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Derivation of Cost-minimizing Depth for Lateral Pipe Drains

J.H. BOUMANS and L.K. SMEDEMA

Euroconsult, P.O. Box 441, 6800 AK Arnhem (The Netherlands)

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ABSTRACT

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Cost-minimizing depths for lateral pipe drains installed in a trench are derived by balancing the installation costs again the required drain length per unit area, following from the Hooghoudt drain spacing equation, applied with a given drainage criterion. The results presented are based on project data and take into account current drainage machinery and materials technology. It was found that the drain depth at which costs would be minimized depends mainly on the desired depth to the water table and on the depth of the impermeable base in the soil profile. For a number of reasons, the drain depth selected in practice will often be deeper than that which minimizes cost.

INTRODUCTION

To design a groundwater drainage system with the aid of a drainage formula like that of Hooghoudt (1940), a drainage criterion has to be chosen, i.e. a selection of the required depth to the water-table and a recharge to achieve efficient drainage (see Fig. 1). Generally a wider drain spacing can be applied when the drains are installed at a greater depth below the soil surface. Since deeper installation will generally increase the unit construction costs of the drainage system, while a wider spacing has the opposite effect, a depth exists at which the construction costs per unit area attain a minimum.

The balancing of drain depth against drain spacing has been investigated by Christopher and Winger (1975) on the basis of USBR bid contracts, but only a limited analysis was made of the influencing factors. The papers by Bhattacharya and Broughton (1978) and by Acharya and Holsambre (1982) on this subject mostly deal with the mathematics of the cost minimization involved. Optimal drain design, including optimal drain depth, has also been discussed by Wiser et al. (1973) and by Dunford et al. (1984), but in these papers too

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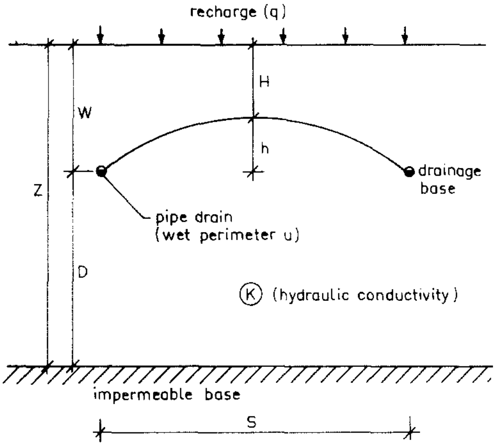

Fig. 1. Outline of the main parameters of a groundwater drainage system.

the emphasis is on optimization methodology rather than on analysis based on actual project conditions and data. Furthermore, the optimization methodology outlined in these two papers also involves the farm benefits derived from drainage.

The scope of the present paper is more restricted: it assumes that the given drainage criterion reflects the desired water-table, and addresses the remaining objective of designing the best parallel pipe system to achieve this control. The drain depth entailing minimum investment cost is obviously an important factor in this respect, although, as will be seen later, the selected depth may be different because a number of other factors also play a role in the selection.

In this paper, drainage costs refer to the installation costs of the underground pipe system only. Cost of the main system and operational costs, which also become higher with deeper drainage, are not included.

COST-DEPTH FUNCTIONS

The cost of construction of lateral drains in an equidistant, parallel pipe drainage system depends on:

(1) the costs per unit length (C_L);

(2) the length of lateral drain per unit area.

Because for this type of system the lateral length per unit area varies inversely with the spacing (S), the construction cost per unit area (C_A) may be expressed as:

$$C_A = C_L/S \qquad (1)$$

The costs per unit length consist of installation costs and material costs. Although both of these components almost always increase with greater drain

TABLE 1

Development of pipe-laying machines

Year of introduction	Type and model	Power (kW)	Max. depth (m)	Max. width (m)	Weight (t)
1955	Tyred wheel trencher	42	1.75	0.22	8
1959	Crawler trencher	90	1.80	0.22	9
1964	Semi-tracked crawler trencher	115	2.00	0.25	10
1966	Crawler trencher ESL175	120	1.75	0.30	14
1967	Crawler trencher ESL210	120	2.10	0.35	14
1972	Crawler trencher GSL250	150	2.70	0.50	19
1979	Crawler trencher BSS320	250	3.20	0.50	30
1982	Crawler trencher GSS325	230	3.25	0.40	25
1983	Crawler trencher BSS360	250	3.60	0.65	35
1983	Crawler trencher BSS400 Super	300	4.00	0.90	45
1974	Trenchless drain plough	150	1.20		
1982	Trenchless delta drain plough	210	2.20		

Data refer to Hollanddrain® machines, courtesy Steenbergen Drainage Machines, Utrecht, The Netherlands.
t, (metric) tonne = 1000 kg.

depth, actual cost–depth relationships vary widely depending on the applied installation methods and the materials used for pipes and envelopes, both of which are subject to rapid technological development. This may be illustrated by the improvement in the capabilities of pipe-laying machinery, which can nowadays install drain pipes at depths down to 4.0 m (see Table 1). Costs, however, have also increased sharply, the purchase cost of a trencher for 3–4 m depth being easily three or four times as much as that of a standard machine for 1–2 m depth. Furthermore, in spite of the greater power of the machines, installation speed decreases with increasing installation depth, and so installation costs per unit length generally show a tendency to increase exponentially with depth (Kraft, 1978). This applies both to trench and trenchless installation techniques, although cost-depth functions are different for the two methods. Moreover the trenchless techniques are still only applicable to a maximum depth of 2.0–2.5 m.

The cost of pipe and envelope material is indirectly determined by the drain depth. For greater depths, wider spacings can be applied, but larger pipes are needed to transport the higher volume of water collected. The envelope costs per metre increase with the diameter of the pipes, because the amount of envelope material required increases with the size of the pipe and trench.

As regards materials for pipes and envelopes, there have also been rapid technological developments during the last 20 yeras. The replacement of clay

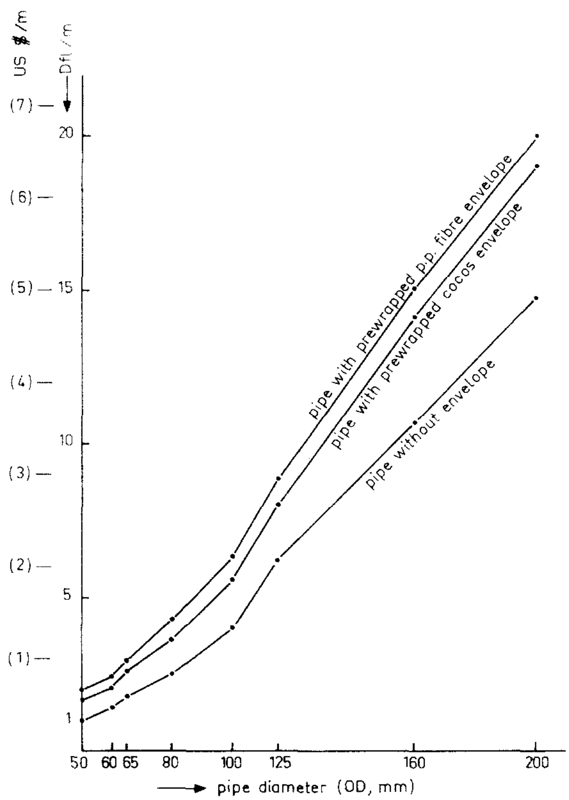

Fig. 2. Purchase costs of corrugated PVC drain pipe with and without envelopes, The Netherlands, 1985. Prices are without value added tax (VAT). Dfl.1.00 ≈ US$0.30.

and concrete pipe by plastic pipe started in the fifties. In Europe, virtually only plastic pipe is used nowadays, and also in less developed counties such as Iraq, Egypt, and Pakistan, where there are large ongoing drainage programmes, plastic is rapidly taking the place of clay or concrete, and the corrugated plastic pipe has become now by far the dominant type in the world. In the use of envelope material there is more variation, although here too certain trends and development can be noticed. Some traditional organic envelope materials found to deterioriate rapidly are being replaced by synthetic materials, while, especially for the larger drain depths (> 2.0–2.5 m) used when drainage is applied for salinity control, there is a general preference for graded gravel envelopes. Shallow drains (≈ 1.0 m), installed for aeration/workability control, are often installed without envelopes when soils are stable and installation is done under dry conditions.

Purchase costs of pipe with and without envelope material for different pipe diameters in The Netherlands are shown in Fig. 2. The costs apply to the commonly used corrugated PVC type for which costs increase more or less propor-

TABLE 2

Compilation of pipe drainage costs from different projects

Country	Drain depth (m)	Pipe diameter (mm)	Cost (US$/m)
The Netherlands	1.20	60	1.25
Egypt	1.40	80	1.50
Iraq	2.20	65	4.00
Iraq	2.20	100	4.50
Iraq	3.00	200	8.50
Dominican Rep.	2.50	200	6.80
China	1.60	80	1.70
United States	1.80	100	3.00
Peru	1.80	100	2.20
Pakistan	1.80	100	4.00

All prices converted to 1985 price levels.

tionally with the amount of base material used per unit pipe length. The envelope costs increase more or less proportionally with the pipe diameter. Together, these factors make up a cost function in which the proportion of the price of pipe and envelope remains fairly constant.

OBSERVED COSTS

The construction costs per unit length, being the sum of the installation and material costs, may be expected to reflect the trends in these component costs. Reliable and comparable construction costs are, however, difficult to obtain for a number of reasons. Data from different projects vary greatly due to difference in local availability of machinery and materials, scale of the project, efficiency and costs of labour, competition between contractors, and so on. This explains the cost differences found for the standard 1.0 m depth pipe drainage in the temperate humid climate. In The Netherlands such a system costs ca. Dfl3.50/m, but this may easily be double or triple in countries with a less competitive, less organized drainage business. Cost differences become even larger for greater drain depths, as contractors may have to make allowances in their prices for their lack of experience with this type of work. This lack of experience may lie with the design/supervising engineer as well as with the contractor. These effects can all be traced in the costs of some pipe drainage projects with which the authors have recently been associated (Table 2). It is particularly for drain depths greater than 1.5–2.0 m that costs vary widely.

TABLE 3

Calculated drainage costs

Installation depth (m)	0.75	1.00	1.50	2.00	2.50	3.00	3.50
Minimum water-table depth (m)	0.50	0.50	0.50	1.00	1.00	1.50	1.50
k/*q* ratio	100	100	100	200	200	500	500
Required spacing *S* (m)*	20	30	45	70	80	120	140
Installation costs (Dfl/m)	0.55	0.70	2.00	3.35	6.00	9.00	14.50
Power of trench digger (kW)	75	75	100-150	100-150	190-225	190-225	> 250
Machine costs (Dfl/h)	200	200	400	750	750	750	1250
Working speed (m/h)	500	400	250	150	150	100	100
Laying costs (Dfl/m)	0.40	0.50	1.60	2.65	5.00	7.50	12.50
Backfill costs (Dfl/m)	0.15	0.20	0.40	0.70	1.00	1.50	2.00
Materials costs (Dfl/m)	1.40	2.20	3.15	5.10	5.10	7.20	7.20
Required pipe diameter (mm)*	50	65	80	100	100	125	125
Corrugated PVC prewrapped with coconut fibre (Dfl/m)	1.35	2.10	3.00	-	-	-	-
Corrugated PVC with gravel envelope (Dfl/m)	-	-	-	4.90	4.90	6.90	6.90
End pipe (Dfl/m)	0.05	0.10	0.15	0.20	0.20	0.30	0.30
Total costs (Dfl/m)	1.95	2.90	5.15	8.45	11.10	16.20	21.70
Taxes, profit, etc., 20% (Dfl/m)	0.40	0.60	1.05	1.70	2.20	3.25	4.35
Total construction costs (Dfl/m)	2.35	3.50	6.20	10.15	13.30	19.45	26.05

*Calculated by the standard method described by Smedema and Rycroft (1983) for wet entry perimeter $u = 0.5$ m, and depth to impermeable later $D = 5$ m.

CALCULATED COSTS

In view of the various inconsistencies affecting contractors' prices for the larger drain depths, costs calculated on the basis of known or estimated machine capacities, market prices of materials, and common rates of labour may present a more reliable picture of the cost-depth relationships of pipe drainage than project data. Such cost calculations have been made for aeration/workability control drainage in humid temperate climates with drain depth $W < 1.5$ m and for drainage for salinity control in arid climates for drain depths $W > 2.0$ m. Results, with details on criteria and materials, are given in Table 3. The results confirm the earlier mentioned steep increase in installation costs with increasing depth, making these costs dominant at greater depth while material costs dominate at shallower depths.

The data in Table 3 have been plotted in Fig. 3 together with the project costs given in Table 2. For drain depths < 1.5–2.0 m there is fair agreement between calculated and actual costs but for drain depth > 2.0 m actual costs are generally higher than those calculated. This could be a reflection of the general lack of experience with deep drains in the countries concerned, resulting in higher than necessary contracting rates. The calculated costs therefore must be considered to approximate the cost level when sufficient experience is available.

The calculated costs closely obey the expression:

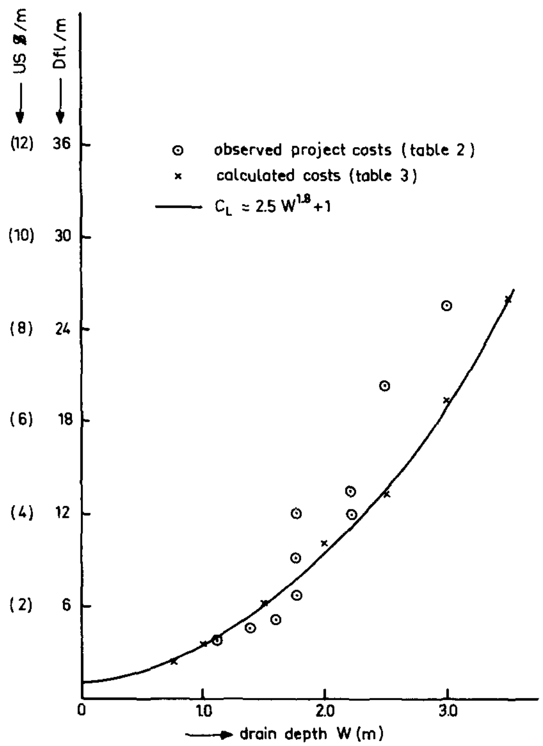

Fig. 3. Cost-depth relationship for pipe drain.

$$C_L = 2.5W^{1.8} + 1.0 \qquad (2)$$

where C_L= drain costs (Dfl/m), and W= drain depth (m).

COST-MINIMIZING DRAIN DEPTH

Combining equations (1) and (2) yields an expression for the drain costs per unit area as a function of drain depth and drain spacing:

$$C_A = (2.5W^{1.8} + 1.0)/S \times 10^4 \qquad (3)$$

where C_A=drain costs (Dfl/m), W=drain depth (m), and S=drain spacing (m).

As mentioned earlier, drain depth and drain spacing are interrelated. This interrelationship can be substituted into equation (3) to attain a relationship between the costs C_A per unit area and the drain depth W, from which the cost-minimizing drain depths W_0 can be calculated.

The relationship between W and S can be derived from Hooghoudt's drain spacing formula which is widely used in drainage design practice. For our purposes the Hooghoudt formula is written as:

$$S^2 = (K/q)(8dh + 4h^2) \qquad (4)$$

All symbols in this formula are explained in Fig. 1, except d, the 'equivalent' depth ($d < D$), which may be approximated by:

$$d = D/[(8D/\pi S)\ \ln(D/u) + 1)] \qquad (5a)$$

for $D < \frac{1}{4} S$ (5b)

$$d = \pi S/[8 \ln(S/u)]$$

for $D \geqslant \frac{1}{4} S$

By inserting h and D (see Fig. 1), equation (4) gives a relationship between S and W for given values of u, K/q, Z and H. Because S in equation (3) cannot be written as an explicit function of W, an iteration technique was used to find the drain depth W_0 where the drain cost C_A is minimal. This has been done for the following values of u, K/q, h and Z:

u = 0.5 m
K/q = 100, 200 and 500
H = 0.5, 1.0 and 1.5 m
Z = 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 10.0, 15.0, 20.0 and 25.0 m for $Z > H$

These parameters range sufficiently cover the range of conditions met in practice to establish a feasible range of W_0 values. The results are presented in Fig. 4.

DISCUSSION

Figure 4, in analysing the conditions and factors which have an influence on W_0, shows that the required water-table depth H is the main determining factor. The depth of impermeable base (Z) also has a considerable influence when this depth is <5–10 m but this influence diminishes with increasing Z. The influence of the K/q ratio is greatest for large Z values but remains a minor factor as compared to the influence of H and Z on W_0. The influence of the wet drain parameter (u) was found to be negligible and has not been further explored. The influence of Z and K/q on W_0 stems directly from the effect of these factors on the required drain spacing S while the influence H on W_0 is of a complex nature.

For given values of H and Z, the drain depth W determines how the section Z–H from water-table to barrier is divided to provide head 2h and the cross-sectional flow zones, h above the drainage base and D below the drainage base. The division of Z–H over h and D for different values of Z is shown by the deviation of the H lines in Fig. 4 from the $W = Z$ line (the H line following the $W = Z$ line indicating $D = 0$ and all of the Z–H height allocated to h). This is more explicitly shown in Fig. 5 for the cases $K/q = 100$ and $K/q = 500$ (the case

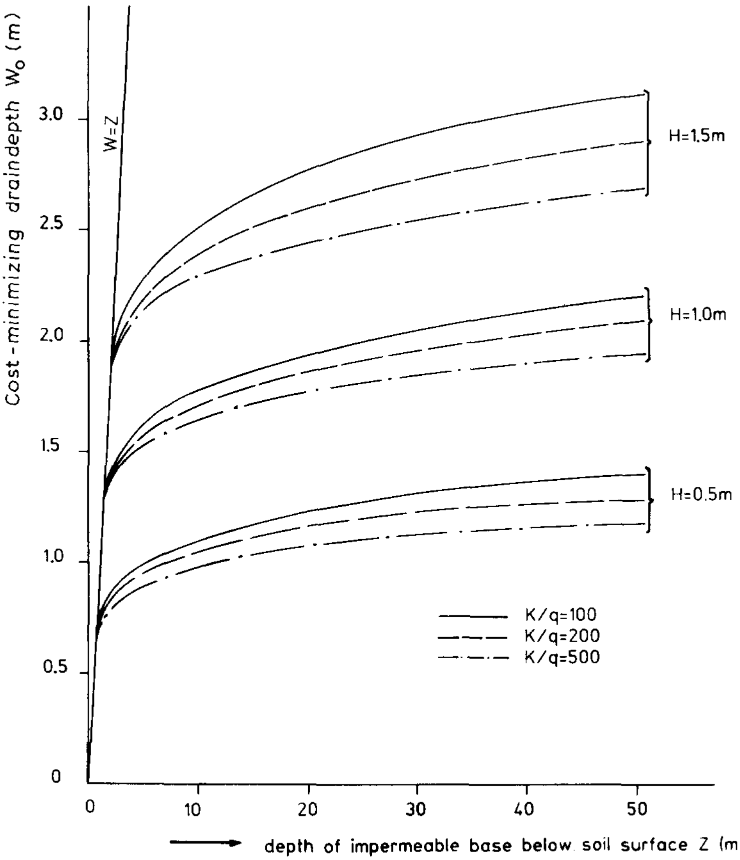

Fig. 4. Cost-minimizing drain depths for a range of conditions.

$K/q = 200$ is not shown but gives a picture intermediately between the two). The figure shows that the allocation of Z–H to the head h soon levels off, and further that the allocation to h is always slightly more when the K/q value is smaller and the H value is higher. This follows also from Fig. 4 where W_0 increases with increasing values of H and decreasing values of K/q.

The cost-minimizing drain depths as read from Fig. 4 are actually of the order commonly applied in practice. In The Netherlands for example, where drainage systems are designed with standard $H = 0.5$ m and $q = 0.007$ m/day, a normal value for K is 0.7 m/day, which gives $K/q = 100$. Drains are commonly installed at a depth $W = 1.0$–1.2 m, which agrees well with the W_0 depths in Fig. 4. The same applies for drainage for salinity control, where drain depths are often in the order of 1.5–2.5 m. This order is indicated in Fig. 4 for $H = 1.0$–1.5 m and $K/q = 100$–200. The shalllow installation depths in Fig. 4 for situations where the impermeable base is at shallow depth, however, are generally not followed in practice. Apart from considerations such as risks of disturbance or

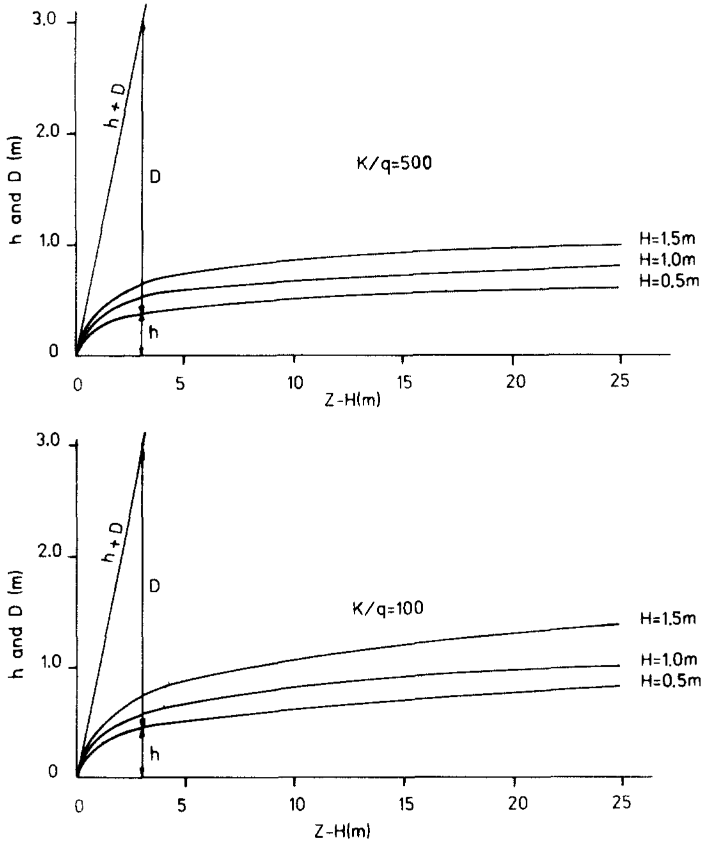

Fig. 5. Water-table head (h) and depth of impermeable base below drainage (D) for drains installed at cost-minimizing depth (W_0).

damage, and penetration by roots when installed at shallow depths, the most important reason to opt for installation deeper than the cost-minimizing depth is that the drainage flow to the pipes stops when the water table has fallen to drain depth. Deep installation therefore guarantees more regular and more continuous discharge, and less risk of silting up of the drains. Deep installation also creates additional storage for the next period with excess water, so the peak design discharge can thereby be reduced. In drainage for salinity control in irrigated areas, drains must be deep enough to stop intermittent salinization by capillary flow between irrigations or during fallow periods. Local conditions (soil layering, outlet conditions, etc.) may of course also have a decisive influence on the choice of the installation depth.

REFERENCES

Acharya, H.S. and Holsambre, D.G., 1982. Optimum depth and spacing of subsurface drains. J. Irr. Drain. Div. Proc. ASCE, 108(IR1): 77–80.

Bhattacharya, A.K. and Broughton, R.S., 1978. Optimization of subsurface drainage system. J. Agric. Eng. Indian Soc. Agric. Eng., 15: 6-10.

Christopher, J.N. and Winger, Jr., R.J., 1975. Economical drain depth for irrigated areas. In: Proc. Speciality Conf.August, ASCE Irrigation and Drainage Division, pp. 264-272.

Dunford, D.S., Podmore, T.H. and Richardson, E.V., 1984. Optimal drain design for arid irrigated areas. Trans. ASAE, 27: 1100-1105.

Hooghoudt, S.B., 1940. Bijdragen tot de kennis van enige natuurkundige grootheden van de grond (Contribution to knowledge concerning some physical properties of the soil), 7. Versl. Landbouwk. Onderz., 46: 515-707.

Kraft, L.E., 1978. Economics and performance advantages of shallow drains. Paper presented at the ASAE Winter Meeting.

Smedema, L.K. and Rycroft, D.W., 1983. Land Drainage. Batsford, London, 288 p.

Wiser, E.H., Ward, R.C. and Link, D.A., 1973. Optimized design of a subsurface drainage system. Trans. ASAE, 17: 175-178.