintaining the machine in good condition and by overhauling the machine thoroughly during the winter months. Further time-saving can be achieved by keeping a good supply of spare parts on hand and by owning a complete set of tools and a portable welder.

One of the most apparent time loss differences between machines was that of making junctions. This delay was practically eliminated



YEAR



174 AVAILABLE WORKING DAYS

Figure 8. Representative Annual Use and the Distribution of Time during the Available Working Days for Drainage Trenching Machines working in Quebec and Ontario (based on a 55-hour week).

by one contractor while another had almost eight percent. It is not necessary to stop the machine, as some contractors do, while making the connection between laterals and the main drains, except perhaps during very wet conditions. Normally, the machine may continue to work while one man remains behind to complete the junction. A portable tile-cutting machine is essential for maximum efficiency in this operation. The number of junctions can also be minimized by planning long laterals with maximum spacing. The use of prefabricated junctions, when available, also aid in saving time.

Improper tile flow into the trench caused misalignment and uneven spacing between tiles, resulting in an average delay of two percent. This seemed especially evident at high digging speeds. By proper adjustment or alteration of the design of the tile chute, this delay can be reduced. It was noted that contractor D, who was installing corrugated plastic tubing, suffered very little from this factor.

Contractor A experienced excessive time losses due to the setting of grade targets. The machine was delayed frequently while the crew set the targets for each lateral after the machine was in position ready to dig. Although it is sometimes difficult to keep ahead of the machine when working with only a 3-man crew, careful planning of the time available can reduce this delay. Some of the unavoidable delays, such as maintenance, repairs and moving to a new job site, may require the attention of only one man while the other two proceed to set targets. Another method of reducing this delay is by the use of the laser system of grade control. However, whether this system is economically advantageous remains a subject for further study.

Other methods of minimizing the time losses include the scheduling of jobs close together to reduce the moving time, and timing the installations on the lands with the poorest drainage conditions to be done during the driest part of the year.

By reducing the delays due to each contributing time factor by a small amount, the improvement in the overall efficiency can become quite apparent. It should be emphasized that a one percent time loss is equivalent to 15 hours of potential digging time (or perhaps 6000 feet of drain installation) during a 1500-hour working season.

Cost of Operation

Procedure

An investigation of the cost of trenching machine operation was made by collecting information in a questionnaire sent to Ontario contractors, and from interviews with Quebec contractors. The objective of the study was to incorporate the collected data into a cost analysis, which would be representative of the industry as a whole.

Results of the Questionnaire

At the end of the 1969 drainage season, questionnaires were sent to 124 contractors operating trenching machines in Ontario. The questions were concerned with machine characteristics, field practices, and costs of operation. The complete questionnaire is shown in Appendix B. Fifty-one of these questionnaires were returned, although some were not complete. A summary of the data which relates to this study is shown in figures 9 to 19, and in table 5.

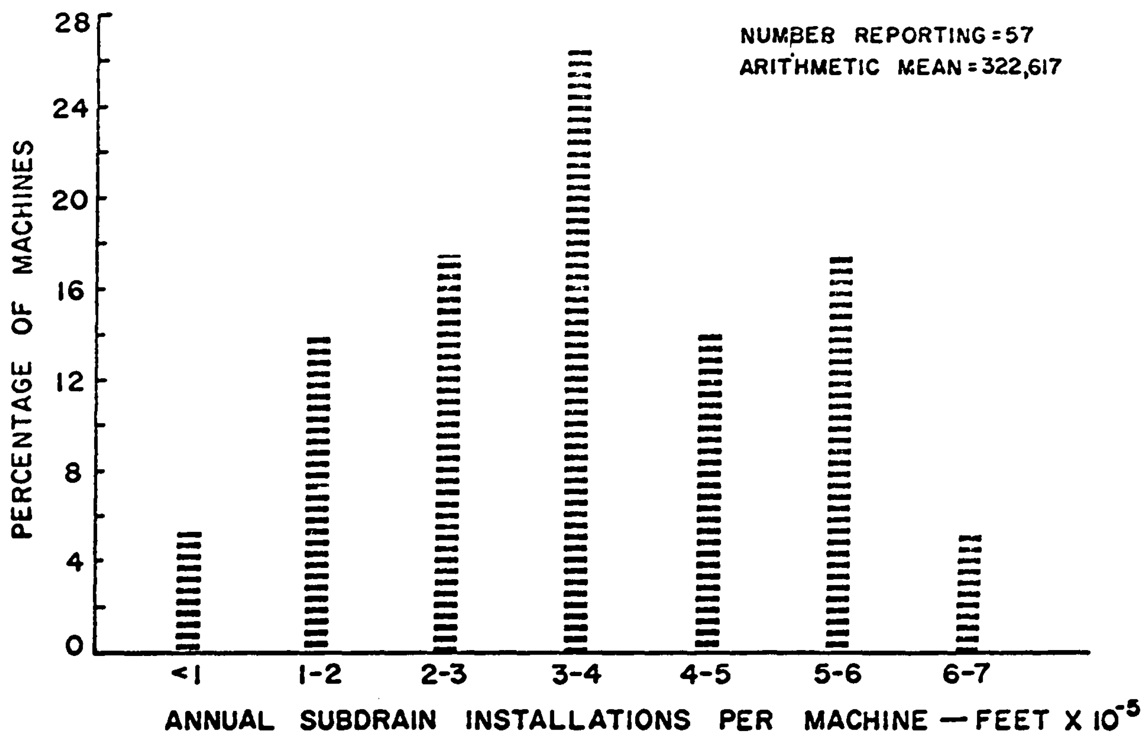


Figure 9. Questionnaire summary of the annual subdrain installation per trenching machine.

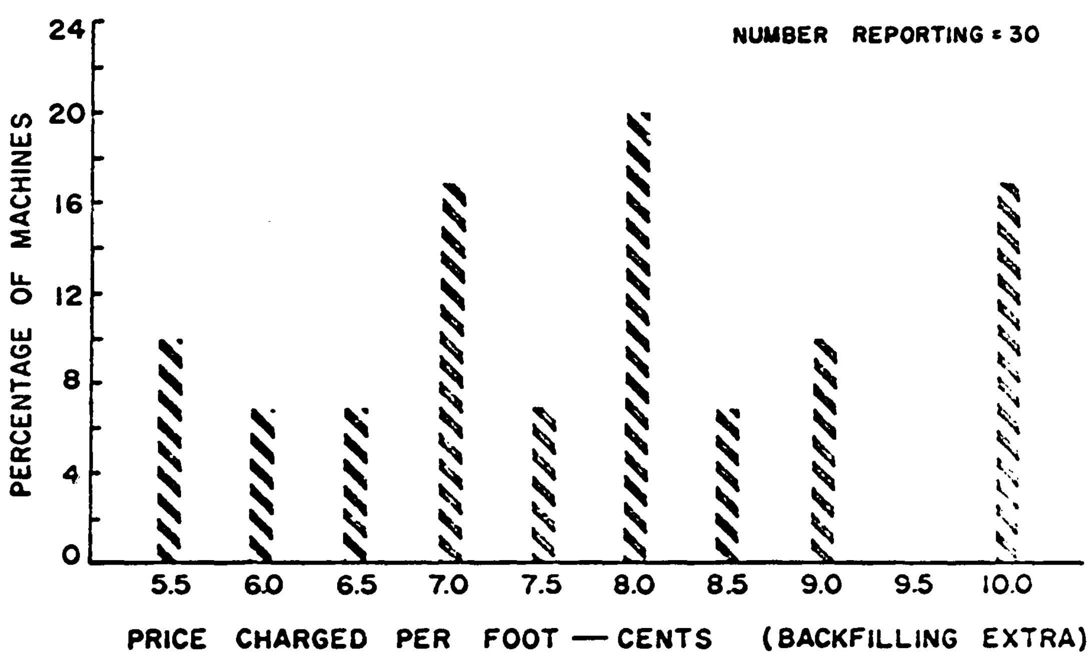


Figure 10. Questionnaire summary of the prices charged for installing underdrainage.

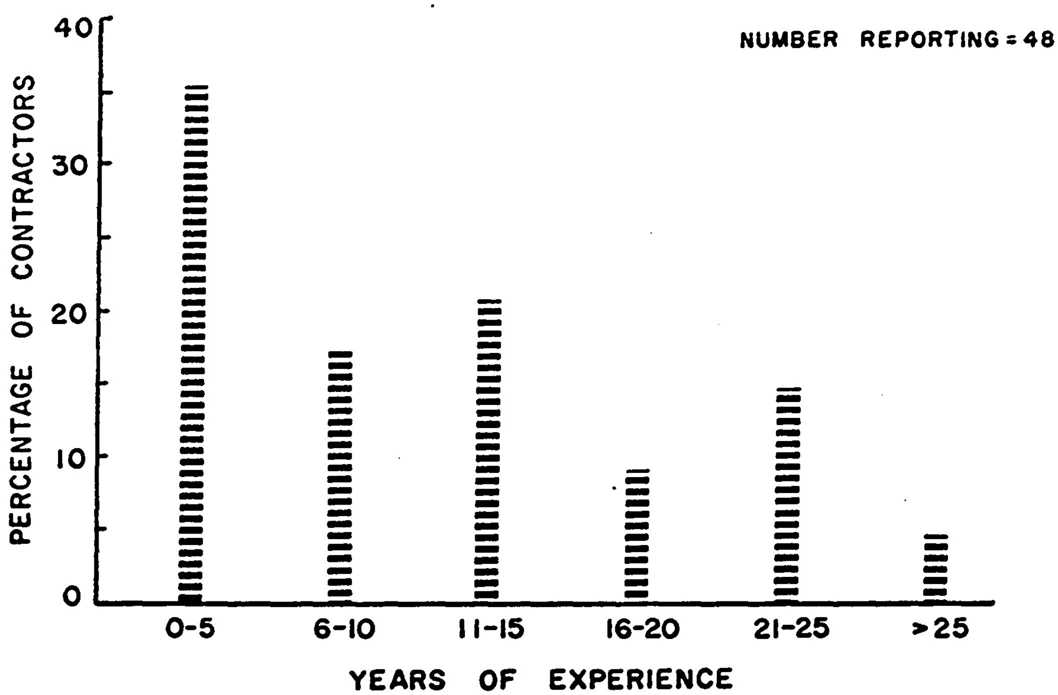


Figure 11. Questionnaire summary of the years of experience of the contractors.

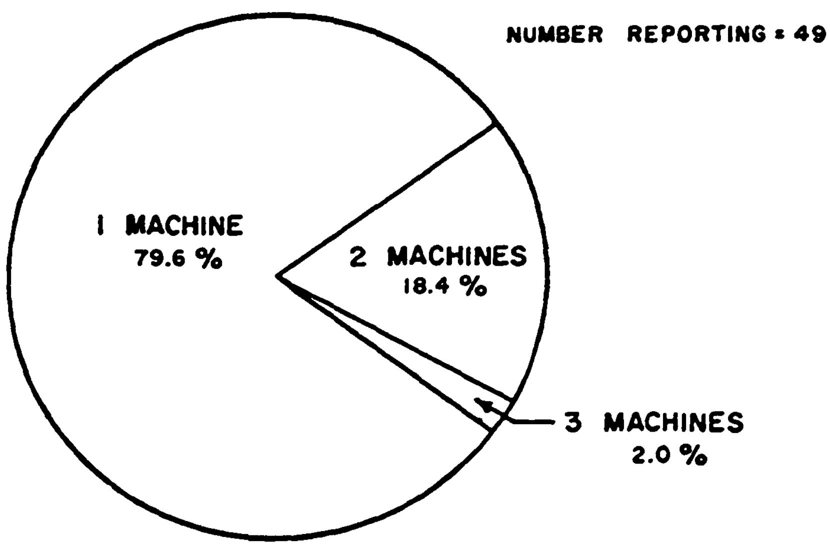


Figure 12. Questionnaire summary of the number of trenching machines per contractor.

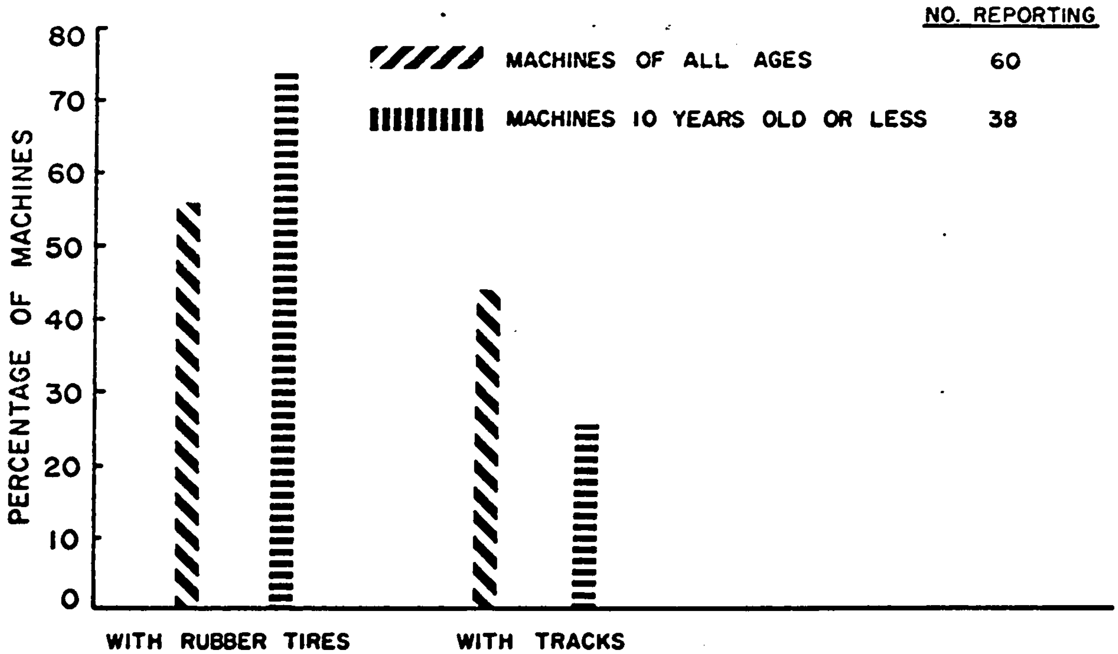


Figure 13. Questionnaire summary of the number of trenching machines with track versus trenching machines with rubber tires.

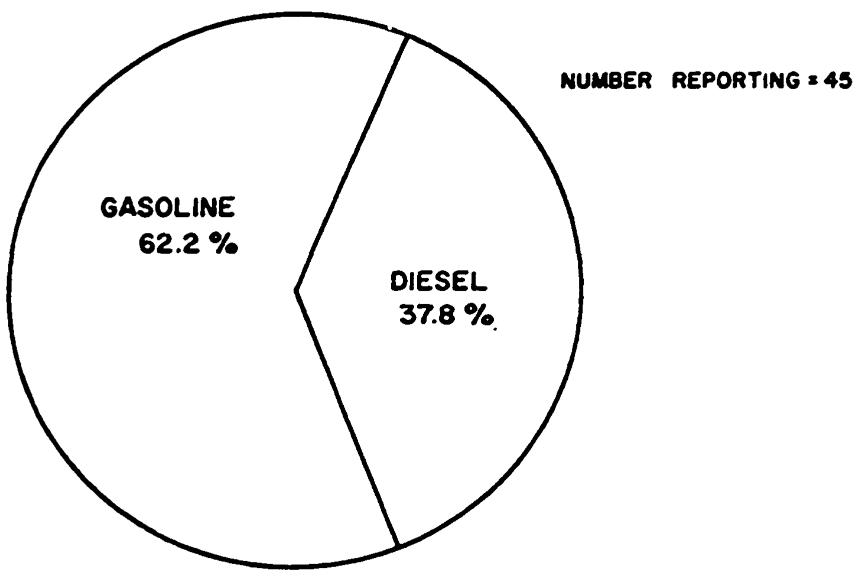


Figure 14. Questionnaire summary of the number of trenching machines powered by gasoline engines versus diesel engines.

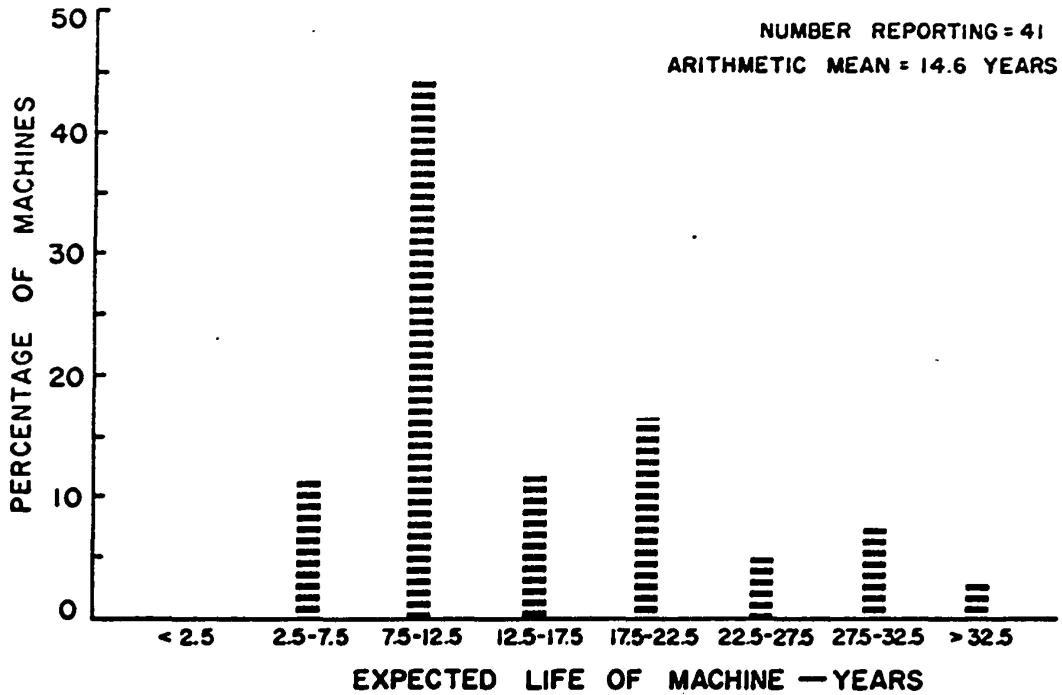


Figure 15. Questionnaire summary of the expected life of the trenching machines.

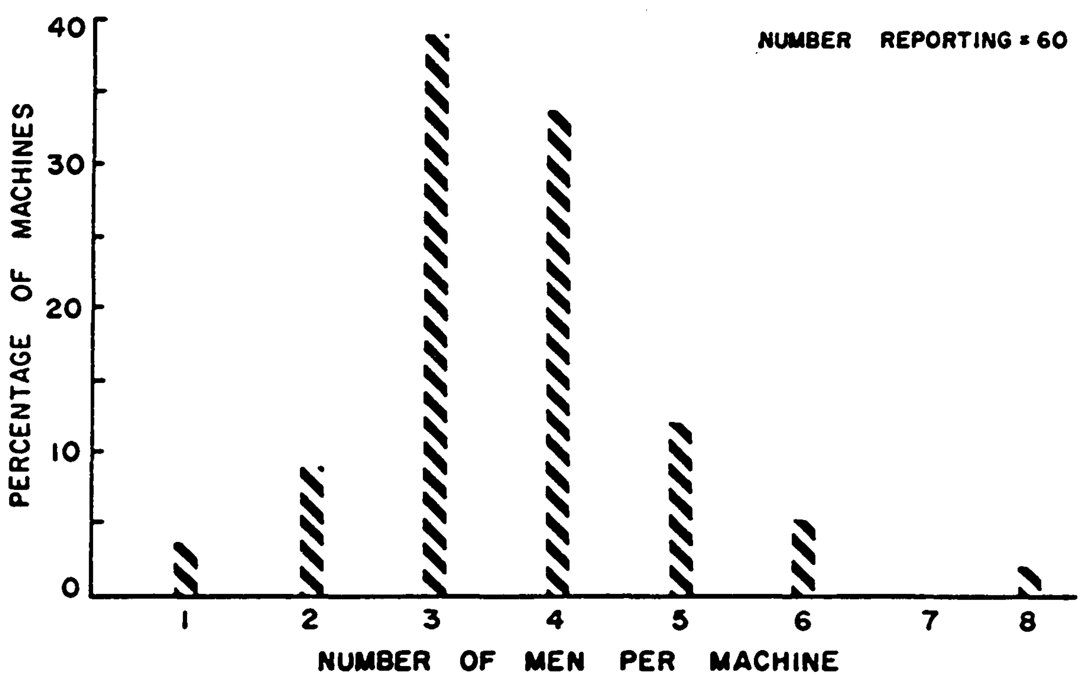


Figure 16. Questionnaire summary of the number of men per trencher.

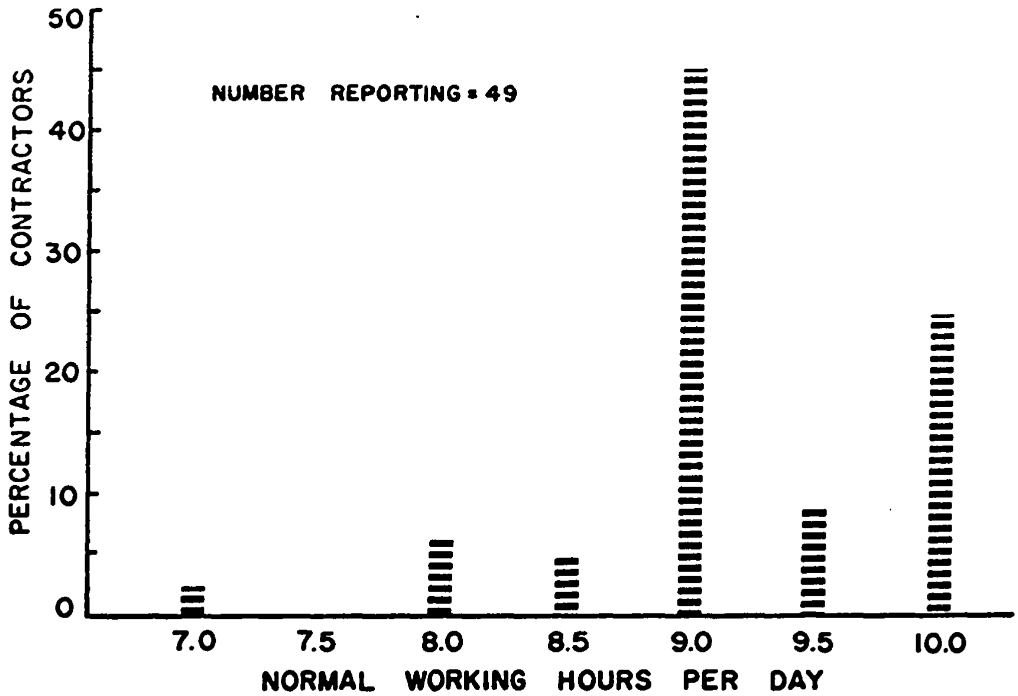


Figure 17. Questionnaire summary of the normal number of working hours per day.

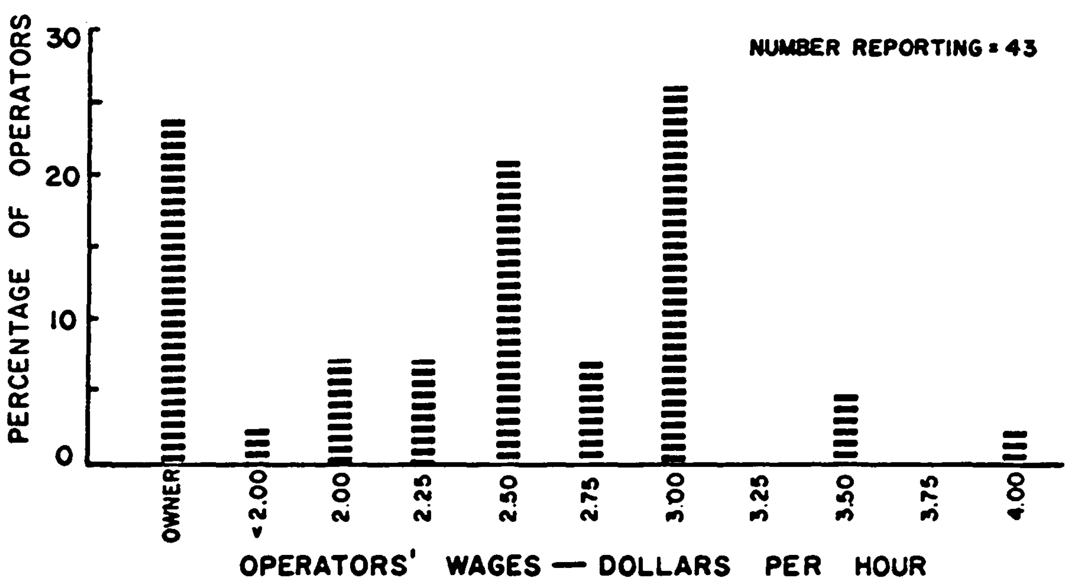


Figure 18. Questionnaire summary of the wages paid to the trenching machine operators.

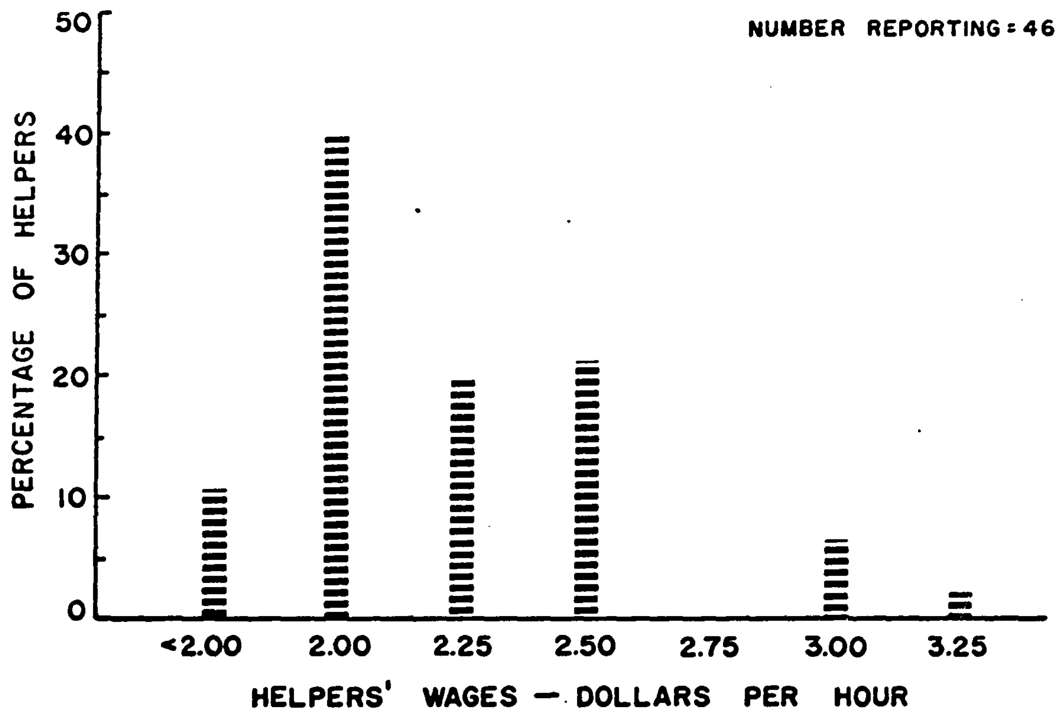


Figure 19. Questionnaire summary of the wages paid to field helpers.

Table 5. Partial Summary of Data from Ontario Drainage Contractor Questionnaire.

Item	Average	Range Reported		Number Reporting
		Maximum	Minimum	
Number of days in working season	170.5	209	111	34
Days lost due to weather	19.4	40	1	34
Days lost due to repairs	7	20	0	30
Fuel Consumption - Gal/hr				
1) Gasoline engines	2.6	5.0	1.0	32
2) Diesel engines	2.0	4.0	1.0	19
Average job size - feet	15,752	40,000	3,000	48
Salvage value of trencher	$4,000.	$14,000.	$0.00	42
Total Capital Investment	$44,750.	$200,000.	$6,500.	46
Operating cost/1000 feet	$48.50	$89.60	$12.50	33

Analysis of Costs

The results of the questionnaire revealed an extreme variation between contractors in every factor concerned with the costs of operation. The range of prices charged to the farmer, as shown in figure 10, reflects this nonuniformity of operating costs. Interviews with Quebec contractors confirmed that an analysis of one machine's operation costs, or even the average costs of all machines, would not be representative of the industry, in general, and might be misinterpreted by anyone who was not fully aware of the many factors which contribute to this variability. It was concluded that the earlier studies by DeVries (6), although valid for the machine observed, did not serve as a model on which to base all machines.

An important source of variation was the cost of labor. In addition to the wide range of hourly wages, as indicated in figures 18 and 19, this factor was further complicated by the variable number of working hours per year, and whether men were hired on a seasonal or annual basis.

The cost of repairs is dependent, to a large extent, on the digging conditions encountered and the annual use. Stoney soils may cause a rapid increase in the repair costs. Perhaps more surprising is the cost increase due to sandy soils. It was observed that after completing 100,000 feet of drain in a sandy soil, one machine required a complete change of digging points, costing over 500 dollars for parts alone. This represents approximately five times the normal rate of wear expected in clay soils. Repair costs are generally increased with greater annual use, and are also dependent on the contractor's capability to do the work himself.

The overhead, or fixed costs, are based on the total capital investment which, as reported in the questionnaire, ranged from $6500 to $200,000 (see table 5). The variable costs are influenced largely by the annual footage (figure 9) and the total hours of use.

Although it was not possible to present a single cost analysis which would be representative of trenching machine operation in general, it was considered of value to construct a proposed cost schedule to introduce the factors involved in the cost of trenching machine operation and to serve as a basis of further discussion. This analysis is shown in table 6, and has been subjected to the following basic assumptions:

1) the average number of available 9-hour working days is 170 days, or 1530 hours of annual use.
2) the average annual production is 600,000 feet and the price charged to the farmer is eight cents per foot.
3) the total initial capital investment is composed of the following:

trencher	$34,000.
tractor	3,500.
pick-up truck	3,000.
surveying equipment	450.
portable fuel tank and pump	250.
tools and shop equipment	500.
tile wagon	200.
miscellaneous	300.
TOTAL	$42,200.

Table 6. A Proposed Cost Schedule for Tile Trenching Machine Operation.

A. OVERHEAD COSTS	
Depreciation: ($42,200 - $5,000)/8 years	$4650.
Interest on average investment (1): 6% x ($42,200 + $5,000)/2	1416.
Housing, insurance, taxes (1): 4% x ($42,200 + $5,000)/2	944.
Management - office, legal and accounting costs (20): 1% of total investment + 5% of gross income	2822.
TOTAL OVERHEAD COSTS:	$9832.
B. OPERATING EXPENSES	
Repairs: ($15.00/1000 ft.)	9000.
Fuel: (3.0 gal/hr x 1530 hr x 40¢/gal)	1836.
Oil, filters, etc.(1): (15% x fuel cost)	275.
Relocation of equipment by float: (15 moves x $45.00/move)	675.
Labor: 1 full-time operator ($165./wk x 52 wk)	8580.
3 seasonal helpers ($2.50/hr x 1530 hr)	11,475.
Payroll taxes: (4% x gross payroll)	802.
Miscellaneous:	500.
TOTAL OPERATING EXPENSES:	$33,143.

TOTAL ANNUAL COST OF OPERATION: $42,975.

COST PER DAY: $ 252.79

COST PER FOOT: $ 0.0716

4) depreciation is calculated on an 8-year useful life, and a $5,000 salvage value (straight-line method).

5) the values in table 6 are based on reference material where cited.

6) other assumptions are as indicated in the table.

The results of the calculations show a cost per foot of 7.16 cents. This is considered as the 'break-even point', and any income in excess of this amount is business profit. The overhead was found to be 22.87 percent of the total cost of operation.

The proposed cost schedule has been prorated, in figures 20 and 21, to indicate the annual cost of operation and the cost per foot, respectively, in relation to the annual footage. It can be seen in figure 20 that the overhead cost remains relatively constant or independent of the annual production, while the operating expenses usually vary directly with production. Although each contractor may have different values in his cost analysis, the principles remain the same.

Methods of Reducing Cost of Operation

As indicated in figure 21, the cost per foot may be reduced by increasing the annual production. This is a result of the division of the overhead costs over a greater number of feet. It should be noted however, that the decrease in cost per foot is relatively small after five hundred thousand feet. In other words, it becomes more difficult to realize significant additional savings after a certain level of production has been reached.

The most profitable method of reducing the cost of operation is

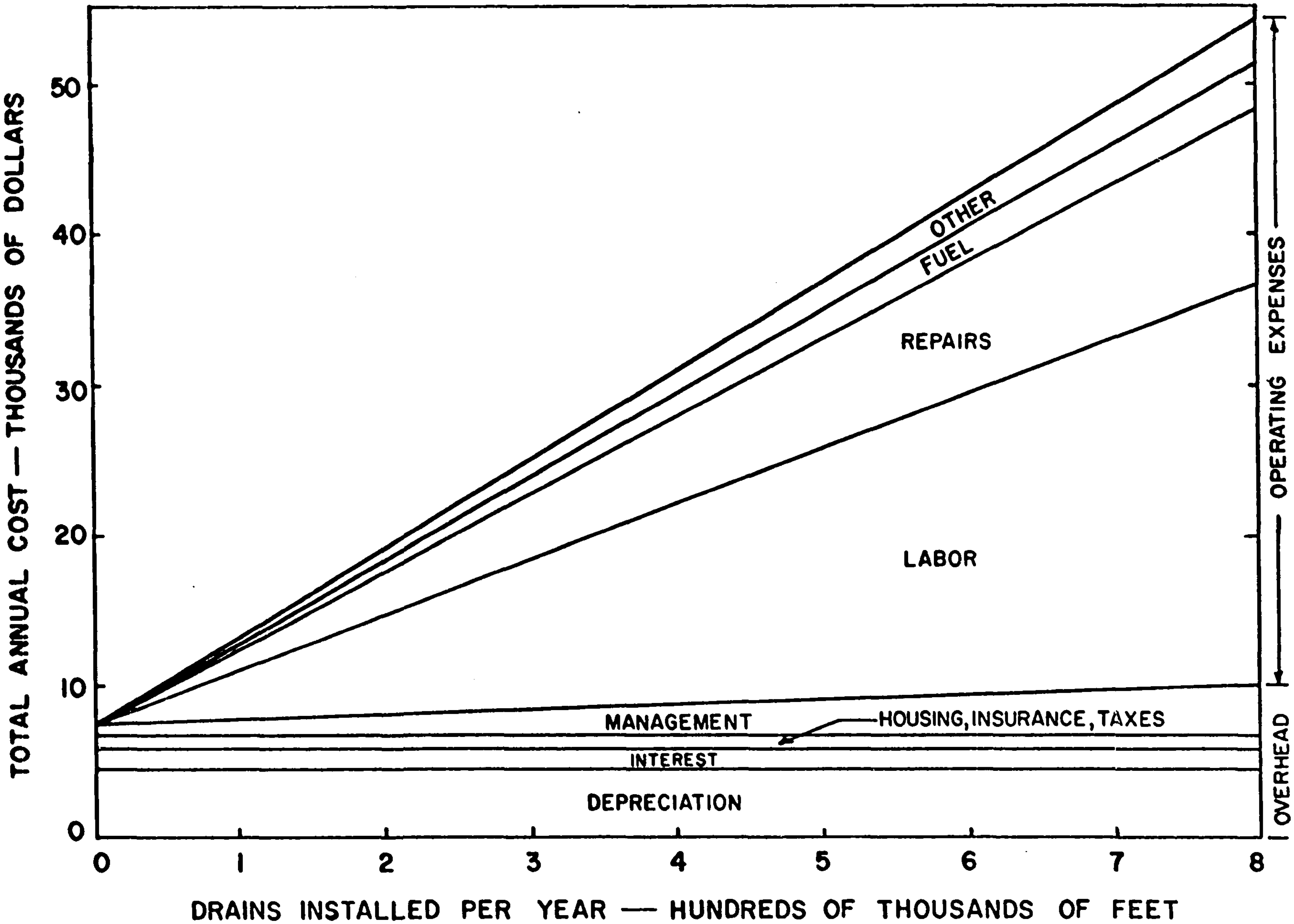


Figure 20. Annual cost of trencher operation in relation to footage.

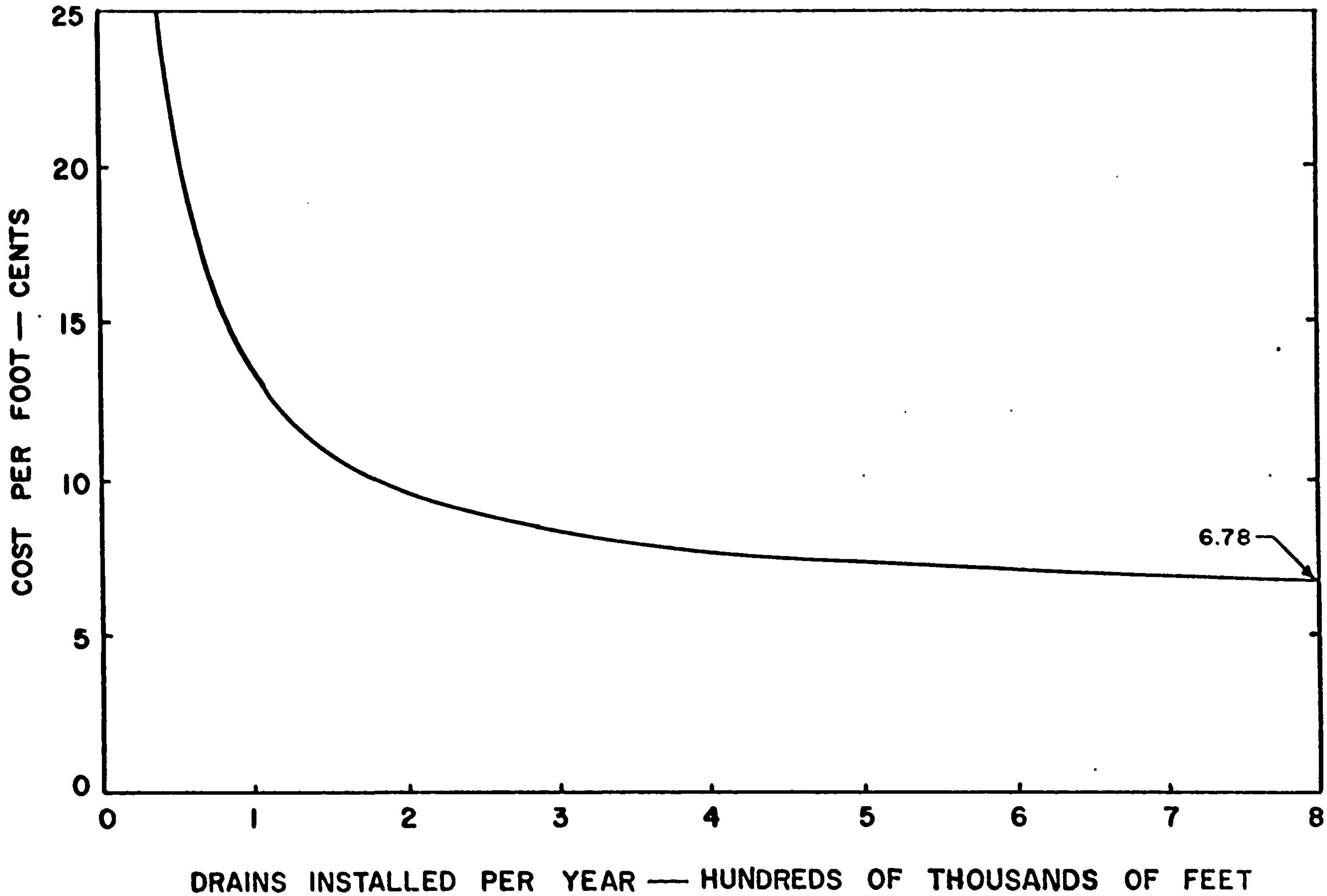


Figure 21. Cost per foot of drain installed in relation to annual footage.

by eliminating some of the time losses which occur. In this manner, production can be increased without increasing either the overhead or the operating expenses. The methods of reducing the machine delays have already been discussed.

It is possible, in some cases, to achieve cost reduction by decreasing some of the operating expenses, although this is usually difficult. Repairs can be kept to a minimum with good maintenance and with a conscientious operator at the controls. The contractor's ability to do his own repair work, including welding, can also reduce repair costs. Transportation costs may be reduced by scheduling jobs close to each other and by doing as many large jobs as possible.

By owning two or more trenching machines, a contractor can reduce his overhead per machine, since some of the initial capital investment, such as tools and shop equipment, may be split between all the machines. This might also justify owning his own moving equipment and reduce the transportation costs per machine. A larger inventory of spare parts would probably be carried, and could prevent a substantial loss in time and money during an emergency.

Reducing the cost per foot to a minimum is not necessarily the most effective method of maximizing profits. As was shown in figure 21, the cost per foot decreases with increased production because of the fixed overhead costs. Therefore, a machine with twice the overhead would have to dig twice as many feet in order to achieve the same cost per foot. However, if the market price for ditching services is higher than the 'break-even point', the same business profit could be realized by digging somewhat less than twice as many feet. For instance, a machine operating according to the proposed cost schedule would dig 600,000 feet at a cost of about seven cents per foot. If the market price for ditching was eight cents per foot, a business profit of one cent per foot, or 6,000 dollars would be realized. A second machine with twice the initial cost would have to dig approximately 1.2 million feet in order to reduce its cost per foot to seven cents. However, if the market price remained at eight cents per foot, this machine would realize 12,000 dollars business profit. A profit of 6,000 dollars would be achieved with an annual production of somewhat less than 1.2 million feet, and a cost per foot greater than seven cents. It is due largely to this principle that the high-speed trenchless drainlaying plows can remain competitive with the conventional trenching machines which cost between one-half and one-third the price.

SUMMARY AND CONCLUSIONS

The recent rapid growth in annual subdrain installations in the province of Quebec, along with the entry of private contractors into the business, prompted this study of the performance and cost of operation of drainage trenching machines. Tests were conducted to investigate the effect of depth on the speed of digging in various soil textures. Work studies were undertaken to determine the time losses which occur during the normal operation of several machines, and thus to establish their efficiencies. The costs of operation of trenching machines were investigated with the aid of questionnaires sent to 124 contractors in Ontario, and by interviews with Quebec contractors. Based on the results of the studies, suggestions were made of methods to increase the digging speed and the efficiency of operating the machines and possible means of reducing the costs of operation.

From the investigation, the following conclusions were drawn:

1) Digging speed was found to vary inversely with depth, over the range of depths observed. Linear regression equations provided negative regression coefficients, which were significant at the $P = 0.01$ level in nine of the ten cases. The tenth coefficient was significant at the $P = 0.20$ level.

2) The coefficients of determination for the nine cases mentioned above indicated that between 35.9 and 79.7 percent of the variation in

digging speed was due to depth. As machine characteristics and soil texture were kept as constant as possible in each case, the remaining 'unexplained' variation must have been due primarily to other external factors which were not measured.

3) Quadratic and cubic regression equations did not add significantly, at the $P = 0.05$ level, to a better fit for the range of depths observed, and were therefore abandoned in favor of the linear equations.

4) The effect of both machine characteristics and soil texture on the depth-speed relationship was too great to permit the use of one regression equation for all the data. Because of this restriction, a general formula for charging on a depth basis is not recommended.

5) The time losses for four different machines ranged from 53.48 to 65.73 percent of the total available time, and averaged 58.60 percent. These percentages do not include the effect of the extraordinary delays of no supply of tiles and no plan available. Based on 174 available working days, the average efficiency of the four machines was 41.4 percent.

6) The largest single delay factor was weather, which accounted for an average of 5.78 percent of the available time. Setting grade targets followed with 5.69 percent. The remaining 47.83 percent lost time was due to sixteen other operating delay factors.

7) The items of time loss which appear to be most easily reduced are setting targets (5.69 percent time loss) and making junctions (3.80

percent time loss). Those most difficult to alter include weather, maintenance and commencing laterals.

8) The results of a questionnaire sent to Ontario contractors showed extreme variation of all factors concerned with the costs of operation of trenching machines. The prices charged to the farmers, which ranged from 5.5 cents per foot to 10.0 cents per foot, reflect the large differences in operating costs between contractors. Because of this wide variation, it was not possible to present a cost analysis which was representative of the industry in general.

9) A proposed cost schedule, based on values within the expected range, showed the total overhead costs to be 22.87 percent of the total annual cost of operation. The cost per foot of drain laid was 7.16 cents in this proposed schedule. Although the schedule could not be claimed to be typical of all trenching operations, it did serve to present the cost factors involved, and to give the reader a general idea of the range of costs to be expected.

10) The most effective method of reducing the cost of operation is by eliminating some of the time losses. Other methods include increasing the annual production per machine, owning more than one machine, or by decreasing some of the individual cost factors. It was also pointed out that a minimum cost per foot does not always infer maximum profit, but that quantity may be the more critical factor.

RECOMMENDATIONS FOR FURTHER STUDY

Some topics related to this Thesis which are seen to merit further study are given below:

1) An investigation of the performance and cost of operation of the trenchless drainlaying plow (e.g. Badger Minor) should be carried out, now that at least two such machines are expected to be operating during 1971 in Quebec and Eastern Ontario. The results could be compared to the conventional trencher operation.

2) A study of the laser system of grade control as a means of saving time and labor should be performed, now that at least two such devices will be functioning in Quebec and two in Ontario during 1971. The advantages should be compared with the economics of the system in order to find the 'break-even point' with respect to annual production. If possible, any differences in the quality of grade control provided should also be established.

3) As some trenching machines are equipped to backfill directly after drain installation, an investigation of the effect of this operation on digging speed and time losses could determine whether backfilling should be done as a separate operation.

4) Because of the additional wear and damage suffered by trenching machines while working in stoney and sandy soil, it would be of

benefit to study these effects in order to establish a reasonable extra charge for these soil conditions.

5) Although this study shows that the costs of operation can be reduced by increasing annual production, there is probably some optimum maximum footage after which it would be more economical to use two machines instead of attempting to increase further the production of one machine. A study of the limiting factors of high production could lead to more information concerning the optimum footage per machine.

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APPENDIX A

Field Work Sheets

Trenching Machine Performance Field Tests
(Depth vs. Speed)

Machine: Location: Date:

Soil Description: No. of Men:

Test No.	Tile Diameter	Duration of test	Distance (ft)	Ft/Min	Depth				Comments	Soil Sample No.
					Start	Middle	End	Average		
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										

Figure A-1. Field work sheet of depth-speed study of drainage trenching machines.

Trenching Machine Performance Field Tests

(Time Losses) Date:

Machine: Location:

Soil Description: No. of Men:

Time of Day	Duration of Delay	Reason for Delay

Figure A-2. Field work sheet of time loss study of drainage trenching machines.

APPENDIX B

Ontario Drainage Contractors' Questionnaire

CONFIDENTIAL - FOR RESEARCH PURPOSES ONLY

Drainage Contractor Questionnaire
Season - 1969

Name: ____________________

Address: ____________________

Telephone Number: ____________________

1. No. of years in drainage business ____________________

2. Number of ditching machines ____________________

3. Make and year of machine(s) ____________________

4. Size and make of motor(s) ____________________

5. Machine on tracks or rubber tires ____________________

6. Initial cost of machine $__________ bought in __________ (date)

7. Expected life of machine __________ years

8. Expected salvage value $ ____________________

9. Other equipment owned and used in drainage operation __________

____

____

10. Total dollar investment $ ____________________

11. No. of men in field crew ____________________

12. Is owner included in field crew? ____________________

13. Average number of working hours per day ____________________

14. Size of average job ____________________ feet.

15. Range of job sizes: Maximum __________ ft. Minimum __________ ft.

16. Area in which machine was working ____________________

17. Do most jobs occur in rolling or flat land? ____________________

18. Are there stone problems on the majority of jobs? ____________________

19. Drainage systems generally Random __________ Systematic __________

20. Most common spacing of laterals in your region_______________ft.

21. Surveying is done by Contractor_____ Government_____ Other________

22. Is a plan usually drawn for each job?___________________________

23. Average hourly fuel consumption of drainage machine______gal/hr.

24. 1969 Season started______________ Season finished________________
(date) (date)

25. Machine works 5 or 6-day week?_________________________________

26. Total footage for the season____________________________________

Feet of plastic tubing____________________________________

Feet of clay tile____

Feet of concrete tile______________________________________

27. Approximate number of days lost because of weather?_____________

repairs?_____________

28. Cost of: Fuel $___________________

Maintenance(oil, grease, filters, etc.) $____________

Labour $___________________

Repairs $___________________

Float Rental $___________________

Insurance $___________________

Bookkeeping and accounting $_________________________

Other $___________________

Comments, if any:____

____

____

29. Wages: Machine operator $__________________ per hour

Others $__________________ per hour

If not on hourly basis, explain system used_____________________

____

Are the men hired on seasonal basis or all year round?__________

____

30. Method of charging farmer:

$__________________ per foot

$__________________ per hour

Extra charge for sand or rocks $______________________________

Charge for backfilling $______________________________

Charge for surveying $______________________________

Charge for extra depth $______________________________

Charge for handling large diameter tiles $____________________

Other charges $______________________________

Explain briefly ____

____

____

____

____

____

Please return to: D. Fisk
Dept. of Agricultural Engineering
Macdonald College, P.Q.

September 15, 1970.