FURROW COMPACTION FOR IMPROVED IRRIGATION EFFICIENCY AND UNIFORMITY

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INTRODUCTION

A significant portion of the surface irrigated cropland in the western United States is located in alluvial valleys. For example, in Wyoming an estimated 350,000 ha of the total of 730,000 ha of surface irrigated land is in alluvial valleys, and there are 21,000,000 ha of surface irrigated lands in the 17 western states (Anon. 1982). Soils in these valleys are typically sandy, and have very high water infiltration rates. The problem of high infiltration rates is particularly severe when minimum tillage practices are used in these soils.

Furrows are normally formed using a furrow opener. This device leaves the furrow surface relatively loose and rough. These factors contribute to high infiltration and to erosion and transport of sediments both within the field and with tail water.

A compaction roller will firm and smooth the furrow wall and bottom. Compaction reduces the infiltration rate, and water advances more rapidly across the field because of the smooth furrow surface. Water intake thus is more nearly uniform along the entire length of the furrow. Less total water is required and water is applied more uniformly. With appropriate compaction

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of irrigation furrows, crop production should be enhanced with less water and with reduced water degradation.

Although not directly addressed in current research, a significant possibility exists for savings of plant nutrients, particularly nitrogen. Assuming that 100mm of excess water becomes deep seepage on the 350,000 ha of surface irrigated area in the alluvial valleys of Wyoming and using values reported by Duke (1978), between 6,700 and 21,000 metric tons of nitrogen are leached to ground waters from alluvial valleys each year in the State of Wyoming. It should be noted that 100mm of deep percolation is a very conservative estimate. Additional benefits of furrow compaction include improved irrigation tail water quality because of reduced erosion and the corresponding reduction in sediments transported to tail water collection facilities or streams.

Compaction of furrow walls provides several direct benefits to irrigation. First, compaction decreases the rate of infiltration of water from the furrow to the surrounding soil. Khalid and Smith (1978) reported approximately 40 percent decrease in the rate of infiltration from compacted furrows in sandy soil.

Soothing furrow walls significantly decreases the resistance to flow of water in furrows. Borrelli, et al. (1982) reported that water advanced approximately 40 percent faster in compacted furrows. The combined effect of reducing the infiltration rate and increasing the rate of water flow in the furrow is to provide a nearly equal opportunity time along the length of the furrow. This means that the uniformity of irrigation and the irrigation efficiency would be increased. Based on results reported by Borrelli (1982), the efficiency of surface irrigation with compacted furrows may be nearly equal to the efficiency of sprinkler irrigation.

The flowrates for all tests were in excess of 100 l/min while for a 0.5% slope, although the maximum nonerosive stream size was 76 l/min (Marr, 1967). By visual inspection, the higher compaction rate rows appeared to have less sediment loss than the noncompacted furrows.

OBJECTIVES

The overall objective of the proposed project was to evaluate compaction of irrigation furrows in sandy soils as a method of increasing irrigation efficiency, decreasing water use and reducing the degradation of ground water and irrigation tail water. Specific project objectives were:

1. To redesign and evaluate a furrow compaction system.
2. To predict the effectiveness of furrow compaction in reducing deep seepage losses.
3. To evaluate the effectiveness of furrow compaction for improving irrigation efficiency and uniformity while reducing water use.

MACHINE DESIGN AND OPERATION

The wheel type furrow compactor is shown diagramatically in Figure 1 and in field operation in Figures 2 and 3. The machine consists of five basic parts; the opener, the packer wheel, the tool bar, the track eliminator and the frame.

The furrow opener was constructed of mild steel and was made to open a 110 degree inclusive furrow. The design allowed minor adjustment of the angle through the attachment to the shank. The shank was mounted to the frame in front of the packer wheel so the wheel served as a depth guide. The vertical height of the opener could also be adjusted relative to the packer wheel.

The packer wheel was constructed of laminated 25.4mm nominal (19mm actual) pine to form the shape shown in Figure 1. Three wheel shapes were considered; parabolic, trapezoidal, and triangular. Due to the ease of construction, the triangular shape was chosen with an inclusive angle of 110 degrees. After the wheel was laminated and shaped to 110 degrees, it was covered with reinforced fiberglass and given a smooth finish. Two steel plates were attached to the sides and connected by long threaded studs.

Two flush mounted bearings were attached to the steel plate. The 25.4mm diameter axle was put in place and held using locking collars. The axle was then attached to the frame using pillow block bearings. Both sets of bearings were of the roller bearing type, with grease fittings and locking collars.

The toolbar was a standard 57mm diamond toolbar with an A-frame attached to allow hook up to the tractor three point hitch.

The track eliminators were used on the tractor wheel rows to eliminate compaction from the tractor wheels. Each rear wheel was followed by three shanks with sheepsfoot, cultivators. By running these at 50-75mm depth, most of the effects of tractor wheel compaction were removed from the furrows.

The frame was made of mild steel angle, flat stock and solid bar. With the exception of the four bar linkage, the entire assembly was welded. The four bar linkage was designed to allow 75mm of vertical travel each way from center height. Weights were fabricated bar stock and weighed approximately 50 N each. Each frame could hold 26 weights or an additional 800 N of weight. The base weight of the frame with the opener and wheel attached was 690 N. The weights were placed so the vertical force component on the wheel was equal to the weight added.

The entire frame assembly was made to ride on the wheel rather than a guide wheel. This led to more accurate depth of compaction and the weight aided in the compaction. The machine was adjusted to allow the toolbar to ride as low to the ground as possible. This allowed the four bar linkage to ride approximately horizontal which in turn allowed full vertical movement of the packer wheel relative to the tool bar.

Initial depth settings were obtained by placing the tractor and compactor on a level surface and lowering the tool bar. After loosening all clamps, the tool bar was lowered until the four bar linkages were approximately horizontal. All the furrow opener clamps were then tightened. The tool bar was then raised approximately 80mm and the track eliminators were tightened in this position. After tightening all clamps, the machine was ready for the field.

Once adjusted, weights could be added or subtracted without further adjustment to the packer wheel toolbar height. The machine could be easily transported to the field using the tractor three point hitch. In the field, the tractor was lined up with the rows, the three point hitch was lowered and the tractor proceeded down the field. The opener was run approximately 70-100mm below the soil surface. This pushed the soil out of the way and allowed the wheel to follow and compact the furrow surface. At the end of the field, the packer was lifted and the tractor was positioned for the return on the next five rows.

BACKGROUND ANALYSIS

Surface irrigation involves the spatially varied, non-uniform flow of water over a porous bed. The process involves introducing a surface stream at the upper end of the field and water advances down the slope. Analyses of the process usually involves advance of water over the field, buildup of impounded surface storage, depletion of surface stored water and recession of water from the surface. These are illustrated in Figure 4 along with the intake opportunity time, which is the time available for water to infiltrate the soil.

Measurement of the time and distance involved in Figure 4, along with inflow and outflow rates allows evaluation of the efficiency and uniformity of the irrigation. Of the several irrigation efficiency measures, the water application efficiency is most useful for evaluating in-field performance. The water application efficiency is beneficially used water divided by the water applied to the field. The water beneficially used by the crop includes the consumptive use and the water required to maintain a suitable soil salt balance (leaching requirement).

The degree of uniformity of water application is determined by the uniformity of the intake opportunity time, and variation of the soil water intake characteristics along the field. Obviously, if the intake characteristics were uniform, one could achieve a high degree of uniformity if the intake opportunity time were constant along the field.

Efficiency and uniformity are often at opposing ends of the spectrum for irrigation evaluation. For example, applying water for very short time intervals may be highly efficient, but there may be insufficient water to even reach the far end of the field. While the efficiency may be high, uniformity will be very poor because a portion of the crop may not receive water. Alternatively, one can achieve good uniformity by applying water for long periods of time. In this case, the intake opportunity time may be nearly equal along the field, but there may be excess tailwater runoff, erosion and water logging in some parts of the field. Thus, uniformity may be good, but at the expense of poor water application efficiency and other problems.

In general, a rapid advance rate followed by a reduced flow when water reaches the far end of the field will produce an efficient-uniform irrigation. Therefore, decreasing the advance time by compacting the furrow to reduce infiltration and smooth the furrow walls should be beneficial in improving furrow irrigation performance.

Trends of benefits obtained by compacting irrigation furrows can be predicted using Hall's (1956) solution of the Lewis-Milne (1938) equation. Although this analysis applies to border irrigation, trends should also be applicable to furrow irrigation.

The Lewis-Milne equation involves Manning's equation (Hansen, et al. 1979) and the Kostiakov-Lewis infiltration function, $z = Kt^a$, where z is the depth of water infiltrated, t is time and K and a are constants. Decreasing the exponent, a, by compacting the soil, would decrease the water infiltrated and would thus increase the advance rate. Hydraulic resistance to advance down the channel is reflected in Manning's coefficient, n. In Manning's equation compacting and smoothing the channel would decrease hydraulic resistance (reduce n) and would increase the advance rate.

In Figure 5, the effect of increasing the infiltration rate (increasing a) is shown in terms of the advance (distance) for various values of Manning's coefficient (n) and times. This plot was developed using estimates for various required values. From the plot, one can observe the following:

1. Compaction is more beneficial in longer furrows.
2. Controlling infiltration (reducing a) is more important than reducing roughness (reducing n) of the furrow.
3. As infiltration becomes high, advance is relatively independent of n. In Figure 5, the curves converge as the infiltration parameter (abscissa) becomes larger. Note also that advance becomes very slow

and essentially ceases at relatively short distances for high infiltration rates.

TEST EQUIPMENT AND PROCEDURES

The furrow packing machine was used with an International Harvester 656 tractor at Torrington and a John Deere 630 tractor at Powell. The rated power output of the International Harvester and John Deere are 52 and 36 kilowatts respectively. Tractor power was not a problem, but lift capacity (ability to raise the implement) was marginal without additional front end weights.

The depth of compaction was varied by adjusting the vertical position of the furrow opener relative to the compaction wheel (Figure 1) and by applying weights to the wheel. Each furrow assembly "floated" relative to the tractor three point hitch, through the parallel linkage attachment. This design allowed some leveling action by the opener, because the final furrow depth was controlled by the trailing compaction wheel.

Weight for compaction was added by placing 50 N weights in sets of four over the compacting wheel. This led to testing of three intervals of compaction; no added weight, 400 N of added weight, and 800 N of added weight. A control set of furrows was also made using only the furrow opener portion of the furrow compaction machine. During the entire experiment at both locations, four sets of data were obtained, those being; no compaction, compaction with no added weight, compaction with half the added weight, and full weight compaction. Data were also collected in wheel furrows, in which the tractor wheel traveled versus furrows in which it did not.

The fields were laid out (Figures 6, 7 and 8) with compaction level as the variable. During layout, the fields were surveyed at 25m intervals to determine slope, and irrigation advance station intervals were established (10m at Torrington and 50m at Powell).

Infiltration was measured using blocked furrow tests 1m in length as shown in Figure 9. A constant head tank, (Figure 9) was used to measure the volume infiltrated. The blocked furrow tests were conducted on the day preceding irrigation.

Water content samples were taken at three depths; surface, 0-18 cm, and 18-30 cm. These readings were taken approximately 20 meters from the head of the field, (Figures 6, 7 and 8).

At Torrington, 10m intervals were established to measure furrow advance. The time of the initial start of the irrigation was recorded and then the time was recorded when the water reached the station. The only difference in the Powell experiment was that the stations were 50m apart.

Recession data were measured by recording the times at which flow stopped in the flume on the head of the furrow, each interval station along the furrow and tail of the furrow. Based on these measurements, the recession curves were established. It should be noted that recession data were very difficult to obtain because of non-uniformities in the field, furrows and variations in the soil-water intake function.

Recession data were obtained only for the July 25 tests at Powell. The tailwater drainage problem prevented meaningful measurements at Torrington, and a rainstorm occurred during the recession phase of the July 2 tests at Powell.

Flow was measured with the use of 60^{o}-V notch trapexoidal flumes, as shown in Figure 10, with an attempt to keep equal flows in all furrows. The flumes were also used for recession measurements although this was not successful at Torrington due to the lack of field slope which allowed water to back up into the field.

Soil penetration resistance measurements were taken with two types of penetrometers, a Soiltest model EL516-010 hand held penetrometer, which is useful for deeper measurements and a Soiltest model EL516-030 pocket penetrometer, which is useful for measurements near the soil surface. The locations within the furrow are shown in Figures 6, 7 and 8. These readings were taken following compaction. Penetration resistance, measured with the hand held penetrometer, was essentially zero prior to compaction.

DATA ANALYSIS

The furrow advance and recession data were analyzed similarly. The first step was to plot cumulative time versus furrow length. This plot indicated the relative position of the water advance at any particular furrow station for each of the compaction treatments. By use of the Elliot and Walker (1982), two point method, modified Kostiakov-Lewis infiltration equations were obtained for each set of data. Once these were obtained, a plot for each compaction treatment with both advance and recession was obtained for cumulative time versus distance. As discussed previously, intake opportunity time is the vertical difference between these curves at a given time. This analysis provided a comparison of relative intake opportunity times for each treatment.

The infiltration data were plotted for depth of infiltration versus time with all four treatments shown on the same graph. The visual interpretation of the data showed the relative comparison of infiltration rates. This also was used to find the required time to allow enough water to infiltrate to satisfy crop needs. When this time was added to the required advance time to reach the last station, an ideal irrigation time was obtained.

Penetrometer resistance data were plotted showing resistance verusus soil depth. This provided a comparison of the relative compaction effort applied to the four treatments. A similar plot was prepared of the wheel rows versus soft rows. The results of this comparison were prepared using a simple average technique.

RESULTS AND DISCUSSION

The main objective of this research was to design, fabricate and evaluate a five row irrigation furrow packing system. The major portion of the evaluation was done with respect to infiltration, compaction, and advance/recession times. Another objective was to determine the affect of different compaction weights on infiltration, compaction and advance/recession times.

General Machine Performance Characteristics

The furrow packer performed satisfactory at both sites, yet due to different soil conditions provided varied results. The degree of compaction was easily changed by the addition or deletion of weights.

In all three tests, when the soil was wet, it tended to stick to the wheels. This was a major problem at Powell during test number three. There was also a problem with loose soil and clods that fell back into the furrow and therefore, affected furrow smoothness.

More compaction occurred in the lower portion of the furrow due to the shape of the wheel and the fact that the soil was more confined in the lower portion. This is reflected in the penetrometer test results shown in Figure 11.

Effects of Compaction on Penetrometer Tests

Compaction was evaluated after forming the furrows using methods as discussed previously. Two types of penetrometer data were collected. The first type was done using the Soiltest pocket penetrometer with the large base foot, $5.07cm^2$. This gave an indication of surface compaction up the furrow wall surface, and worked well in Torrington, yet did not provide good results in Powell. A combination of change in soil type and inadequate compaction weight led to the poor results at Powell. A summary of the results are shown in Figure 11.

The second method of obtaining penetrometer resistance data was done using the Soiltest hand held penetrometer fitted with a standard (ASAE, 1983) small cone, $1.3cm^2$ base area. Readings were taken at the bottom of the furrow at 2.5mm intervals of depth. Plots of this data are shown in Figure 12.

Again, the Torrington data were as expected while both of the Powell plots show that the compaction weight was inadequate, and therefore, the results produced more of a surface compaction and smoothing effect. In the check area of Powell on July 25, a hard pan was evident yet this did not show on the data of July 2.

A compaction plot of wheel rows versus soft rows, (Figure 13), shows that the track eliminators removed the effects of tractor wheel compaction. After a depth of 5-7.5cm the tractor wheel rows had a lower resistance to penetration suggesting the track eliminators were running deeper than necessary.

Effects of Compaction on Infiltration

Infiltration data were collected following furrow compaction treatments. Readings were taken for both wheel rows and soft rows, but no difference in infiltration was observed.

The infiltration data for Torrington and Powell on July 2 were as expected. With an increased weight of compaction, a corresponding decrease in infiltration resulted. The data taken at Powell on July 25 did not follow this trend, due to a number of factors. These include; soil cracks formed during compaction, granular soil structure and rapid lateral movement of the wetting front. Other factors include variation of soil characteristics and antecedent moisture. The soil water content was high at the time of the third test because 17.2mm of rain was recorded 4 days pervious to irrigation. Plots of the average infiltration versus time are shown in Figure 14.

Effects of Compaction on Advance and Recession Rates

The two tests at Powell yielded the expected results for advance. The best results were obtained at Powell on July 2, while the results on July 25 were variable due to high soil moisture content. The Torrington data were adversely affected by the short length of run and difficulty in measuring time values over short advance intervals. All compaction treatments produced faster advance compared to check rows in all tests. Plots of the data are shown in Figure 15.

Recession data were taken only at Powell on July 25 because of problems with drainage at Torrington and a rainstorm on July 3 during the recession phase of the tests being completed on that date. Advance and recession data, are shown in Figure 16, for the July 25 tests.

Efficiency and Uniformity

By plotting advance and recession with cumulative time versus distance, intake opportunity time can be obtained. The area between the advance and recession curves was calculated and plotted as a single curve of cumulative time versus distance down the furrow. For ideal uniformity, straight line with zero slope would result. A plot of the three treatments and the check is shown in Figure 17. The areas under the curves were then divided by the area under a straight line of time equal to 723 minutes. The full weight compaction yielded the best coverage of this area with 92% of the coverage of the ideal area. The other two treatments covered approximately 88% of the area and the check covered 84% of the area. The percentages would have been spread out over a larger range of values if the set time had been reduced.

Table 2 shows Kostiakov-Lewis equations for the various treatments. These were obtained using the Elliot and Walker (1982) two point method for advance/recession data. The second column shows the time to infiltrate to the required depth at any point in the furrow. The third column shows the advance time to the last station in the furrow. The final column is a summation of the second and third columns. Third column values therefore, represent the minimum time required to irrigate the amount of water necessary for plant growth.

In the two Powell tests, the half weight compaction treatment gave the best overall time confirming that more surface compaction and smoothing were accomplished than deep compaction. This result was expected based on the previous analysis of the Lewis-Milne equation. That is, in the Powell tests, there was insufficient compaction to significantly reduce infiltration. Therefore, the smoothing affect of the packer was a dominant factor. The Torrington data were not used in this analysis due to the very short advance time versus the infiltration times.

Benefit/Cost Analysis

If the only costs associated with the use of the packer are limited to the ownership, fuel, lubricants and operation time of the tractor along with the operators wages, the total cost of operation is 51¢ per furrow. This was calculated as follows:

1.	Ownership Costs	\$6.28 per hour
2.	Fuel and Lubricants	1.80 per hour
3.	Drivers wages	10.00 per hour
	Total Cost	\$18.08 per hour

The tractor speed was 3.54km/hr, multiplying this time a 50/60 work hour, 2.94m of field was covered each hour. Since each furrow was 0.40km in length and were packing 5 furrows at a time, then 35.42 furrows per hour giving a cost per furrow of 51¢.

Based on an application of 100mm of excess water, there would be an average loss of 143 Kg per ha of NO_3-N (Duke, et al. 1978). Since the furrow size was 0.762m X 400m, the calculated expected loss would be approximately 4.36kg of NO_3-N per furrow for 100mm of excess water applied (deep percolation). Neglecting the cost of application, and with a cost of NO_3-N of \$0.42/kg, the benefit of preventing 100mm of deep percolation would be \$1.83 per furrow. Using the cost calculated above of \$0.51 per furrow for packing, the estimated benefit/cost ratio would be 3.59.

CONCLUSIONS

1. The furrow packer performed satisfactorily, although more compaction weight would have been beneficial for clayey soils in the Powell area.
2. The furrow packer increased both furrow irrigation efficiency and uniformity.
3. Based primarily on controlling deep seepage and the associated losses of nitrogen, the benefit/cost ratio of using the packer was 3.59.

TABLE 1

Compaction treatment	Infiltration equation $Z=Kt^a$	Time to infiltrate to required depth (minutes)	Time of advance (minutes)	Total time (minutes)
Torrington				
Full weight	$1.22t^{.502}$	185	30	83
Half weight	$1.125t^{.533}$	139	27	166
No weight	$1.094t^{.538}$	137	27	164
Check	$2.376t^{1.010}$	122	30	152
Powell #1				
Full weight	$2.523t^{.613}$	231	94	325
Half weight	$2.217t^{.686}$	156	73	229
No weight	$1.866t^{.722}$	154	88	232
Check	$3.057t^{.452}$	109	295	404
Powell #2				
Full weight	$2.307t^{.654}$	189	123	312
Half weight	$1.695t^{.762}$	135	148	283
No weight	$2.753t^{.601}$	223	278	501
Check	$3.073t^{.451}$	106	730	836

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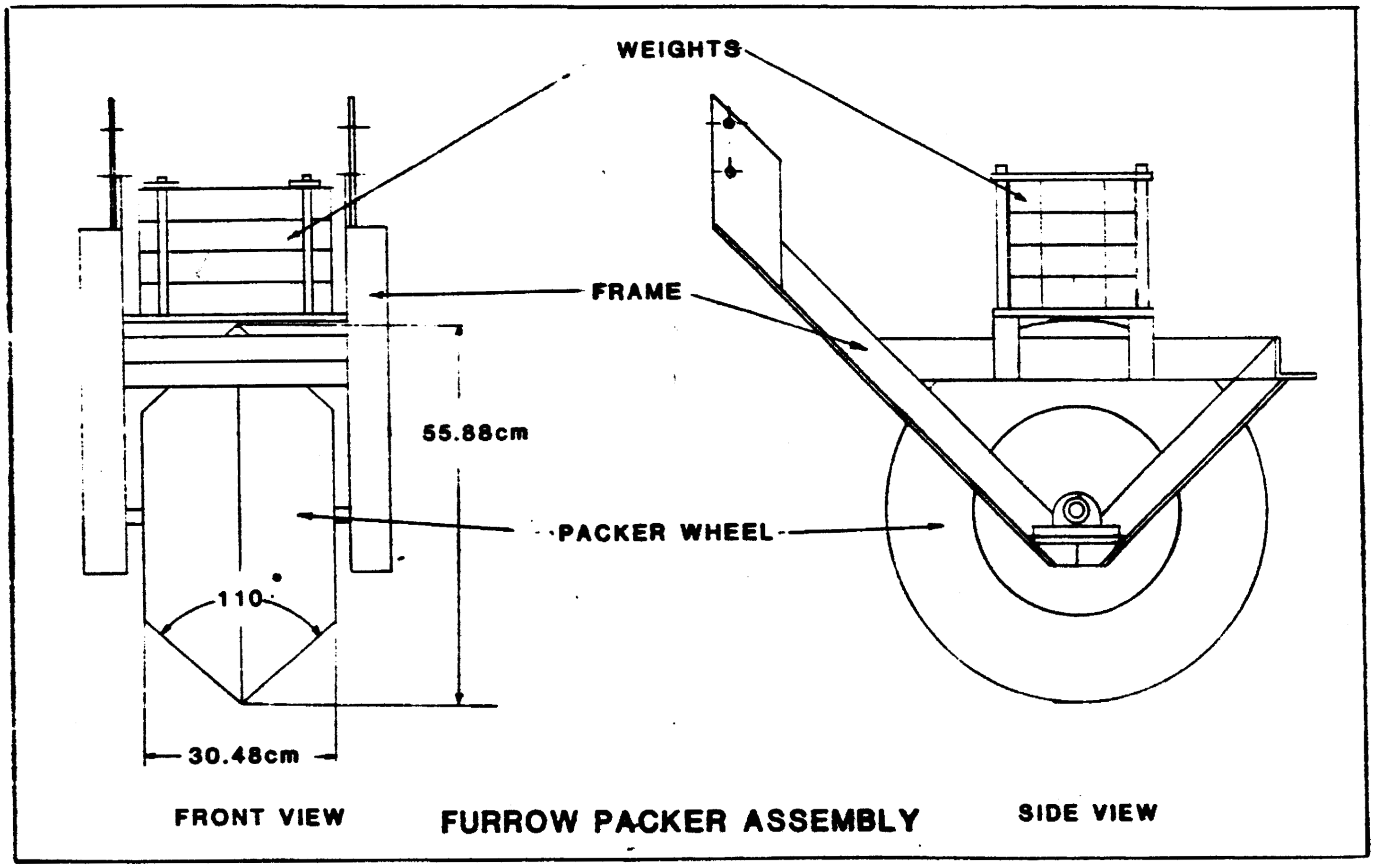

Figure 1. Schematic of furrow compaction machine.

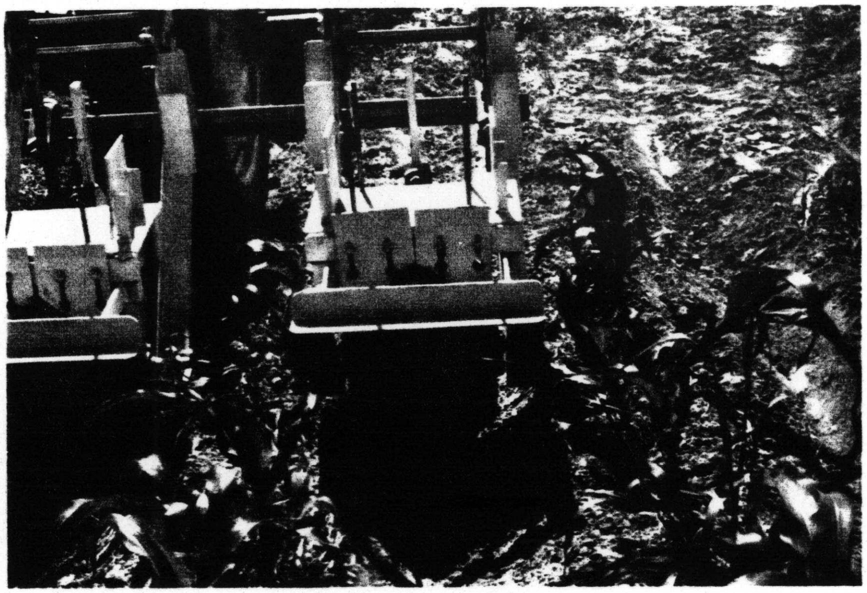

Figure 2. Packer wheel in field.

Figure 3. Furrow compactor.

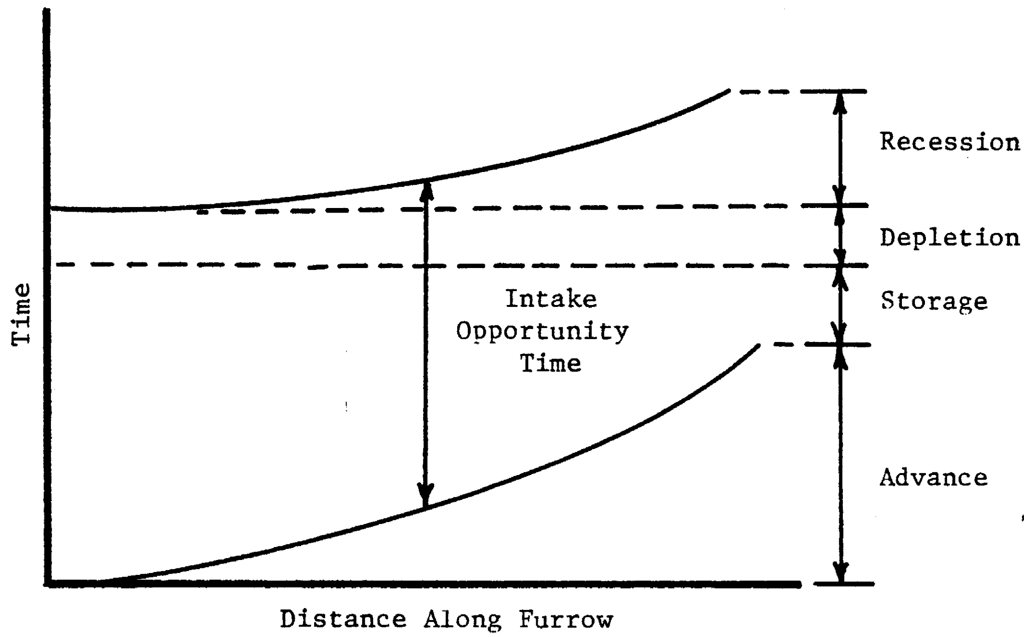

Figure 4. Idealized furrow irrigation.

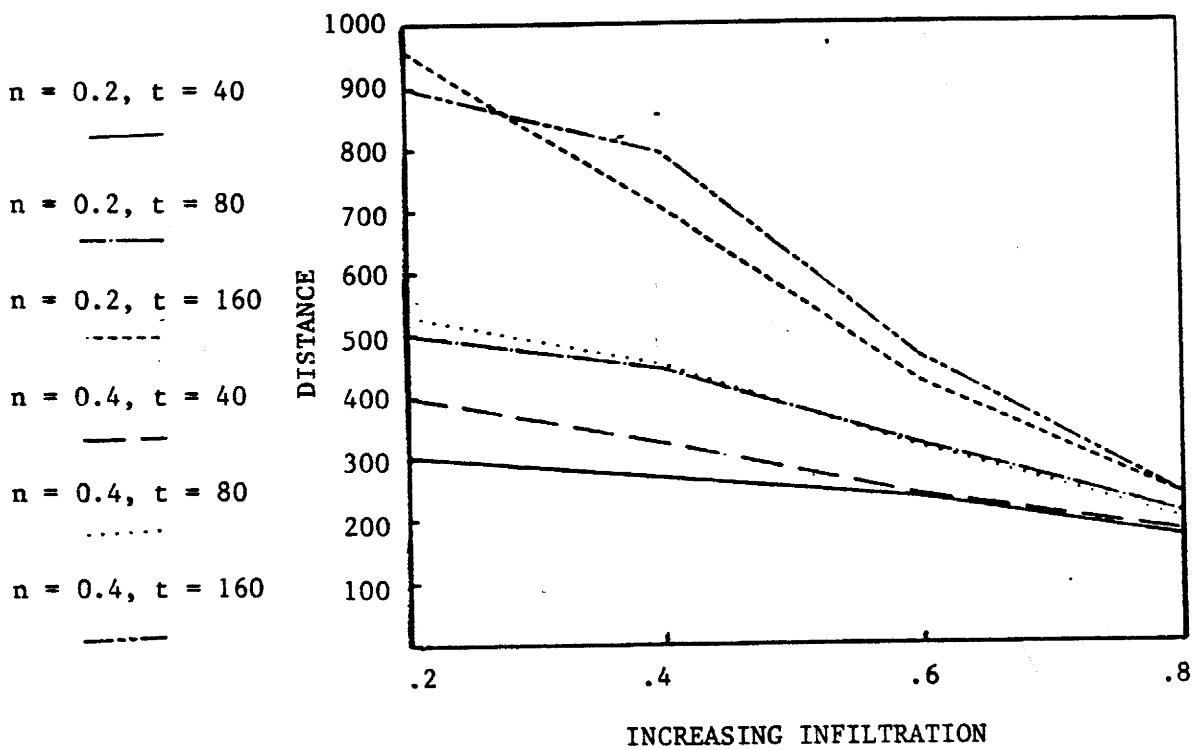

Figure 5. Effects of smoothness and infiltration on water advance down a border. Adopted from Hall (1956).

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*  1--------X---FULL WEIGHT COMPACTION--SOFT ROW---------------@
*  2--------X---FULL WEIGHT COMPACTION-WHEEL ROW----------------
*  3--------X---FULL WEIGHT COMPACTION--SOFT ROW-----O----------
*  4--------X---FULL WEIGHT COMPACTION-WHEEL ROW----------------
*  5--------X---FULL WEIGHT COMPACTION--SOFT ROW-----S----------
*  6--------X---FULL WEIGHT COMPACTION--SOFT ROW----------------
*  7--------X---FULL WEIGHT COMPACTION-WHEEL ROW-----O----------
*  8--------X---FULL WEIGHT COMPACTION--SOFT ROW----------------
*  9--Y-----X---FULL WEIGHT COMPACTION-WHEEL ROW-----------Y----
* 10--Y-----X---FULL WEIGHT COMPACTION--SOFT ROW-----------Y----
* ############GUARD FURROW######################################
* 11--Y-----X---HALF WEIGHT COMPACTION--SOFT ROW-----------Y----
* 12--Y-----X---HALF WEIGHT COMPACTION-WHEEL ROW-----------Y----
* 13--------X---HALF WEIGHT COMPACTION--SOFT ROW-----O----------
* 14--------X---HALF WEIGHT COMPACTION-WHEEL ROW----------------
S 15--------X---HALF WEIGHT COMPACTION--SOFT ROW-----S----------
E 16--------X---HALF WEIGHT COMPACTION--SOFT ROW----------------
R G17-------X---HALF WEIGHT COMPACTION-WHEEL ROW-----O----------
V A18-------X---HALF WEIGHT COMPACTION--SOFT ROW----------------
I T19-------X---HALF WEIGHT COMPACTION-WHEEL ROW----------------
C E20-------X---HALF WEIGHT COMPACTION--SOFT ROW----------------
E D############GUARD FURROW#####################################
  21--------X-----NO WEIGHT COMPACTION--SOFT ROW----------------
R F22-------X-----NO WEIGHT COMPACTION-WHEEL ROW----------------
O 123-------X-----NO WEIGHT COMPACTION--SOFT ROW-----O----------
A F24-------X-----NO WEIGHT COMPACTION-WHEEL ROW----------------
D E25-------X-----NO WEIGHT COMPACTION--SOFT ROW-----S----------
* 26--------X-----NO WEIGHT COMPACTION--SOFT ROW----------------
* 27--------X-----NO WEIGHT COMPACTION-WHEEL ROW-----O----------
* 28--------X-----NO WEIGHT COMPACTION--SOFT ROW----------------
* 29--Y-----X-----NO WEIGHT COMPACTION-WHEEL ROW-----------Y----
* 30--Y-----X-----NO WEIGHT COMPACTION--SOFT ROW-----------Y----
* ############GUARD FURROW######################################
* 31--Y-----X------------NO COMPACTION--SOFT ROW-----------Y----
* 32--Y-----X------------NO COMPACTION-WHEEL ROW-----------Y----
* 33--------X------------NO COMPACTION--SOFT ROW-----O----------
* 34--------X------------NO COMPACTION-WHEEL ROW----------------
* 35--------X------------NO COMPACTION--SOFT ROW-----S----------
* 36--------X------------NO COMPACTION--SOFT ROW----------------
* 37--------X------------NO COMPACTION-WHEEL ROW-----O----------
* 38--------X------------NO COMPACTION--SOFT ROW----------------
* 39--------X------------NO COMPACTION-WHEEL ROW----------------
* 40--------X------------NO COMPACTION--SOFT ROW----------------

LEGEND       PENETROMETER                BLOCKED FURROW
             TEST LOCATIONS: X           TEST LOCATIONS: O

             SOIL MOISTURE               FLUME LOCATIONS: Y
             TEST LOCATIONS: S
                                         DRAIN: @
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Figure 6. Field Layout - Torrington, Wyoming

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*    1--------X---FULL WEIGHT COMPACTION--SOFT ROW----------------@
*    2--Y-----X---FULL WEIGHT COMPACTION-WHEEL ROW----------------@
*    3--------X---FULL WEIGHT COMPACTION--SOFT ROW-----O----------@
*    4--Y-----X---FULL WEIGHT COMPACTION-WHEEL ROW----------------@
*    5--------X---FULL WEIGHT COMPACTION--SOFT ROW-----S----------@
*    6--Y-----X---FULL WEIGHT COMPACTION--SOFT ROW----------------@
*    7--------X---FULL WEIGHT COMPACTION-WHEEL ROW-----O----------@
*    8--Y-----X---FULL WEIGHT COMPACTION--SOFT ROW----------------@
*    9--------X---FULL WEIGHT COMPACTION-WHEEL ROW----------------@
*   10--Y-----X---FULL WEIGHT COMPACTION--SOFT ROW----------------@
*   ############GUARD FURROW#####################################@
*   11--------X---HALF WEIGHT COMPACTION--SOFT ROW----------------@
*  H12--Y-----X---HALF WEIGHT COMPACTION-WHEEL ROW----------------@
*  E13--------X---HALF WEIGHT COMPACTION--SOFT ROW-----O----------@
*  A14--Y-----X---HALF WEIGHT COMPACTION-WHEEL ROW----------------@
S  D15--------X---HALF WEIGHT COMPACTION--SOFT ROW-----S----------@
E   16--Y-----X---HALF WEIGHT COMPACTION--SOFT ROW----------------@
R  D17--------X---HALF WEIGHT COMPACTION-WHEEL ROW-----O----------@
V  I18--Y-----X---HALF WEIGHT COMPACTION--SOFT ROW----------------@
I  T19--------X---HALF WEIGHT COMPACTION-WHEEL ROW----------------@
C  C20--Y-----X---HALF WEIGHT COMPACTION--SOFT ROW----------------@
E  H############GUARD FURROW#####################################@
    21--------X-----NO WEIGHT COMPACTION--SOFT ROW----------------@
R   22--Y-----X-----NO WEIGHT COMPACTION-WHEEL ROW----------------@
O   23--------X-----NO WEIGHT COMPACTION--SOFT ROW-----O----------@
A   24--Y-----X-----NO WEIGHT COMPACTION-WHEEL ROW----------------@
D   25--------X-----NO WEIGHT COMPACTION--SOFT ROW-----S----------@
*   26--Y-----X-----NO WEIGHT COMPACTION--SOFT ROW----------------@
*   27--------X-----NO WEIGHT COMPACTION-WHEEL ROW-----O----------@
*   28--Y-----X-----NO WEIGHT COMPACTION--SOFT ROW----------------@
*   29--------X-----NO WEIGHT COMPACTION-WHEEL ROW----------------@
*   30--Y-----X-----NO WEIGHT COMPACTION--SOFT ROW----------------@
*   ############GUARD FURROW#####################################@
*   31--------X------------NO COMPACTION--SOFT ROW----------------@
*   32--Y-----X------------NO COMPACTION-WHEEL ROW----------------@
*   33--------X------------NO COMPACTION--SOFT ROW-----O----------@
*   34--Y-----X------------NO COMPACTION-WHEEL ROW----------------@
*   35--------X------------NO COMPACTION--SOFT ROW-----S----------@
*   36--Y-----X------------NO COMPACTION--SOFT ROW----------------@
*   37--------X------------NO COMPACTION-WHEEL ROW-----O----------@
*   38--Y-----X------------NO COMPACTION--SOFT ROW----------------@
*   39--------X------------NO COMPACTION-WHEEL ROW----------------@
*   40--Y-----X------------NO COMPACTION--SOFT ROW----------------@

LEGEND        PENETROMETER               BLOCKED FURROW
              TEST LOCATIONS: X          TEST LOCATIONS: O

              SOIL MOISTURE              FLUME LOCATIONS: Y
              TEST LOCATIONS: S
                                         TAIL WATER
                                         DITSH: @
```

Figure 7. Field Layout, Powell, Wyoming - July 2.

```
*   1--Y----X---FULL WEIGHT COMPACTION--SOFT ROW-----------Y---@
*   ############GUARD FURROW#######################################@
*   ############GUARD FURROW#######################################@
*   2--Y----X---FULL WEIGHT COMPACTION-WHEEL ROW-----------Y---@
*   ############GUARD FURROW#######################################@
*   3--Y-O--X---FULL WEIGHT COMPACTION--SOFT ROW-----------Y---@
*   ############GUARD FURROW#######################################@
*   ############GUARD FURROW#######################################@
*   4--Y-O--X-S-FULL WEIGHT COMPACTION-WHEEL ROW-----------Y---@
*   ############GUARD FURROW#######################################@
*   ############GUARD FURROW#######################################@
*   5--Y----X---HALF WEIGHT COMPACTION--SOFT ROW-----------Y---@
* H ############GUARD FURROW#######################################@
* E ############GUARD FURROW#######################################@
* A 6--Y-O--X---HALF WEIGHT COMPACTION-WHEEL ROW-----------Y---@
S D ############GUARD FURROW#######################################@
E   7--Y-O--X---HALF WEIGHT COMPACTION--SOFT ROW-----------Y---@
R W ############GUARD FURROW#######################################@
V A ############GUARD FURROW#######################################@
I T 8--Y-S--X---HALF WEIGHT COMPACTION-WHEEL ROW-----------Y---@
C E ############GUARD FURROW#######################################@
E F#############GUARD FURROW#######################################@
    9--Y----X-----NO WEIGHT COMPACTION--SOFT ROW-----------Y---@
F D ############GUARD FURROW#######################################@
G I ############GUARD FURROW#######################################@
A T10--Y-O--X-----NO WEIGHT COMPACTION-WHEEL ROW-----------Y---@
D C ############GUARD FURROW#######################################@
* H11--Y-O--X-----NO WEIGHT COMPACTION--SOFT ROW-----------Y---@
*   ############GUARD FURROW#######################################@
*   ############GUARD FURROW#######################################@
*  12--Y-S--X-----NO WEIGHT COMPACTION-WHEEL ROW-----------Y---@
*   ############GUARD FURROW#######################################@
*   ############GUARD FURROW#######################################@
*  13--Y----X------------NO COMPACTION--SOFT ROW-----------Y---@
*   ############GUARD FURROW#######################################@
*   ############GUARD FURROW#######################################@
*  14--Y-S--X------------NO COMPACTION-WHEEL ROW-----------Y---@
*   ############GUARD FURROW#######################################@
*  15--Y-O--X------------NO COMPACTION--SOFT ROW-----------Y---@
*   ############GUARD FURROW#######################################@
*   ############GUARD FURROW#######################################@
*  16--Y-O--X------------NO COMPACTION-WHEEL ROW-----------Y---@
*   ############GUARD FURROW#######################################@

LEGEND        PENETROMETER                BLOCKED FURROW
              TEST LOCATIONS: X           TEST LOCATIONS: O

              SOIL MOISTURE               FLUME LOCATIONS: Y
              TEST LOCATIONS: S
                                          TAIL WATER
                                          DITSH: @
```

Figure 8. Field Layout, Powell, Wyoming - July 25.

Figure 9. Blocked furrow infiltration test.

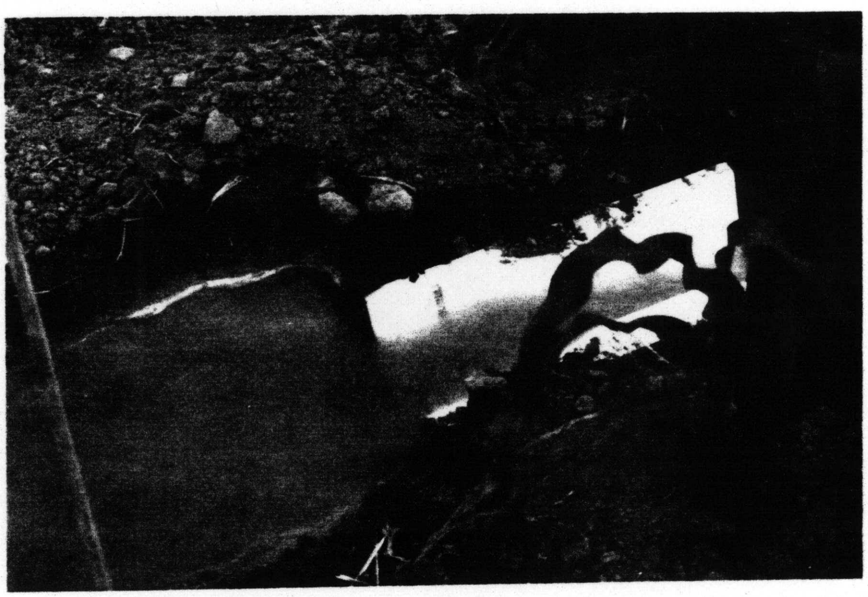


Figure 10. 60°-V Notch Trapezoidal Flume installed in furrow.

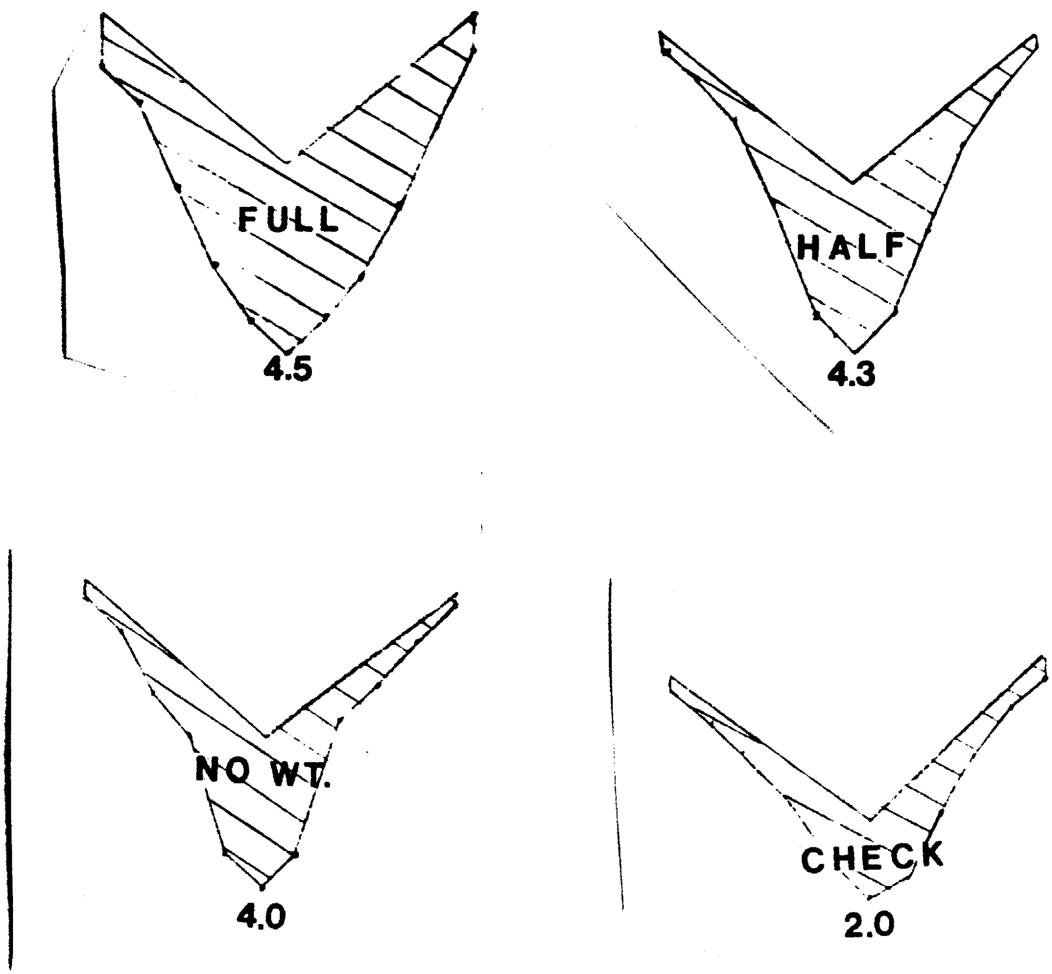


Figure 11. Surface Penetration Test Results, using pocket penetrometer. Shaded areas indicate depth to which surface penetration resistance values given were sustained.

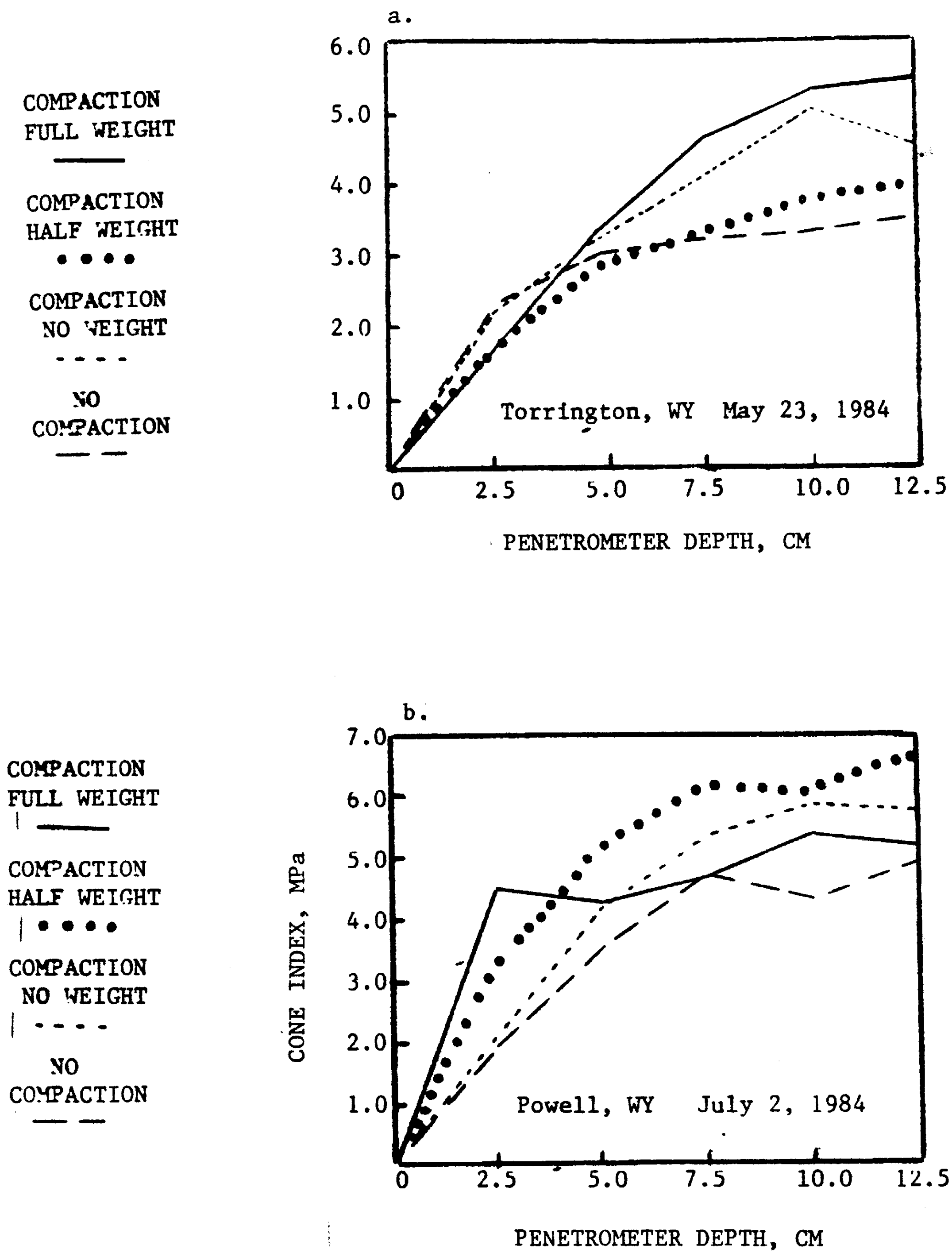


Figure 12a and 12b.

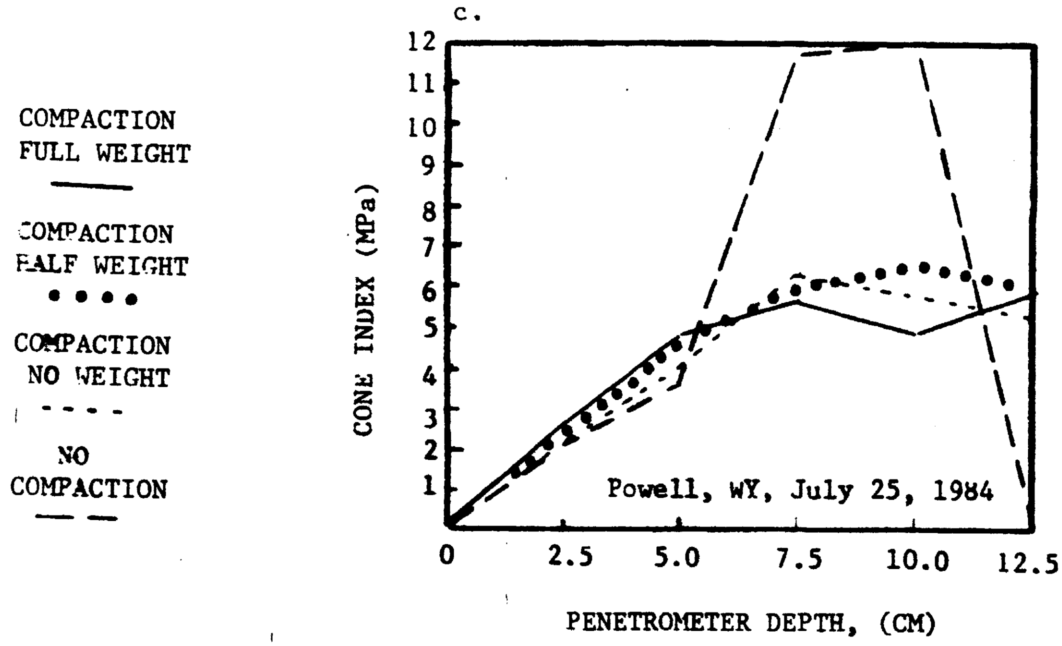


Figure 12c. Penetrometer resistance obtained with ASAE standard penetrometers.

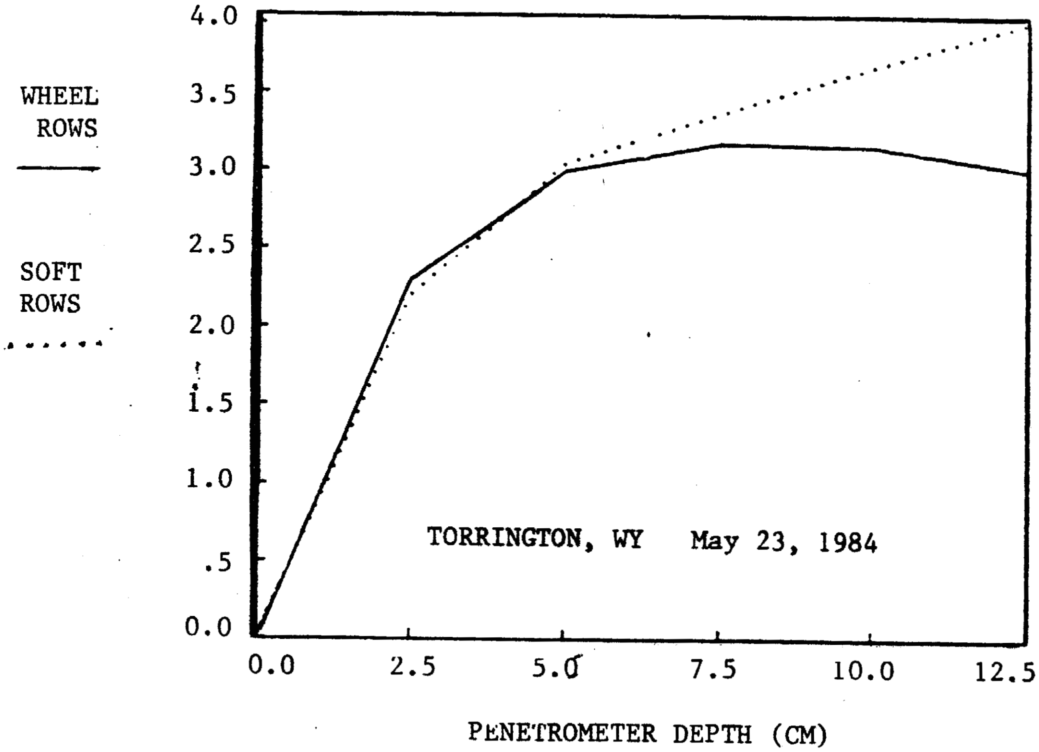
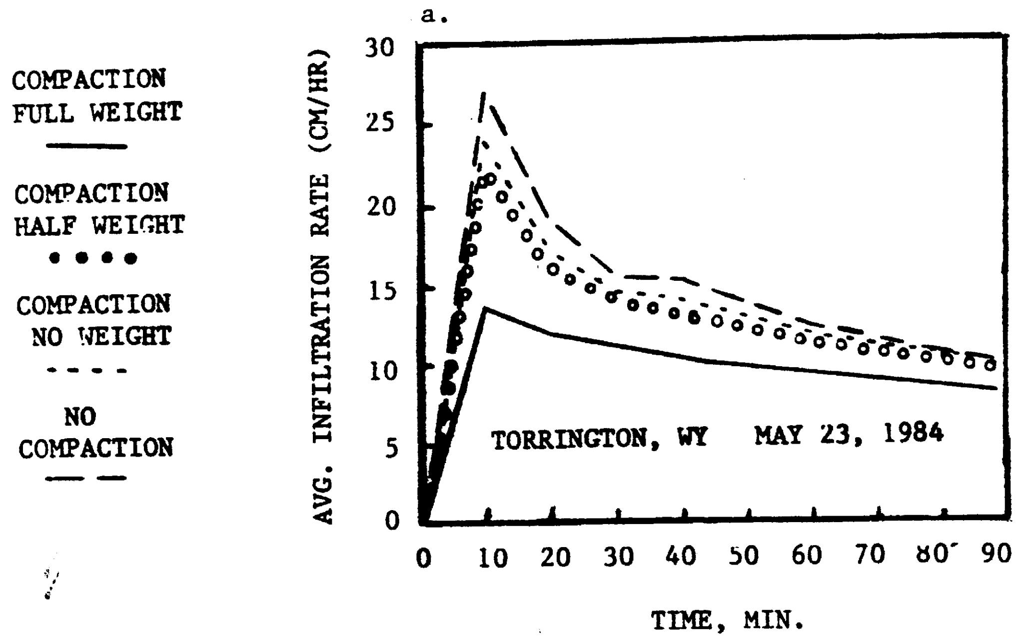
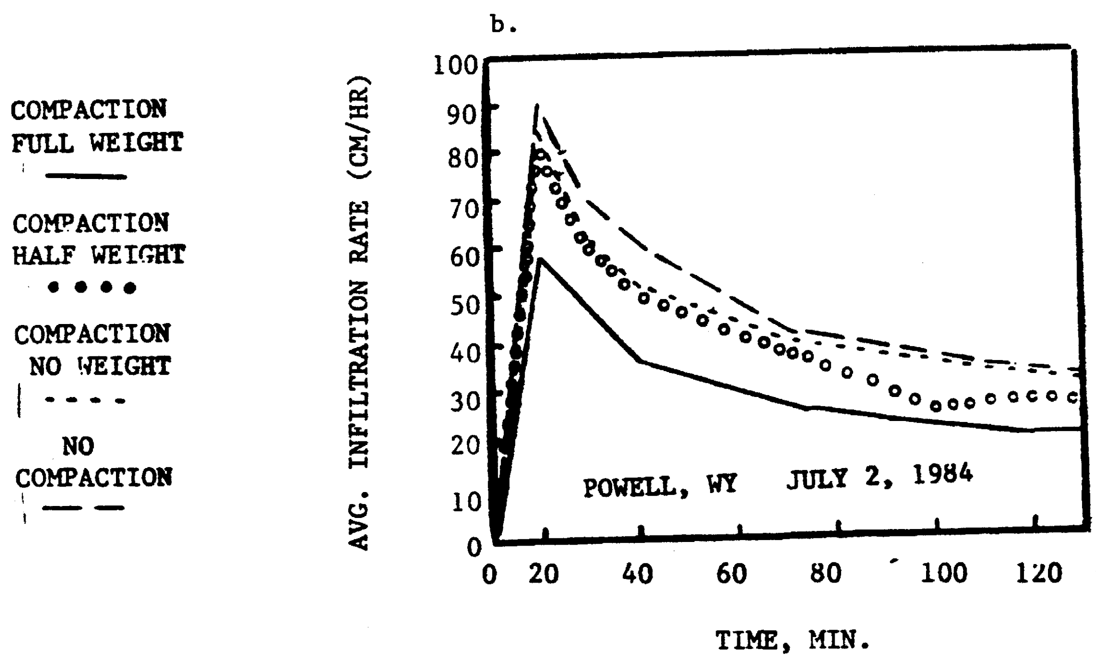


Figure 13. Comparison of penetration resistance of wheel and soft rows, using hand held penetrometer and ASAE standard cone.





Figures 14 a and b.

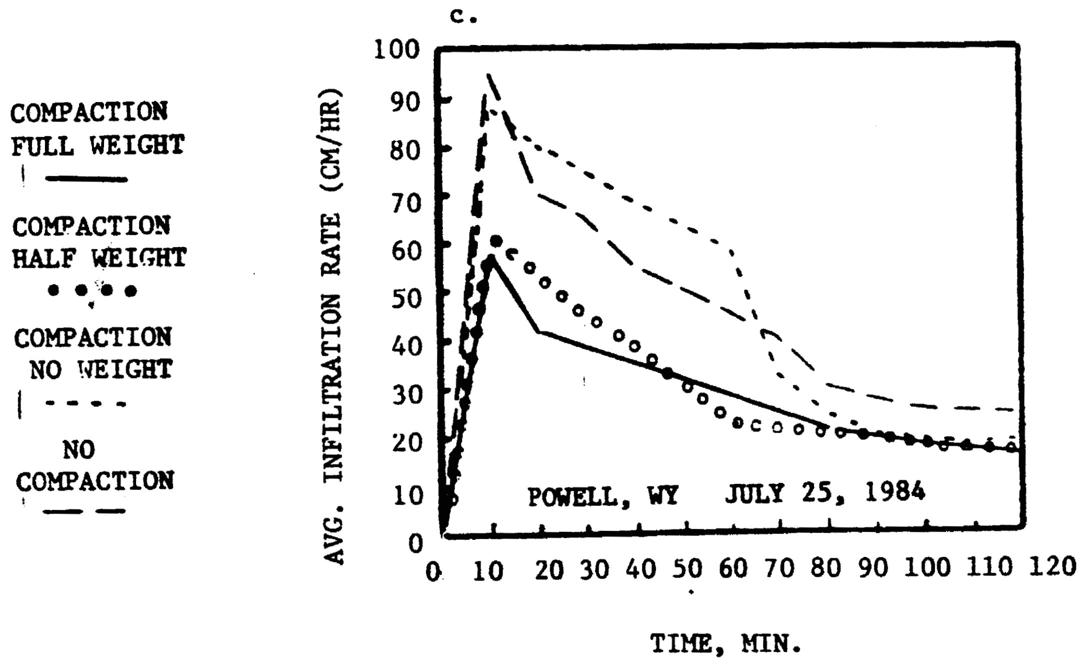
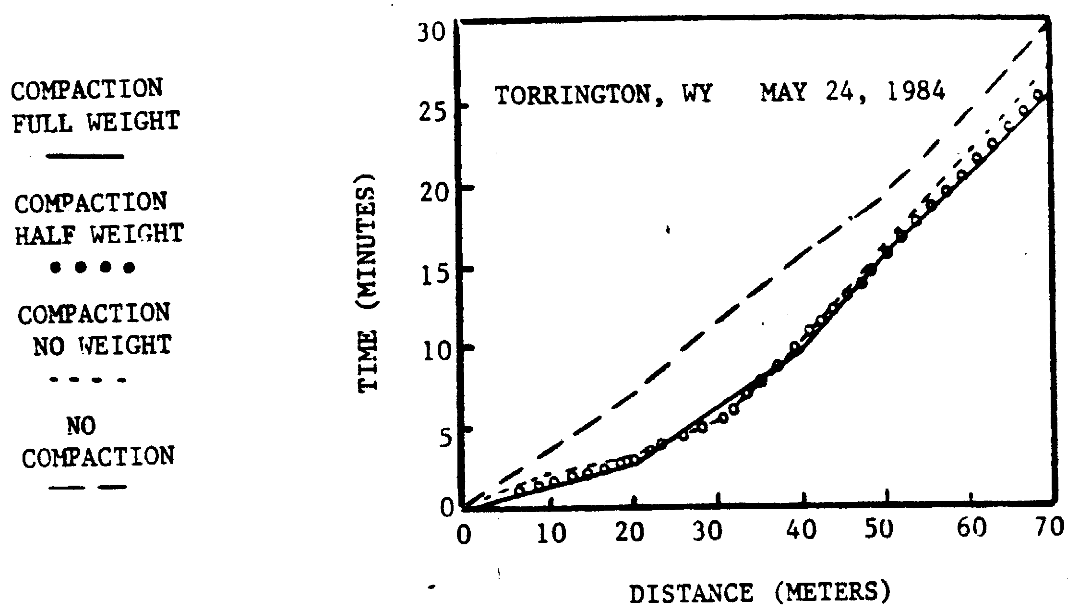


Figure 14c. Blocked furrow infiltration test data.

a.



b.

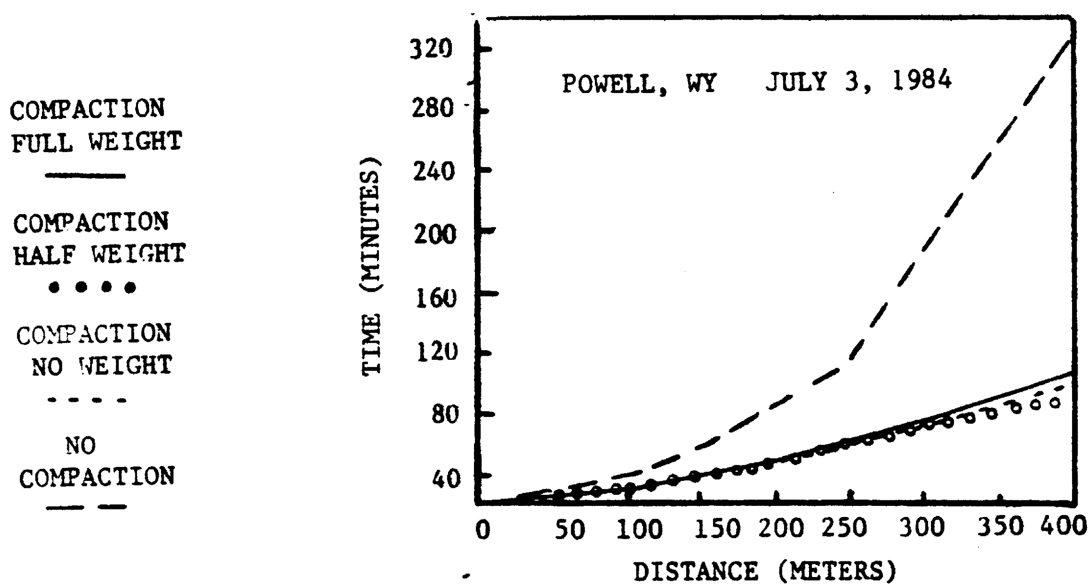


Figure 15 a and b.

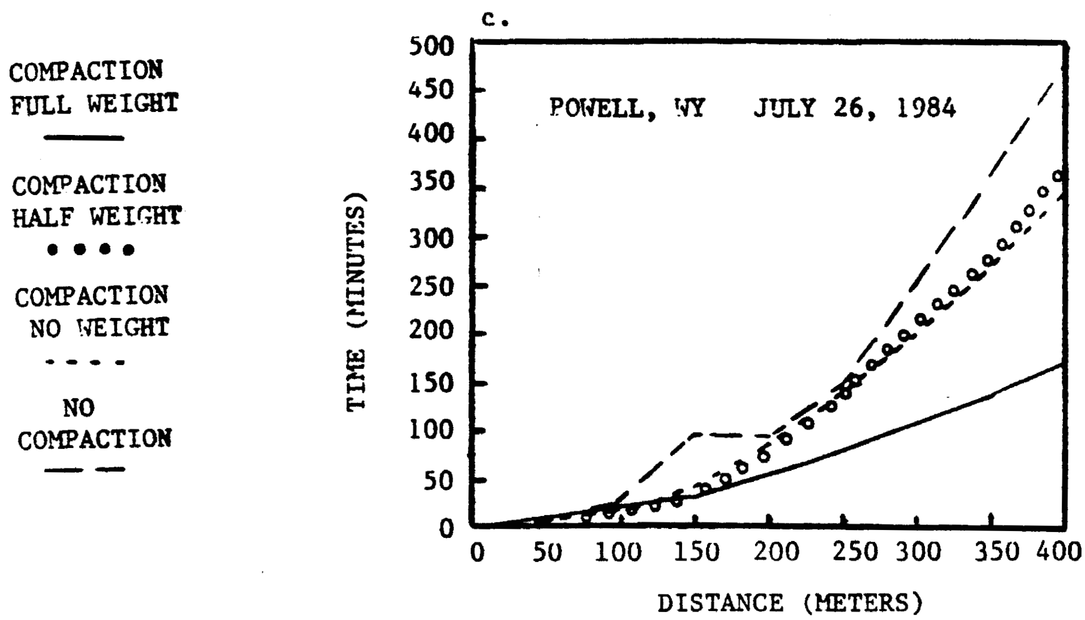


Figure 15 c. Furrow advance, Torrington.

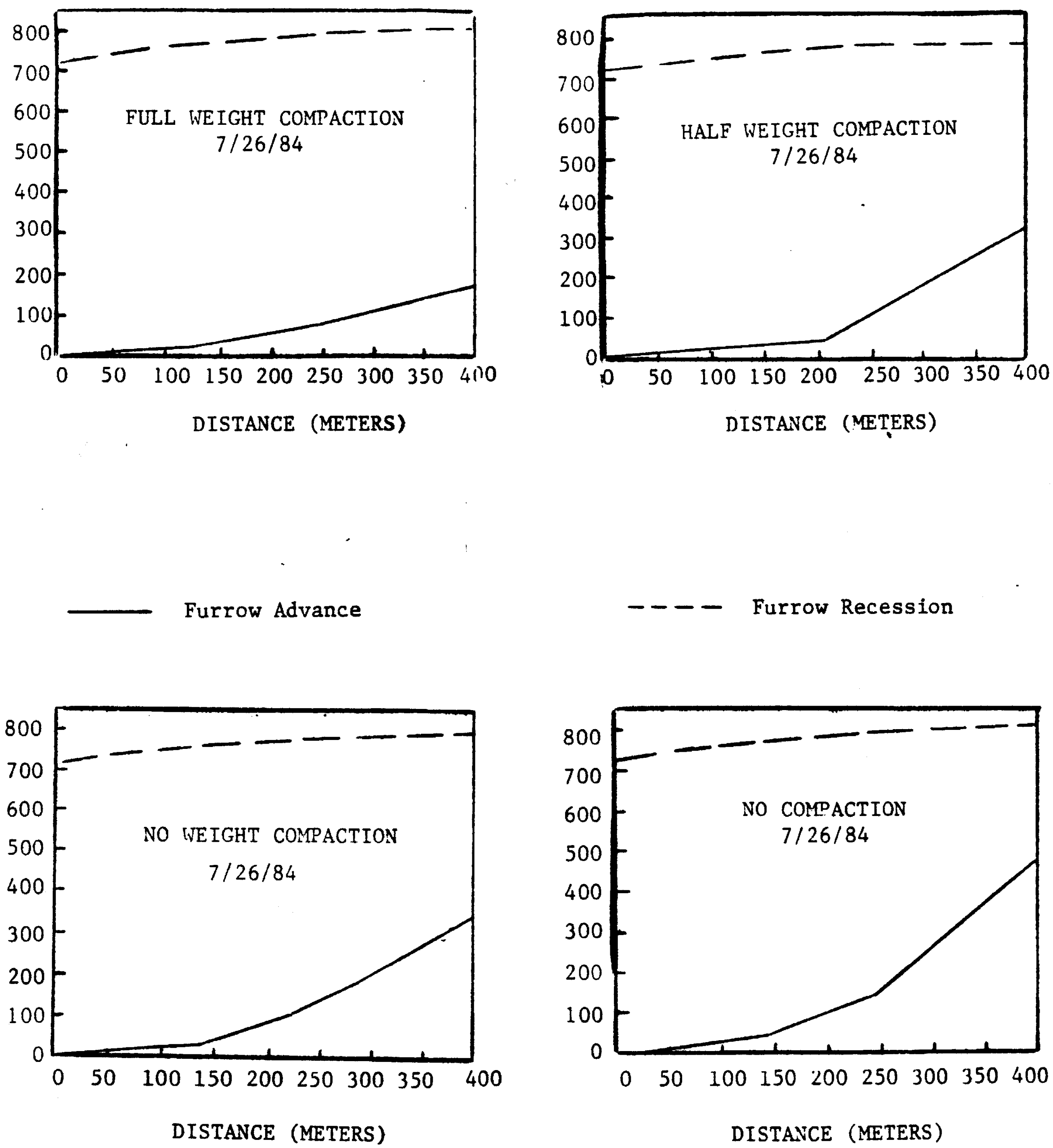


Figure 16. Furrow Advance and Recession, Powell, July 25.

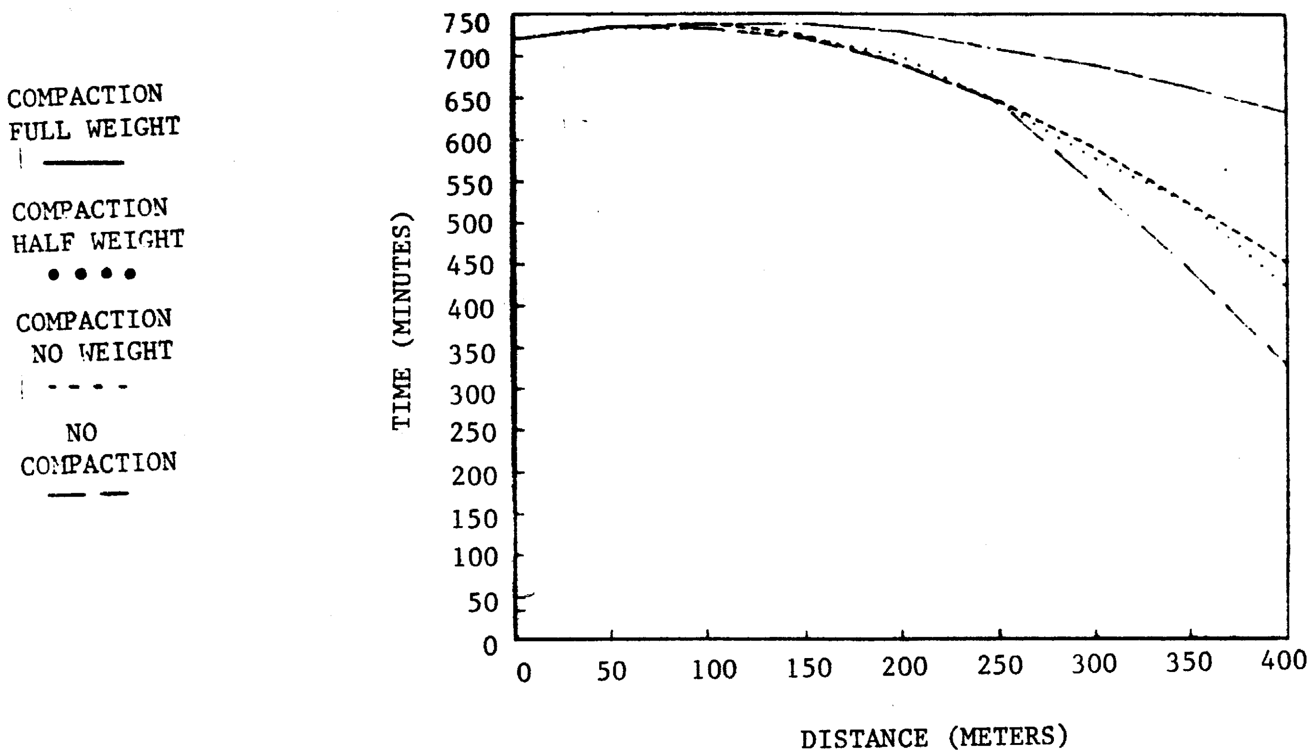


Figure 17. Intake Opportunity Times, Powell, July 25.