

GRADE CONTROL CAPABILITY OF A PULL BEHIND DRAINAGE PLOW

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ABSTRACT

In September 2001 at the Don Scott Air Field, Columbus, Ohio, forty-four experimental mock subsurface drainage installations were executed using a Liebrecht drainage plow, laser transmitters, GeoStar GPS system, and a John Deere 9400 tractor. The focus of the study was to evaluate the grade control capability of the Liebrecht pull-behind drainage plow under experimental conditions and to develop a testing method for similar drainage plows. The GeoStar GPS system was used to estimate the tubing boot outlet elevation during long field runs that were structured to test for speed, depth of operation, grade change and crossing an extreme land slope change. The data were analyzed to determine if the average standard deviation of the plow's tubing boot outlet elevation met the installation criteria set forth by ASTM 449-02 and other past standards, although there were several individual deviations that exceeded these standards. Through the complex interaction of speed, depth, grade changes and direction of slope, the drainage plow's grade control capability was influenced but no direct link could be made to any one factor.

Keywords. Agricultural Subsurface Drainage, Drainage Installation, Drainage Plow, Laser Grade Control

INTRODUCTION

The mechanization of agricultural drainage installation began over 100 years ago with the advent of wheel-type trenching machines. Due to convention in the early days of installing clay or cement tile, it became widely accepted that a trench needed to be dug for installation. Although after corrugated plastic tubing came into the market place, the modern method of using a trenchless drainage plow was introduced in the 1970's (Broughton and Fouss 1999). These original "floating beam" plows were developed to be used on track-type machines that were able to develop the high draft forces required during tubing installation (Fouss 1968). The large tracked machines developed into several different designs and became popular for their speed of installation. Recently, smaller drainage plows that are similar to other pull-behind farm implements have been manufactured and marketed for use with farm tractors.

These smaller drainage plows that can be operated by a power source that farmers currently own, offer several advantages. Knueven (2002) listed several reasons as follows: control of installation timing, smaller job applications, cost savings, and farmer's perceived knowledge of drainage systems. Pull-behind drainage plows offer the owner/operator the ability to install tubing on their chosen time frame and field rotation. Contractors who have traditionally installed tubing can sometimes have a backlog of jobs waiting to be done. It can also be difficult to get a contractor to come out for a smaller job because of transportation costs, which are less critical for the pull-behind drainage plow. Pull-behind drainage plows are also relatively low-cost compared to large commercial drainage plows, so the farmer can make use of their own labor and existing machinery to recover the additional equipment costs for installing their own drainage system. Finally, most often farmers may feel that they already have a fairly good working knowledge of drainage from past experience; so, by using other educational sources, they can develop the remaining skills required for installing a drainage system.

Pull-behind drainage plows may also be applicable for medium-sized producers, for tractors as small as 110 kilowatts are being used to install drainage pipe. Plows range in price from \$2,800 to \$13,000 for basic plows to \$15,000 to \$30,000 for models with a complete laser grade control

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setup. Although the price of the laser grade control may be half the investment, it is still recommended for installing a functional drainage system because of the ground speed of the plow and the operator's limited manual response time (Fouss, 1968; Fouss et al., 1972; Knueven, 2001).

Although there are many perceived producer benefits of the small drainage plows, they have also drawn concern from land improvement contractors and some drainage experts starting in the late 1990's. These concerns were directed to the USDA-Agricultural Research Service (ARS), Soil Drainage Research Unit (Columbus, OH) and The Ohio State University for unbiased answers about these plow's grade control ability. Some of the areas in question are summarized by Knueven (2002) as follows: grade control ability, air filled rubber tires, speed of operation, design of plow, trench safety, hydraulic power, tilting of plow shank, tubing stretch, proper tubing supporting groove, hidden costs such as additional equipment, design and layout, and installation experience.

Currently there is only a very limited amount of research on pull-behind drainage plows that stemmed from the concerns of the drainage industry. Knueven (2002) in September of 2001 at the Ohio State University's Don Scott Air Field, tested a Liebrecht drainage plow under experimental conditions. To monitor the apparent tubing depth, Knueven used the GeoStar System manufactured by Spectra Precision, in Dayton, Ohio (parent company is Trimble Navigation Limited). The GeoStar system is composed of an analog mast with a shuttle that moves electronically up and down to engage a laser plane projected over the field, thereby tracking the elevation in the z-direction. The system then uses correction signals from the U.S. Coast Guard to achieve x-y plane positioning. The system's z-direction accuracy is +/- 0.46 cm depending on weather and laser transmitter setup.

With the analog mast being mounted directly above the tubing boot outlet, the GeoStar system was then able to monitor the apparent boot outlet elevation. Also, when mounted on a separate vehicle, the GeoStar System was used to record the ground elevation so that the ground surface and tubing boot outlet could be compared for a relative depth. At the test site, three different experimental conditions were tested: extreme land surface changes perpendicular, extreme land surface changes angled, and long-field runs with two grade breaks. For the long-field runs' experimental condition, each run was structured so that the factors of speed, depth, direction of slope and grade changes could be analyzed.

In the analysis, the grade was subtracted out of the data for each segment of each run of the extreme land surface changes perpendicular and the long-field runs, and normalized about 1.0, so that deviations were about the normalized value. From these data the average standard deviation and mean were determined. For each prescribed condition, the average standard deviation could then be compared for differences in speed, depth, direction of slope, and grade changes. Student's t-tests were used to determine statistical differences. The deviations were also evaluated against several criteria from ASTM and ASAE subsurface drainage standards by looking for deviations that exceeded these standards. Because of the error introduced to the GeoStar receiver by the tipping of the drainage plow, the extreme land surface changes angled results were not analyzed. The complete results of the analysis and experimental conditions explanation can be found in (Knueven, 2002).

The focus of the work presented in this paper included additional analyses of the data collected under experimental conditions, and investigating different ways to quantify the deviations from grade in the experimental runs. The following analysis ensued to further synthesize the data collected for the long-field runs of September 2001. Although the methods of deviation detection are different, the steps to analysis the deviations are generally the same.

METHODS: QUANTIFYING DEVIATIONS IN DON SCOTT FIELD DATA

Four different detection methods were developed and used to identify deviations caused by negative grade, operator override, rocks hit, and grade change deviations. The first two methods below are a very intensive study of the data aimed at "smoothing out" the deviations. The third method then uses an overall design grade in determining the deviations of the points identified by the first two methods. The fourth method uses linear regression lines fitted to each continuous segment. All four methods are relevant to the current analysis since they quantify the deviations in a slightly different way than the original analysis by Knueven (2002).

The first approach involved methodically going through the data starting at the lowest elevation

of each run and working up slope, picking out the points that would cause a negative grade, such as the points at 32.3 and 41.5 m in Figure 1. Once these points were identified, the next point further upgrade that would yield a flat grade or greater was identified, such as the points 41.5 and 44.2 m (Figure 1). The lowest point in-between these endpoints then would be located and used to identify the segment, such as the points at 39.6 and 42.4 m (Figure 1). A grade line was then established between the end points shown as Method II below. The deviation between this grade line and the low point was then determined and recorded. Overall this method was more of a smoothing approach for the data to remove the negative grade since the grade line slope varied from segment to segment. This method broke the data into small sections for each individual deviation.

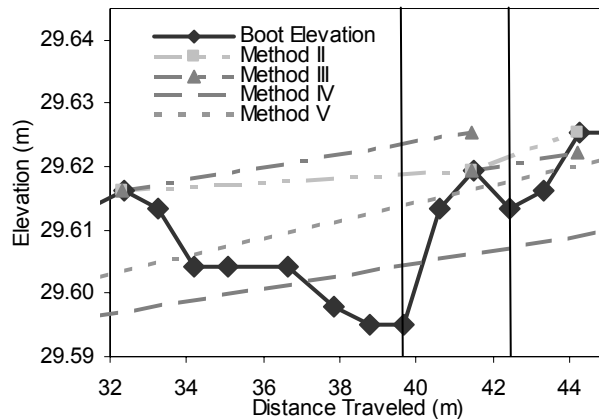


Figure 1: Portion of long-field run 2 (32-45 m) at 2.4 km/h.

Method III then used the same points found by the first step in Method II that would cause a negative grade, i.e., points at 32.3 and 41.5 m. But instead of selecting a point further upgrade to establish a grade line, the design grade was used to create a grade line. These design grade lines would start from the points selected in step one and run past the point which would create the largest deviations shown in Figure 1 as Method III, where the design grade was 0.1%. The deviation was then determined between the Method III grade line and the largest deviating point and recorded. Method III was used to avoid the variability in grade that Method II experienced when following the Method II grade line.

Method IV used an overall grade line for each continuous segment starting at the low elevation end of each segment. These grade lines were laid out shown as Method IV in Figure 2. The deviations between the overall design grade and the low points used for Methods II and III were then determined and recorded. Method IV introduced more variability in deviations since the low points sometimes would fall above and below the grade line (Figure 1) at points 39.6 and 42.4 m. The third approach shows the deviations from the ideal installation depth of a perfect grade line. For all four methods, a negative deviation value indicated that the low point deviation was above the grade line and positive values indicated that the deviation was below the grade line.

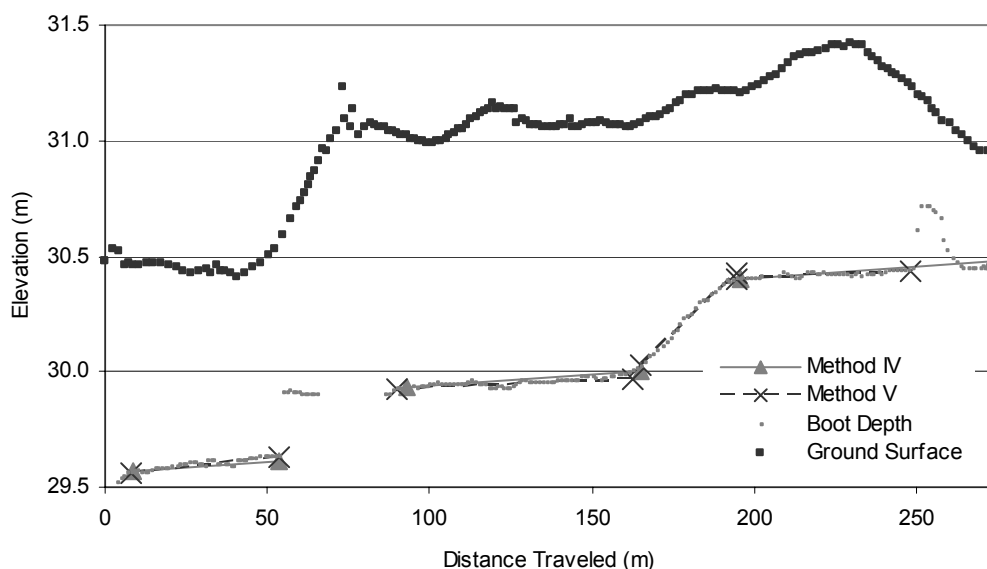


Figure 2: Long-field run 2 (0-274 m) at 2.4 km/h.

The fourth method used to determine deviations used linear regression lines fitted to the long, uninterrupted segments of each run. Figure 2 shows how long-field run 2 was broken into four individual segments of 8 to 53 m, 90 to 162 m, 165 to 194 m and 194 to 248 m. To determine the

deviations, the boot elevation was subtracted from the regression line at each boot elevation point and then recorded as Method V. The lines fitted by Method V varied in slope from segment to segment and from the design grade slope. An example can be seen in Figure 1 by comparing the Method IV grade line to that of Method V. One limitation to Method V is that deviations in the area of grade changes, and changing of mast height, are not quantified since the regression lines were not projected through these areas of transition.

RESULTS OF DEVIATION DETECTION METHODS

0.1 % Grade Deviations

Once all the long runs were analyzed for deviations, the results of the deviation detection methods were summarized in Tables 1 and 2. The average standard deviation data in Table 1 exclude deviations where rocks or other inaccuracies occurred, such as equipment or operator errors, while Table 2 includes these errors. The speed groupings of 1.3 and 1.6 km/h were pooled in both tables since there was only one replicated field condition at 1.3 km/h for the up-slope and down-slope direction. The data in both tables are presented according to depth, speed, direction and deviation detection method. The original deviation detection analysis by Knueven (2002) is shown as Method I.

Table 1: Average standard deviation values (m) of grade deviations broken down by depth, speed, direction and deviation detection method for 0.1% grade with errors due to rocks removed.

Depth (m)	Method	Up Slope			Down Slope		
		1.6 (km/h)	2.4 (km/h)	3.2 (km/h)	1.6 (km/h)	2.4 (km/h)	3.2 (km/h)
0.3-0.9	I	0.008	0.012	0.010	0.028	0.025	0.022
	II	0.006	0.012	0.010	0.018	0.016	0.024
	III	0.007	0.013	0.011	0.016	0.013	0.017
	IV	0.010	0.018	0.014	0.016	0.011	0.019
	V	0.007	0.008	0.009	0.015	0.008	0.009
0.9-1.5	I	0.029	0.024	0.029	0.009	0.013	0.022
	II	0.017	0.012	0.013	0.018	0.015	0.013
	III	0.013	0.012	0.013	0.016	0.015	0.018
	IV	0.018	0.013	0.019	0.017	0.015	0.016
	V	0.008	0.010	0.011	0.009	0.009	0.010

Table 2: Average standard deviation values (m) of grade deviations broken down by depth, speed, direction and deviation detection method for 0.1% grade without removing errors due to rocks.

Depth (m)	Method	Up Slope			Down Slope		
		1.6 (km/h)	2.4 (km/h)	3.2 (km/h)	1.6 (km/h)	2.4 (km/h)	3.2 (km/h)
0.3-0.9	I	0.008	0.049	0.009	0.023	0.024	0.023
	II	0.031	0.063	0.010	0.030	0.016	0.022
	III	0.032	0.062	0.011	0.029	0.014	0.016
	IV	0.031	0.059	0.014	0.030	0.015	0.018
	V	0.007	0.008	0.009	0.017	0.009	0.009
0.9-1.5	I	0.029	0.023	0.029	0.008	0.012	0.021
	II	0.018	0.012	0.026	0.011	0.016	0.011
	III	0.014	0.012	0.027	0.010	0.017	0.015
	IV	0.017	0.014	0.020	0.013	0.017	0.081
	V	0.009	0.010	0.010	0.008	0.010	0.011

Generally, the standard deviation increased from the up-slope direction to the down-slope direction, for both depth ranges, for detection Methods II and III. For Method I the same pattern holds for the shallow depth, but is reversed for the deeper depth range. While for Methods IV and V there seems to be no difference because of direction. The larger average standard deviations for the down-slope direction could be attributed to the fact that the runs made down-slope were conducted on the east side of the field where there could have been more rocks that were not detected and documented. Also, Methods II and III are more of microanalysis approach, while Methods IV and V are a macro-analysis approach.

The average standard deviations generally fell within the range of 0.008 to 0.019 m for the data without rocks errors with some exceptions. Three were lower than 0.008 m and came from the 1.6 km/h speed run. One exceeded 0.019 m and came from the 3.2 km/h speed run, Method II detection, and seven came from Method I detection. The one average standard deviation from Method II at 3.2 km/h that exceeds the above range had only a small number of deviations, and therefore the average standard deviation was heavily affected by a few large values. The seven Method I deviations exceeding 0.019 m can be attributed more to the method of detection.

These average standard deviations generally fall within the standard of 0.0305 m maximum

deviation set by ASTM 449-02. On average, the pull-behind plow seemed to perform within the standards. Also note the number of average standard deviations that increased when the rock errors were included in which some of these increases exceeded the current ASTM standard. These large increases in average deviation indicate that whenever an operator detects a rock, they need to document these spots and return to them to check for excessive deviations and make repairs.

1.3 % Grade Deviations

For the 1.3% grade segments of each long run, detection Methods II, III, and IV yielded only four deviations each, so there were not enough data points to properly evaluate these methods. Methods I and V were however able to detect the deviations presented in Table 3. Following the same format as Table 1 for the lower two speed-ranges. The steeper grade was not analyzed for depth of operation, and the data summary with the rocks are not included since there were only minor differences between the data sets.

Table 3: Average standard deviation (m) of grade deviations for the 1.3% grade with errors due to rocks removed.

Method	Up Slope			Down Slope		
	1.6 (km/h)	2.4 (km/h)	3.2 (km/h)	1.6 (km/h)	2.4 (km/h)	3.2 (km/h)
I	0.009	0.012	0.015	0.008	0.007	0.012
V	0.008	0.012	0.014	0.008	0.006	0.009

The average standard deviations for 1.3% grade easily fall into or below the range of 0.008 to 0.019 m from the data on the 0.1% grade runs. The maximum average standard deviation for the 1.3% grade data is below the value of 0.029 m from the 0.1% grade with the rock errors removed.

Comparison of Slopes

From the best-fit linear lines used for detection Method V, the slopes of these lines for each segment can be compared to the design grades of 0.1% and 1.3%. Although, out of 73 segments over 17 experimental runs, only 5.5% actually matched the design grades. A summary of these slopes can be found in Table 4. The mean values of the regression slopes for both directions at 0.1% grade are below the design grade, and the 1.3% mean grade values are above and below the actual design grade. The steeper grade also has a larger variation in slope than the flatter grade, which is opposite the pattern seen in deviations from grade. In some occurrences, the best-fit line was even opposite in sign than the actual design grade. In summary, the actual grade of each segment matched the design grade only a small percentage of the time and the steeper grades tended to vary more in slope from run to run.

Table 4: Mean, standard deviation, minimum and maximum values of slopes from the linear regression lines used in Method V deviation detection.

Value	Up Slope		Down Slope	
	0.10 %	1.30 %	0.10 %	1.30%
mean	0.08	1.33	0.08	1.28
s.d.	0.03	0.07	0.02	0.07
min.	0.01	1.23	-0.02	1.15
max.	0.16	1.44	0.15	1.36

Distance Traveled to Re-Establish Grade

The distance traveled to re-establish a minimum of a flat grade or greater was also found from the Method II detection process. This distance is the length between the two endpoints used to determine the grade line. The collective results are in Table 5. The same conditions as Table 1 apply.

Table 5: Average standard deviation and mean distance traveled (m) during a grade deviation by Method II detection with errors due to rocks removed.

Value	Depth (m)	Up Slope			Down Slope		
		1.6 (km/h)	2.4 (km/h)	3.2 (km/h)	1.6 (km/h)	2.4 (km/h)	3.2 (km/h)
s.d.	0.3-0.9	3.7	7.4	4.5	5.5	2.9	5.6
	0.9-1.5	8.5	7.2	5.6	4.4	5.5	14.3
mean (m)	0.3-0.9	4.6	7.6	5.9	6.0	4.7	7.8
	0.9-1.5	7.2	8.1	6.7	5.7	5.0	12.5

The average standard deviations for distance generally fell within the range of 3.0 to 7.6 m with one exception, the down-slope direction at the deeper depth range traveling at 3.2 km/h. The reason for this outlier is that three of the eleven occurrences to match these conditions had values

larger than 30 m, which substantially shifted the standard deviation. It is interesting to note that even though the standard deviation may be 14.3 m, the true problem at a specific location could be more or less extensive than it actually appears to be. For the deeper depths, the standard deviation of distance yielded greater values than for the shallower depths, and the distance traveled had a range in length of 1.8 to 39.6 m. This large variation from one situation to the next may make it very difficult in determining how much repair due to rocks, grade breaks or other known obstacles may be required in a system after installation, especially at deeper depths

Deviations Exceeding Set Criteria

Once the deviations by the above detection methods had been identified, they were then evaluated on the number of occurrences that exceeded four different set criteria, as follows:

- Deviations greater than 3.05 cm;
- Deviations great than 3.05 cm in a distance of 3.05 m;
- Deviations greater than 3.81 cm; and
- Deviations greater than 5.09 cm.

The first criterion comes from an older ASAE EP 463 specification adopted in February of 1985, where the maximum allowable deviation is 3.05 cm. The second criterion comes from the current ASTM standard 449-02, where the maximum allowable deviation is 3.05 cm in 3.05 m. The final two criteria are derived from the past ASTM standard 449-97 where the maximum allowable deviation is one-half the pipe diameter. For a 7.62 cm pipe, one-half the inside diameter is 3.81 cm, and for a 10.16 cm pipe, 5.09 cm.

A summary of the number of occurrences where deviations exceeded the above criteria are presented in Table 6. Evaluating the data against criteria 1, three and four was straightforward. However, for the criterion of greater than 3.05 cm in 3.05 m, a more complex approach was taken as following:

$$D_{3.05} \equiv 3.05D/L \quad (1)$$

where:

$D_{3.05}$ = unit length deviation;

D = specific deviation being examined (m); and

L = length over which the deviation occurred (m).

Equation (1) was used to convert each deviation to a unit length deviation where it could then be evaluated if it exceeded 3.05 centimeters or not.

Table 6: Number of occurrences exceeding the set criteria by method, direction and data set.

Data Set	Direction	Criteria (cm) and Method															
		>3.05 cm				>3.05cm in 3.05 m				>3.81 cm				>5.09 cm			
		II	II I	I V	V	II	II I	I V	V	II	II I	I V	V	I	II I	I V	V
Overall	Up Slope	2	2	3	5	1	1	1	5	1	1	2	3	8	7	7	1
	Down Slope	9	8	9		8	3	2		6	8	2					
Overall w/out Rocks	Up Slope	2	2	3	4	1	1	1	4	1	1	1	2	4	3	5	0
	Down Slope	3	0	3		5	0	1		1	3	8					
Negative Grade	Up Slope	1	1	1	1	5	4	1	1	7	9	8	1	3	1	2	0
	Down Slope	3	1	3				2									
Rocks	Up Slope	7	1	2	4	1	1	6	4	2	7	8	2	0	0	0	0
	Down Slope	7	7	8	1	1	1	9	1	2	6	4	1	0	1	2	0
Changing of Mast Position	Up Slope	5	7	5	1	3	3	1	1	4	4	3	1	3	3	1	1
	Down Slope	7	6	8	8	2	2	3	7	5	5	6	6	3	4	4	5
Grade Change	Up Slope	1	7	6	-	1	9	5	-	9	5	6	-	4	3	4	-
	Down Slope	4				3											
Grade Change	Up Slope	5	3	4	-	4	3	3	-	5	3	4	-	3	0	0	-
	Down Slope	2	1	4	-	1	0	0	-	0	1	3	-	0	0	1	-
Grade Change	Up Slope	1	1	1	-	0	0	0	-	0	0	0	-	0	0	0	-
	Down Slope																

From the data in Table 6, three general trends can be noted. The first is obvious, that as the restricting criteria increases in magnitude, the number of occurrences decreases. One exception to this is for the greater than 3.05 cm in 3.05 m criterion. For all four detection methods, this criterion tended to have a lower number of occurrences than the >3.81 cm criterion. This exception could be attributed to the uniqueness of this criterion when compared to the other criteria. The second trend is that the data from the down-slope direction tended to have fewer occurrences than the up-slope direction. The final trend is that Method V had fewer occurrences exceeding the criterion than the other methods, which is to be expected since Method V is a linear regression line fitted to the data. Also note that under Method V, for the last two data sets there are no values because it was not used to analyze the areas of transition in elevation and grade change.

Even though the standard deviations fell within the range of 0.008 to 0.019 m, the large number of deviations exceeding the criteria counteracts the overall performance of the plow, since any deviation exceeding the set criteria would be detrimental to the performance a subsurface drainage system. Also note the number of occurrences for lowering and raising the laser receiver mast, as these values reflect the need for careful planning and using proper grade break equipment so that the number of situations of having to vary the mast position manually can be eliminated.

CONCLUSIONS

In re-analyzing the data collected by Knueven (2002) for the long-field runs at Don Scott Field in September 2001, four additional methods were used to determine deviations from grade. From these four methods, an average standard deviation range of 0.008 to 0.019 m was determined, and this overall average deviation range is well within the most stringent maximum allowable deviation of 3.05 cm. Although the overall average standard deviation may have been acceptable, there were numerous occurrences where the plow deviated even greater than the most flexible past standard of 5.09 cm. The steeper grades also tended to have smaller and fewer deviations than the flatter grades while varying more in the overall grade. It was also found that the distance traveled to re-establish a flat grade or greater during a deviation varied greatly from one occurrence to the next.

The manual changing of the laser mast position yielded a large number of occurrences that exceeded the installation standards. The magnitude of the deviations during these instances may be questionable though because of possible tipping error in the data collection system, since it was rigidly mounted to the plow shank which pitches forward and backwards during elevation changes. Quantifying this tipping error needs to be addressed in future experiments. Also in this experiment only one machine's performance was analyzed although there are a number of different pull-behind plows on the market. In future experiments, it is recommended to analysis as many different drainage plows as possible along with at least one commercial type unit.

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